

# Static and Fatigue Analysis on Polypropylene and Microcellular Rubber Used for Prosthetic Foot Implant

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**Abstract:** This study proposes the PP–MCR foot, a modified Jaipur Foot design that uses Polypropylene (PP) as the primary structural material with a Microcellular Rubber (MCR) surface coating. A geometrically precise three-dimensional model was constructed based on Indian foot size 6 dimensions using CATIA V5 to provide an accurate representation of load transfer during gait. Finite element analysis was performed with ANSYS to assess mechanical performance under standing-phase loads ranging from 500 N to 700 N. Static structural study was carried out on both the proposed PP-MCR foot and the current MCR foot (jaipur foot) under same loading conditions. Fatigue analysis of the PP-MCR foot predicts a minimum life of  $1 \times 10^7$  cycles, with good safety factors and uniform damage distribution, showing enhanced long-term durability under cyclic loads. Furthermore, topology optimization was carried out on the PP–MCR foot in order to enhance material efficiency and identify non-critical areas. Overall, the combined static, fatigue, and topology optimization results show that the proposed PP-MCR Jaipur Foot is a more durable, structurally efficient, and cost-effective alternative to the conventional MCR design.

**Keywords:** PolypropuFinite Element Analysis, Topology optimization, Catia V5, Ansys.

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## I. INTRODUCTION

### ➤ Background and Motivation

The level of lower-limb amputation is an important factor in defining prosthetic foot design requirements. The most prevalent and clinically significant amputation type for the development of prosthetic feet is transtibial amputation because of its high potential for rehabilitation and retained knee function. To restore natural gait mechanics, prosthetic feet for transtibial amputees must offer efficient energy return during toe-off, controlled deformation during mid-stance, and good shock absorption during heel impact [5] [6]. Lightweight and flexible forefoot structures are also required for partial foot amputations in order to make up for the loss of push-off function. In low-resource settings, cost-effective prosthetic feet such as the Jaipur Foot are widely used; however, limitations such as excessive deformation and limited structural durability necessitate engineering-based optimisation approaches such as finite element analysis to improve mechanical performance while lowering production costs [1] [2]. The Jaipur Foot is a cost-effective prosthetic foot that was developed in 1968 in Jaipur, India, to address the functional and social demands of lower-limb amputees in

nations with limited resources. Professor P K Sethi, a doctor of orthopaedics at Sawai Man Singh (SMS) Medical College in Jaipur, developed up with the idea and worked with local craftsmen, especially Master Ram Chandra, to make it happen. The prosthesis was made to be distinctive from Western prosthetic feet, specifically the Solid Ankle Cushioned Heel (SACH) foot [3], which didn't work well for walking, seated position or functioning in rural and uneven stretches of India. Prosthetic feet can be categorized into the following.

- Solid Ankle Cushion Heel (SACH).
- Elastic Keel Foot.
- Dynamic Response Foot.
- Jaipur Foot.

The Jaipur Foot was developed with several crucial features: [1][2][3]

- It is flexible and waterproof because it is made of wood/aluminium and vulcanized rubber or micro-cellular rubber (MCR).
- Inexpensive and simple to make with supplies that are readily available locally.

- Permits running, squatting, cross-legged sitting, and barefoot walking.
- Lightweight and simple to replace.
- Customized using HDPE or polypropylene for the socket, which further lowers expenses.

A core wooden ankle block, a stronger micro-cellular rubber (MCR) block at the forefoot, and a highly compressible elastic MCR block at the heel make up the Jaipur Foot's handcrafted interior structure [3]. Technicians hand carve and assemble these components, bind them together using fiber-reinforced nylon-rubber strands, and cover them with rubber cement. To develop a durable, flexible prosthetic foot, the component is subsequently covered in soft, skin-coloured rubber and vulcanised using heat and pressure [7].

