Journal of Engineering and Sustainable Development
Vol. 30, No. 01, January 2026
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.2850

Comfortable Design of Adjustable Dimension Prosthetic Socket: Finite Element Case Study

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Article Info

Received	17/07/2024
Revised	05/11/2025
Accepted	05/11/2025

Abstract

The prosthetic socket is the primary component of a lower-limb prosthesis and must be replaced when the patient's stump size changes. This study aims to design an adjustable socket that can be adjusted to the required size without manufacturing a new socket. In this study, the model was developed in SolidWorks and analyzed numerically using ANSYS. A tensile and fatigue test was performed for the materials used in manufacturing the socket, as well as an F-Socket test on an amputated person to measure the interface pressure between the stump and the socket to be used as a boundary condition during the numerical analysis process. The results demonstrated key achievements: the model was designed to serve as an alternative to the traditional model, thereby reducing costs in socket manufacturing due to growth or changes in stump size. The results also indicated the feasibility of using carbon fiber filament as an alternative to polypropylene and of employing additive manufacturing instead of the currently expensive methods.

Keywords: Additive manufacturing, Fatigue, Numerical Analysis, Prosthetic, Socket.

1. Introduction

A prosthetic limb is used to compensate for the loss of a limb due to amputation of the upper or lower extremity. Amputation of the limbs occurs due to accidents, diabetes, tumors, or terrorist acts. This study examines the lower prosthetic limb, which consists of three main components: the foot, the pylon, and the socket [1]. It may include a knee joint if the amputation was above the knee. Developing and poor countries face a problem in providing artificial limbs for people with special needs because they are expensive in their countries, as well as in societies whose members are of limited income. Child amputees require frequent adjustments to their prosthetic limbs, particularly the socket, due to ongoing growth and lengthening, thereby increasing maintenance costs. For example, instead of providing an artificial limb every few years for an adult amputee, the need will arise to provide two limbs for an amputee child due to growth, which may make obtaining the limbs difficult due to limited financial resources. Therefore, this study addresses the problem by developing a prosthetic socket that can be adjusted in dimensions and used for extended periods, thereby eliminating the need to manufacture a new socket and incurring additional costs.

Many previous studies have focused on the development of prosthetic sockets. Górski et al. [2] examined the applicability of 3D printing for developing fitted prosthetic sockets. The study focuses on the application of 3D printing for the rapid fabrication of individualized patient sockets, improved comfort, and time savings. Chen et al. [3] focused on dynamic prosthetic socket designs in which the socket can change its configuration based on the user's activity level (walking, running, or standing). McGeehan et al. [4] examined biomechanical optimization strategies for enhancing prosthetic socket configurations. The researchers employed pressure mapping and gait analysis to identify high-stress areas and redesign the sockets. Dickinson et al. [5] described the use of artificial intelligence to enhance prosthetic socket interfaces. Software checked limb scans and pressure data to recommend changes in the individual's position. Kahle et al. [6] examined the effects of prosthetic socket fit on gait and energy cost, employing an experiment in which they recorded users' motion and metabolic rate to assess the impact of ill-fitting sockets. Paternò et al. [7] examined the application of sensor technology in prosthetic sockets to measure pressure and temperature and provide real-time feedback to the amputee and the clinician. Rezvanifar et al. [8] demonstrated the use of improved materials for prosthetic socket linings to enhance thermal control. The study also shows that, to enhance user comfort, particularly when the device is worn for extended periods, heat accumulation must be controlled. Dickinson et al. [9] established a relationship between changes in residual limb volume and the socket fit and comfort of the prosthesis user. In the study, the researchers observed diurnal variations in limb volume and sought strategies to modify the socket. Vennam et al. [10] applied patient-specific 3D modeling to create prosthetic sockets that fit the patient's body well, thereby eliminating pressure points that cause discomfort. Amudhan et al. [11] assessed the application of suction systems in prosthetic socket architectures to minimize mobility between the socket and the residual limb. Xie et al. [12] focus on the application of adjustable liners to fit prosthetic sockets, addressing volume changes in residual limbs and user comfort. Hoque et al. [13] explore various materials used in the construction of prosthetic sockets, with an emphasis on their comfort, flexibility, and durability.

