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FABRICATION OF A LOWER LIMB PROSTHETIC SOCKET USING TOPOLOGY OPTIMIZATION AND ADDITIVE MANUFACTURING

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The contact between the artificial leg (prosthesis) and an amputees residual limb is a significant factor in the success of prosthetic fitting and overall comfort. An improper interface can result in issue such as pressure sores, skin irritation, residual limb pain and discomfort for the amputee. The prosthetic socket bridges the gap between the two. In this work, the customized complex geometry of the prosthetic socket is developed using advanced 3D scanning technology of the residual limb. Following the accurate 3D scan of the residual limb, the development of a Computer-Aided Design (CAD) model is a critical next step in the development of customized prosthetic socket. The raw 3D scan data undergoes a process that transforms the information into a more refined and functional design suitable for manufacturing the socket. Given the strength-to-weight ratio already presented as a challenge for socket, the prosthetic socket needs to be made as light as possible. This makes it challenging to maintain strength and optimal structure for the prosthetic socket by just removing unwanted material; therefore, the topology optimization technique is adopted. The process revealed that extra material existed at the stress location on the socket. In the following stage a new customized design is developed possessing low weight maintaining the structural as well as functional integrity of the socket. The final geometry of the customized socket is almost impossible to fabricate from conventional method. Hence it was printed using Fused Deposition Method (FDM), and used for the patient.

Keywords: topology optimization, additive manufacturing, reverse engineering, prosthetic socket.

1. Introduction

The challenges faced by amputees in low-income, rural areas of under developing countries are significant due to the limited access to both prosthetic devices and healthcare infrastructure. High accident rates and poor working conditions are the main causes of an increased number of limb losses. According to World Health Organization (WHO) assessment, only $5-15\%$ of the 40 million amputees living in underdeveloped nations have access to rehabilitation services or prosthetic devices [1]. Due to this lack of access, millions of amputees suffer from restricted movement, which impacts their condition of life [2].

Furthermore, the majority of the healthcare facilities are situated in urban areas, which requires further travel expenses for fitting and maintenance. There is also a shortage of prosthetic workshops due to lack of materials and qualified personnel [3-5]. Traditional methods of making prosthetic sockets are expensive and labour-intensive. Users may experience discomfort, skin irritation, and other health problems as a result of improper socket fitting [6]. Excessive contact pressure or friction between the skin and socket can cause ulcers creating wounds or other diseases on this part [7].

The development of better or customized methods for fabricating prosthetic limbs is key to improving rehabilitation outcomes and patient care. Innovations in prosthetic design, materials, and manufacturing

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processes can significantly enhance the overall experience for users by offering faster, more affordable, and higher-quality solutions. A Rapid Prototyping (RP) is indeed an emerging technology with significant potential, particularly in the field of prosthetics and other areas of medical device development [7-8]. The integration of 3D printing, 3D scanning, and reverse engineering represents a powerful combination of technologies, particularly for the manufacturing of complex shaped and profiled custom components [9-13].

The layer-by-layer material deposition approach used by additive manufacturing (AM) technology, which allows for the creation of intricate and freeform shapes with remarkable simplicity and precision [14, 15]. The FDM-based 3D printer was selected from various Rapid prototyping processes, due to its numerous advantages, including minimal post-processing requirements and good mechanical properties [16, 17]. Selective Laser Sintering (SLS) is a hopeful method for manufacturing prosthetic sockets because it produces intricate, patient-specific designs with no need for moulds or extensive manual labour. This could greatly enhance comfort and fit in prosthetic sockets thus reducing pressure points and enhancing the overall life quality of people who have had amputations [18]. Additive Manufacturing (AM) technologies like FDM open up new avenues for creating complex and custom-made prosthetic sockets. Thus, these methods can do away with the challenges presented by traditional manufacturing methods leading to better designed systems that improve wearer's SLS and comfort and minimize excessive contact pressures on sensitive areas of the residual limb [19, 20].

The integration of Topology Optimization (TO) with Additive Manufacturing (AM) offers affective strategy to improve the design and functionality of prosthetic sockets [21]. The use of Topology Optimization indeed allows for the creation of designs that are tailored for specific load conditions and material properties, resulting in highly efficient and optimized structures. However, these optimized designs often feature complex geometries that cannot be easily produced using traditional manufacturing techniques. These complex structures can be made using AM technologies thus enabling implementation of optimization [22].

The use of Topological Optimization and Additive Manufacturing (AM) in fields like medical applications and automobile sectors [23]. Specifically in medical applications, the focus is often on tissue scaffolds, which are critical for supporting tissue growth and regeneration. It is therefore possible to conclude that these technologies have the potential to enhance both comfort and performance of prosthetic devices for amputees [24]. Integrating Fused Deposition Modelling (FDM) with Topological Optimization and Additive Manufacturing (AM) technologies indeed has the potential to revolutionize the manufacturing of prosthesis sockets, especially in low-income settings and rural areas. The development is expected to significantly improve the living standards and rehabilitation outcomes for millions of amputees worldwide [25].

The design and fabrication of prosthetic sockets are vital for the comfort and functionality of lower limb prostheses. Traditional methods are often labour-intensive and yield suboptimal results. Advances in computational design, especially topology optimization (TO) and additive manufacturing (AM), offer significant improvements. TO enables efficient material distribution under load conditions, enhancing strength-to-weight ratios. In prosthetics, it reduces socket weight while preserving strength and comfort. Studies report up to 30% weight reduction using TO without compromising mechanical performance [26].

Recent work by Falcinelli *et al.* has demonstrated the effectiveness of combining topology optimization with additive manufacturing for prosthetic socket design, particularly focusing on structural performance and advanced numerical modelling. However, the present study distinguishes itself by integrating patient-specific strain-derived loading conditions, applying optimization to clinically used socket geometries, and emphasizing a cost-effective FDM-based manufacturing approach suitable for low-resource settings, supported by a combined experimental–computational framework [27].

