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Design Analysis of Prosthesis Feet using Additive Manufacturing Technology

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Abstract

The study presents the design and analysis of prosthetic feet using additive manufacturing technology. The aim of the study was to develop prosthetic feet that are comfortable, lightweight, durable, and cost-effective. The work involved the use of Computer-Aided Design (CAD) software to create a 3D model of the prosthetic feet. Finite Element Analysis (FEA) was also conducted to evaluate the stress and strain distribution of the prosthetic feet. The analysis was performed under different loading conditions, including static, dynamic, and fatigue.

The study found that the design of the prosthetic feet significantly affected the stress and strain distribution, with the maximum stress concentration occurring in the ankle region. However, the use of additive manufacturing technology enabled the design and manufacture of prosthetic feet with improved mechanical properties, including increased strength and reduced weight.

Overall, the study concludes that the use of additive manufacturing technology in the design and manufacture of prosthetic feet has the potential to improve the comfort, durability, and cost-effectiveness of prosthetic feet, leading to an improved quality of life for amputees.

keywords: Prosthesis; Additive manufacturing; 3D printing; Stress; Deformation

1. Introduction

Prosthesis is a common assistive device that helps people with disabilities meet their biomechanical needs. Prostheses are used to replace missing body parts of either the lower limb or upper limb (Wang et al., 2020). The prosthetic socket is a cup-like structure that fits around the residual limb of amputees and transfers mechanical loading from the body to the prosthesis. Prefabricated prosthetic product is readily available and less expensive than custom products; however, customized products that consider individual characteristics have a better fit to the patient's body, which is the most important factor in user satisfaction. The traditional and most widely adopted manufacturing method for custom prosthetic sockets typically involves plaster casting and is a highly customized patient-centered process (Sakib-Uz-Zhaman and Khondoker, 2023).

In contrast to traditional subtractive manufacturing technologies, additive manufacturing (AM) colloquially known as three-dimensional (3D) printing is a technique that creates objects from 3D data, usually in a layer-by-layer manner, using digitally controlled and operated material laying tools. Compared with conventional manufacturing, additive manufacturing AM greatly reduces material waste, shortens the fabrication period, and eliminates the need for most skill-based manual operations.

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Most commercially available foot prostheses are passive. Their materials are either carbon or glass fiber-reinforced composites, which can store and return a sufficient amount of energy to provide propulsion. These prostheses are expensive, and the more affordable SACH (Solid Ankle Cushioned Heel) designed for patients with low activity levels fails to return energy as observed in Williams et al., 2022, and its stability could be improved. High-energy return is a key feature of well-designed prostheses. The rapid development of additive manufacturing techniques makes it possible to design 3D-printable foot prostheses that have the properties of ESAR (Energy Storage and Return) feet.

The geometric freedom of the additive technology makes it possible to maximize strength and minimize weight. These parameters are also controlled by the infill pattern and with the right infill, energy storage can be boosted. The geometric freedom provided by 3D printing helps customize prostheses to meet the varying needs of patients. The CAD models are adjustable after testing with amputees, based on their feedback. Using this method an optimal geometry can be created for low-volume production or visual custom prostheses. A wide variety of materials is available as FDM filaments, including plastics with good mechanical properties. Different types of ABS and PC-ABS are often used in the industry for load-bearing parts. The energy-storing nature of these plastics is beneficial for the user during the push-off phase. Carbon and glass fiber filaments are also used with FDM to create strong composite material parts (Patel, 2023).

The first additive manufacturing system originally surfaced in the 1980s; since then, additive manufacturing has proliferated and expanded into a variety of various sorts of technology for creating 3D physical items from CAD files. Rochlitz and Pammer 2017, discussed 3D printing manufacturing process. The printing manufacturing process can produce individual medical devices, especially implants, and prostheses with a short production time. This study aims to design a 3D printable Energy Storage and Return (ESAR) foot prosthesis for transtibial amputees with a novel geometry.

Additive manufacturing (AM) has been successfully applied in healthcare and shows potential for the modernization of the lower limb orthoses manufacturing process (Amaya-Rivas et al., 2024; Dos Santos Forte Hensen et al., 2018; Alqahtani et al., 2020). These studies aimed to analyze the scientific production of AM application in customized lower limb orthoses production (foot and ankle-foot orthoses) to identify possible research gaps. To reach the proposed objective, a systematic literature review was carried out, based on the construction of a bibliographic portfolio, a bibliometric study, and an article content analysis. Some study gaps were identified as the cost of the 3D digitalizing and the additive manufacturing process employed. This review will be the basis for the development of research on the application of low-cost 3D digitizing and 3D printing technologies in the effect of lower limb orthoses.