Turner et al. [14] examined the role of psychological perspective in socket fit among prosthetic users to elucidate the psychological effects of discomfort and poor fit. Estillore et al. [15] reviewed the application of prosthetic sockets incorporating both soft and rigid materials, which may provide optimal comfort and stability. Bombek et al. [16] aim to establish the applicability of carbon fiber composites for the fabrication of prosthetic sockets, with emphasis on strength-to-weight ratio and durability. Carbon fiber is famous for its lightweight and very high tensile strength and, therefore, is a proper fit for prosthetic uses. Kadhim et al. [17] discuss the development of new hybrid composite materials in which carbon fiber is incorporated with flexible polymers to achieve both rigidity and flexibility in prosthetic sockets.

In previous studies, the idea was not mentioned. This study aims to design and analyze an adjustable prosthetic socket that allows the dimensions to be adjusted to match the patient's stump. Also, to manufacture the prosthetic socket using additive manufacturing technology, which is cost-effective.

In traditional prosthetics, polypropylene is used to manufacture the socket. The process of manufacturing the socket from polypropylene, with the advancement of technology, has become expensive in terms of time and material, as the manufacturing steps include casting from gypsum, the casting carving process, the process of pouring polypropylene into the mold, and the process of cutting the socket borders according to Measurements, grinding, and smoothing process of cut edges. Traditional manufacturing steps require a time of two to three days to complete. In this study, the prosthetic socket is planned to be manufactured via additive manufacturing using a 3D printer, and the model is generated by scanning the stump to produce an STL file for printing. It is also low-cost and requires less time to manufacture than the traditional model. The material used to manufacture the socket is carbon fiber filament, characterized by its low density, excellent mechanical properties, and low cost. The process of manufacturing prosthetic sockets using additive manufacturing technology is considered a good development in the field of manufacturing that can contribute to providing sockets more easily, especially in developing country communities, because they will be more available to individuals who suffer from amputation, thus improving their lifestyle through their ability to return to their daily activities. To achieve this study, the following steps will be taken.

2. Materials and Methods

2.1. Design Prosthetic Socket Model

The socket is the part that connects the residual part of the amputation with the parts of the prosthetic limb. The socket is the same shape as the stump because it surrounds it; its shape often resembles an inverted pear. The shape of the traditional socket is connected circumferentially, and its measurements cannot be changed except by manufacturing a new socket. However, in this study, the socket was designed so that it can change its size according to the size of the stump without the need to manufacture a new socket, thus reducing the costs necessary to manufacture a new model If the amputee needs to change the socket to fit the new stump size when growing, such as weight gain or loss, or growth in children. The suggested socket design is shown in Fig. 1.

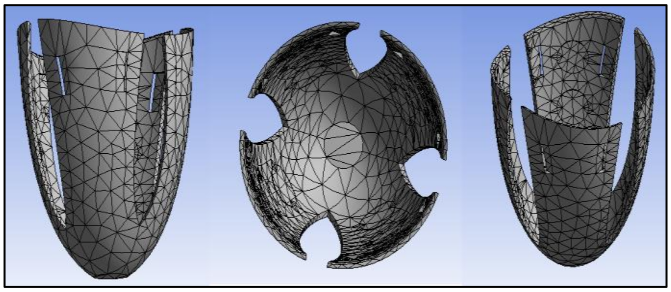

Figure 1. The suggested design of the resizable prosthetic socket model.

2.2. Material Selection

Currently, the socket is made of polypropylene or a composite material. These materials are more expensive and heavier than the material suggested in this study, which is carbon fiber filament. The proposed material is lightweight, inexpensive, and has excellent mechanical properties suitable for this application.

