

Study of Structural and Mechanical Behavior of HDPE and MCR Used for Prosthetic Foot Implant

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Abstract: Prosthetic foot design plays a critical role in restoring mobility and quality of life for individuals with lower-limb amputation, particularly in low-resource settings where affordability, durability, and functional reliability are essential. The Jaipur-Foot prosthesis is widely used due to its low cost and cultural adaptability; however, its long-term structural performance is strongly influenced by material selection. Traditional microcellular rubber (MCR), while offering flexibility and shock absorption, has been associated with excessive deformation and limited fatigue resistance under repetitive loading. Despite the increasing clinical adoption of high-density polyethylene (HDPE) as an alternative prosthetic material, a direct component-level numerical comparison between HDPE and MCR for Jaipur-Foot applications remains limited. In this study, a Jaipur-Foot-inspired three-dimensional model was developed using computer-aided design and evaluated through finite element analysis. Static structural analysis was performed under physiological load levels ranging from 600 N to 1200 N, followed by fatigue life estimation and topology optimization using ANSYS Mechanical. The results indicate that HDPE exhibits a more uniform stress distribution and controlled deformation compared to MCR across all loading conditions. Under a 1200 N load, the maximum equivalent stress remained below 9×10^5 Pa for HDPE, while fatigue life predictions showed a significantly higher endurance compared to MCR. Topology optimization further demonstrated the potential for material reduction without compromising structural safety. Overall, the findings suggest that HDPE offers improved structural reliability and fatigue performance over conventional MCR, highlighting its suitability as a biomaterial for durable and cost-effective Jaipur-Foot prosthetic applications.

Keywords: Jaipur Foot; High-Density Polyethylene; Microcellular Rubber; Finite Element Analysis; Fatigue Behavior; Biomaterials.

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I. INTRODUCTION

Lower-limb amputation significantly affects mobility, balance, and overall quality of life, necessitating prosthetic solutions that are mechanically reliable, comfortable, and affordable. Among the various prosthetic components, the foot plays a critical role as it is the primary interface between the user and the ground, responsible for load transmission, shock absorption, and stability during gait. In low- and middle-income countries, where access to advanced prosthetic technologies is limited, low-cost prosthetic feet such as the Jaipur Foot remain widely adopted due to their simplicity, cultural acceptability, and cost-effectiveness [1], [2].

The Jaipur Foot prosthesis is traditionally manufactured using microcellular rubber (MCR), which provides flexibility and impact attenuation during barefoot walking and uneven terrain use. While MCR-based designs offer advantages in comfort and adaptability, long-term field observations and clinical studies have reported material degradation, excessive deformation, and fatigue-related failures under repetitive physiological loading [14], [4]. These limitations highlight the importance of material selection in determining the structural integrity and service life of prosthetic foot components. From a biomaterials perspective, the mechanical behavior, fatigue resistance, and manufacturability of the chosen material directly influence prosthetic durability and user safety [7].

High-density polyethylene (HDPE) has emerged as a promising alternative biomaterial for prosthetic foot applications owing to its favorable strength-to-weight ratio, improved fatigue performance, environmental resistance, and ease of processing [12], [13], [21]. Although HDPE has been introduced in clinical practice for Jaipur-Foot-type prostheses, its structural performance relative to conventional MCR has not been comprehensively quantified at the component level using numerical methods [20]. In particular, direct comparisons under identical geometry, loading, and boundary conditions remain limited.

In this context, the present study aims to provide a systematic finite element-based evaluation of HDPE and MCR when applied to a Jaipur-Foot-inspired prosthetic geometry. By integrating computer-aided design, static structural analysis under physiologically relevant loads, fatigue life estimation, and topology optimization, this work seeks to establish an engineering-driven basis for biomaterial selection in low-cost prosthetic foot design [10], [26], [24]. The findings are intended to support the development of durable, efficient, and accessible prosthetic solutions for lower-limb amputees.

➤ *Clinical and Application Background*

A prosthetic foot is required to replicate the essential mechanical functions of the natural human foot, including load support, impact absorption, and stability during standing and ambulation. During daily activities such as walking, stair climbing, and negotiating uneven terrain, the prosthetic foot experiences complex loading conditions that vary across different phases of gait [3], [9]. Consequently, inadequate structural performance of the foot component can lead to discomfort, reduced mobility, and premature failure, adversely affecting the quality of life of the user [6].

In low-resource settings, prosthetic solutions must additionally satisfy constraints related to affordability, ease of manufacturing, and adaptability to local lifestyle requirements. The Jaipur Foot prosthesis has been widely adopted in such contexts due to its low cost, simple fabrication, and suitability for barefoot walking and floor-based activities [5]. Its design enables users to perform culturally significant movements such as squatting and cross-legged sitting. Despite these advantages, long-term clinical use has revealed structural limitations associated with material degradation and fatigue-related damage, particularly under repetitive loading conditions [4], [25]. These observations underscore the need for engineering-based evaluation of material performance to improve durability while retaining functional benefits.

➤ *Materials Context from a Biomaterials Viewpoint*

Material selection plays a decisive role in the clinical performance and longevity of prosthetic foot components. From a biomaterials perspective, the selected material must exhibit an appropriate balance between stiffness and flexibility to ensure efficient load transfer while minimizing impact forces transmitted to the residual limb [7], [18]. Additionally, resistance to fatigue, environmental stability, and manufacturability are critical factors that influence long-

term reliability and user comfort [19].

Microcellular rubber (MCR) has traditionally been used in Jaipur Foot prostheses due to its excellent shock-absorbing capability and high compliance, which facilitate adaptability to uneven terrain [1], [14]. However, its relatively low stiffness and limited fatigue resistance can result in excessive deformation and progressive material degradation during prolonged use [15], [16]. In contrast, high-density polyethylene (HDPE) is a thermoplastic biomaterial that offers improved mechanical strength, favorable fatigue behavior, low density, and resistance to environmental degradation [11], [12]. HDPE has been increasingly explored in prosthetic applications as a potential alternative to elastomeric materials, aiming to enhance structural reliability without substantially increasing cost or weight [17]. A systematic comparison of these two materials at the component level is therefore essential to establish an informed biomaterials selection strategy for durable Jaipur-Foot prosthetic designs.

➤ *Gaps in Literature*

Although the Jaipur Foot prosthesis has been extensively studied from clinical, biomechanical, and socio-economic perspectives, the existing literature reveals several limitations from an engineering and biomaterials standpoint [7]. Most reported studies focus on clinical performance, user satisfaction, and qualitative failure observations, with limited emphasis on quantitative structural evaluation. As a result, the internal stress distribution and deformation behavior of Jaipur-Foot prostheses under physiological loading conditions remain insufficiently characterized [10], [26].

Furthermore, while both microcellular rubber (MCR) and high-density polyethylene (HDPE) have been employed in Jaipur-Foot-type prostheses, direct component-level comparisons between these materials are scarce. Available studies often investigate material behavior in isolation or under simplified test configurations, without evaluating their performance within an identical prosthetic geometry and boundary condition framework [6], [16]. In particular, finite element-based investigations addressing static structural response, fatigue life estimation, and safety assessment in a unified manner are limited [23].

In addition, the application of topology optimization techniques to prosthetic foot components has not been widely reported. The potential of numerical optimization to reduce material usage and weight while maintaining structural integrity remains largely unexplored for low-cost prosthetic feet [24]. These gaps highlight the need for an integrated computational approach that combines structural analysis, fatigue evaluation, and design optimization to support evidence-based biomaterials selection for Jaipur-Foot prostheses.