Additive manufacturing (AM), especially 3D printing, enables the creation of complex, customized prosthetic sockets tailored to individual users. It allows for faster production and improved fit and comfort. Studies have demonstrated AM's effectiveness in producing patient-specific sockets. Integrating topology optimization (TO) with AM enhances design efficiency, enabling lightweight, adaptive structures. Materials like nylon, TPU, and carbon-fibber-reinforced polymers are increasingly used in AM for prosthetics due to their strength, flexibility, and biocompatibility, making this synergy ideal for biomedical applications. Recent studies have explored the use of cellular and lattice structures to enhance the mechanical performance and comfort of prosthetic sockets. For instance, cellular architectures have been shown to improve energy absorption, reduce weight, and enable better stress distribution within the socket structure [28]. Similarly, lattice-based designs have demonstrated improved biomechanical compatibility and adaptability to patient-specific requirements [29]. While these approaches focus on predefined structural patterns, the present study adopts topology optimization to generate material distributions directly based on physiological loading conditions, offering a more adaptive and performance-driven design strategy.

This paper focuses on integrating topology optimization and additive manufacturing to design a prosthetic socket using Polylactic Acid (PLA) with the fused deposition method (FDM) technique. The dimensions of socket are determined through three-dimensional (3D) scanning of residual limb, which accurately captures the digital representation of its shape and contours. Also, load measurements reobtained using strain data under half, full and walking condition. The magnitude of loading condition for the 3D model was provided in ANSYS simulation system for topology optimization of the socket. Finally, the optimized socket, with material remove from the area experiencing low stress, is fabricated using 3D printing technology.

2. Materials and methods

2.1. Collection of data

To collect strain data effectively, three significant loading conditions were monitored: half load, full load, and walking, the details are shown below in Table 1.

Table 1. Different loading conditions.

Half load	Represents partial weight-bearing during static standing ($\sim 50\%$ body weight).
Full load	Represents full weight-bearing during quiet standing ($\sim 100\%$ body weight).
Walking condition	Represents dynamic loading during gait, approximated as $1.2-1.5$ times body weight, based on gait biomechanics literature.

For this study, nine trans-tibial amputee volunteers were selected based on clinically relevant criteria, such as amputation causes: vascular disease, trauma (P2), diabetes (P7), infection (P4), short stump (P2), long stump (P3), and accidental injuries (P1, P5, P8). All patients, who were unilateral below-knee amputees ranging in the age from 26 and 70 years, employed cotton liners and patellar tendon-bearing (PTB) sockets that were uniformly $5\,mm$ thick. The youngest patient, P8, aged 26, had been using a prosthesis for 12 years, enabling a slightly faster walking pace, highlighting effective function replacement of the ankle and foot joints for smooth movement. Additionally, three below-knee male amputees participated in this study, comprising two unilateral and one bilateral case. Patient data is detailed further in Table 2.

Table 2. Dimensional specification of socket models.

Parameter	Length (mm)	Diameter (mm)	Area (mm^2)
Patient 1	355.36	129.04	98064.51
Patient 2	167.72	103.08	53185.56
Patient 3 (left)	251.92	104.70	68290.98
Patient 3 (right)	248.89	103.30	62893.46

2.2. Transtibial socket model preparation

Four distinct socket models initially used by patients were selected for investigation. Each socket, made of Plaster of Paris (POP), was scanned with a contactless laser scanner to capture precise surface geometry, followed by the reconstruction of a detailed surface model. The 3D scanning process utilized COMET PLUS software (Steinbichler, Germany), enabling the extraction of the four socket models, as depicted in Fig.1. After 3D model extraction, measurement tools were applied to identify and isolate the optimal design domain. Relevant dimensional details were meticulously recorded, providing crucial data on socket geometry. This analysis of the socket models supports precise customization to enhance the fit and comfort for each patient's prosthetic needs.