2.3. Material Test

To ensure that the suggested material (carbon fiber filament) is suitable for use in this study, it must be tested to determine its mechanical properties. The tests that will be performed on the material are tensile and fatigue tests. Tensile and fatigue tests were done in the Mechanical Engineering Department at Al-Nahrain University. To perform the tensile test, three tensile samples were printed using a Creality CR-10 3D printer. The dimensions of the samples were measured in accordance with ASTM D-638 [18]. The carbon fiber filament tensile specimen is shown in Fig. 2. The samples were printed at 100% density. For the fatigue test, the samples were printed at 100% density and with dimensions corresponding to the device's standard samples. To compare the mechanical properties of the material proposed in this study (carbon fiber filament) with those of the material currently used in laboratories to manufacture sockets (polypropylene), tensile and fatigue tests were also performed on polypropylene. The dimensions of the tensile and fatigue samples used to test polypropylene are the same as those for carbon fiber samples. The polypropylene tensile specimen is shown in Fig. 3. Tensile testing was performed using a Testometric device, and fatigue testing was performed using a HI-TEICH device.

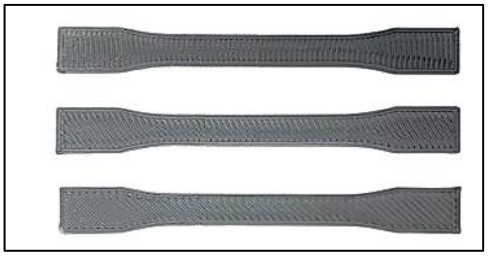

Figure 2. The tensile specimen of carbon fiber filament material.

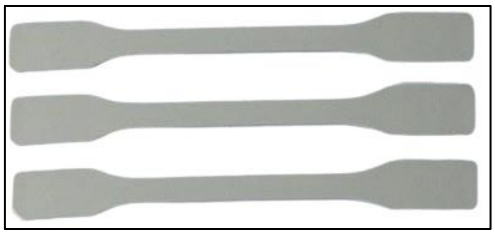

Figure 3. The tensile specimen of polypropylene material.

2.4. F-Socket Test

The purpose of this test is to measure the values of the interface pressure between the stump and the socket. In this study, previously measured interface pressures from an above-knee amputee were applied to the model, which was then analyzed numerically to predict its success or failure before manufacturing and use. To perform the test, place the sensor strip in the socket, positioning it between the stump and the socket. When the amputee wears the socket, an interface pressure is generated between the stump and the socket, as shown in Fig. 4, and is measured in this test. Interface pressure is measured in four directions within the socket: anterior, posterior, medial, and lateral.

Figure 4. The pressure sensor is located in the anterior region of the socket.

2.5. Test The Design Model by Numerical Analysis

To determine whether the socket design is successful, it is necessary to conduct a numerical analysis of the model. In the numerical analysis, the same conditions that the socket experiences when used by an amputee are applied. In this study, the boundary conditions will include applying pressure to the socket walls and fixing the socket at its lower end, as shown in Fig. 5. The pressure on the socket walls is generated by the amputee's weight while wearing the prosthetic. The boundary conditions also include incorporating the results of mechanical tests on carbon fiber filament into the numerical analysis program as input data. Using numerical analysis, the von Mises stress, deformation, and safety factor for the designed model are obtained.

