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Static Structural Analysis on Different Topology Optimization Transtibial Prosthetic Socket Leg

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Abstract. The transtibial Prosthetic Socket serves as the primary connection between the residual limb of an amputee and the prosthesis. The socket must provide a secure and stable base for the amputee to bear their body weight and move around comfortably. Topological optimization is a process that aims to improve the mechanical properties of the prosthetic socket. It involves designing a structure that minimizes stress concentrations and maximizes strength while using the least amount of material. The objective of this study is to improve the parametric design of the transtibial socket prosthesis through topology optimization and determine the stress performance of 3D-printed transtibial sockets using static structural analysis. The method used is Finite Element Analysis (FEA) simulations of forces onto the socket during phases of walking on different topology-optimized socket designs and using the same material, which is ABS. Furthermore, the results were analyzed through static structural analysis using ANSYS software. The analysis revealed that a reduction in the weight of the model correlates with an increase in stress thus may contribute to material fatigue and reducing long term performance.

Keywords: FEA; Prosthetic; Static; Topology optimization; Transtibial

1. Introduction

A prosthetic leg socket allows patients who have had a limb amputated below the knee to place their limb inside the socket and link it to the prosthetic leg. It is known as a transtibial socket for a prosthetic leg. Demet *et al.* (2003), patients with lower limb amputations reported a worse quality of life and greater problems integrating into society than the general population. Lower limb prosthesis users have identified the socket as the most important aspect of their overall happiness with their prosthesis. Thus, the primary goal of this project is to ensure that consumers are more comfortable and pleased when wearing their sockets. A study conducted by Iridiastadi, Vani, and Yamin (2020) also affirms that musculoskeletal disorders influenced by abnormal working conditions can be alleviated by providing practitioners with well-designed handling aids.

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Topology optimization and Finite Element Analysis (FEA) will be used to achieve the major aims of this research. Topology optimization is a structural optimization approach for predicting material and load distribution by specifying design parameters. Kentli (2020) Topology optimization provides the optimum material distribution based on stated limitations and preserves zones to achieve superior structural performance.

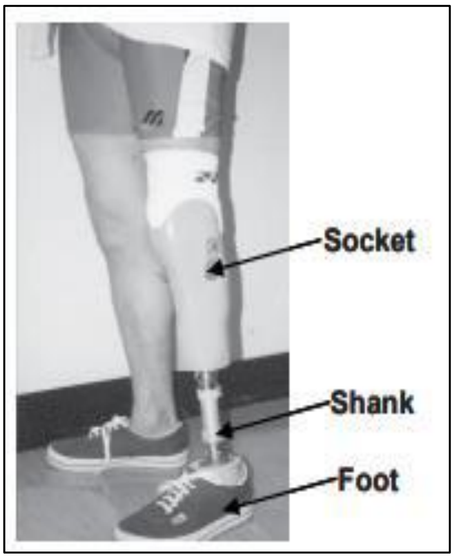


Figure 1 Typical transtibial prosthesis

The Finite Element Method (FEM) is a powerful tool for analyzing the behavior structures of the prosthesis socket to find out the contact pressure between computer-interfaced prostheses. Shankar *et al.* (2020); Faustini *et al.* (2006) FEM were used to look at the designs of compliant features to reduce pressure between the stump and socket. Moreover, FEM plays a crucial role and provides significant benefits in the study conducted by Irsyad *et al.* (2020). This is because FEM allows the analysis of the mechanical integrity of various materials, ensuring the strength of the hub in withstanding the equivalent forces caused by accidental falls and the grip of surgeons.

Similarly, Portnoy *et al.* (2008) made a patient-specific FE parametric biomechanical model of the residual limb that predicts stresses transmitted through the muscle flap by the shin bones during static and dynamic loading. The topology optimization technique is used to find possible structure designs that reduce mass and improve socket performance.

Faustini *et al.* (2006) used topology optimization to find the best compliant features, which they then put into the geometry of the socket. Finite element analysis can be used to generate ideas and provide an overview of the design process, particularly for materials within their yield strength. In this case, the method was applied to a prosthetic socket to replicate how it moved when loaded at the top while leaving the bottom surface unchanged. The consistency of the FEA was demonstrated by considering four factors: the geometry, the mesh, the material properties, and the boundary conditions. The results of the FEA provide valuable insights into the design and customization of prosthetic sockets.

Integration of new technology can make a big difference in how the socket is designed and analyzed, and 3D printing technology has significantly impacted the production of transtibial sockets. Whulanza *et al.* (2020) has different logical assumptions about this process, only that it cannot produce millions of quantities in a shorter time. In spite of that, 3D printing can create these sockets at a faster production time (but low quantity), easier customization, lower costs, and improved performance. Based on Walker *et al.*, (2020), the stump's complex shape and the fact that it is different for each amputee make it hard to design prosthesis sockets. The prosthetist chooses the best socket design based on the condition of the patient's skin and where the missing limb is Peery, Ledoux, and Klute (2005). The main way to make the patient feel better is to reduce the pressure between the stump and socket and reduce the temperature surrounding the stump.