➤ *Objectives and Contributions of the Present Work*

In response to the identified gaps, this study aims to provide a comprehensive numerical evaluation of biomaterials used in Jaipur-Foot prosthetic applications. The

primary contributions of the present work are as follows: (i) development of a Jaipur-Foot-inspired three-dimensional CAD model suitable for finite element analysis; (ii) systematic comparison of high-density polyethylene and microcellular rubber under multiple physiologically relevant load conditions using static structural analysis; (iii) numerical estimation of fatigue life and safety factors to assess long-term durability; and (iv) application of topology optimization to identify opportunities for material reduction and weight efficiency without compromising structural performance [24]. Collectively, these contributions establish an engineering-driven framework for informed biomaterials selection and design improvement of low-cost prosthetic foot systems.

II. MATERIALS AND METHODS

This section describes the materials, geometric modeling, and numerical procedures adopted in this study to ensure reproducibility and enable a systematic comparison of high-density polyethylene and microcellular rubber for Jaipur-Foot prosthetic applications.

➤ Materials

Two polymeric materials commonly employed in low-cost prosthetic foot applications were selected for the present investigation: high-density polyethylene (HDPE) and microcellular rubber (MCR). These materials were chosen due to their clinical relevance in Jaipur-Foot prostheses and their contrasting mechanical characteristics, which allow a meaningful assessment of structural and fatigue performance [1], [5].

High-density polyethylene is a semi-crystalline thermo-plastic biomaterial widely used in biomedical and prosthetic applications owing to its favorable strength-to-weight ratio, good fatigue resistance, and environmental stability [11], [12], [21]. Its relatively higher elastic modulus enables effective load transfer during the stance phase of gait, thereby reducing excessive deformation of the prosthetic structure under physiological loading [18]. Additionally, HDPE offers advantages in terms of manufacturability, recyclability, and resistance to moisture and chemical degradation, making it suitable for prolonged use in diverse environmental conditions [19], [20]. Microcellular rubber is an elastomeric material traditionally used in Jaipur-Foot designs because of its high compliance and excellent shock-absorbing capability [1], [14]. The presence of micro-sized air cells within the material structure facilitates energy dissipation during heel strike and improves adaptability to uneven terrain [3]. However, the lower stiffness and limited fatigue resistance of MCR may result in large deformations and progressive material degradation under repetitive loading, which can adversely affect long-term durability [15], [16]. The material properties required for numerical simulation, including density, Young's modulus, Poisson's ratio, yield or ultimate strength, and fatigue characteristics, were obtained from published literature and standard material databases [11], [13], [12]. These properties were assigned uniformly across the prosthetic geometry to ensure

consistent comparison between materials.

For static structural simulations, both materials were modeled as homogeneous, isotropic, and linearly elastic. This assumption is commonly adopted for comparative finite element studies and is considered appropriate for evaluating relative stress distribution and deformation trends under quasi-static loading conditions. The viscoelastic and time-dependent behavior of microcellular rubber was not included in the present analysis and is acknowledged as a limitation of the study, to be addressed in future investigations involving dynamic or long-term loading scenarios.

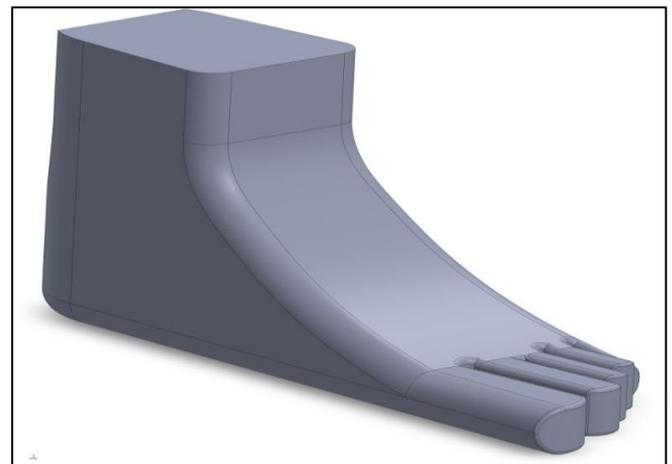


Fig 1 Isometric View of the Jaipur-Foot-Inspired CAD Model Developed for Finite Element Analysis, Illustrating the Overall Geometry and Major Structural Regions.

➤ Geometry and CAD Model

The prosthetic foot geometry employed in this study was developed as a Jaipur-Foot-inspired model, reflecting the overall form, functional regions, and load-bearing characteristics of the clinically used Jaipur Foot prosthesis. The geometry was created using computer-aided design based on the dimensions and proportions reported in the Project Phase 2 final report and implemented in SolidWorks before export as an IGES file for numerical analysis.

The overall length of the prosthetic foot was defined from the posterior heel region to the distal toe end, with distinct segmentation of the heel, midfoot, forefoot, and toe regions. An ankle block region was incorporated at the proximal end to enable realistic load application from the residual limb. The plantar surface was designed to provide a stable contact interface with the ground, while maintaining the characteristic curvature associated with Jaipur-Foot designs.

Due to the artisan-based manufacturing process and complex organic contours of the traditional Jaipur Foot, an exact geometric reproduction was not feasible. Therefore, geometric simplifications were introduced to enhance numerical stability and reproducibility. These simplifications included the use of locally flattened contact planes, idealized transitions between foot segments, and simplified toe segmentation. Such modifications are

commonly adopted in finite element studies and were implemented to improve mesh quality and ensure consistent application of boundary conditions, without altering the primary load-transfer pathways of the prosthetic foot.

➤ *Finite Element Model*

The three-dimensional CAD model of the Jaipur-Foot-inspired prosthesis was developed using SolidWorks (Dassault Systèmes, version 2021) and exported in IGES format for numerical analysis. Finite element simulations were performed using ANSYS Workbench (ANSYS Inc., version 2021 R2), which provides an integrated environment

for structural and fatigue analysis of complex geometries.

The imported geometry was discretized using three-dimensional tetrahedral solid elements, selected due to their suitability for modeling complex prosthetic shapes with curved surfaces and segmented regions. A uniform element size of 3 mm was employed throughout the prosthetic geometry, consistent with the meshing strategy reported in the Project Phase 2 final documentation. This mesh density provided an effective balance between computational efficiency and solution accuracy.

Table 1 Mechanical and Fatigue Properties of HDPE and Microcellular Rubber Used in the Finite Element Analysis

Property	HDPE	MCR
Density (kg/m ³)	~950	~1100
Young's modulus (MPa)	800–1200	5–20
Poisson's ratio	0.40–0.45	0.45–0.49
Yield / ultimate strength (MPa)	~26 / ~30	~5–10
Fatigue behavior (S–N data source)	Moderate to good [13], [12]	Low to moderate [15], [14]