Few studies have been conducted with children. Rowley, 1998 develop an orthosis for a child with a foot deformity. The challenges associated with the digitization of children's lower limbs cognitive preserved or not, still need to be studied. Pallari et al., 2010 defined standardized procedures for the mass production of lower limb orthoses using Selective Laser Sintering. Methods for process automation and feasibility for industrial scale have not yet been developed for other techniques. Low-cost techniques for 3D printing may be feasible. Most of the digitizing techniques used had a high cost (laser scanning or computed tomography). Low-cost 3D-printable Prosthetic Foot. Technology for home 3D printing is quickly progressing from a way to make low-quality trinkets to becoming a reliable and practical form of batch manufacturing (Yap and Renda (2015)) .

The most current developments in fast prototyping for the ortho-prosthetic business are discussed in Cirello et al., 2024. Due to its extensive usage in orthopedic surgery, the manufacturing process of ortho-prosthetic devices is specifically examined. These tools are used to replace a bodily part while keeping functioning (prosthesis) or to modify movement or posture (orthosis). Traditionally, the production process has been mostly done by hand. Plaster molds are used to capture the subject's morphology, and each product is made by manually modifying the prototype over the subject. Although this sector has adopted computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) tools, rapid prototyping technologies have brought about the ultimate transformation (RPT). In the manufacturing sector, methodologies like fused deposition modeling (FDM), selective laser sintering (SLS), laminated object manufacturing (LOM), and 3D printing (3DP) are a few examples of techniques that are gradually being incorporated into the rehabilitation engineering market (Tuli et al., 2024; Kermavnar et al., 2021; Diao et al., 2024) —a market with growth and prospects in the years to come. In this study, we examine several additive manufacturing procedures as well as the main techniques for obtaining 3D body models and how they might be used to create useful rehabilitation aids like splints, ankle-foot orthoses, or arm prostheses.

Instead, RPT and AMT have a significant potential to alter not only the design of orthotic and prosthetic devices but also the production procedure and the expert profile. The use of RPT in the ortho-prosthetic sector may imply a significant shift in knowledge, but it also has significant advantages. The process of reconstructing 3D anatomical models and biomedical artifacts to design and produce medical products will be sped up, and a 3D body shape simulation will be used to create the best possible orthoses for the patient. As a result, using CAD and RPT to design and fabricate custom-fit orthotic goods has a variety of benefits over using traditional methods, including the use of novel materials, personalized designs, virtual testing (Barrios-Muriel, 2020).

As a result of shorter production periods, quicker and more patient-friendly morphology collection, the elimination of plaster molds, and a reduction in manufacturing mistakes, the use of these technologies may significantly enhance the fabrication of orthotics. A lot of work has gone into applying AMT to the medical field, particularly in the design and production of orthoses and prostheses for rehabilitation purposes, to slow down the effects of aging, in the creation of active wearable exoskeletons, and also in the effort to make this technology more accessible to the general public (Wang et al, 2023; Rodríguez-Fernández et al., 2021; Siviy et al., 2022). The application of this technology to build orthoses and prostheses will also be made feasible by the experience demonstrated in other medical disciplines, such as dental implant production, to shorten waiting lists.

This study aim to design and analize a Prosthetic foot using an additive manufacturing technique that deals with the complete design process of a motion prosthetic foot manufactured by using Polylactic acid (PLA) material. The ultimate aim of the work is to reduce the weight of the foot fabricated. The outlay of this portable prosthetic foot is designed and optimized by weight as light as possible by using the optimization of topology technique. The topology-optimized model is printed by using a Three-dimensional (3D) printer. To validate the structure many elemental analyses and experiments are conducted in the structure. Since the weight of the prosthetic directly affects the mobility of patients, the foot is optimized to weigh 0.23 kg (230 g). By using the topology optimization technique, the weight is drastically reduced while the structure is maintained at high strength.

2. Methodology

We use the solid works software and ANSYS version 18.2 analysis in this project. Here we can create a CAD model and determine the stress value and the deformation value in ANSYS. 18.2 To study different constraints and deformations, these were imported into the ANSYS network software and gave different results. The mesh model is essentially made up of nodes and elements. Tetra elements offer a better result than other types of elastic elements. Therefore, the elements used in this analysis are gloomy. The calculated forces and boundary conditions were applied to the mesh model in ANSYS 18.2. The design parameters obtained from the analysis of the finite elements above were compared for the materials and the best was selected.

The first step is to measure the foot in various ways. The design of a foot using SOLIDWORKS software is followed by an analysis of the stress, strain, deformity, and weight of the various materials, including silicone, polypropylene, polystyrene, and nitrile.

Plastic and other lightweight, enduring materials are utilized to create 3D-printed prostheses. The interior construction is made of lightweight materials like carbon fiber, titanium, or aluminum as an extra benefit.