#### ➤ *Role of Polymers in Prosthetic Foot*

Considering polymers offer superior mechanical performance, flexibility, durability, and cost-effectiveness than other material classes for this application, polymers are essential to the Jaipur Foot's design, functionality, and general acceptance. During movement, squatting, and walking on uneven terrain, the Jaipur Foot is subjected to diverse loading conditions that include cyclic compression, bending, torsion, and impact. Through controlled deformation and energy dissipation, polymeric materials—such as microcellular rubber, elastomers, and, in more recent versions, thermoplastics like polypropylene—are particularly well-suited to meet these objectives [12] [18]. In order to improve fatigue resistance and longevity while maintaining affordability, polymers will play a key role in the Jaipur Foot's future through material optimisation and standardisation. Thus, it is still essential to carefully choose and develop polymer systems in order to develop the Jaipur Foot without sacrificing its core design principles.

#### ➤ *Identified Gaps in Literature*

Despite extensive clinical usage and socioeconomic relevance, the Jaipur Foot's engineering development has not kept current with field implementation. The majority of current research is still experience-based, with little incorporation of structural validation, material science, and performance-based design techniques. Since most studies still rely on traditional rubber-MCR-wood assemblies or conduct simplified property-based comparisons without connecting polymer selection to durability, fatigue resistance, environmental stability, and manufacturability, material substitution has not been thoroughly investigated [4]. With poor life-cycle prediction under cyclic gait loads and numerous reports of cracking and interfacial failure in high-load sections like the heel and forefoot, durability assessment is still inadequate [5]. Additionally, the majority of numerical studies dismiss realistic ground contact interactions and interface behaviour in preference for idealised boundary limitations and simplified static loading conditions [9]. The dynamic loading effects of gait phases and inertia have yet to be fully investigated. Long-term reliability prediction is limited by the occasional incorporation of fatigue-based evaluation utilising stress-life or strain-life approaches [11]. Furthermore, despite their potential to increase structural efficiency and reduce weight, topology optimisation and

design-driven material redistribution have not gotten much attention. For the development of Jaipur Foot, these gaps demonstrate the necessity of an integrated mechanics-driven design framework [7] [8].

The use of polypropylene as a principal structural material in Jaipur Foot designs has not been documented in the current peer-reviewed literature, despite the fact that it is frequently used in prosthetic sockets and orthotic applications due to its advantageous mechanical qualities and economic effectiveness [4]. Conventional rubber, microcellular rubber, and wood-based structures are still the primary areas of current research; polypropylene-based foot designs have not been thoroughly assessed. A crucial gap that requires concentrated study attention is the lack of experimental and numerical studies evaluating the structural performance, fatigue behaviour, and durability of polypropylene-integrated Jaipur Foot designs.

#### ➤ *Objectives of the Proposed Work*

The objectives of the current work, which address material constraints, structural performance failings, and the absence of durability-oriented validation in traditional Jaipur Foot designs, are directly drawn from the gaps found in the literature and are intrinsically linked. The primary objectives of this study are as follows:

- To develop a polypropylene–microcellular rubber (PP–MCR) based Jaipur Foot configuration.
- To perform a comprehensive static structural evaluation under physiologically relevant standing-phase loads.
- To assess the fatigue performance of the PP–MCR Jaipur Foot using stress-life (S–N) methodology.
- To investigate the structural efficiency of the proposed design through topology optimization.
- To comparatively evaluate the mechanical performance of the proposed PP–MCR foot against the conventional MCR-based design.

## II. MATERIALS AND METHODS

The materials, geometric modelling, and numerical techniques used in this study to ensure consistency and permit a methodical comparison of Polypropylene and microcellular rubber for Jaipur-Foot prosthetic applications will be addressed in this section.

#### ➤ *Materials*

The present study focused on two polymeric materials typically used in low-cost prosthetic foot applications: Polypropylene (PP) and Microcellular Rubber (MCR). Based on their beneficial mechanical properties, availability, manufacturability, and potential for prosthetic usage in resource-constrained contexts, these materials were selected.

Polypropylene had been selected as the principal structural material due to its high strength-to-weight ratio, low density, good fatigue resistance, and easy processing. PP outperforms traditional wood-based components in terms of dimensional stability, moisture resistance, and mechanical

performance under repeated loading [12] [15]. Additionally, due to its thermoplastic nature, it can be fabricated inexpensively using moulding and forming methods, allowing for large-scale production while keeping material costs low.

Furthermore, the comparatively high elastic modulus of PP improves load-bearing capabilities and avoids excessive deformation, increasing structural stiffness and durability of the prosthetic foot.