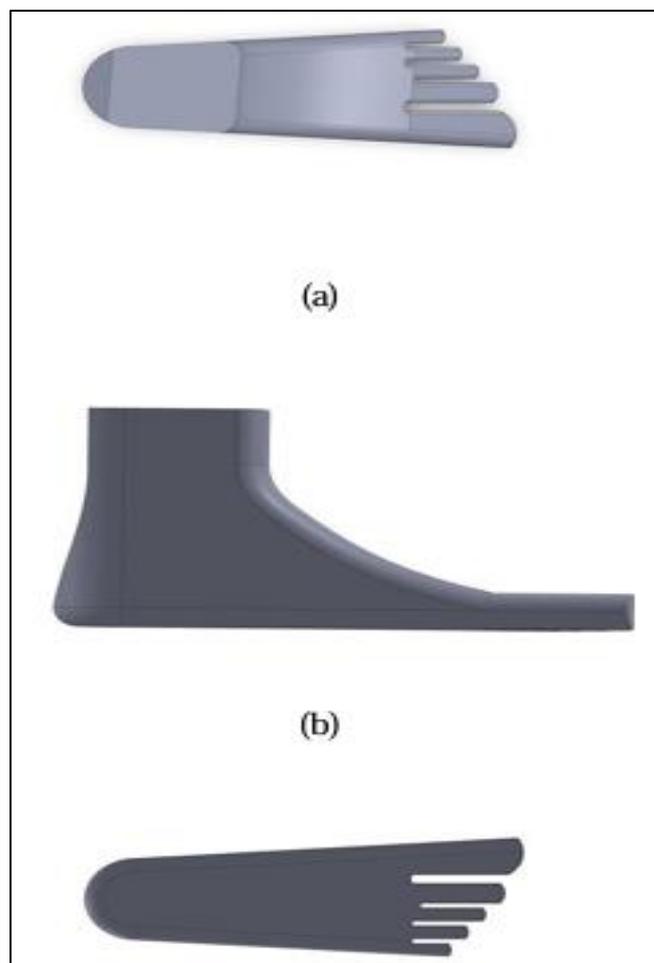


Fig 2 Orthographic Views of the Prosthetic Foot CAD Model: (a) Top View, (b) Side View, and (c) Bottom View, Showing Geometric Proportions and Contact Surfaces.

Mesh quality was evaluated by examining element skewness, aspect ratio, and Jacobian metrics to ensure numerical stability of the simulations. A brief mesh sensitivity assessment was conducted by locally refining

the mesh in regions of anticipated high stress, confirming that further refinement resulted in negligible changes in peak stress values. The finalized mesh configuration was applied consistently for both HDPE and microcellular rubber models to ensure an unbiased comparative analysis.

➤ *Boundary Conditions and Load Cases*

Boundary conditions were defined to replicate the load transfer and ground contact experienced by a prosthetic foot during standing and ambulation. The plantar surface of the prosthetic foot, including the heel and forefoot contact regions, was assigned a fixed support condition. This constraint restricted all translational and rotational degrees of freedom on the selected faces, representing firm contact with a rigid ground surface during stance. The fixed plantar support assumption is commonly employed in prosthetic foot simulations to evaluate internal stress distribution under worst-case loading scenarios.

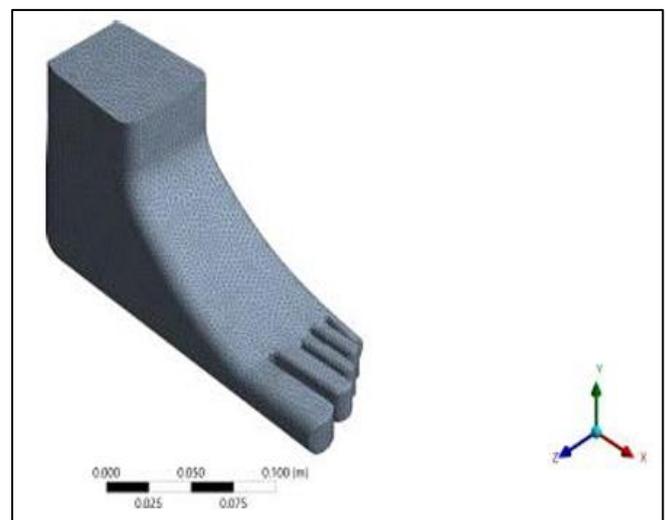


Fig 3 Finite Element Mesh of the Jaipur-Foot Prosthetic Model, Highlighting Local Refinement in Regions Prone to Stress Concentration.

Table 2 Summary of Load Cases Applied to the Jaipur-Foot Prosthetic Model and their Corresponding Physiological Interpretations

Load case ID	Load magnitude (N)	Interpretation
LC1	600	Standing load
LC2	800	Normal walking load
LC3	1000	Increased gait load
LC4	1200	Dynamic / impact load

Vertical compressive loads were applied at the proximal ankle block region of the prosthetic model to represent force transmission from the residual limb. The load was distributed uniformly over the top surface of the ankle block to avoid artificial stress concentrations. All loads were applied in the negative vertical direction, aligned with the global gravitational axis, under quasi-static conditions.

Four load magnitudes were considered in the analysis: 600 N, 800 N, 1000 N, and 1200 N. These values were selected to represent a range of physiological loading conditions, including body weight during standing, increased loads during normal walking, and higher transient loads associated with dynamic or impact-related activities. Contact between the prosthetic foot and the ground was assumed to be rigid, with no relative sliding or deformation at the interface, to focus the analysis on the structural response of the foot materials.

➤ *Analysis Types and Solver Settings*

Static structural analysis was performed to evaluate the deformation, stress distribution, and elastic strain response of the prosthetic foot under the defined loading conditions. Both HDPE and microcellular rubber were modeled as homogeneous, isotropic, and linearly elastic materials. Linear static analysis was adopted, as the objective of the study was to compare relative structural responses between materials under quasi-static physiological loads. Small deformation theory was assumed for all simulations, which is considered appropriate given that the predicted deformations remained within acceptable limits relative to the overall geometry.

Fatigue life estimation was conducted using the stress–life (S–N) approach available within the ANSYS Mechanical fatigue module. Equivalent von Mises stress obtained from the static structural analysis was used as the fatigue input parameter. Material-specific S–N data were defined based on published literature and material databases, enabling estimation of fatigue life, damage accumulation, and safety factors at critical stress locations. Fully reversed loading conditions were assumed to provide a conservative assessment of fatigue performance.

Topology optimization was applied to identify regions of low structural contribution within the prosthetic foot model. The optimization objective was defined as material mass minimization, subject to a prescribed volume reduction constraint while maintaining structural stiffness. Stress and displacement constraints obtained from the static analysis were enforced to ensure that the optimized design remained within safe operational limits. The

optimization results were used to assess potential design improvements toward lightweight and material-efficient prosthetic configurations.

Numerical convergence was controlled using default AN-SYS solver tolerances, with force and displacement residuals limited to 10^{-3} . Second-order tetrahedral solid elements were employed to improve solution accuracy in regions of geometric complexity. All simulations were solved using the sparse direct solver to ensure numerical robustness and consistency across material comparisons.

➤ *Output Metrics and Evaluation Criteria*

The structural and fatigue performance of the Jaipur-Foot prosthetic model was evaluated using a set of quantitative output metrics extracted from the finite element simulations. These metrics were selected to characterize the mechanical response of the prosthetic foot under physiological loading conditions and to enable a direct comparison between HDPE and microcellular rubber.

Equivalent von Mises stress was used as the primary indicator of internal stress distribution and was employed to identify critical regions prone to material yielding or failure. Total deformation was evaluated to assess the overall stiffness of the prosthetic structure and to quantify material-dependent differences in load-induced displacement. Equivalent elastic strain was monitored to examine localized deformation behavior and to support interpretation of stress concentrations within the prosthetic foot geometry.

Fatigue performance was assessed in terms of predicted fatigue life, expressed as the number of load cycles to failure, and cumulative fatigue damage obtained from the stress–life analysis. In addition, the factor of safety was computed to provide a relative measure of structural reliability under each load case and material configuration.

