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Enhancing Transtibial Limb Socket Design Through Topology Optimization

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ABSTRACT

The prosthetic transtibial limb socket is the device that attaches the stump of the amputee to the prosthesis. Achieving a comfortable design and fit is crucial for satisfactory use over time. Many individuals using prosthetics with transtibial sockets encounter issues like discomfort due to heavy sockets and inadequate airflow, impacting their musculoskeletal health. This research aims to address these challenges by developing, evaluating, creating, and analyzing an innovative transtibial socket. To begin, precise measurements and the raw shape of the patient's stump are identified using 3D scan technology. This data is then utilized to construct a new transtibial socket, ensuring an exact fit for the stump's interior through 3D modeling. Autodesk Fusion 360 and Meshmixer are employed to edit and design the socket based on the 3D stump model. Topology optimization is utilized to evaluate various iterations of the socket design, aiming to achieve an optimal design with geometric constraints while ensuring breathability. Finite element analysis is conducted to determine the force distribution within the socket design accurately. Through the redesigning, optimizing, and analysis of the socket in this project, its performance is enhanced, thus resolving the issues experienced by patients.

INTRODUCTION

A prosthetic implant is an artificial device that replaces a missing body part to restore the normal functions of the missing body part. In general, prosthetics have 4 types, which are transracial, transfemoral, transtibial, and transhumeral. In this project, the transtibial scope will be discovered.

The transtibial prosthesis is a device for the replacement of a missing anatomical segment from below the knee (Laing et al., 2011). Prosthetic transtibial components consist of several parts: the socket,

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suspension, shank, ankle joint, and foot. The socket part is the most important part of the prosthetic because it is the main connection and critical contact between the residual limb and the prostheses (Laing et al., 2011). Several functions can be provided by transtibial sockets, such as a comfortable interface for the transmission of body weight, stability during the stance phase, and weight-bearing capabilities. Based on Stevens et al. (2019), the purpose of lower limb prostheses is to transfer loads under both static and dynamic conditions with minimal movement between the limb and the prosthesis.

Nowadays, lower limb amputations are becoming more common worldwide due to the growing number of traffic accidents, vascular-related disorders, and diabetes (Laszczak et al., 2015). In the United States, approximately 1.3 million of the 1.6 million people have an amputation of the lower limb (Herzog et al., 2020). However, in Malaysia, 16% of upper limb amputations are from the total number of amputees, while lower amputations are 84% (Razak et al., 2016) Thus, lower limb amputations often use a prosthesis as a rehabilitation tool for their appearance and daily activities.

In the research, the problems that prosthetic transtibial faced were low air circulation and musculoskeletal pain. For air circulation problems, the socket design must be a breathable concept to prevent heat from accumulating inside the socket, which can make the stump sweat. Existing moist skin can easily affect the stump skin condition due to the presence of friction when walking or doing any movement, such as skin irritation, ulcers, and reamputation (Mollae et al., 2024). The second problem occurred because of the misfitting at the transtibial socket interface and the overall weight of the prosthesis. With that, inadequate rehabilitation can affect both physical and mental health outcomes (Yazgan et al., 2021).

In the project, advancements in the 3D scan, designing, topology optimization, finite element analysis, dynamic analysis, and 3D print technology will be utilized. The flow of the project started with a 3D scan patient's stump to get the correct dimension of the stump, design a transtibial socket based on a 3D model of the stump, topology optimization of the transtibial socket in order to achieve preserving zones, finite element analysis, and dynamic analysis to check the distribution of force at the transtibial socket. Furthermore, the constraint that might be faced is the use of 3D scans, which is limited due to the device's capabilities in performing a task that details the scan 100% in the same way as the original human part.

For sustainability, the 3D scan method can replace the traditional ways of gaining a stump's size by reducing the material of cellophane, plaster cast, and moulding material. Hence, it can sustain material management.

METHODOLOGY

Interview Session

An interview session was conducted at the UiTM Innovational Laboratory with a prosthetic transtibial limb socket user. The main aim of the interview session was to understand the experiences of a prosthetic transtibial limb socket user and to gather insights into the current problems the user faces while using the existing prosthetic transtibial limb socket. Before proceeding with the interview session, ethical consent was obtained from both the research team and the prosthetic limb socket user.