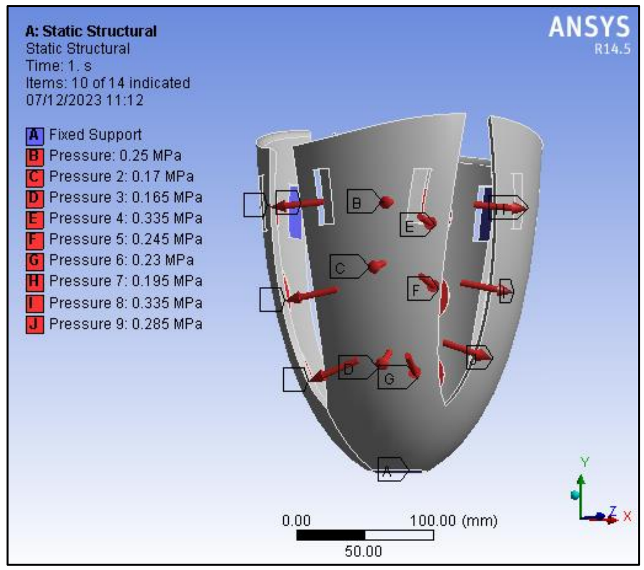

Figure 5. The boundary conditions applied to design the prosthetic model

3. Results and Discussions

Tensile and fatigue tests were conducted on the material proposed in this study (carbon fiber filament) and compared with the traditional material used in socket manufacturing (polypropylene). The stress-strain curves for both tested materials are shown in Fig. 6 and Fig. 7. The results of the fatigue test are shown in Fig. 8 and Fig. 9. The tensile failure specimens of carbon fiber filament and polypropylene material are shown in Fig. 10 and Fig.11. The results can be summarized in Table 1, as follows:

The results indicate that the proposed material for socket manufacturing exhibits superior mechanical properties compared with the traditional material and is lightweight and low-cost.

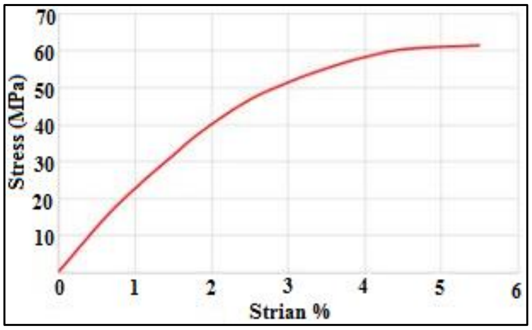

Figure 6. The stress-strain curve of carbon fiber filament material.

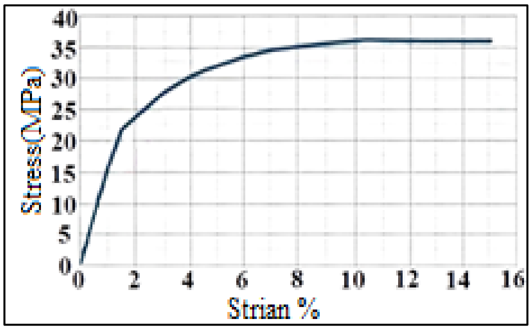

Figure 7. The stress-strain curve of polypropylene material.

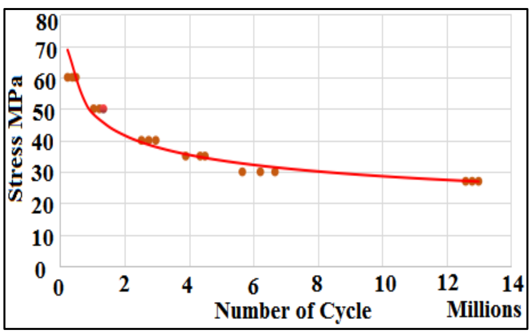

Figure 8. The stress-number of the cycle curve of carbon fiber filament material.

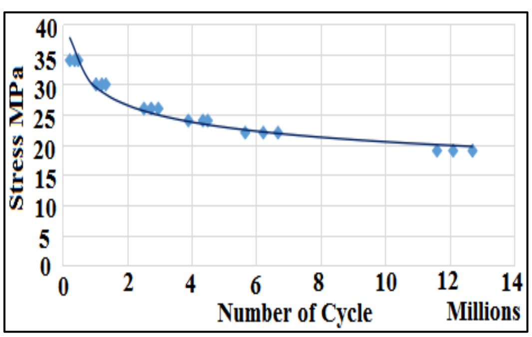

Figure 9. The stress-number of the cycle curve of polypropylene material.

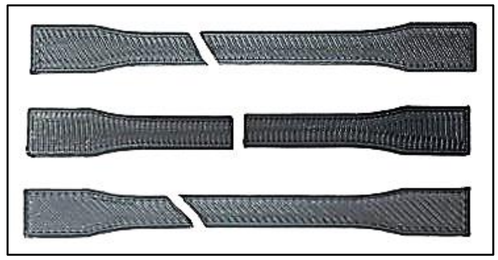

Figure 10. Tensile failure of carbon fiber filament material under spermine.