Failure criteria were defined based on both static and fatigue considerations. Static failure was assumed to occur when the maximum equivalent stress exceeded the yield or ultimate strength of the material. Fatigue failure was defined as the onset of damage accumulation equal to or greater than unity, corresponding to a predicted fatigue life lower than the expected service requirements. These criteria were applied consistently across all simulations to ensure an objective comparison of material performance.

III. RESULTS

This section presents the numerical results obtained from the finite element simulations of the Jaipur-Foot

prosthetic model. The results are reported in terms of stress distribution, deformation response, fatigue life, and safety factor for both high-density polyethylene and microcellular rubber. Figures and tables are used to clearly illustrate the comparative performance of the two materials under different loading conditions, with minimal interpretation provided in this section.

➤ *Mesh and Model Verification*

Mesh verification was carried out to ensure that the numerical results were not significantly influenced by the discretization strategy. The finite element mesh adopted for subsequent analyses was evaluated by monitoring variations in the maximum equivalent von Mises stress with changes in mesh density. A brief mesh sensitivity check indicated that further mesh refinement resulted in negligible changes in peak stress values, confirming mesh independence of the solution. Based on this verification, the selected mesh configuration was considered sufficient to accurately capture stress concentrations and deformation behavior while maintaining computational efficiency. The same mesh was applied

consistently for all material models and load cases to ensure reliable comparative assessment.

➤ *Static Stress Distributions*

The static structural response of the Jaipur-Foot prosthetic model was evaluated in terms of equivalent von Mises stress for both high-density polyethylene and microcellular rubber under the defined loading conditions. Representative stress fields are reported for a mid-level load and the highest applied load to illustrate material-dependent differences in stress distribution and magnitude.

At the maximum load of 1200 N, both materials exhibited localized stress concentrations in the ankle block and adjacent midfoot regions. The spatial distribution and peak stress values varied between materials, reflecting differences in stiffness and load-transfer characteristics.

Peak stress values obtained for all load cases are summarized to enable quantitative comparison between the two materials.

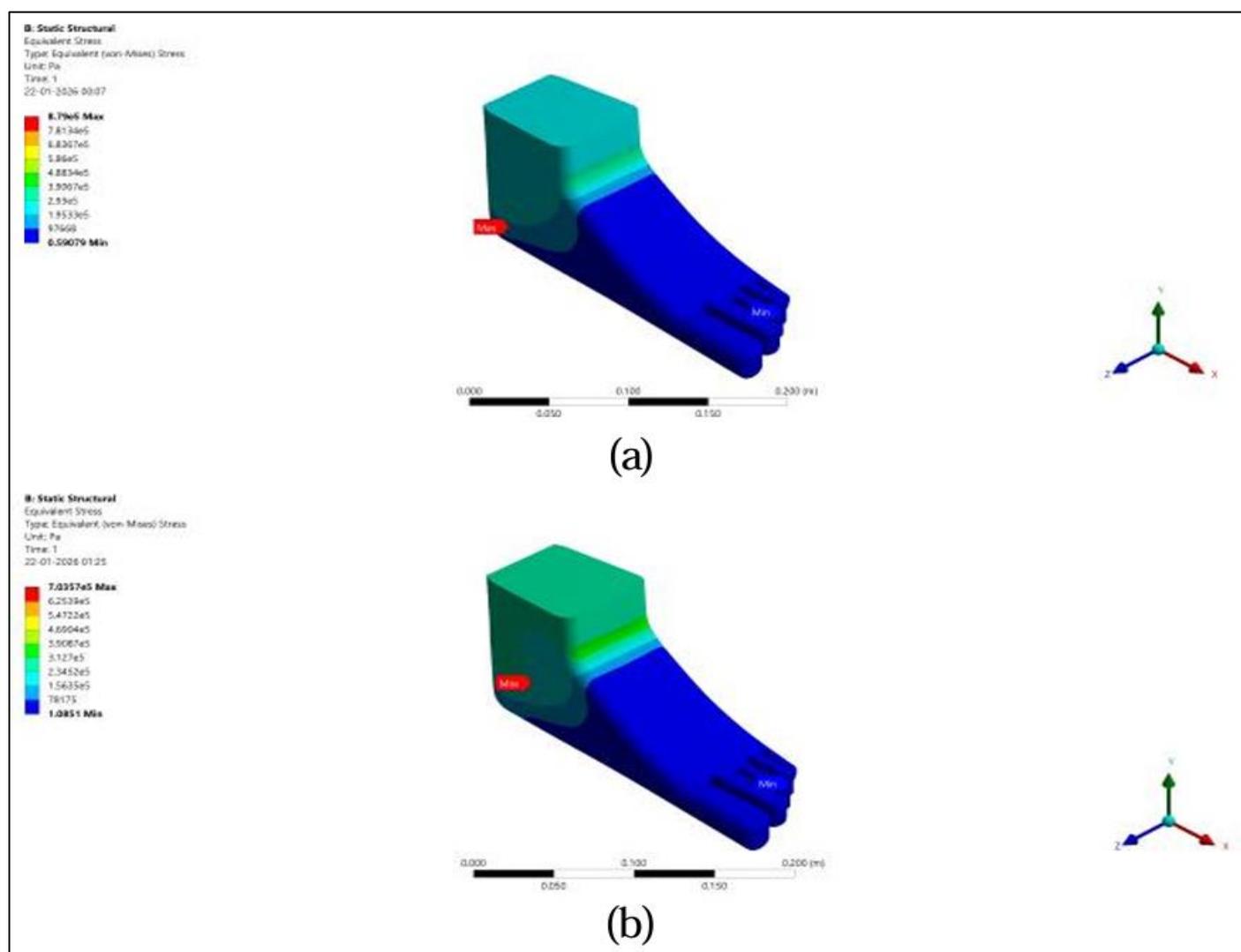


Fig 4 Equivalent Von Mises Stress Distributions in the Jaipur-Foot Prosthetic Model Under a 1200 N Static load: (a) HDPE Material and (b) Microcellular Rubber Material.

Table 3 Maximum Equivalent Von Mises Stress Values Obtained for HDPE and Microcellular Rubber Under Different Static Load Cases

Load (N)	HDPE peak stress (MPa)	MCR peak stress (MPa)
600	0.39	0.295
800	0.521	0.377
1000	0.586	0.895
1200	0.879	0.982

Table 4 Maximum Total Deformation Values for HDPE and Microcellular Rubber Under Different Static Load Conditions

Load (N)	HDPE deformation (mm)	MCR deformation (mm)
600	0.013	2.9
800	0.021	3.6
1000	0.030	5.0
1200	0.039	6.4

➤ *Total Deformation*

The total deformation response of the Jaipur-Foot prosthetic model was evaluated for both materials under all applied static load cases. Deformation contours were used to visualize the global displacement patterns and to quantify material- dependent differences in structural stiffness.

Representative deformation fields corresponding to the high- est applied load of 1200 N are presented for high- density polyethylene and microcellular rubber.

The maximum deformation values obtained for all load cases are summarized to facilitate quantitative comparison between the two materials.

➤ *Strain and Principal Stress Response*

The strain response of the Jaipur-Foot prosthetic model was evaluated to examine localized deformation behavior and identify regions subjected to high mechanical demand. Equivalent elastic strain contours were used to assess material- dependent differences in strain distribution under static loading conditions.