Fig 1 shows the measuring process of the existing socket used by the user. The thickness of the socket is 9 mm, measured using a vernier caliper and other general information of the user (patient) is stated in Table 1.

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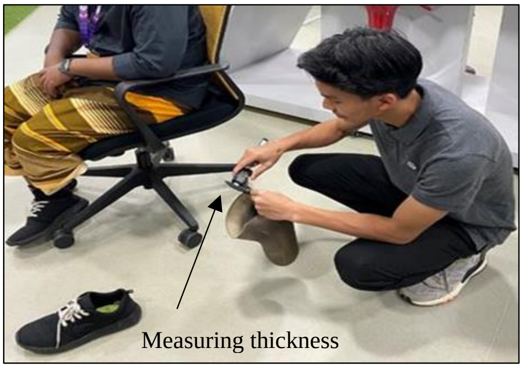

Fig. 1. Measuring patient's silicone socket.

Table 1. Details of patient

Information of patient	
Gender	Male
Age	23 years
Weight	85 kg
Height	175 cm
Socket thickness	9 mm
Silicone soak thickness	5 mm
Shank diameter	23 mm

3D Scanning

3D scan technology, also known as 3D scanning or 3D digitization, was a process that captured the three-dimensional shape and appearance of real-world objects and converted them into digital 3D models. The primary purpose of 3D scanning was to obtain accurate and detailed representations of physical objects, enabling various applications such as visualization, analysis, and design. The process of 3D scanning typically involved using a 3D scanner, which was a specialized device that captured the geometry and texture of an object. The scanner emitted light or laser beams onto the object's surface, and the device measured the time it took for the light to bounce back. By analysing these measurements, the scanner calculated the distance between the scanner and the object's surface points, creating a point cloud.

Fig 2(a) and Fig 2(b) show the 3D scanner model used in the study, which is the EinScan Pro HD (the model manufactured in China in 2023) and scanning process that was made in the session, which is 3D scanning residual limb without any silicone sock respectively. The scanner is known for its high-resolution capabilities, which make it suitable for capturing detailed and accurate 3D models. Its ability to capture both shape and appearance is crucial for creating a well-fitted and realistic prosthetic socket.

The first scanning process focused on capturing the three-dimensional shape and appearance of the patient's left residual limb without any attachments. The patient's residual limb was positioned and stabilized on a suitable platform to ensure minimal movement during the scanning process. The 3D scanner was then operated to capture multiple scans from different angles, creating a comprehensive and detailed 3D model of the stump (Fig 3). Furthermore, the patient's stump was scanned again for the second scanning process, but this time with the attached silicone socks. Silicone socks are used to create a protective barrier between the residual limb and the prosthetic socket. By scanning the residual limb with the silicone socks in place, the resulting 3D model captured the shape and appearance of the stump when it is inside the prosthetic socket. These 3D models would be used to design a prosthetic transtibial limb socket that fits accurately to the unique shape of the patient's residual limb. The tight fit of the socket helps reduce any looseness or discomfort when the patient wears the prosthetic limb.

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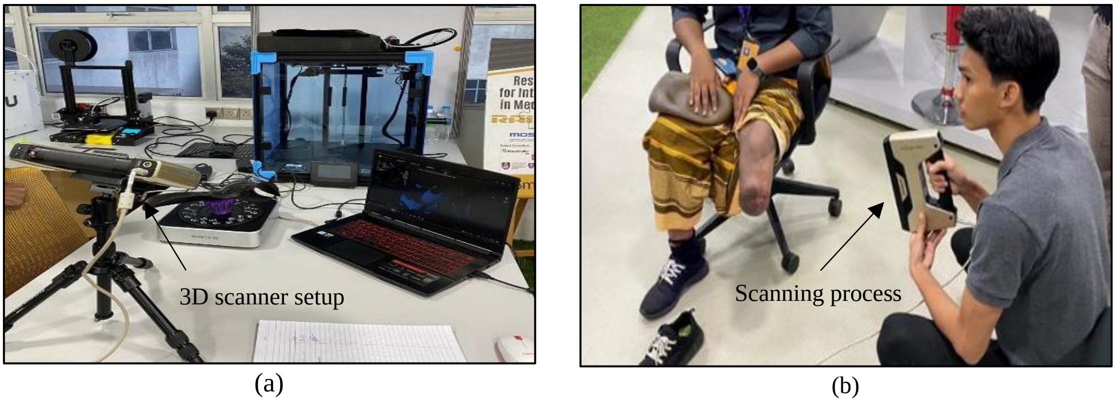

Fig. 2. Scanning session (a) 3D scanner setup and (b) scanning residual limb.