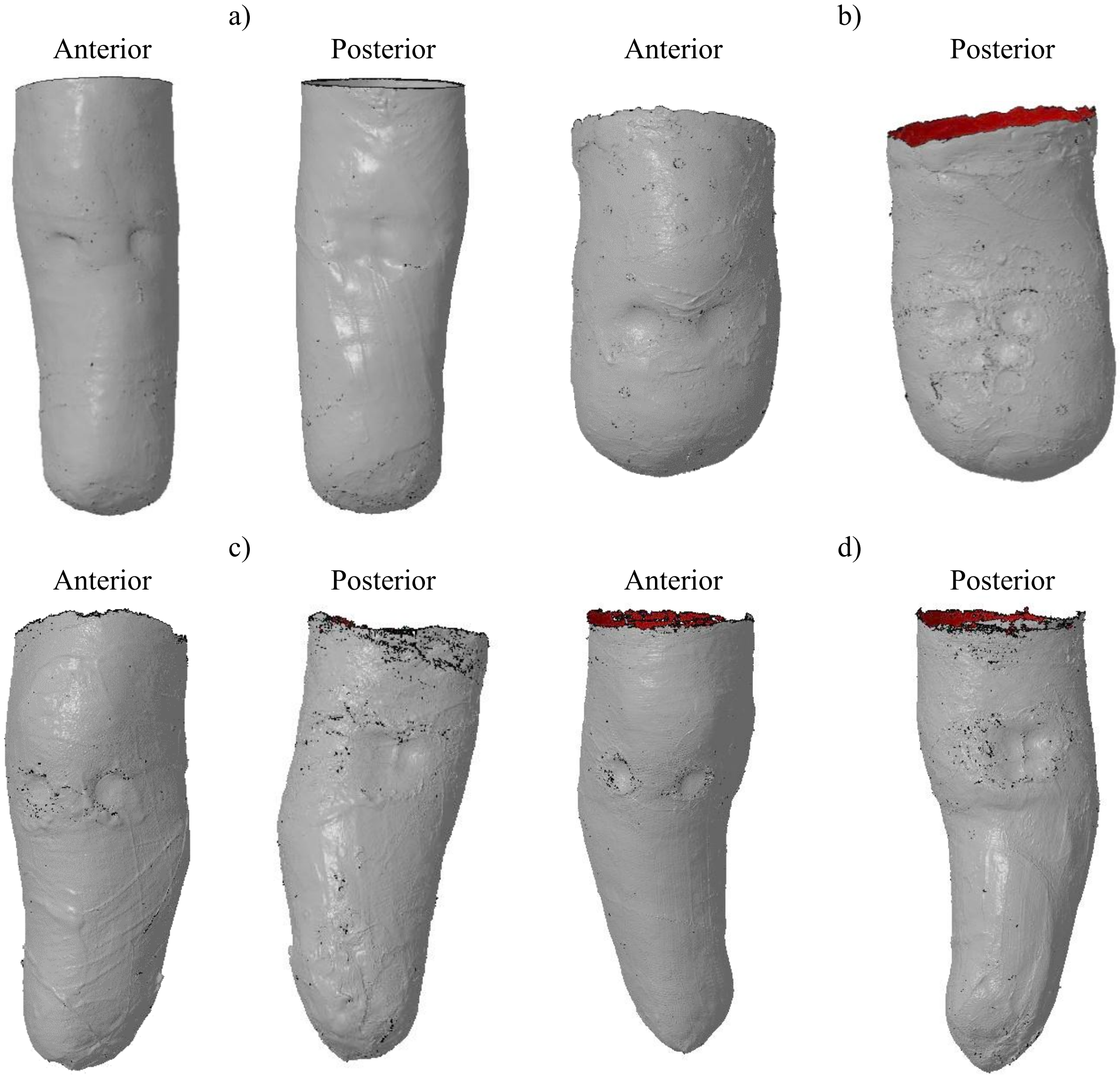


Fig.1. Scanned original socket model: a) Patient 1, b) Patient 2, c) Patient 3 [Left], d) Patient 3 [Right].

In the Final phase the design is using the SIMP (Solid Isotropic Material with Penalization) technique that includes an ideal transitional density material penalization factor which helps in determining a factor of safety for appropriate design problem. The selection of the SIMP penalization factor plays a critical role in controlling the material distribution during topology optimization. In the present study, a penalization factor of $p = 3$ was adopted based on standard practice reported in the literature, as it provides a good balance between numerical stability and clear solid–void separation. To assess the sensitivity of the results, additional analyses were conducted with $p = 2$ and $p = 4$. It was observed that a lower penalization factor $(p = 2)$ resulted in intermediate density regions (gray areas), indicating less distinct material distribution. Conversely, a higher penalization factor $(p = 4)$ produced a more discrete solid–void topology but introduced potential numerical instabilities and convergence difficulties. Based on these observations, $p = 3$ was selected as an optimal value, ensuring a stable optimization process while maintaining physically meaningful and manufacturable designs.

This value gives reliable structural performance through making a balance between strength and material distribution. Many critical presumptions came before the topology optimization study was undertaken, such as that the socket material possessed homogeneous and isotropic properties. These presuppositions help an effective optimization strategy that fulfils the necessary safety criteria by streamlining the analysis and making it easy to understand the finding better.

2.2.1. Material properties

The material properties of PLA used in the finite element analysis were adopted from reported literature values for FDM-printed specimens. It is acknowledged that FDM-produced PLA exhibits anisotropic behaviour depending on printing parameters such as layer orientation, raster angle, and build direction. However, for the purpose of simplifying the numerical analysis, the material was assumed to be homogeneous and isotropic with linear elastic behaviour. This assumption may influence the accuracy of stress predictions and is therefore recognized as a limitation of the present study. Future work will focus on incorporating anisotropic material models to better represent the actual mechanical response of additively manufactured PLA. The properties of material used is shown in Tab.3.

Table 3. Material properties.

Property	Value
Elastic modulus (E)	$2.8 - 3.5\,GPa$
Poisson's ratio (v)	0.35
Material behavior	Linear elastic
Material nature	Homogeneous, isotropic

2.3. Topology optimization of socket model

The mesh for the optimization of the prosthetic socket is generated using tetrahedral elements for getting more accuracy. A mesh sensitivity analysis was conducted to ensure the numerical accuracy and reliability of the finite element results. Three different mesh densities-coarse, medium, and fine-were generated using tetrahedral elements to evaluate the influence of mesh refinement on the predicted response. The results indicated that the variation in maximum stress and displacement between the medium and fine meshes was less than 5%, demonstrating that the solution is effectively mesh-independent. Based on this analysis, the medium mesh was selected for subsequent simulations to achieve an optimal balance between computational efficiency and solution accuracy. The use of tetrahedral elements was adopted to accurately capture the complex geometry of the prosthetic socket.

The structural reliability of the socket depends on this accuracy in geometry and stress distribution. The topology optimization is done by using Altair's OptiStruct software, which is assisted by HyperMesh and

HyperView. The CAD model is then discretized using the pre-processing program HyperMesh, and boundary conditions such as material property definition, optimization of analysis settings for static analysis, or modal analysis is implemented. The model is exported and processed in OptiStruct for the optimization stage once it was finished being built up in HyperMesh.

HyperView was used for post-processing and evaluation of the OptiStruct results, which revealed information on the optimal structure of the socket. In order to enable regular gait movement without twisting or bending under strain, a socket that is both strong and flexible has to be designed. By improving comfort and lowering the prosthetic device's total weight and expense, this helps amputee rehabilitation.

This method uses a FE-model of the socket, where design and non-design parts are given separate attributes. The problem formulation and boundary condition optimization are done using the Altair HyperWorks and OptiStruct interface. The goal of this technique is to maintain the bottom surface fixed while simulating the socket's compliance under vertical force at the top.

2.3.1. Loading conditions and boundary conditions

The loading applied to the prosthetic socket was primarily considered in the vertical (axial) direction, corresponding to the transmission of body weight from the residual limb to the prosthetic system during weight-bearing activities. This assumption is consistent with biomechanical studies of transtibial prostheses, where the dominant load component arises from ground reaction forces acting along the longitudinal axis of the limb during standing and the stance phase of gait.

In addition to the axial load, a minor anterior–posterior (A–P) component was incorporated to account for dynamic effects associated with walking. During gait, the ground reaction force vector is not perfectly vertical; instead, it shifts anteriorly and posteriorly relative to the limb, generating shear forces at the socket–limb interface. These A–P forces arise due to forward propulsion and braking phases of walking, where the prosthetic limb experiences alternating posterior (braking) and anterior (propulsive) shear components.