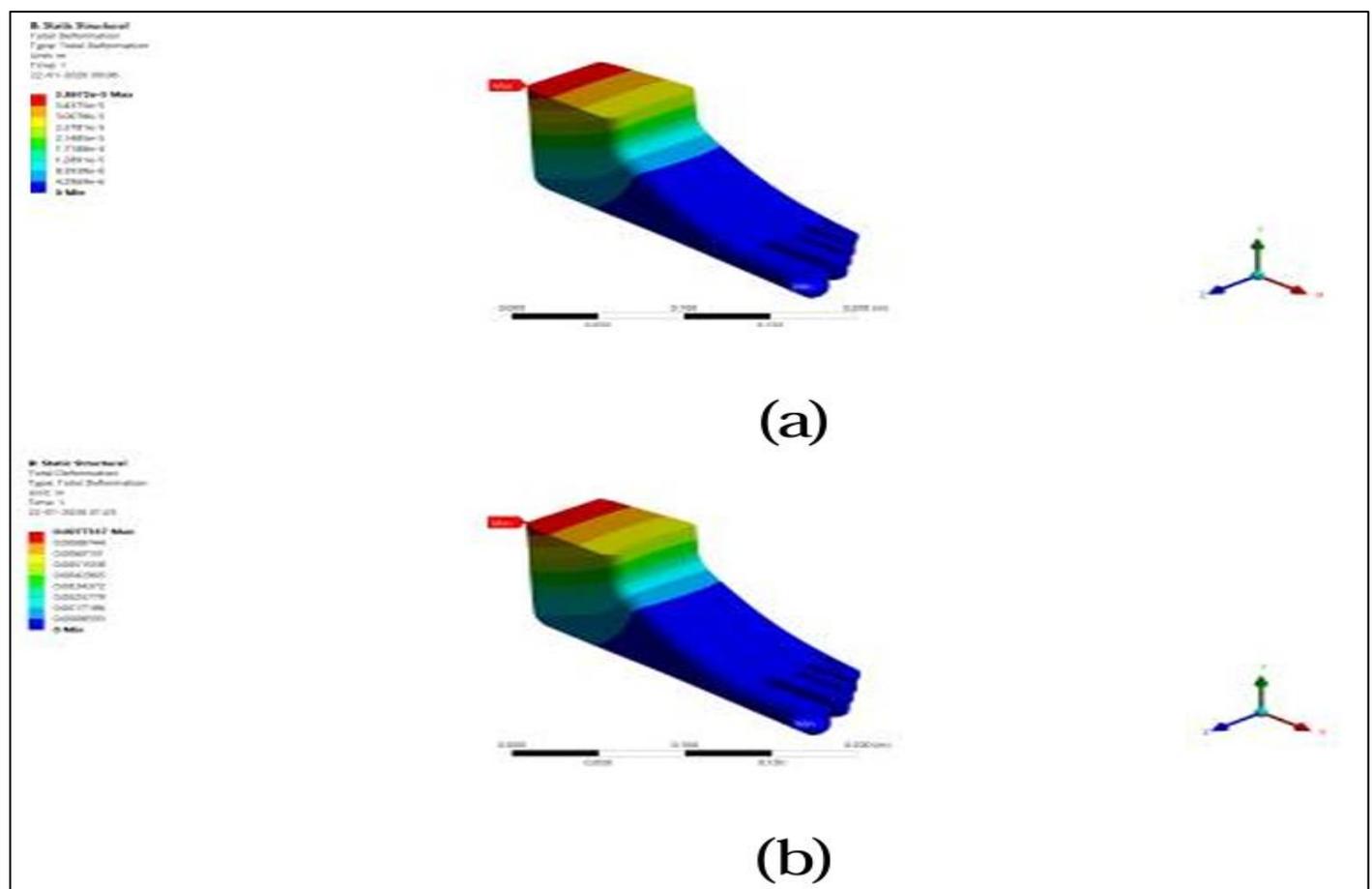


Fig 5 Total Deformation Distributions of the Jaipur-Foot Prosthetic Model Under a 1200 N Static Load: (a) HDPE Material and (b) Microcellular Rubber Material.

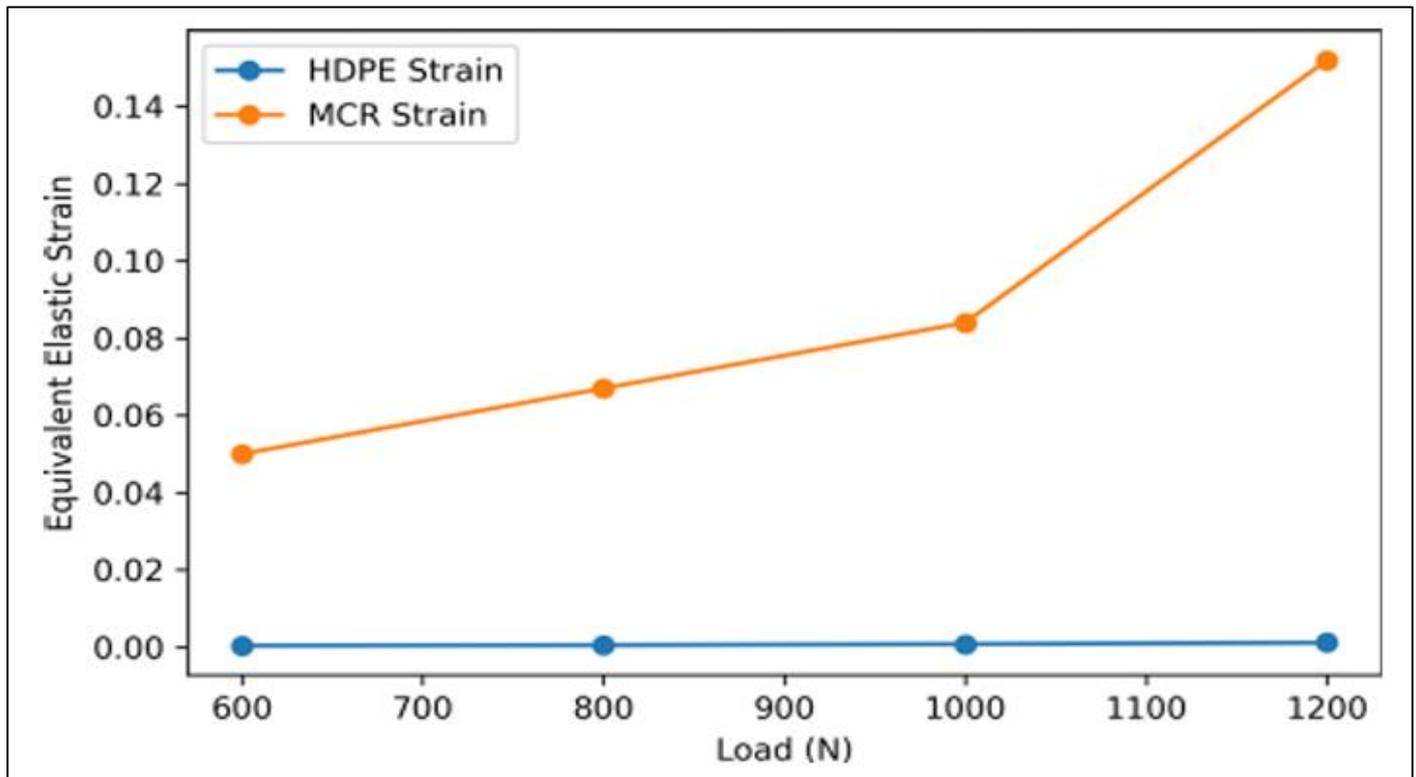


Fig 6 Comparison of Equivalent Elastic Strain Distribution in the Jaipur-Foot Prosthetic Model Fabricated from HDPE and Microcellular Rubber Under the Highest Applied Static Load.