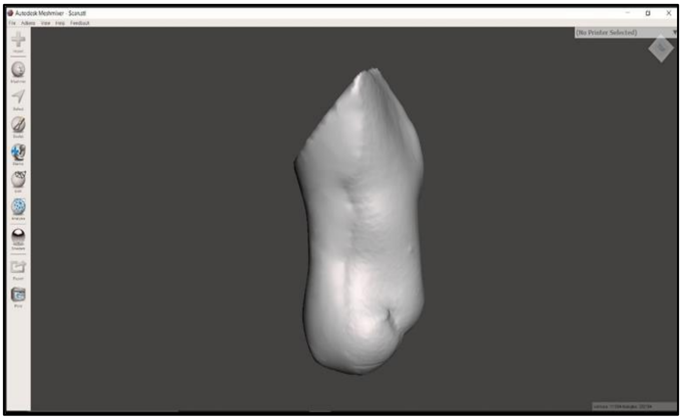

Fig. 3. Residual limb 3D model.

Design of Socket

Following the completion of the 3D scanning process, the resulting 3D model of the stump was exported to the Meshmixer software to be edited. The 3D residual model has been altered to remove elements deemed unnecessary while improving the model's dimensioning. During the editing process, three processes were carried out: first, unneeded components were eliminated; second, an unconnected 3D model was united into a solid object; and last, the surface quality of the 3D model was improved.

Next, as shown in Fig 4, a shank holder with a 23 mm diameter was positioned at center on the point of the socket where the center of gravity is located. The design of the Total Surface Bearing (TSB) socket, in which the upper section of the socket covered half of the patellar part, served as inspiration for the concept of the shape of the socket. Because of how the TSB socket was designed, weight was distributed evenly across the entire residual limb. This ensured that there was no point of peak pressure, which resulted in minimum pressure being applied to the skin.

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Fig. 4. Transtibial limb socket 3D model.

Topology Optimization

Topology optimization was used in the study as a design optimization technique. Its primary objective was to find the optimal distribution of material within a given design space to achieve specific performance goals while satisfying specified constraints. In the context of the socket structure, topology optimization analysed the initial design and iteratively removed unnecessary material or redistributed it to achieve the targeted mass reduction while ensuring the structural integrity and mechanical performance were maintained. This technique was performed using Autodesk Fusion 360 the ABS plastic material was selected for utilization for the socket.

With the fundamental parameters in place, the shape optimization criteria were thoughtfully adjusted. The overarching aim was to generate an optimized shape that retained approximately 40% of the original mass, all the while maximizing the stiffness characteristics of the component.

Finally, the model was subjected to the solution process, ultimately yielding the highly anticipated optimized shape. Fig 5 shows the outcomes shape was successfully retrieved from the cloud-based storage system.

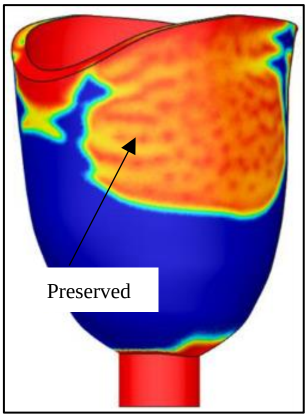

Fig. 5. Topology optimization outcome shape; also referred as Design 1.

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Redesigning Socket

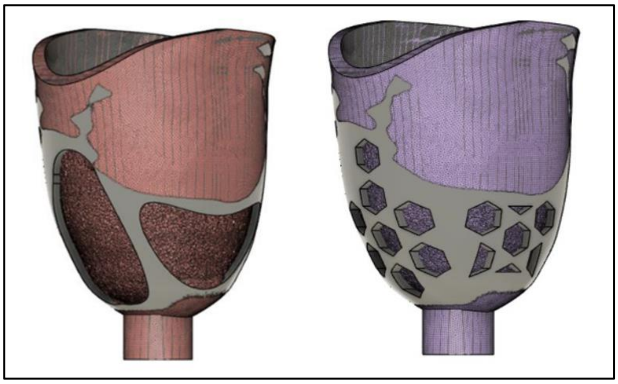
Based on the topology optimization result, the socket model was detailed with the regional area that needs to be preserved and the region that can safely be removed. The result was transferred to the design workbench to edit the unwanted region. The unwanted region was edited by sketching at the unwanted region surface to extrude it in terms of reducing the weight of the current socket design.