The magnitude of the anterior–posterior load component was assumed to be a fraction (typically $10-20\%$) of the vertical load, based on established gait biomechanics literature. This simplified representation captures the essential physiological loading behavior while maintaining computational efficiency.

Overall, the combined loading condition (dominant vertical load with secondary anterior–posterior component) provides a realistic approximation of in vivo prosthetic loading, ensuring that the topology optimization reflects both static weight-bearing and dynamic walking conditions.

Table 4. Topology optimization parameters.

Objective	Increase the stiffness (minimize the weight compliance)
Constraints	1) Volume Fraction Upper Bound (VFUB) $=0.50$ 2) Max displacement of the centre node $=2\,mm$
Design variables	The density of every element in the design space
Manufacturing constraints	Minimum member size $=15\,mm$
Optimization method	SIMP (Solid Isotropic Material with Penalization)
Penalization factor (p)	3
Volume constraint	Volume Fraction (VF) ≤ 0.50
Displacement constraint	Maximum displacement $\leq 2\,mm$
Design variables	Elemental density distribution
Number of iterations	$40-60$ iterations
Convergence criteria	Change in objective function $<1\%$ between successive iterations

Reducing the socket's volume without sacrificing its strength is the main goal. Table 4 outlines the parameters considered for volume minimization. After obtaining an optimized design, the stress values are checked under the same constraints to ensure they remain within the socket's yield strength, verifying that the design maintains necessary durability.

The volume fraction upper bound $(VF = 0.50)$ was selected to achieve an optimal balance between weight reduction and structural integrity of the prosthetic socket. This value allows for a significant material reduction of approximately $30-40\%$ while ensuring that the socket can safely withstand physiological loading conditions encountered during daily activities. A lower volume fraction would result in excessive material removal, leading to increased deformation and potential structural instability. Conversely, a higher volume fraction would retain more material, thereby limiting the benefits of weight reduction and reducing the overall efficiency of the design. Therefore, $VF = 0.50$ was adopted as a compromise between mechanical performance and lightweight design requirements.

2.4. FDM based additive manufacturing for generating topology optimised sockets

Since the STL file format works with digital manufacturing, it is frequently utilized in rapid prototyping. A BCN3D Epsilon 50 3D printer was used to produce the STL model for this project after it was created using a 3D scanner. The CAD model is stored in STL format before the printing process starts, ensuring that there are no non-manifold edges on the design surface. The model can be reoriented and repaired using programs like Netfabb and MeshMixer, which will optimize it for printing in high quality.

The model is then divided into layers using the Slic3r program, which modifies print parameters before producing the G-code. Before extrusion begins, the printer's extruder head and bed are preheated to predetermined temperatures. Molten plastic is layered from the bottom up to make the model. An acetone solution is applied for extra stickiness during printing, and a polyetherimide sheet is placed on the printer bed in order to ensure secure adherence. With this configuration, the printer can create a sturdy, accurate prototype that closely resembles the digital design layer by layer.

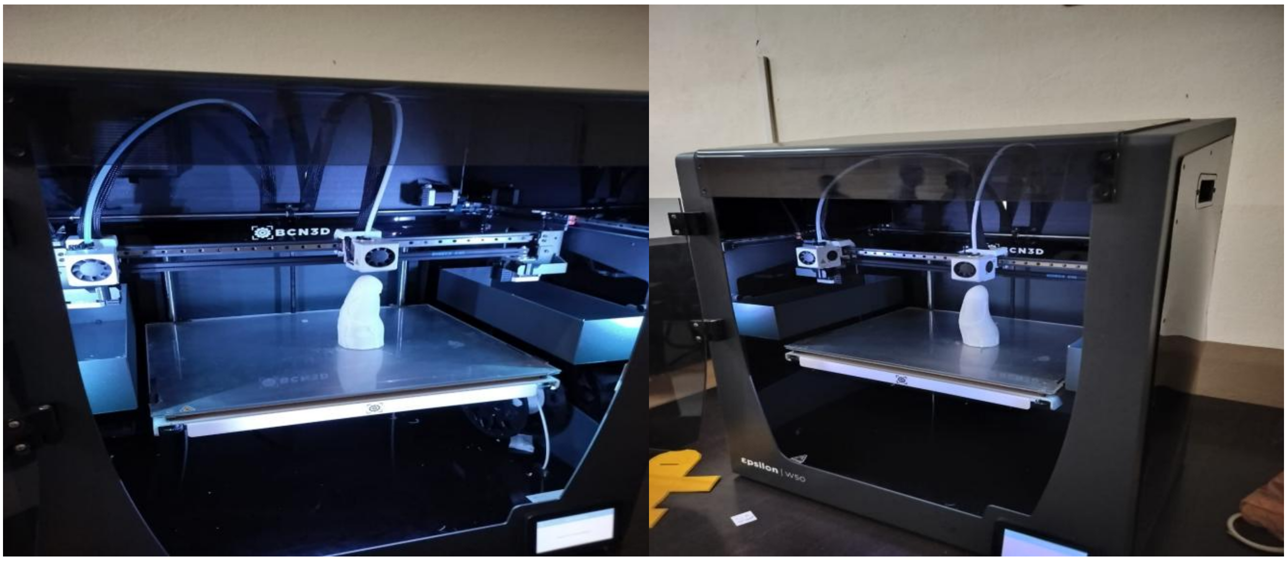


Fig.2. BCN3D Epsilon 50 Fused Filament Fabrication (FFF) Printer.

The BCN3D Epsilon 50 printer is characterized by a heated bed platform that is horizontal motion in the *x-y* axis and an extruder with the capability for vertical motion in the z-axis, along with a nozzle to provide accurate extrusion for component creation. The extensive build area is of $690 \times 530\,mm$, with a maximum build height of $900\,mm$, as shown in Fig.2, which can print large components. This machine uses layer-by-layer extrusion, taking a $1.8\,mm$ diameter Polylactic Acid (PLA) filament and feeding it into a $0.15\,mm$ diameter heated nozzle, controlled by a stepper motor. Parts are made with a layer thickness of $0.075\,mm$, perfect for high-resolution builds.