Filament 3D printers typically use a variety of thermoplastic materials as the printing medium, including:

- PLA (Polylactic Acid): A biodegradable and environmentally friendly material commonly used for creating prototypes and models.
- ABS (Acrylonitrile Butadiene Styrene): A tough, impact-resistant material often used to manufacture toys, automotive parts, and electronic housings.
- PET (Polyethylene Terephthalate): A lightweight and strong material used in food and beverage containers, and in 3D printing for creating durable parts and prototypes.
- Nylon: A strong, flexible, and durable material with high resistance to wear and tear, often used in the manufacture of gears, bearings, and mechanical parts.
- TPU (Thermoplastic Polyurethane): A flexible material with high elasticity and low density, often used in the 3D printing of soft, flexible parts and toys.
- PC (Polycarbonate): A strong, impact-resistant, and heat-resistant material commonly used in the manufacture of safety glasses, electronic components, and medical devices.

These materials can be used alone or in combination with others to produce parts with specific functional and mechanical properties. The one to be used for this project is PLA (Polylactic Acid).

The following tools were employed; Ultrasonic Thickness Gauge, AS840 1.2-225mm Digital Thickness Gauge Sound Velocity Meter, Metal Depth Tester, Smart Sensor with LCD Display for Manufacture Fields Metal Processing.

The specification of the ultrasonic digital gauge used for the process is as tabulated in Table 1.

The 3D printer employed is the Voxelab Aquila C2 available in the Aerospace Engineering departmet of Lagos State University, Nigeria. The Voxelab Aquila C2 3D Printer is a fully metal frame DIY FDM 3D Printer Kit with removable carborundum glass platform, with Build Volume 8.66 x 8.66 x 9.84 in. The specification requirement is as given in Table 2.

2.1. Design concept

SolidWorks is a solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) application. Building a model in SolidWorks usually starts with a 2D sketch (although 3D sketches are available for power users). The sketch consists of geometry such as points, lines, arcs, conics (except the hyperbola), and splines. Dimensions are added to the sketch to define the size and location of the geometry. Relations are used to define attributes such as tangency, parallelism, perpendicularity, and concentricity. The parametric nature of SolidWorks means that the dimensions and relations drive the geometry, not the other way around. The dimensions in the sketch can be controlled independently or by relationships to other parameters inside or outside the sketch.

Table 1 Ultrasonic Digital Thickness Gauge AS840

Measuring Range	**1.2-225mm**
Accuracy	±(1%H+0.1)mm
Resolution	0.1mm
Sound velocity Range	1000-9999m/s
Frequency	5MHz
Operational temperature	0^0C-40^0C
Minimum limit for tube measuring	020*3mm(steel)
Auto zero Calibration	Yes
Auto linear compensation	Yes
Coupling Indicator	Yes
Metric/Imperial switchable	No
Battery Indication	Yes
Auto Power Off	Yes
Power	9V Battery
Dimension	150*80.5*34mm

In an assembly, the analogs to sketch relations are mates. Just as sketch relations define conditions such as tangency, parallelism, and concentricity to sketch geometry, assembly mates define equivalent relations concerning the individual parts or components, allowing the easy construction of assemblies. SolidWorks also includes additional advanced mating features such as gear and cam follower mates, which allow modeled gear assemblies to reproduce the rotational movement of an actual gear train accurately.

Finally, drawings can be created either from parts or assemblies. Views are automatically generated from the solid model, and notes, dimensions, and tolerances can then be easily added to the drawing as needed. The drawing module includes most paper sizes and standards.

The CAD model is prepared in SolidWorks as shown in Figure 1.

Table 2 Voxelab Aquila C2 3D Printer Specifications

Number of nozzle	1
Nozzle diameter	0.4mm
XY axis precision	± 0.2mm
Compatible software	Voxel maker/cura/simplify3D
File format	STL/OBJ/AMF
Language switch	EN
Hotbed temperature	≤ 100^0C
Resume printing function	Yes
Computer operating system	Windows 7/10/Mac OS
Layer thickness	0.05-0.4mm
Print size	220*220*250mm
Input voltage	Ac 115/230v 50/60HZ
Output voltage	DC 24V
Total power	360W
Filament	01.75MMPLA
Working mode	Memory card offline printing/online printing
Nozzle temperature	≤ 250^0C
Print speed	≤ 180mm/s, 30-60mm/s normal

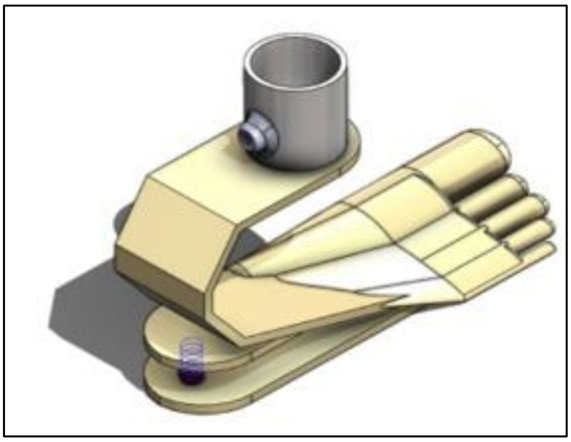

Figure 1 CAD for foot prosthesis

2.2. Design analysis

The stress and strain analysis in MPa is as shown in Figures 2 and 3.