Two new socket designs were created from the process; the first one was edited to cover 60% of the unwanted region with random extruded shape, and the second one was edited to cover only 30% of the region by applying the lattice honeycomb structure as shape to be extruded. This lattice honeycomb was chosen as the bee honeycomb patterns is commonly used as infills of additive manufacturing parts to keep parts lightweight (Goldmann et al., 2022). The purpose of the process was to analyze which one of the socket models would be the best if finite element analysis were conducted.

An analysis of the topology optimization results was carried out on the existing socket model using Autodesk Fusion 360 Software. The analysis aimed to identify areas of the socket model that needed to be preserved for structural integrity and regions that could potentially be removed without compromising performance.

To begin the redesigning process, the topology optimization result was transferred into a detailed socket model within a design workbench environment. The detailed model retained essential structural features while indicating the regions that were deemed unnecessary for maintaining desired performance. Then, the regions identified as non-essential were edited using sketching tools. The sketches were created on the surface of the unwanted region, marking the areas to be removed.

Thus, the extrusion option was involved in extending the sketches in a specific shape, effectively removing material from the model. Two new socket designs were created from the process (Fig 9). Design 2 was edited to cover 60% of the identified area, and the extrusion shape was randomly chosen, whereas Design 3 was edited to cover only 30% of the identified area with the extrusion shape specifically chosen as a lattice honeycomb structure. The primary objective of the redesigning process was to determine which of the redesigned socket models would perform better when subjected to finite element analysis (FEA). The two designs are shown in Fig 6(a) and Fig 6(b). Design 1 was the original solid shape and not run into the topology redesigning process.



(a) (b)

Fig. 6. Redesigning of transtibial limb socket using topology optimization (a) Design 2 and (b) Design 3.

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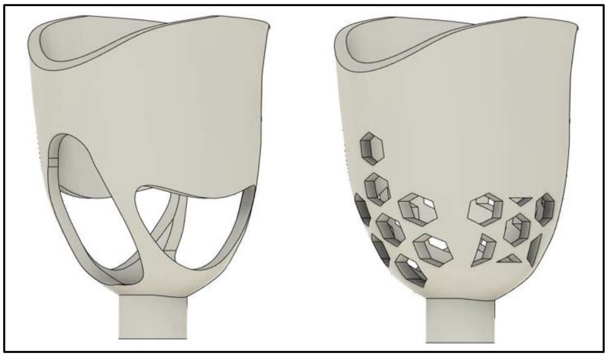
In Fig 7, these two designs were done to improve the structural durability of the socket while concurrently achieving the concept of breathable sockets. The shank holder dimension and thickness for all designs are same which are 23mm and 9mm, respectively.



(a) (b)

Fig.7. The revised model of transtibial limb sockets (a) Design 2 and (b) Design 3.

Finite Element Analysis

The study employed finite element analysis to enable a virtual exploration and comprehensive understanding of how the object would react under diverse pressures and constraints. The selection of materials, namely polypropylene, polyethylene, and Acrylonitrile Butadiene Styrene (ABS), was rooted in previous research when designing the socket using generative CAD analysis (Avila et al., 2021). These materials, each possessing unique properties, were chosen to investigate how the sockets responded to pressure and constraints, considering factors such as elasticity, Poisson's ratio, and yield strength.

The choice of 3D printing materials plays a significant role in the performance of prosthetic sockets. In this study, ABS plastic was selected for its favorable properties, including high impact resistance and flexibility. ABS is an optimal material for additive manufacturing in bioinspired structures, as it can maintain the balance between flexibility and durability (Johnson et al., 2021). Similarly, the use of low-cost 3D-printed materials for prosthetic sockets, emphasizing their strength and the ability to withstand daily use (Stelt et al., 2022).

The comparison of results for the three designs provided valuable insights into the mechanical responses of the models, focusing on parameters such as maximum stress, displacement, and safety factors. This evaluation ultimately led to the identification of the most optimal socket design, highlighting the intricate relationship between material selection, geometric configuration, and mechanical performance.