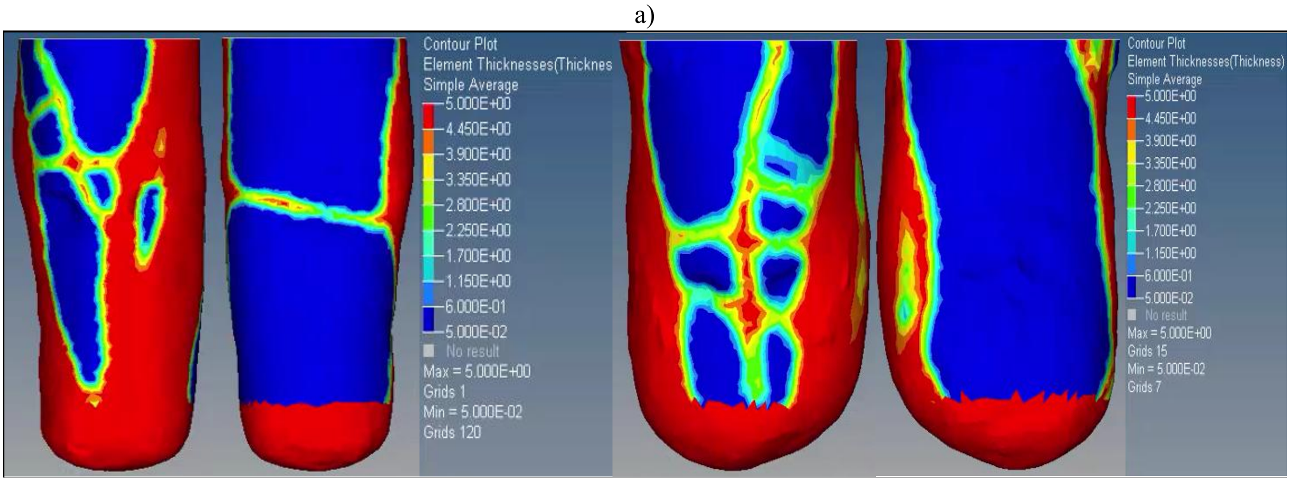
The temperature is set to $220°C$ in the extruder during the manufacture process, with the filament entering at $210°C$ for the first and outer layers, while the bed at $60°C$. The extruded PLA filament is making the socket layer by layer, thus ensuring its quality in build. It might need slight sanding or a sandpaper polish for smooth seams or burrs, considering the extrusion process of the socket may affect the finish and comfort when completed for end-use as prosthetics.

3. Results

3.1. Result of topology optimization

The optimization process aims to simulate prosthetic socket compliance under vertical load, with a fixed base, minimizing volume while maintaining structural integrity. The results revealed that the volume of the original socket design can be significantly decreased without the loss of robustness through the topology optimization. The final proposed design could bear everyday loads without failure because the optimization produced trustworthy outcomes that corresponded to the material's yield strength.

a)



b)

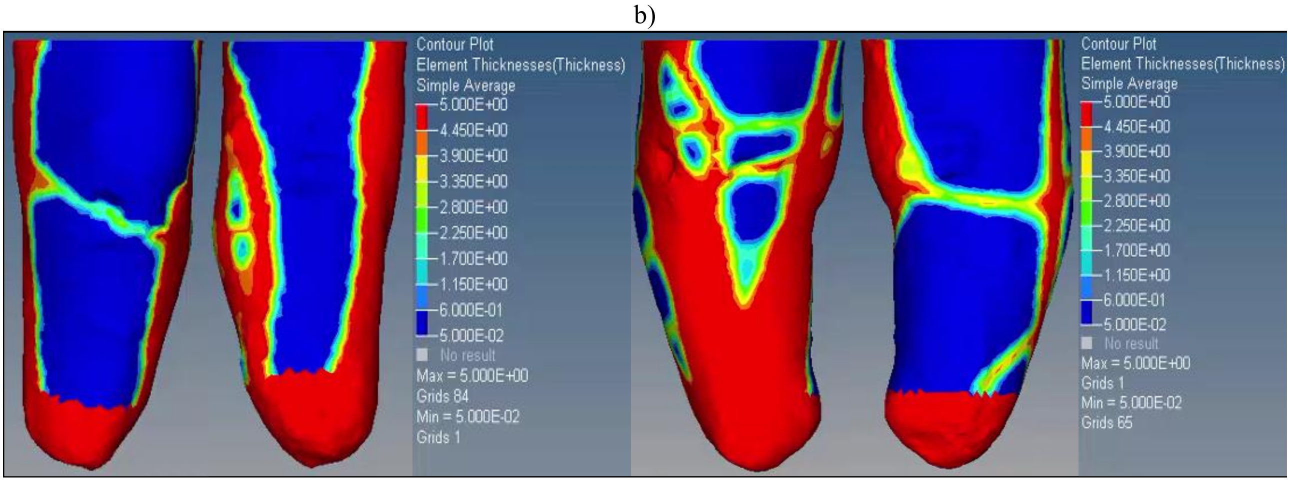


Fig.3. a) Elemental thickness distribution of P1 (left) and P2 (right), b) Elemental thickness distribution of P3 (left) and P3 (right).

The topology optimization for patients P1, P2, and P3 is shown in Fig.3, where the elemental thickness distribution in the left and right sockets is given. Red zones are occupied by material and blue zones for possible void zone. This distribution is very important, since it calls for variable thickness within the socket, and material placement need to be optimized according to the pressure demands. Regions under higher pressure need a greater thickness to provide more strength, whereas in low-pressure regions, the area can be thinned out. This approach not only enhances comfort and functionality but also minimizes material use, making the prosthetic both cost-effective and performance-optimized.