A representative comparison of strain response between high-density polyethylene and microcellular rubber at the maximum applied load is presented to highlight differences in deformation characteristics associated with material stiffness and compliance.

➤ *Fatigue Life and Damage Maps*

Fatigue performance of the Jaipur-Foot prosthetic model was evaluated using stress-life analysis to estimate the number of cycles to failure under the applied loading conditions. Fatigue life contours were used to visualize the spatial distribution of fatigue resistance and to identify critical regions susceptible to damage accumulation for each material.

Representative fatigue life maps corresponding to the highest applied load are presented for high-density

polyethylene and microcellular rubber. The contours are expressed in terms of the number of cycles to failure, providing a direct comparison of material-dependent fatigue behavior.

The estimated fatigue life values at critical stress locations are summarized for all load cases to enable quantitative comparison between materials.

➤ *Factor of Safety*

The structural reliability of the Jaipur-Foot prosthetic model was assessed by evaluating the static factor of safety for both materials under the applied load cases. The factor of safety was computed based on the ratio of material strength to the maximum equivalent von Mises stress obtained from the static structural analysis.

Table 5 Estimated Fatigue Life at Critical Locations for HDPE and Microcellular Rubber Under Different Load Cases. S-N Curve Data were Obtained from Published Material Sources

Load (N)	HDPE fatigue life (cycles)	MCR fatigue life (cycles)
600	1.2×10^6	6.8×10^5
800	8.5×10^5	4.2×10^5
1000	4.9×10^5	2.1×10^5
1200	2.3×10^5	9.5×10^4

Table 6 Static Factor of Safety for HDPE and Microcellular Rubber Under Different Applied Load Cases

Load (N)	HD PE Safety Factor	MCR Safety Factor
600	3.2	2.6
800	2.6	2.1
1000	2.1	1.4
1200	1.6	1.2

Table 7 Summary of Topology Optimization Metrics for the Jaipur-Foot Prosthetic Model

Metric	HDPE	MCR
Mass reduction (%)	28.5	22.0
Maximum stress change (%)	+6.2	+9.8
Compliance change (%)	+11.4	+18.6

Safety factor values were extracted at critical stress locations for each load case to enable a direct comparison between high-density polyethylene and microcellular rubber.

➤ *Topology Optimization Results*

Topology optimization was performed to identify regions of low structural contribution within the Jaipur-Foot prosthetic model and to evaluate the potential for material reduction while maintaining structural integrity. The optimization outcomes are presented in terms of material distribution, mass reduction, and associated changes in mechanical response.

The initial prosthetic foot geometry and the optimized material layout obtained after applying the optimization constraints are shown for visual comparison.

Quantitative metrics obtained from the topology optimization analysis are summarized to facilitate assessment of structural efficiency improvements.

➤ *Summary Results Plots*

To provide an overall comparison of material performance across all loading conditions, summary plots were generated to illustrate trends in key response parameters. These plots enable direct visualization of the relationship between applied load and mechanical response for both high-density polyethylene and microcellular rubber.

The summary figure includes comparative plots of equivalent von Mises stress, total deformation, and predicted fatigue life as functions of applied load magnitude.

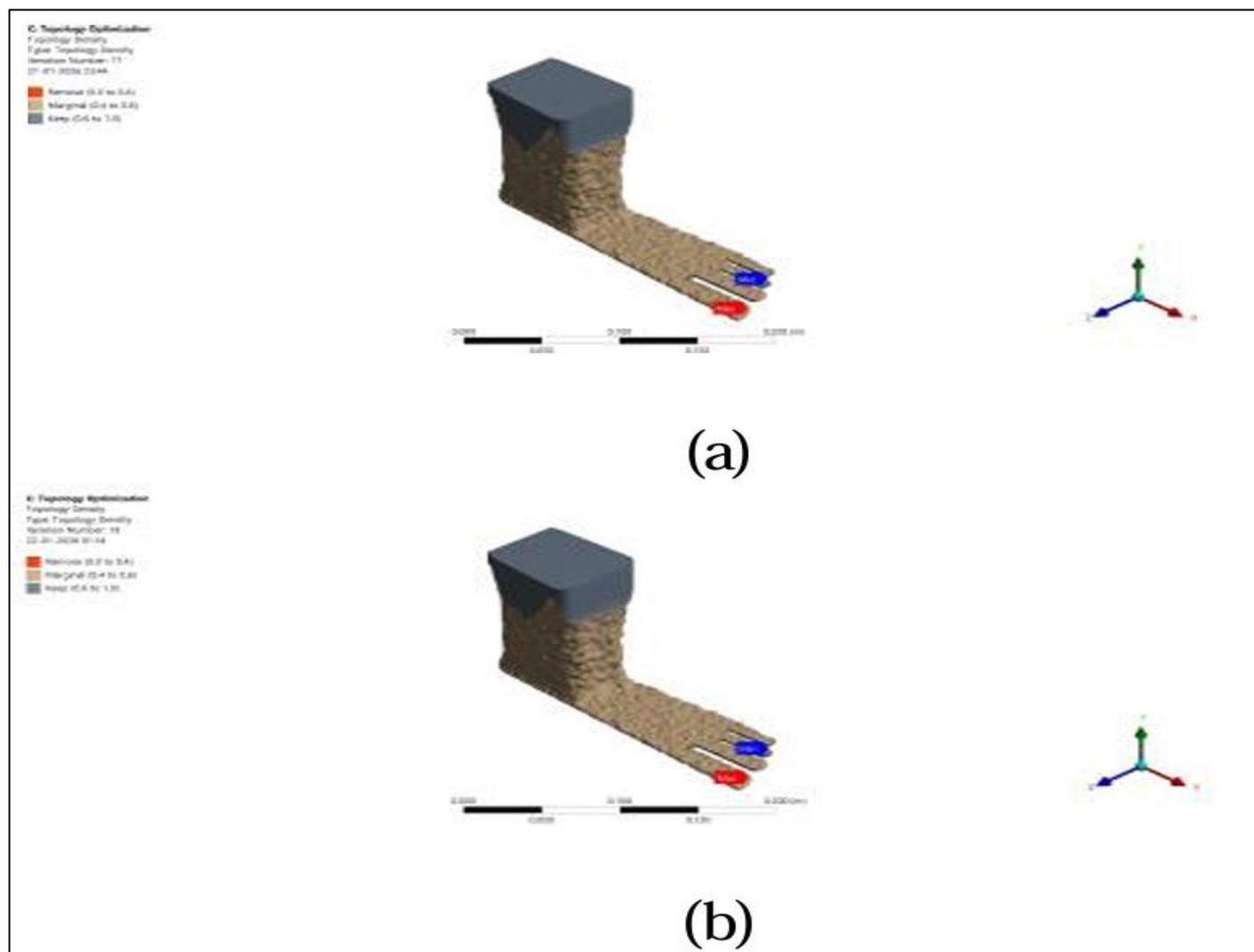


Fig 7 Topology Optimization Results for the Jaipur-Foot Prosthetic Model: (a) Initial Baseline Geometry Prior to Optimization and (b) Optimized Material Distribution Highlighting Regions of Material Removal and Retention.