RESULTS AND DISCUSSION

Analysis of Maximum Stress Distribution

Stress is a measure of the internal resistance of a material to deformation when subjected to an applied load where the maximum stress value indicates the highest stress experienced by the material within the prosthetic transtibial limb socket under the given loading conditions.

Fig 8 shows the result of the relationship between the type of socket design and the maximum stress of the prosthetic transtibial limb socket. Design 1 serves as the baseline, representing a basic prosthetic limb

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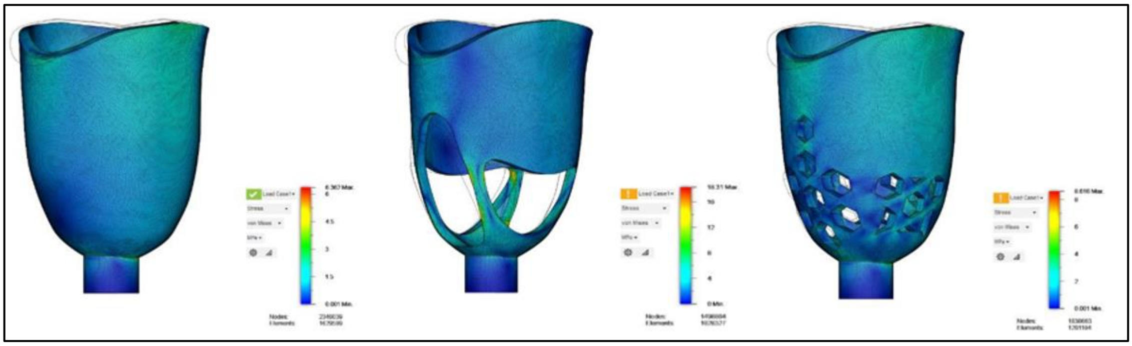
socket configuration. The recorded stress of 3.31 MPa indicates the highest stress concentration experienced within the socket structure.

Next, Design 2 explores the implementation of topology optimization, utilizing 60% of the designated area with a randomly generated shape. The notable increase in maximum stress from Design 1 (3.31 MPa) to Design 2 (18.31 MPa) suggests that the initial random shape selection might not be conducive to minimizing stress concentrations. Further refinement of alternative optimization strategies is necessary to achieve improved stress distribution. Lastly, Design 3 capitalizes on topology optimization by employing 30% of the designated area and adopting a lattice honeycomb shape. The recorded maximum stress value of 8.616 MPa demonstrates a reduction in stress concentrations compared to Design 2. This indicates that the lattice honeycomb structure contributes to distributing stress more evenly within the socket, potentially enhancing its overall mechanical integrity.



(a) (b) (c)

Fig. 8. Comparison of maximum stress distributions for three designs: (a) Design 1, (b) Design 2, and (c) Design 3.

Other work also emphasized the importance of socket design in preserving residual-limb skin health by reducing high pressure concentrations, a critical factor that was considered in the design of the current study (Rink et al., 2016). The optimization in this study also successfully reduced pressure points, minimizing the likelihood of discomfort and skin irritation. Previous research that highlighted the importance of suspension mechanisms and overall design in ensuring that prosthetics are comfortable and functional over time, a key consideration in the development of the current socket design (Shuaili et al., 2019).

Evaluation of Structural Deformation

Fig 9 shows the relationship between the type of socket design and the displacement of the prosthetic transtibial limb socket. Design 1 representing the basic type of prosthetic limb socket, is positioned at the leftmost end of the graph with a displacement value of 0.6367 mm. This serves as the initial reference point for comparison.

Next Design 2, exhibits a substantially higher displacement of 2.995 mm. This result indicates that introducing topology optimization with a random shape has led to increased deformation in the prosthetic limb socket compared to the basic design. In contrast, Design 3 leverages topology optimization by utilizing 30% of the area with a lattice honeycomb shape. This design shows a notable reduction in displacement, measuring 0.9831 mm. The lattice honeycomb structure has contributed to enhanced stiffness and load distribution, resulting in a more rigid prosthetic limb socket compared to Design 2.