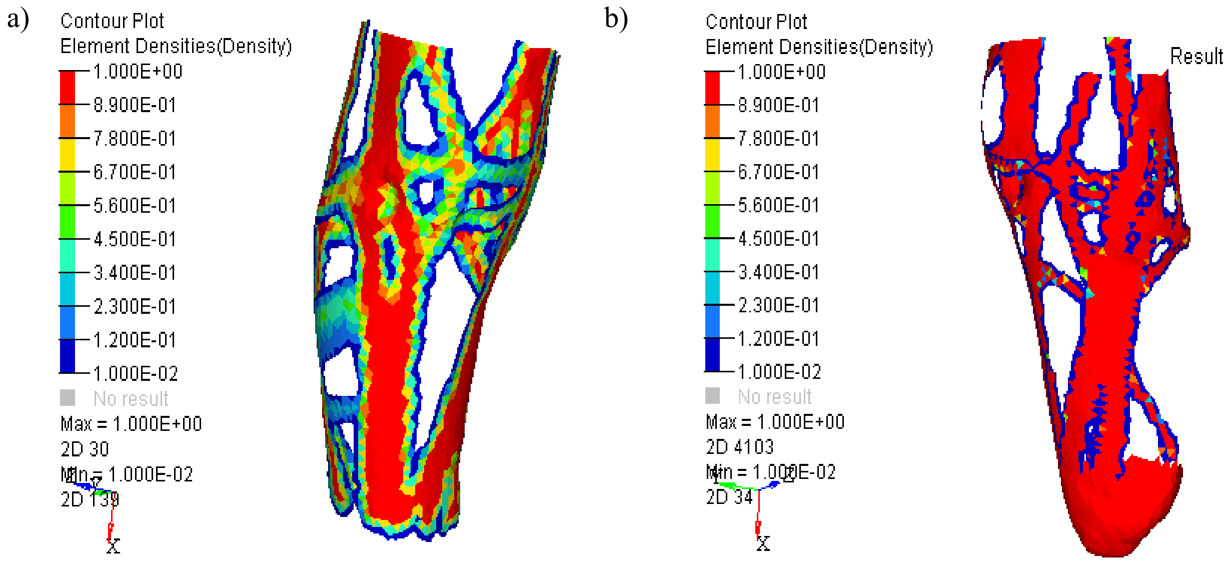


Fig.4. Elemental density distribution for a) Patient 1 b) Patient 2.

The elemental density distribution results, illustrated in Fig.4, reveal the optimized material layout after convergence of the topology optimization. In these density plots, red zones represent critical areas where material presence is essential to withstand loads, while blue zones show areas with minimal material distribution, which could be safely removed or redesigned. The transitional regions, marked by intermittent density, indicate areas where material gradually thins out. Also displays irregular, string-like designs, highlighting the concentration of material in regions experiencing higher stress, consistent with previous findings. The load-bearing regions are denoted as solid, while voids appear in unloaded zones.

As suggested by the results, material removal within the original prosthesis should be approached thoughtfully. The elemental density distribution does not simply suggest material elimination; rather, it guides the structural redesign of the socket for performance and durability. For cases with high mass reduction, the prosthesis must maintain a stress level within 30% of the material's yield strength, effectively preventing fatigue-related concerns in short-term applications. This approach ensures that material density is optimized without compromising the integrity of the prosthesis, ultimately improving its durability while achieving significant mass reduction and maximizing patient comfort and mobility.

3.2. Dimensional evaluation of drafted prototype

The efficiency of any system is closely tied to its inspection planning strategy; hence, an optimized inspection approach is essential to yield accurate and quick results. The dimensional evaluation of both the additively manufactured (AM) prosthesis socket and the Plaster of Paris (PoP) socket was conducted using Steinbichler INSPECTPLUS software. As shown in Fig.5, average deviation data for each STL file (AM and PoP sockets) were aligned electronically for precise comparison. Due to the complex free-form surfaces involved, a best-fit alignment method was selected to ensure accurate dimensional evaluation.

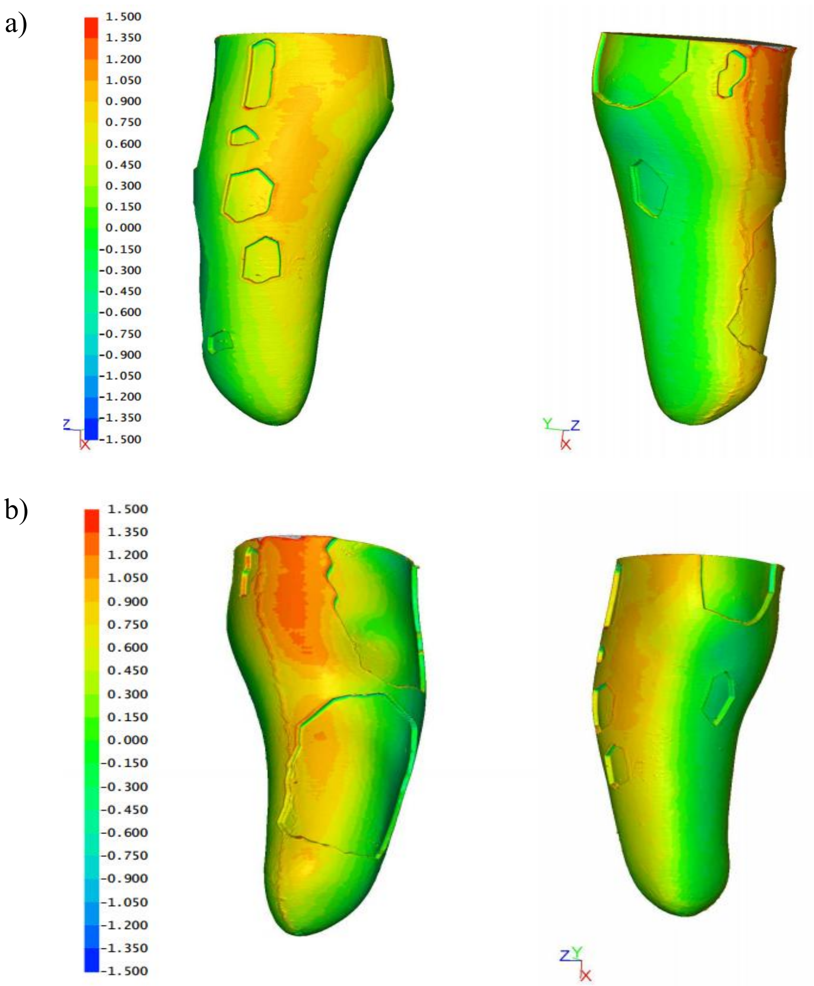


Fig.5. Average deviation illustrated: a) lateral and medial views, b) posterior and anterior views.