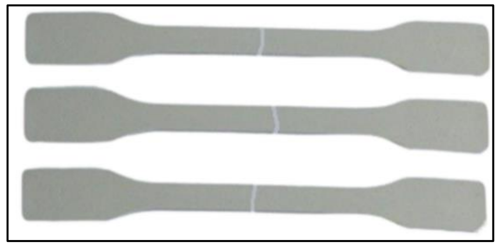

Figure 11. Tensile failure of spermine-treated polypropylene.

Table 1. The results summary of the mechanical tests

Material	Yield stress (MPa)	Ultimate stress (MPa)	Modules of elasticity (GPa)	Endurance stress (MPa)
Carbon fiber filament	46	62	1.82	28
Polypropylene	25.7	36.7	1.21	19

The values of the intervening pressure between the socket and the stump were measured in four directions: anterior, posterior, medial, and lateral. Pressure values over time were obtained for each region; for example, the pressure curve for the middle lateral region is shown in Fig. 12. The pressure values for each area are summarized in Table 2. The interface pressure was applied to the socket as a boundary condition to determine the resulting stresses and deformations, thereby validating the model and the material used in its manufacture.

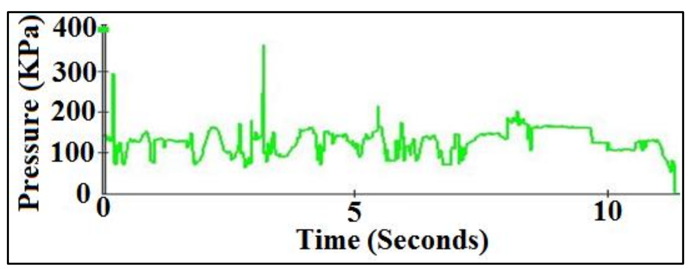

Figure 12. The interface pressure measured values at the middle lateral region of the socket.

Table 2. The interface pressure measured values at all the region sockets

Region	Interface Pressure Distribution (KPa)	Socket Group
	250	Upper
Anterior	170	Middle
	165	lower
	146	Upper
Lateral	115	Middle
	130	lower
	195	Upper
Medial	355	Middle
	285	lower
	335	Upper
Posterior	245	Middle
	230	lower

The numerical analysis results showed that the maximum stress does not exceed the yield stress; the maximum von Mises stress is 16 MPa, as shown in Fig. 13, whereas the yield stress is 62 MPa. This indicates a substantial gap between the two stresses, reinforcing the selection of the carbon fiber filament material in this study and confirming the successful model design .As for the values of the resulting deformations in the stump, while applying the boundary conditions and analyzing them numerically, these deformations occurred as a result of loads being applied to the stump. Fig. 14 shows that the maximum deformation is 3.7 mm, which is considered acceptable to provide patient comfort during movement and to absorb the load applied to the stump .Fig. 15 shows that the safety factor, 1.98, exceeds 1.25, indicating that the designed model is safe from mechanical failure and is technically successful. The fatigue safety factor is considered safe in design if it is equal to or greater than 1.25 [19], [20].

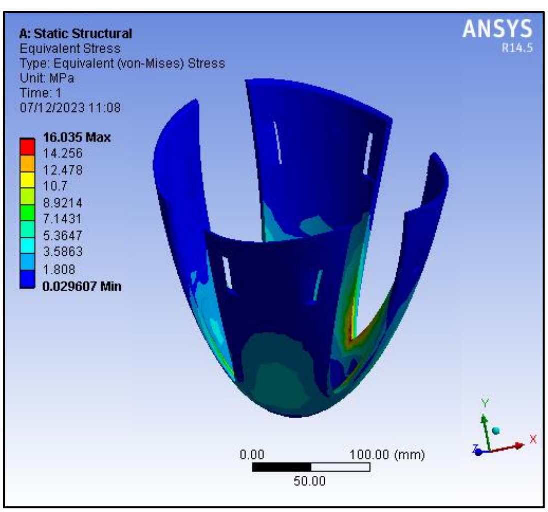

Figure 13. The Von-Mises stress contour for the design socket model.