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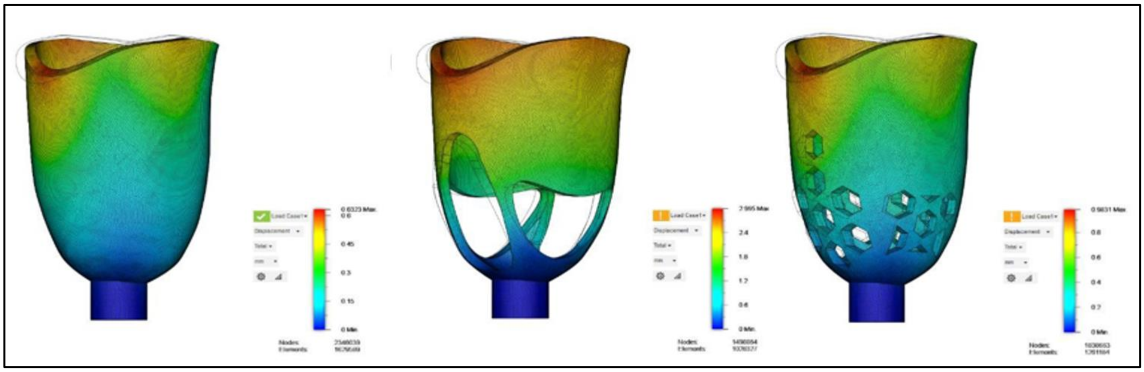

(a) (b) (c)

Fig. 9. Illustration of deformation results for (a) Design 1, (b) Design 2, and (c) Design 3, emphasizing differences in structural responses.

The figures underscore the significance of design modifications in influencing the structural performance of prosthetic limb sockets. It is evident that Design 3, with the lattice honeycomb shape, has achieved a more favorable balance between optimization and structural integrity, as evidenced by its lower displacement value in comparison to both the basic type (Design 1) and the topology-optimized random shape (Design 2).

The incorporation of ABS and the lattice Design 3 resulted in a reduction of displacement, with a measured value of 0.9831 mm, compared to 2.995 mm in Design 2. This supports the findings of previous studies, which demonstrated that lattice structures in prosthetics effectively distribute load and minimize deformation (Anand et al., 2021).

Safety Factor Comparison Across Designs

The safety factor was used in engineering to ensure that the prosthetic socket was designed and operated with a sufficient margin of safety. It is the ratio that relates the capacity or strength of a structure to the expected or allowable loads or stresses it will experience during its intended use. The range for the minimum acceptable number of safety factors for prosthetics was 1.5. The minimum safety factor was stated to ensure that the socket would not deform or break under certain circumstances.

Fig 10 shows the relationship between the type of socket design and the displacement of the prosthetic transtibial limb socket. The graph starts with an impressive safety factor of 6.042 for Design 1. The design stands out as a robust and dependable choice, capable of withstanding substantial loads. Its high safety factor indicates a significant margin of safety, suggesting that the design has been engineered with a strong emphasis on structural integrity. Referring to Design 2, a significant drop in the safety factor to 1.092. Advancing the x-axis to Design 3, a safety factor of 2.321. The design incorporates 30% topology optimization with a lattice honeycomb shape. Although the safety factor is higher than that of Design 2, it still falls short of the robustness seen in Design 1. The lattice honeycomb shape offers some benefits in weight reduction while maintaining a moderate safety margin. The use of lattice structures to reduce material weight while enhancing mechanical performance aligns with previous work (Nayak et al., 2017), who found that topology optimization effectively minimized material usage while maintaining structural integrity in transtibial prosthetic sockets.

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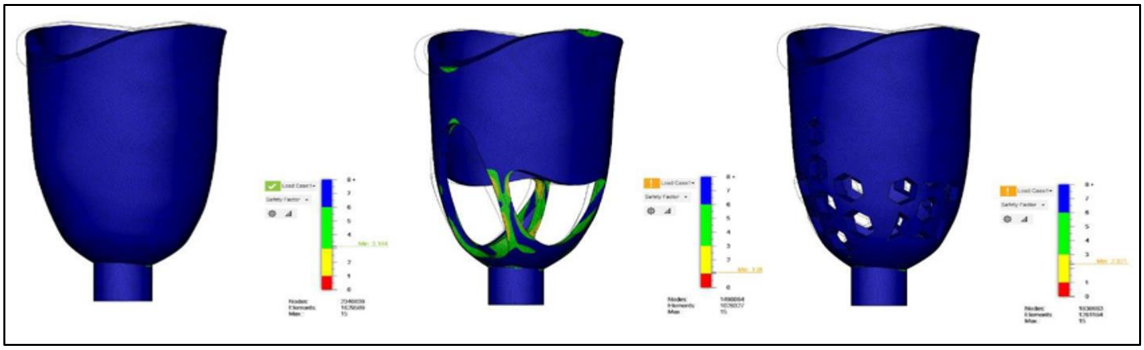