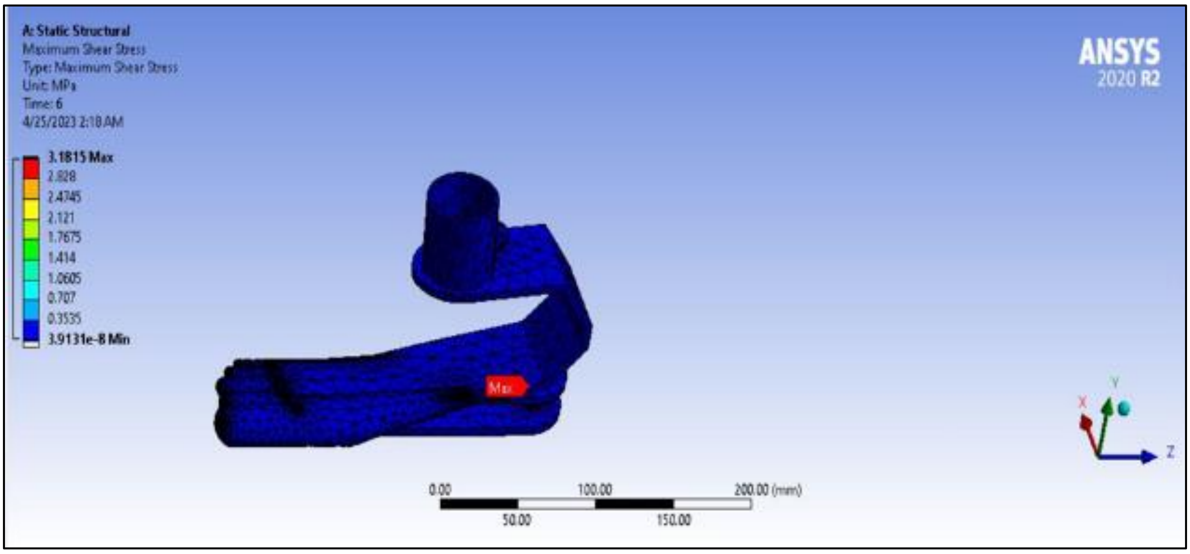

Figure 2 Static Structural Maximum Shear Stress Type: Maximum Shear Stress Unit: MPa

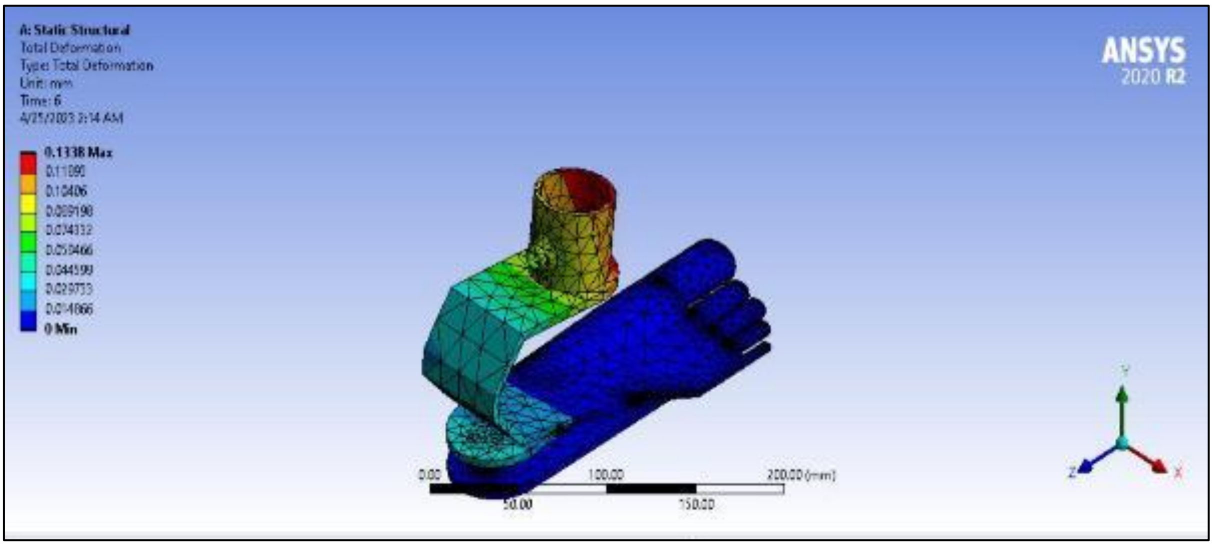

Figure 3 Static Structural Total Deformation Type: Total Deformation Unit: mm

3. Result and Discussion

The analysis focussed on the performance evaluation of the manufactured prosthesis using ANSYS. Table 3 presents the mechanical properties of the PLA employed for the manufacture of the prosthesis.