Hence, new designs are being constructed to reduce pressure and the temperature surrounding the stump for the patient's comfort. Dakhil *et al.* (2020) states that topology optimization is a design method that aims to minimize the size of a structure while maintaining its strength. Geometry reduction of the socket influences the stress distribution of the socket, which ultimately improves performance and comfortability.

For the static analysis of the transtibial socket, it was assumed that the mechanical properties of the liner, bones, and socket were linear, elastic, isotropic, and homogeneous. According to Zachariah and Sanders (2000), the strength and durability of prosthetic components are evaluated using the ISO 10328 test standard, which provides guidelines for static proof, ultimate strength, and cycle testing as three distinct tests.

The Ansys program, which enables the simulated test forces to be applied at a rate of 100 N/s, is used to conduct all experiments. The maximum loading at various points of the walking cycle is related to the test loading configurations (I and II) mentioned in the standard. The maximum loading during the early stance phase of walking is related to Configuration I, while the maximum loading during the late stance phase is related to Configuration II. Neo, Lee, and Goh (2000) Figure 2 shows the model for the transtibial leg.

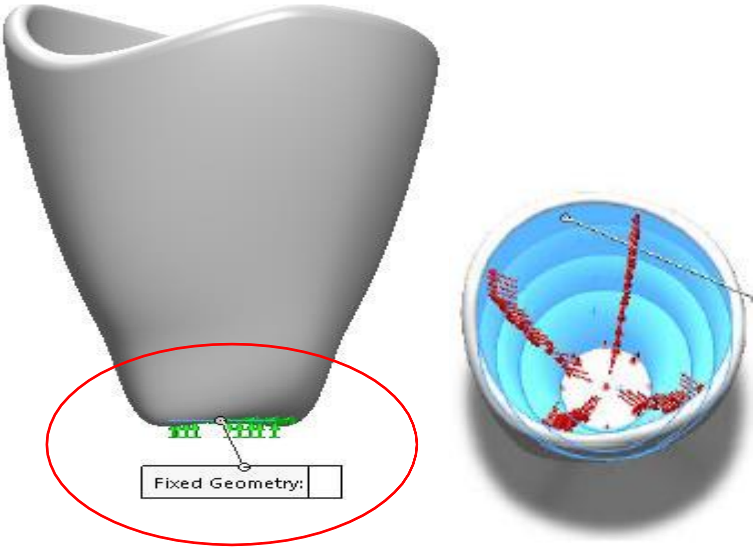


Figure 2 A model for transtibial leg

2. Methods

2.1. 3D Scanning

The patient’s limb was 3D scanned using Sense3D Scanner, as shown in Figure 3, to get the geometric shape of the limb to make sure the device is a perfect fit for the patient, thus giving better ergonomic and patient-specific value. Then, 3D scanning was converted into a 3D model, and Solidworks software was used to run a few analyses, such as topology optimization and FEA.

Figure 3 3D scanning process of patient's limb

2.2 Topology Optimization

The topology design of the transtibial socket model was optimized by reducing the weight, resulting in the creation of 5 different optimized sockets, as illustrated in Figure 4.

(a) Design 1 (b) Design 2

(c) Design 3 (d) Design 4

(e) Design 5

Figure 4 Topology Optimized Designs

2.3 Analysis Method

The static structural analysis ignores inertia and damping effects. The project analyzed 5 different model designs based on the weight reduction achieved through the topology optimization of the transtibial socket using the same material, which is ABS. The criteria considered for analysis include stress analysis, safety factors, and weight ratio. Stress analysis, safety factors and weight ratio are the criteria to be considered.

3. Results and Discussion

3.1. Static Structural Analysis

3.1.1. Weight of the socket

From the topology optimization process of the transtibial socket, the weight is reduced for each design. Thus, each design does not have the same weight. The weight reduction of the transtibial socket range is between 10% and 21% for each design, as shown in Figure 5. Design 4 has the highest weight percentage of reduction, which is 74.22%.