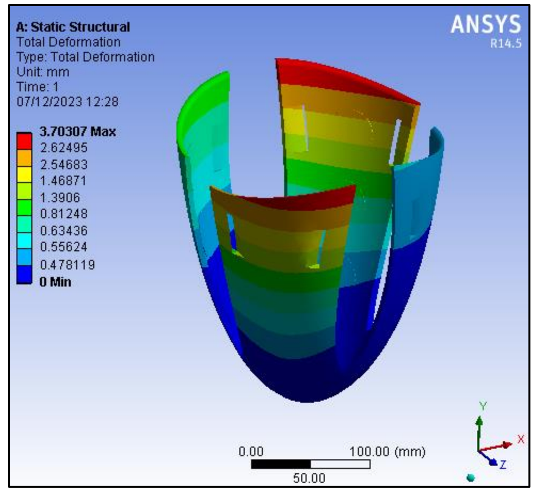

Figure 14. The deformation contour for the design socket model.

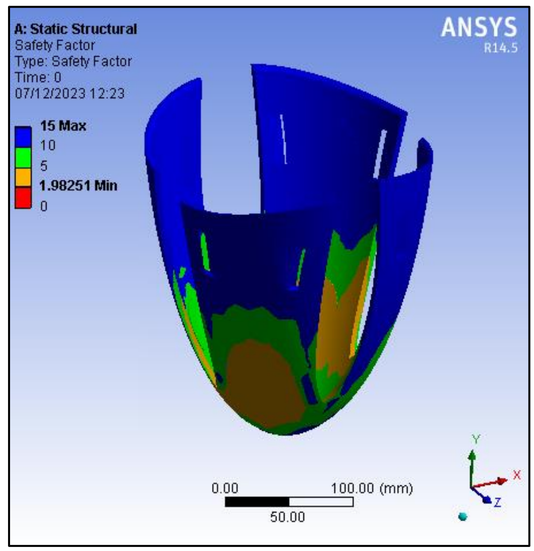

Figure 15. The safety factor contour for the design socket model.

4. Conclusions

The adjustable socket prosthetic design demonstrates favorable performance in withstanding mechanical loads and forces likely encountered during everyday use without structural failure. This confirms that the adjustable components retain their strength under pressure, thereby ensuring long-lasting performance and user safety.

The use of carbon fiber filament in 3D printing offers numerous advantages over conventional polypropylene. Carbon fiber provides high tensile strength and stiffness to the prosthetic, thereby enhancing structural integrity; its low weight enables a low-weight prosthetic. This results in a stronger, more comfortable fabric than polypropylene and provides improved performance and durability.

The model designed for the socket is successful from an engineering standpoint and can be an alternative to the traditional prosthetic socket currently used, especially in poor communities and developing countries because the socket will be able to be resized without the need to manufacture a new when the stump grows for the amputee, especially the category of children who are in a state of continuous growth.

The success of selecting carbon fiber for socket manufacturing will alter the current manufacturing steps and technologies and enable the use of additive manufacturing.

Manufacturing the socket using additive manufacturing technology will save time, reduce the number of technicians required, and eliminate material waste and losses during manufacturing, while producing an accurate, high-quality model.

The mechanical test results showed that carbon fiber exhibits higher and better mechanical properties than polypropylene. The yield stress, ultimate yield stress, and Young's modulus of carbon fiber are 46.3%, 40.8%, and 33.5% higher, respectively, than those of polypropylene.

Conflict of Interest

The author states that no conflicts of interest are involved.

Author Contribution Statement

Fahad Mohanad and Jumaa Salman suggested the research problem.

Fahad Mohanad and Jumaa Salman developed the design and verified the analytical methods.

Fahad Mohanad, Jumaa Salman, and Mujtaba A. Flayyih. discussed the results and contributed to the final manuscript

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