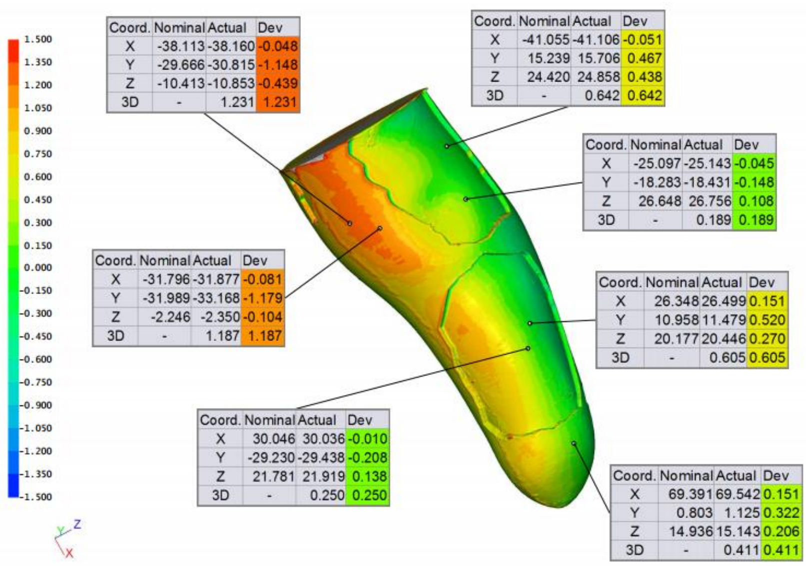


Fig.6. Point-to-point deviation compared to the actual CAD model.

Following alignment, a surface comparison was performed between the two STL files, with results presented in Fig.6. The comparison chart illustrates a deviation distributed across the profile, with the maximum discrepancy between the AM and PoP sockets at approximately $2.2\,mm$. The dimensional comparison between the additively manufactured socket and the conventional Plaster of Paris (PoP) socket revealed a maximum deviation of approximately $2.2\,mm$. In clinical practice, acceptable tolerance levels for prosthetic socket fabrication are typically reported within the range of $1-3\,mm$, depending on the anatomical region and fitting requirements. Therefore, the observed deviation falls within clinically acceptable limits and is unlikely to adversely affect socket performance. Minor geometric variations of this magnitude can generally be accommodated through the compliance of soft tissues and the use of liners, without significantly compromising fit or comfort. Furthermore, when compared to traditional fabrication methods, which often involve manual processes and operator-dependent variability, the achieved accuracy demonstrates that the proposed digital workflow provides comparable, if not improved, dimensional consistency. These findings support the feasibility of the proposed approach for practical prosthetic socket manufacturing. This level of deviation aligns closely with conventional tolerances, suggesting that the proposed method could be a viable alternative. Such accuracy in the dimensional match enhances confidence in the proposed approach, indicating its potential for reliable use in prosthesis socket production, aligning with industry standards.

3.3. Outcome of additive manufacturing

Figure 7. show a test socket that was created using an FDM-based additive manufacturing machine after topology optimization. The printed socket is then analysed for dimensional accuracy to ensure that it meets the required specifications. To check any geometric variation, the original socket is compared with its original CAD model before further proceedings with the final print.

Fig.7. Topology-optimized prosthetic socket fabricated via additive manufacturing.

Use Steinbichler inspection software to scan and inspect the printed socket as the first part of the inspection process. This process involves comparing the computer model against the printed reality, ensuring any discrepancy is thoroughly dealt with to ensure dimensional accuracy so that the final product may be adapted for fit and refinement and the optimal design can then successfully meet the patient's needs for prosthetic comfort and functionality.

After the prosthesis socket was created with a 3D printer in *480 minutes*, the prosthetic weighed *256 grams*. The wall thickness of the socket was designed to provide individualized support according to the patient's anatomy; it was from *3.2 mm* at the distal end up to *4.5 mm* around the patella-tendon region. Using the proposed integrated RE and AM, the manufacture time of the socket was reduced to *250 minutes*, thus having a very good efficiency improvement against conventional methods. It also helps improve the common digital process that removes the usual complaints of traditional methods of prosthetic fabrication, namely long production time and poor fitting. The completed socket, shown at the bottom of Fig.7, demonstrates the improved accuracy and flexibility provided by AM technology, providing a lighter, better-fitting prosthetic solution for the user.