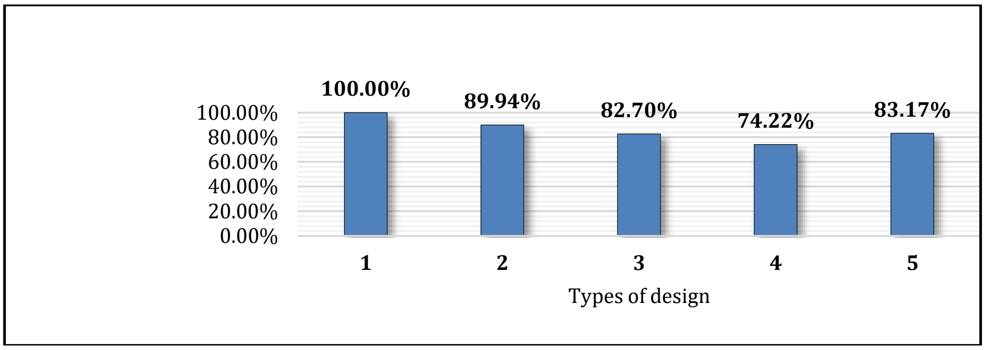
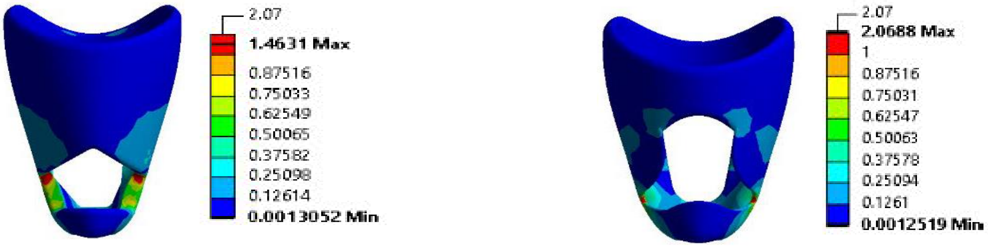


Figure 5 Weight percentage of the socket after redesigning with topology process

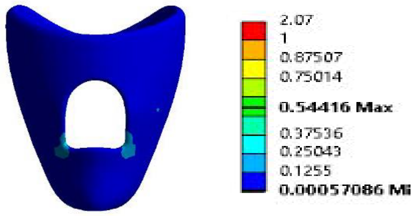
3.1.2. Stress distribution on the socket

The strength of the socket is based on the material selection and the design itself. The material used in this study is plastic ABS. Figure 6 shows the front view of stress distribution happening at the socket for each design.

(a) Design 1 (b) Design 2



(c) Design 3 (d) Design 4



(e) Design 5

Figure 6 The front view of stress distribution in the socket at different designs (1) - (5) for static structural analysis

(a) Design 1 (b) Design 2 (c) Design 3 (d) Design 4 (e) Design 5

Figure 7 The upper view of stress distribution in the socket at different designs (1) – (5) for static structural analysis

Table 1 Comparison of stress distribution in the socket at different designs (1) – (5)

Type of Design	1	2	3	4	5
1250N	0.1731 MPa	0.5895 MPa	1.4631 MPa	2.0688 MPa	0.5442 MPa

According to Table 1, the simulation shows that Design 4 has the highest stress value on the socket with a maximum stress magnitude of 2.068 MPa, while Design 1 has the lowest stress value, which is 0.1731 MPa. Comparing the stress on the model with the weight reduction shows that as the weight reduction of the model increases, the stress on the model also increases.

3.1.3. Safety factor in the socket

As depicted in Figure 8, the safety factor graph obtained from the simulation reveals that Design 1 has the highest safety factor, reaching 62.7. On the other hand, Design 4 has the lowest safety factor, measuring 12.2. This decrease in safety factor is attributed to the significant weight removal in Design 4, causing a reduction in the model's strength.

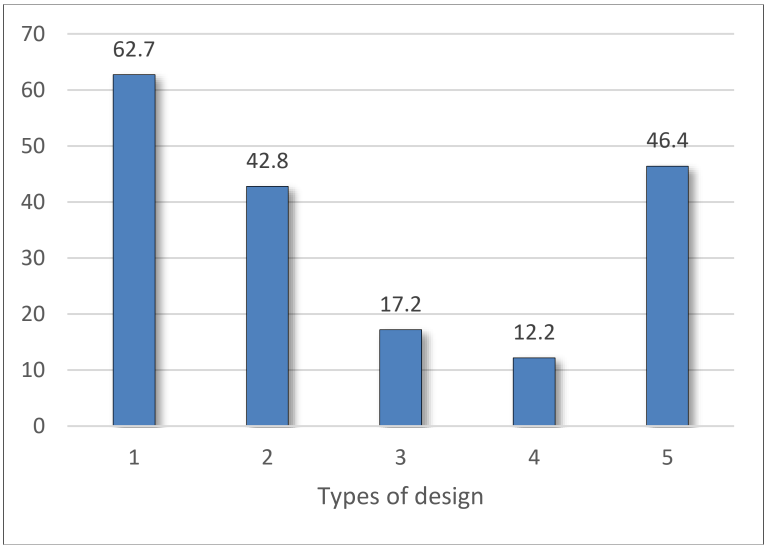


Figure 8 Safety Factor in the socket model at different designs (1) - (5) for static structural analysis

4. Conclusions

In this study, the topology optimization for the transtibial socket for a prosthetic leg was designed and analyzed using static structural analysis. The socket is the material ABS. The analysis shows that the socket is under more stress when its weight is reduced. Hence, weight reduction might change the model's mass distribution and lead to higher stress at particular spots due to the loss of the support that the removed material provided. However, the observed stress patterns have the potential to influence various aspects of the prosthetic leg's functionality, comfort, and durability. The ultimate goal of this project is to successfully design a customized transtibial socket prosthetic leg, thereby achieving the overall objectives.

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