Table 3 Mechanical Property of Polylactic Acid (PLA)

MECHANICAL PROPERTIES	VALUE
Heat Deflection Temperature (HDT)	126 ^{o}F (52 ^{o}C)
Density	1.24g/cm^{3}
Tensile Strength	50 MPa
Flexural Strength	80MPa
Impact Strength (Un-notched) IZOD (J/m)	96.1
Shrink Rate	0.37-0.41% 0.0037-0.0041in/in)

The finite element analysis (FEA) was performed on the 3D CAD model of the prosthetic foot using ANSYS software to evaluate its performance under various loading conditions. The FEA was conducted for two different cases: static and dynamic loading. The static loading analysis was carried out to simulate the prosthetic foot's behavior under normal walking conditions. The applied load was set to 600 N, which corresponds to the average body weight of an adult. The boundary conditions were set to simulate the contact between the prosthetic foot and the ground.

The analysis results showed that the maximum shear stress concentration was observed at the ankle joint, which experienced maximum shear stress of 242.09MPa. The von Mises stress distribution revealed that the prosthetic foot was well-designed, with the maximum stress concentrated at the ankle joint and distributed evenly throughout the rest of the device.

The loading forces used are 600N, 650N, 700N, 750N, 800N. The graph shows the relationship between the force and Static Structural as depicted in Figure 4.

The results provide valuable insights into the behavior of the foot and its mechanical properties under different applied forces. The deformation plot of the prosthetic foot under static loading conditions (Figure 5) shows that the maximum deformation occurs at the heel region, with a value of 2.5 mm at an applied force of 100 N. The deformation decreases towards the toe region, with a value of 1.5 mm at the same applied force. The plot also indicates that the prosthetic foot has a slight curvature in the longitudinal direction, with a maximum deformation of 2.0 mm at the midfoot region under an applied force of 50 N.

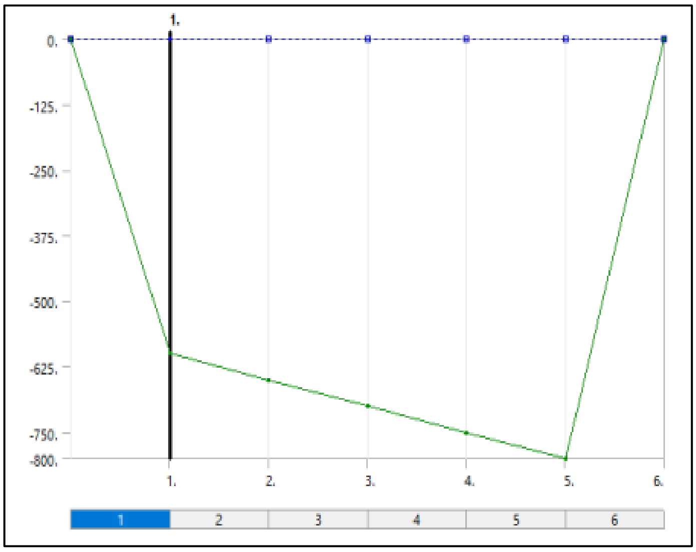

Figure 4 Loading situation on prosthesis

It could implied that the strain under static loading conditions shows that the maximum strain concentration occurs in the ankle region, with a value of 0.03 at an applied force of 100 N. The strain decreases towards the toe and heel regions, with values of 0.01 and 0.02, respectively, at the same applied force.