Table 1 Mechanical Properties of Polypropylene Material [12] [13] [14] .

Property	Value	Unit
Density	0.90	g/cm <sup>3</sup>
Poisson’s Ratio	0.42	-
Young’s Modulus	1100	MPa
Tensile Yield Strength	32	MPa
Tensile Ultimate Strength	28	MPa

Microcellular rubber is being utilised as the outer functional layer due to its high energy absorption capacity, compressive resilience, and near-incompressible behaviour, all of which are essential for minimising impact pressures during heel strike and ensuring user comfort [19]. The cellular microstructure of MCR allows for excellent shock dissipation

and vibration reduction, which reduces stress transmission to the residual limb. The combination of a PP structural core and an MCR surface coating allows for a more balanced design approach, combining mechanical strength and fatigue resistance with impact absorption and biomechanical compliance.

Table 2 Mechanical Properties of Microcellular Rubber [19]

Property	Value	Unit
Density	0.45	g/cm <sup>3</sup>
Poisson’s Ratio	0.48	-
Young’s Modulus	3	MPa
Tensile Strength	1.5 – 4	MPa

➤ *Geometry of the Model and CAD Model*

The three-dimensional geometric model of the Jaipur Foot is created with CATIA V5, a popular parametric computer-aided design (CAD) software for mechanical and biomedical engineering applications. In this particular study, the Jaipur Foot was modelled following an Indian foot size 6, which is a regularly used standard size in prosthetic manufacturing.

During standing and walking, the model takes into account the entire foot profile needed for load transmission, balance, and ground contact. During finite element analysis, care was made to provide smooth geometric transitions to prevent false stress concentrations.

Furthermore in the modelling phase, the plantar profile, heel geometry, and total foot thickness were defined in accordance with functional specifications like shock absorption and weight bearing. To maintain structural features important to mechanical behaviour while guaranteeing numerical stability, simplifications were made where needed.

All things considered, the technical modelling of the Jaipur Foot using CATIA V5 offers a solid digital basis for biomechanical assessment and engineering optimisation, assisting in the creation of dependable and effective prosthetic solutions. The 3D modelled Jaipur Foot is shown below with Isometric view.

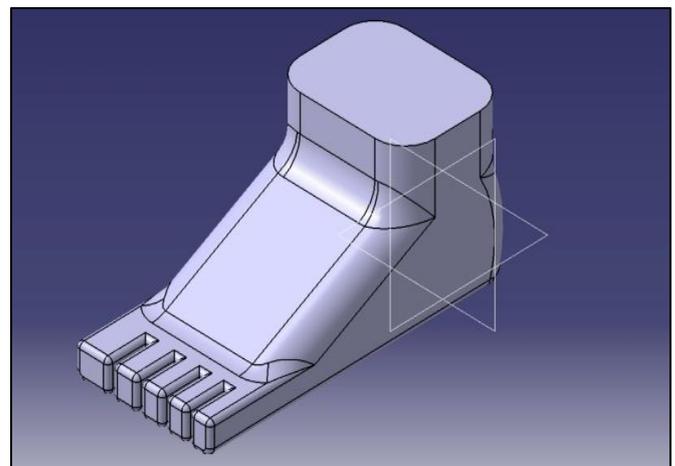
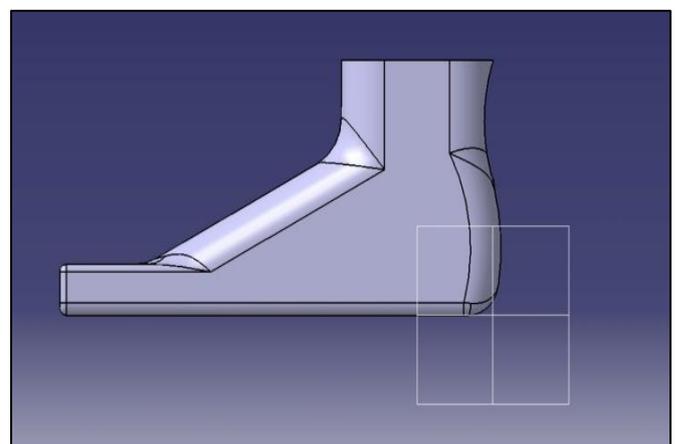
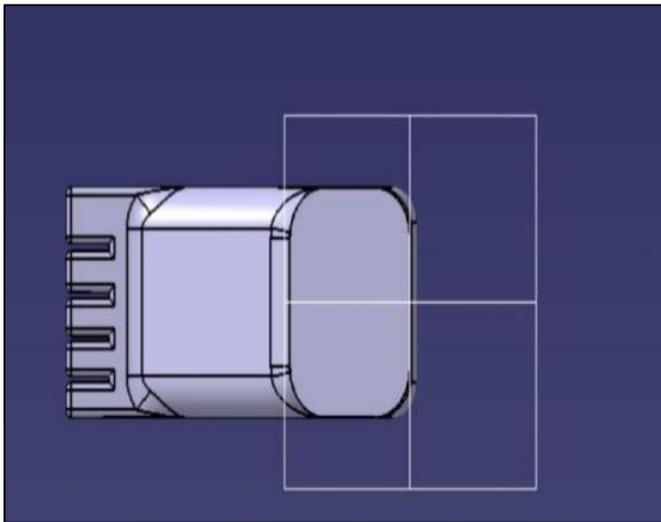