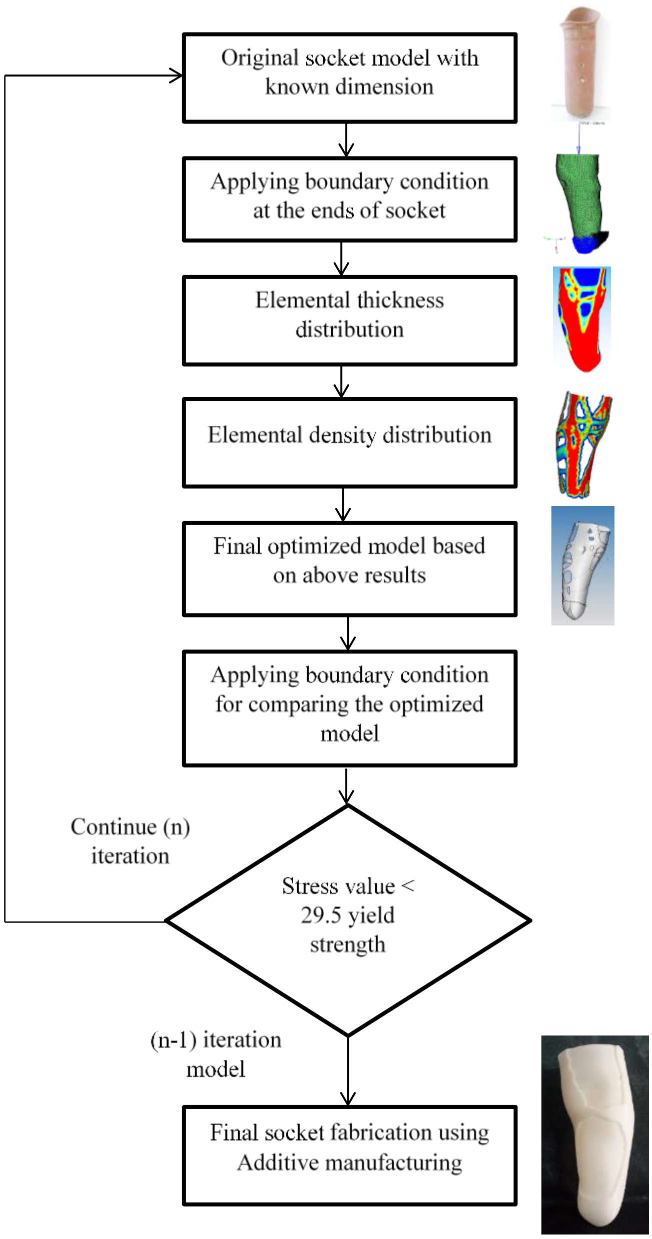


Fig.8. Flowchart illustrating the topology optimization process for the prosthetic socket.

4. Discussion

This work develops a customized complex geometry of the prosthetic socket using advanced 3D scanning technology to precisely capture the anatomy of the residual limb. In addition, focuses on the integration of topology optimization and additive manufacturing to design and fabricate a prosthetic socket using Polylactic Acid (PLA) through the fused deposition modelling (FDM) technique. It is found that fabrication of lower limb prosthetic sockets through these two technologies represents the transforming approach in prosthetic design. Such techniques will offer critical key challenges such as structural efficiency, comfort and personalization, which will make prosthetics more functional and user-friendly.

It involves the innovative process of creating customized prosthetic sockets through advanced 3D scanning and CAD modeling. It ensures an accurate fit by precisely capturing the geometry of the residual limb, enhancing the comfort and functionality of the prosthetic. It also helps in stress redistribution to prevent high-pressure zones on the residual limb, which is a common issue with traditional socket designs. CAD models refine raw data for manufacturing and enable personalized designs. A well-known challenge is to make a light yet robust socket, efficient structures tailored for each user, critical to user comfort and functionality. As such, topology optimization plays a huge role when identifying areas of stress that are minimal, meaning materials here can be removed without the structural integrity being compromised. This reduces weight and ensures the prosthesis stays solid enough to allow mobility and utilization.

The importance of digital manufacturing techniques, like FDM, in the manufacture of complex geometry prosthetic sockets is highlighted. Most traditional approaches cannot reproduce such detailed designs due to their inherent lack of precision and adaptability. It is in these aspects that FDM, as an additive manufacturing process, brings out the most definite, patient-specific geometries directly from digital models. This approach will provide an accurate, functional fit to the patient's specific needs. The use of FDM is overcoming the problems associated with the fabrication process while enabling rapid prototyping and cost-effectiveness. It is one of the biggest breakthroughs in personalized prosthetic development and has greatly improved patient care outcomes. AM is overcoming most of the traditional manufacturing constraints associated with it and providing intricate internal structures and patient-specific fits. Techniques such as 3D scanning of the anatomy of the residual limb are computer-aided designed into a specific socket model to avoid discomfort during its usage and less chance of readjustment in post-fabrication.

In the present study, the residual limb was not explicitly modeled, and no direct contact interaction between the limb and the prosthetic socket was defined within the finite element framework. Instead, the loading conditions applied to the socket were represented as equivalent external forces derived from experimentally measured strain data under different loading scenarios. While this approach simplifies the analysis and enables efficient evaluation of structural performance, it does not capture the complex biomechanical interaction at the socket–limb interface, particularly the effects of soft tissue deformation, pressure distribution, and frictional behavior. The compliance of soft tissues and their nonlinear material characteristics may significantly influence load transfer and stress distribution within the socket. Therefore, this simplification is acknowledged as a limitation of the current study. Future work will focus on incorporating detailed contact mechanics, including appropriate contact formulations, friction coefficients, and nonlinear soft tissue material models, to provide a more physiologically accurate representation of the socket–limb interaction.

5. Conclusions

This paper attempt to fabricate the prosthetic sockets for lower limb amputees using additive manufacturing (AM) following topology optimization. Conventional prosthetic sockets are often restricted in material choices, long production times and complexity in design. The artificial leg itself has its own weight therefore it is important to reduce the weight of socket without any compromise of strength. Utilizing additive manufacturing techniques allowed the fabrication of lightweight, customized, and high-performance prosthetic sockets. The concepts of topology optimisation provide a feasible solution in weight reduction but with complex geometry.

Thus, topology optimization was employed to improve the structural design of the socket, suggestively reducing material usage without compromising strength. By improving comfort and load distribution, the optimised design made sure that the socket would fit the residual limb well. The resulting prosthetic socket offers improved production timelines from $480\,min$ to $250\,minutes$. Also, the significance of additive manufacture is observed, fused deposition model (FDM) is capable of fabricating this prosthetic socket with a high level of accuracy with the weight reduced from $289\,grams$ to $256\,grams$. Since these sockets require high level of customization, the combination of topology optimization with additive manufacturing will ease the process. In summary, this study provides a significant step in manufacturing tailormade prosthetics, paving the way for innovations in patient-specific, high-performance and customized prosthetic solutions.AI-driven topology optimization is another promising area, accelerating the design process while further improving performance.

Nomenclature

E	– elastic modulus (GPa)
p	– SIMP penalization factor
VF	– volume fraction
$VFUB$	– volume fraction upper bound
ν	– Poisson's ratio
FE	– finite element
FDM	– Fused Deposition Modelling
FFF	– Fused Filament Fabrication
PLA	– Polylactic Acid
PoP / POP	– Plaster of Paris
RP	– Rapid Prototyping
$SIMP$	– Solid Isotropic Material with Penalization
SLS	– Selective Laser Sintering
STL	– Standard Tessellation Language

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Conflict of interest

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Data availability

My manuscript has no associate data

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