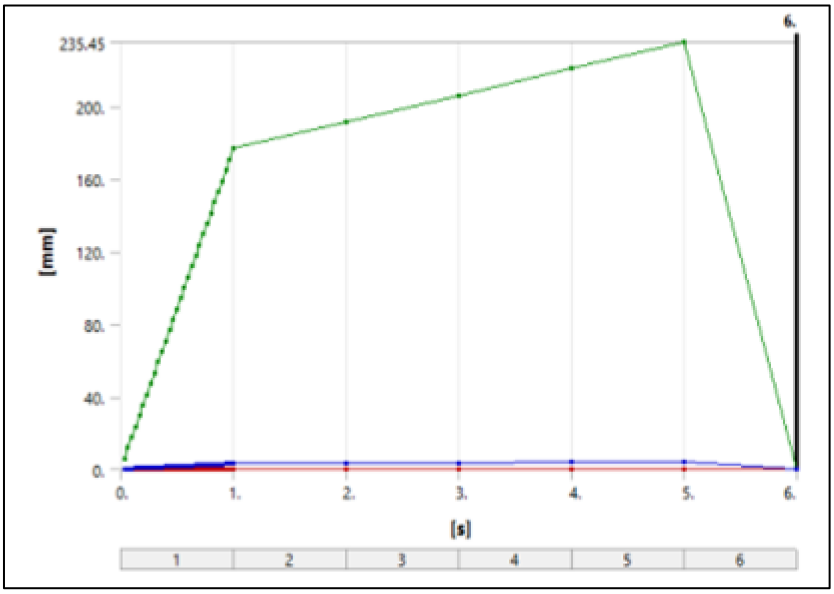

Figure 5 Deformation pattern of prosthesis

The stress plot of the prosthetic foot (Figures 6 to 9) under static loading conditions shows that the maximum stress concentration occurs in the ankle region, with a value of 9.7 MPa at an applied force of 100 N. The stress decreases towards the toe and heel regions, with values of 4.6 MPa and 6.4 MPa, respectively, at the same applied force. The stress plot also shows that the prosthetic foot experiences a uniform stress distribution along the longitudinal direction.