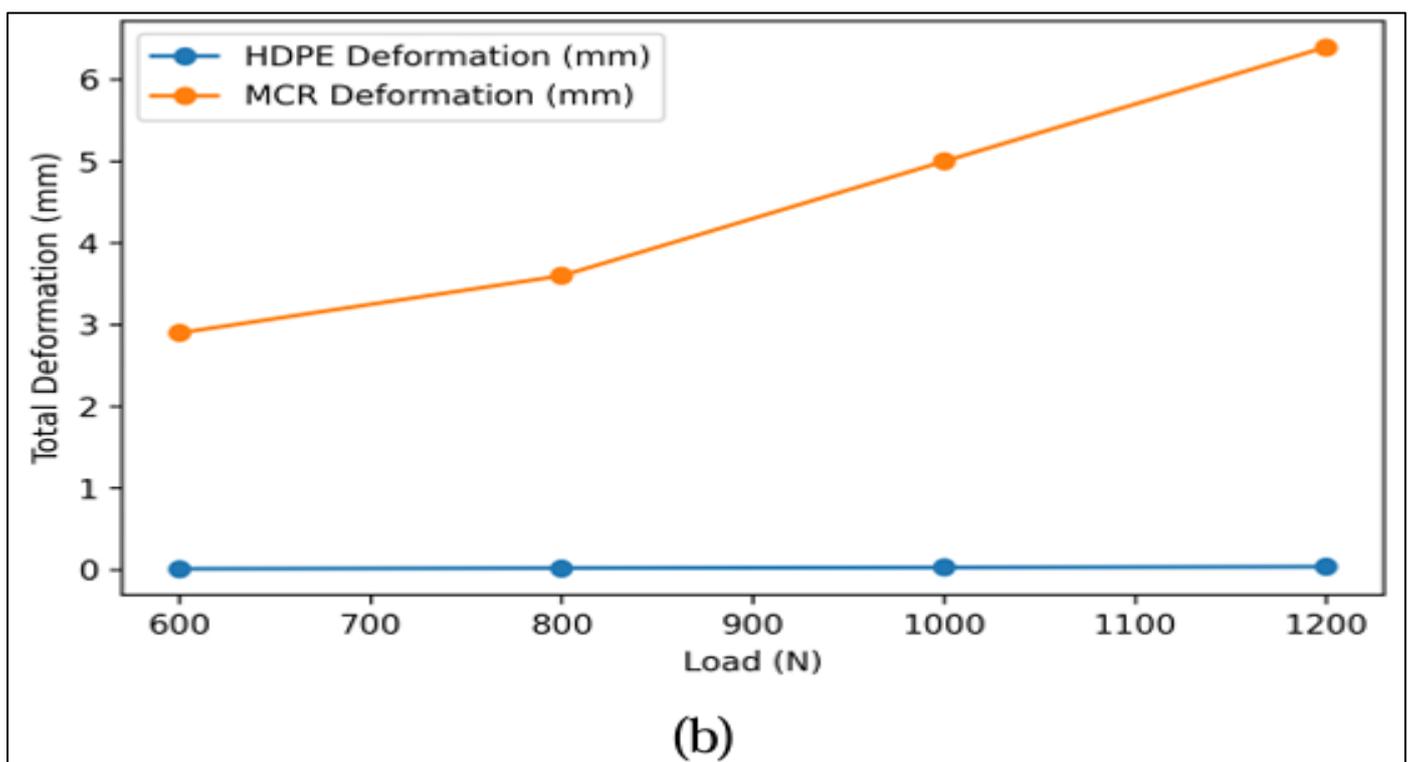
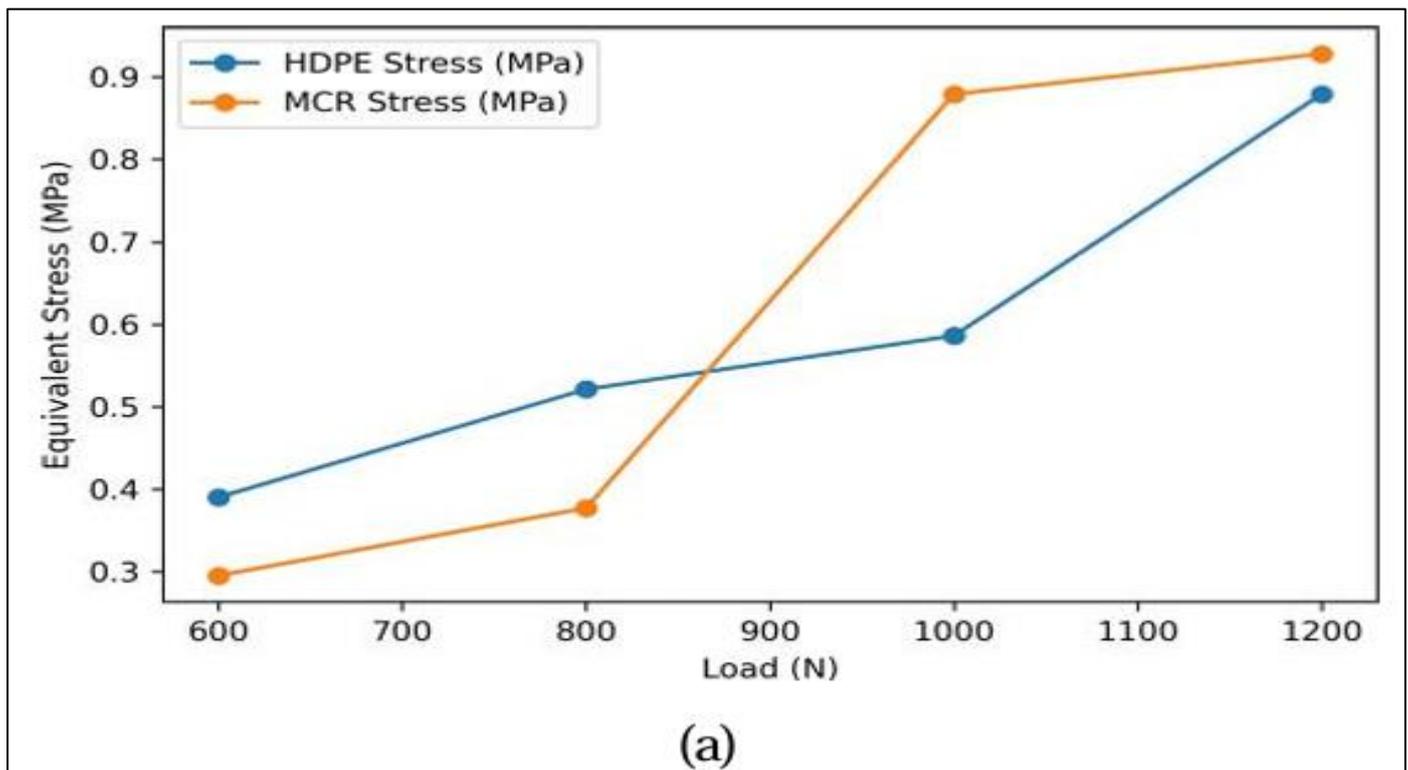


Fig 8 Summary Plots Illustrating the Variation of (a) Maximum Equivalent Von Mises Stress and (b) Total Deformation with Applied Load for HDPE and Microcellular Rubber.

IV. DISCUSSION

➤ Comparison of HDPE and Microcellular Rubber

The comparative numerical results demonstrate distinct mechanical and fatigue responses for high-density polyethylene and microcellular rubber when applied to the Jaipur-Foot prosthetic geometry. These differences can be

primarily attributed to the contrasting stiffness, energy dissipation mechanisms, and fatigue resistance inherent to the two materials.