(a) (b) (c)

Fig. 10. Safety factor analysis results for the evaluated designs: (a) Design 1, (b) Design 2, and (c) Design 3.

The current study aimed to investigate the effects of topology optimization and the use of various 3D printing materials on the design of transtibial prosthetic sockets, with a focus on reducing maximum stress and displacement and improving safety factors. The findings are consistent with previous research, which highlights the crucial role of socket design and material properties in ensuring comfort and structural integrity.

Maximum stress, displacement, and safety factor, the results of the finite element analysis (FEA) showed that the maximum stress in Design 3 was significantly lower (8.616 MPa) than that in Design 2 (18.31 MPa), demonstrating the effectiveness of the honeycomb structure in distributing stress. This finding is consistent with the previous study (Steer et al., 2021), which emphasized the importance of geometric configuration in prosthetic socket design to achieve even stress distribution across the residual limb.

In terms of safety factors, the current study found optimized honeycomb design in Design 3 achieved a safety factor of 2.321, which, while lower than Design 1, provided sufficient structural integrity while reducing weight. This convinced the statement that prosthetic designs optimized through finite element analysis often maintain adequate safety factors, even with material reduction, ensuring that the prosthetic can withstand everyday use without failure (Kassab et al., 2016).

Additional studies, have explored applications of FEA in prosthetic design, reinforcing the notion that material selection and structural design optimization are crucial in ensuring long-term prosthetic performance (Dong et al., 2018). It is also highlighted the potential of dynamic socket improving the adaptability and comfort of transtibial prostheses under real-life conditions, a concept that could further enhance future iterations of the current study's design (Martin et al., 2021).

Finally, other study on dynamically process mapping the socket loading condition has shown how real-time feedback and optimization can further improve prosthetic design (Fu et al., 2018). This, coupled with work on composite prosthetic blades, points to the port more advanced, structurally sound, and lightweight prosthetic designs through future innovations (Alizadeh, 2020).

In summary, the results of this study reinforce the critical role of topology optimization prosthetic socket design. The combination of a lattice honeycomb structure and ABS material effectively reduces both maximum stress and displacement while maintaining an acceptable safety factor. These findings contribute to the growing body of literature on the optimization of transtibial prosthetic sockets and underscore the importance of advanced design techniques in enhancing the quality of life for amputees.

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CONCLUSION

This study successfully achieved its objectives, focusing on the designing of sockets for prosthetic limbs customized to specific individual amputation dimensions. Using topology optimization and FEA analysis, the study gathered insights to design sockets ensuring comfort, stability, and functionality. The findings recommend ABS plastic as an excellent material choice and highlight Design 3, featuring a honeycomb lattice structure, as the most promising socket configuration. This optimal combination promises durability, comfort, and mobility enhancements, laying a solid foundation for future advancements in prosthetic limb socket design and improving amputees' quality of life.

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CONFLICT OF INTEREST STATEMENT

Two of the authors, Jamaluddin Mahmud and Mohd Afzan Mohd Anuar are the Editor in Chief and the Section Editor of the Journal of Mechanical Engineering (JMechE), respectively. The authors have no other conflict of interest to note.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: Mohd Hazwan Mohamed Norli, Amer Fahmie Zaidy, Jamaluddin Mahmud, Abdul Halim Abdullah; data collection: Mohd Hazwan Mohamed Norli, Amer Fahmie Zaidy; analysis and interpretation of results: Mohd Hazwan Mohamed Norli, Mohd Afzan Mohd Anuar, Muhammad Hanif Ramlee, Abdul Halim Abdullah; draft manuscript preparation: Mohd Hazwan Mohamed Norli, Amer Fahmie Zaidy, Abdul Halim Abdullah. All authors reviewed the results, provided critical feedback, and approved the final version of the manuscript.

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