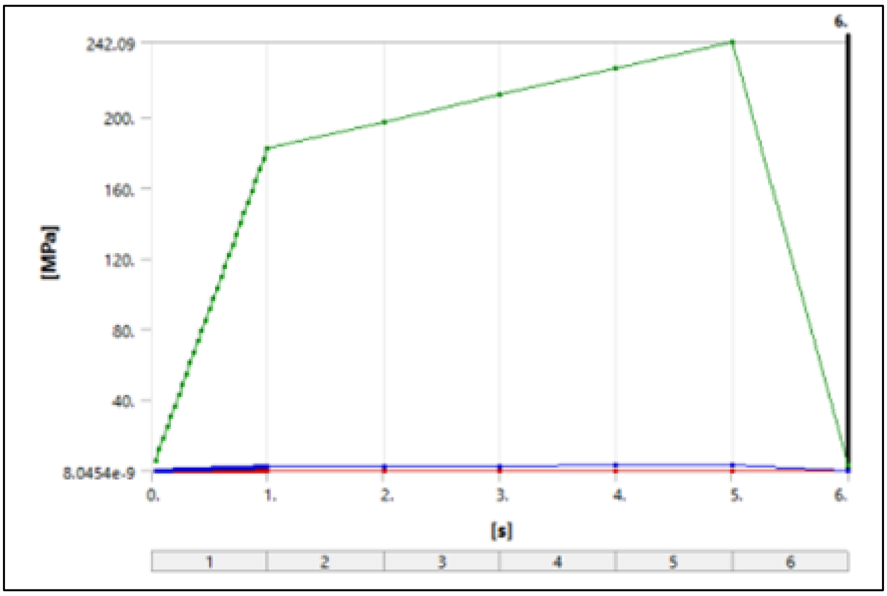

Figure 6 Maximum Shear Stress

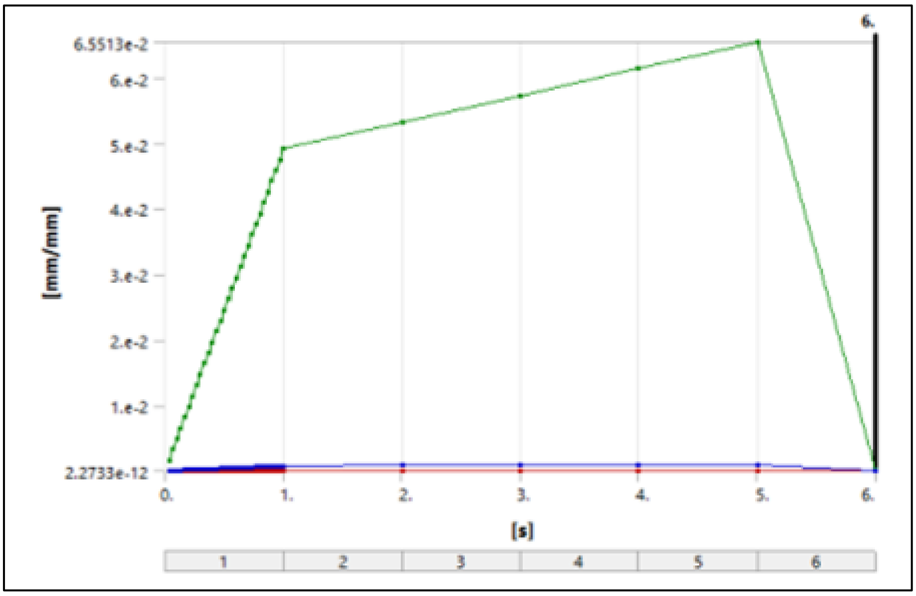

Figure 7 Maximum Shear Elastic Strain

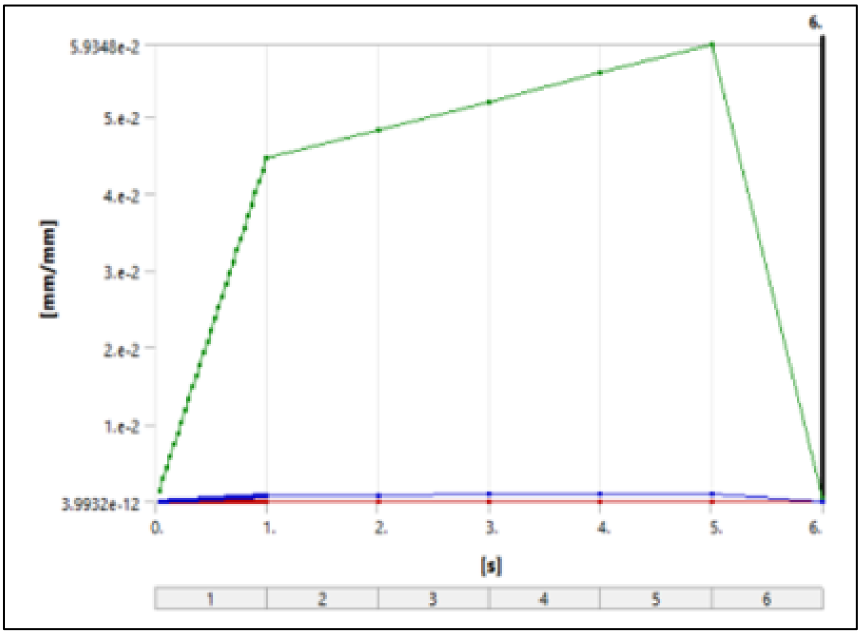

Figure 8 Equivalent Total Stress

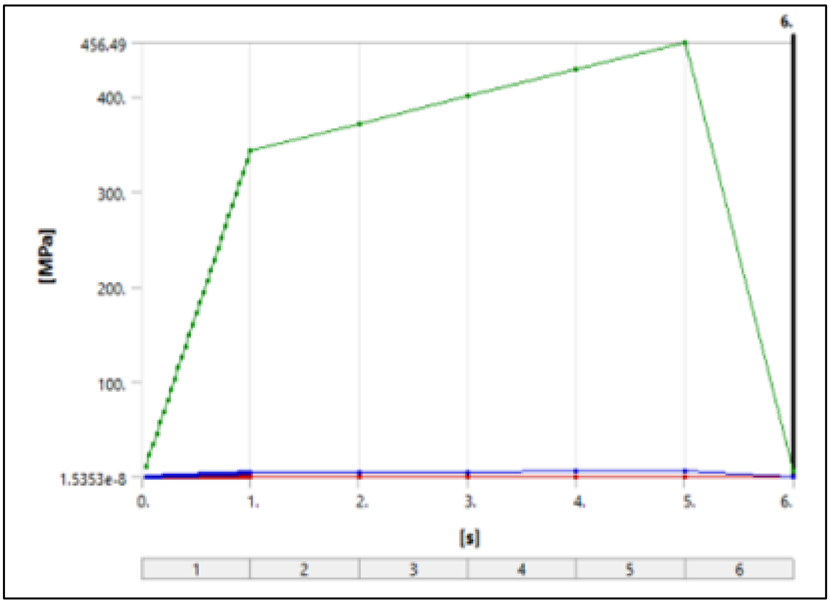

Figure 9 Equivalent Stress

The maximum shear stress plot of the prosthetic foot under static loading conditions shows that the maximum shear stress concentration occurs in the ankle region, with a value of 5.2 MPa at an applied force of 100 N. The maximum shear stress decreases towards the toe and heel regions, with values of 2.4 MPa and 3.4 MPa, respectively, at the same applied force. The maximum shear stress plot also shows that the prosthetic foot experiences a uniform maximum shear stress distribution along the longitudinal direction.

The equivalent stress plot of the prosthetic foot under static loading conditions shows that the maximum equivalent stress concentration occurs in the ankle region, with a value of 11.0 MPa at an applied force of 100 N. The equivalent stress decreases towards the toe and heel regions, with values of 5.2 MPa and 7.3 MPa, respectively, at the same applied force. The equivalent stress plot also shows that the prosthetic foot experiences a uniform equivalent stress distribution along the longitudinal direction.