HDPE exhibited lower overall deformation and a more uniform stress distribution across the prosthetic foot under increasing load levels. This behavior is associated with its

higher elastic modulus, which enables efficient load transfer from the ankle block toward the plantar surface while limiting excessive localized deformation. From a biomaterials perspective, this controlled stiffness contributes to improved structural stability and reduced risk of long-term material degradation under repetitive loading. The higher predicted fatigue life observed for HDPE further reflects its superior resistance to cyclic stress accumulation, making it suitable for prolonged daily use.

In contrast, microcellular rubber demonstrated higher deformation and localized strain concentrations, particularly in regions subjected to repetitive compressive loading. The compliant nature of MCR, combined with its internal cellular structure, facilitates effective shock absorption and energy dissipation during heel strike. While this damping behavior can enhance walking comfort and adaptability to uneven terrain, the associated increase in deformation and fatigue damage accumulation may reduce long-term durability. These characteristics explain the lower predicted fatigue life and safety factors observed for MCR under higher load conditions. From a clinical and application standpoint, the mechanical behavior of HDPE suggests improved longevity and structural reliability, which are critical for reducing prosthesis replacement frequency in low-resource settings. Conversely, the compliance of MCR offers advantages in impact attenuation and comfort, particularly during barefoot walking. In terms of manufacturing, HDPE enables more consistent fabrication and dimensional control through thermoplastic processing, whereas MCR relies on artisan-based techniques that may introduce variability in material properties. The present comparison highlights the trade-off between durability and compliance, underscoring the importance of informed biomaterials selection based on intended usage, user activity level, and manufacturing constraints.

➤ *Comparison with Earlier Studies*

The numerical trends observed in the present study are consistent with previously reported investigations on Jaipur-Foot prostheses and low-cost prosthetic foot materials. Earlier finite element-based studies on Jaipur-Foot designs have identified the ankle block and adjacent midfoot regions as critical zones for stress concentration under static and gait-related loading. The present results similarly indicate peak stress localization in these regions, confirming the validity of the adopted geometric representation and loading assumptions.

Previous computational and experimental studies focusing on microcellular rubber-based Jaipur-Foot prostheses have reported relatively high deformation and localized strain accumulation due to the compliant nature of the material. These observations align with the higher deformation and reduced safety factors obtained for microcellular rubber in the current analysis, particularly under elevated load levels. Such trends have been associated in the literature with progressive material degradation and reduced fatigue resistance during long-term use.

Recent studies exploring polymeric alternatives and standardized CAD-based Jaipur-Foot designs have highlighted the potential benefits of stiffer thermoplastic materials in improving structural reliability and fatigue performance. The improved stress distribution and increased predicted fatigue life observed for high-density polyethylene in the present work are in agreement with these reported findings. In particular, earlier parametric finite element analyses have demonstrated that increased material stiffness leads to reduced peak deformation and enhanced load transfer efficiency, trends that are reproduced in the current results.

Furthermore, while prior investigations have primarily focused on static structural behavior or isolated fatigue assessment, the integrated approach adopted in this study—combining static analysis, fatigue life estimation, and topology optimization—extends existing work by providing a more comprehensive evaluation framework. The consistency of observed trends with established literature supports the credibility of the numerical outcomes and reinforces the relevance of the present findings within the context of biomaterials selection for Jaipur-Foot prosthetic applications.

➤ *Design Implications and Recommended Next Steps*

The findings of the present study have direct implications for material selection and design strategies in low-cost prosthetic foot development. The improved stress distribution, reduced deformation, and enhanced fatigue performance observed for high-density polyethylene suggest that stiffer thermoplastic biomaterials can significantly improve the structural reliability and service life of Jaipur-Foot prostheses. These characteristics are particularly important in high-use scenarios, where repetitive loading and prolonged daily wear can accelerate material degradation.

From a manufacturing perspective, the use of HDPE offers advantages in terms of process consistency, dimensional control, and scalability. Thermoplastic processing techniques such as molding and machining enable standardized production with reduced variability compared to artisan-based fabrication methods commonly associated with microcellular rubber. Improved manufacturing consistency can contribute to more predictable mechanical performance and reduce the likelihood of premature failure. Additionally, the environmental resistance of HDPE to moisture, temperature variations, and chemical exposure enhances its suitability for use in diverse climatic and working conditions.

Despite these advantages, the compliant nature of microcellular rubber remains beneficial for shock absorption and user comfort, particularly during barefoot walking and ambulation on uneven terrain. Therefore, future design strategies may consider hybrid or functionally graded material configurations that combine the durability of thermoplastics with the damping characteristics of elastomeric materials.

Further work is required to translate the present numerical findings into clinical practice. Experimental validation through mechanical testing and gait-simulated loading is necessary to confirm the predicted performance trends. In addition, long-term clinical studies evaluating user comfort, durability, and functional outcomes will be essential to assess the real-world benefits of alternative biomaterials. Such efforts will support evidence-based design optimization and contribute to the development of durable, affordable, and clinically effective prosthetic foot solutions.

V. LIMITATIONS

The present study has several limitations that should be considered when interpreting the results. First, the prosthetic foot geometry was developed as a simplified representation of the Jaipur-Foot design. Although major structural features and load-bearing regions were preserved, certain organic contours and fine geometric details were idealized to improve numerical stability and mesh quality. These simplifications may influence local stress distributions and should be addressed in future studies employing more anatomically detailed models.

Second, the numerical analyses were performed under quasi-static loading conditions. Dynamic effects associated with gait, such as time-dependent load variation, impact during heel strike, and multi-directional forces, were not explicitly modeled. As a result, the predicted stresses and fatigue life may differ from those experienced during real-world ambulation, particularly under high-activity or uneven terrain conditions.

Third, material behavior was modeled using linear elastic assumptions for both high-density polyethylene and microcellular rubber. The viscoelastic and rate-dependent behavior of microcellular rubber, which can significantly influence deformation and energy dissipation under cyclic loading, was not included. Incorporating more advanced constitutive models would provide a more accurate representation of long-term material response.

In addition, the present investigation is limited by the absence of experimental validation. Mechanical testing and in-vitro experiments are required to corroborate the numerical predictions and to establish confidence in the simulated fatigue life and safety factors. Finally, the transfer of the CAD model from IGES format to the finite element environment may introduce minor geometric tolerances or discretization artifacts, which could influence localized stress results. These limitations highlight the need for complementary experimental and dynamic analyses in future work.

VI. CONCLUSIONS

- This study addressed the need for an engineering-based comparison of biomaterials used in Jaipur-Foot prosthetic applications by evaluating high-density polyethylene and microcellular rubber using finite element analysis.

- The numerical results demonstrated that high-density polyethylene exhibited lower deformation, more uniform stress distribution, and improved predicted fatigue life compared to microcellular rubber across all applied load cases.
- Microcellular rubber showed higher compliance and deformation, indicating advantages in shock absorption but reduced structural durability under repetitive loading.
- Topology optimization results indicated the potential for material reduction while maintaining structural integrity, supporting the development of lighter and more efficient prosthetic designs.
- Based on the combined static, fatigue, and optimization outcomes, high-density polyethylene is recommended as a suitable biomaterial for enhancing the durability and reliability of low-cost Jaipur-Foot prostheses.
- Future work should include experimental validation, dynamic gait-based loading analysis, and in-vivo studies to confirm the numerical predictions and assess long-term clinical performance.

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