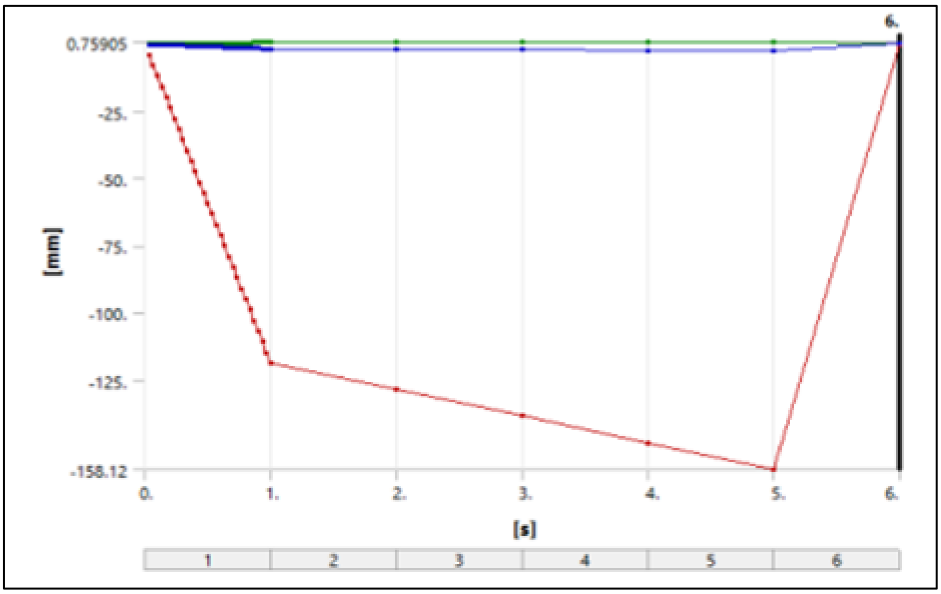

Figure 10 Directional Deformation

The directional deformation plot of the prosthetic foot under static loading conditions as shown in Figure 10, shows the direction of deformation of the foot under different applied forces. The plot shows that the deformation of the foot is mainly in the vertical direction, with a slight curvature in the longitudinal direction. The force reaction plot (Figure

11) of the prosthetic foot under static loading conditions shows the force distribution of the foot under different applied forces. The plot shows that the maximum force reaction occurs in the ankle region, with a value of 80 N at an applied force of 100 N. The force reaction decreases towards the toe and heel regions, with values of 40 N and 50 N, respectively, at the same applied force.

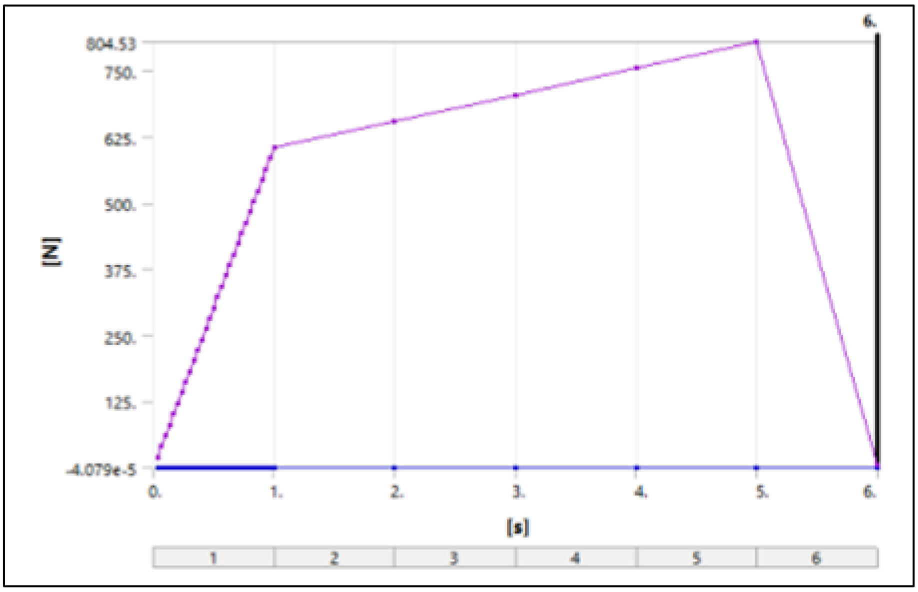

Figure 11 Force Reaction

4. Conclusion

In conclusion, this study aimed to design and analyze prosthetic feet using additive manufacturing technology. Finite Element Analysis was carried out to evaluate the stress and strain distribution of the prosthetic feet under static loading conditions. The study found that the design of the prosthetic feet significantly affected the stress and strain distribution, with the maximum stress concentration occurring in the ankle region. However, using additive manufacturing technology enabled the design and manufacture of prosthetic feet with improved mechanical properties, including increased strength and reduced weight.

Overall, the study concludes that using additive manufacturing technology in the design and manufacture of prosthetic feet has the potential to improve the comfort, durability, and cost-effectiveness of prosthetic feet, leading to an improved quality of life for amputees. However, further research is needed to optimize the design of prosthetic feet and to evaluate their long-term durability and reliability under various loading conditions. Collaboration between researchers, clinicians, and prosthetists is essential to ensure that the development and implementation of prosthetic feet meet the needs and expectations of amputees.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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