Fig 1 Isometric View of the Jaipur-Foot-Inspired CAD Model.



(a)



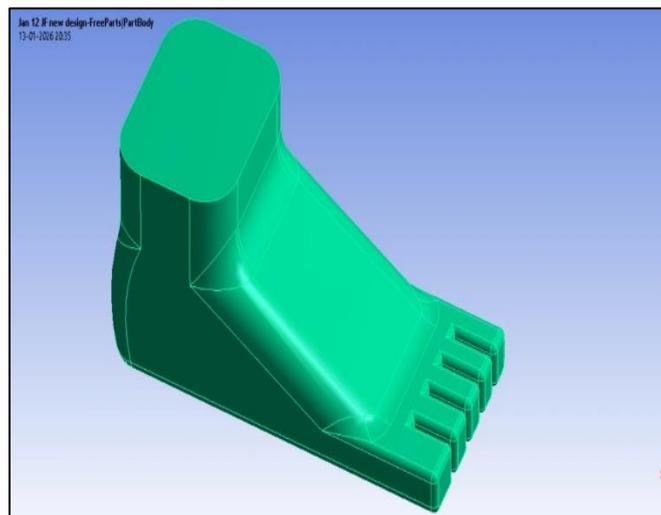
(b)  
 Fig 2 Orthographic Views of the Prosthetic Foot CAD Model. (a) Side View and (b) Top View

➤ *Finite Element Model*

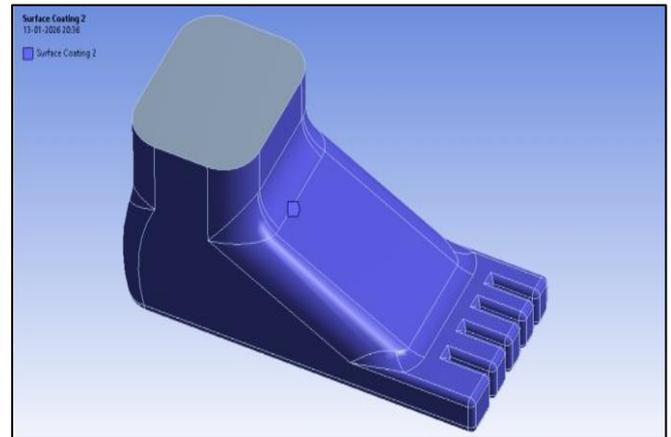
The developed 3D model of the Prosthetic Foot was created using CATIA V5 and the IGS format was exported for numerical analysis. ANSYS Workbench (ANSYS Inc., version 2022) was software used to carry out the Finite element simulations, which provides an integrated environment for structural and fatigue analysis of complex geometries.

The material was assigned to the imported prosthetic foot model: the core material was considered and assigned as Polypropylene (PP). Further the prosthetic foot was surface coated with Microcellular Rubber (MCR) to improve the shock absorption under the loading conditions. Hence the proposed model is named as PP-MCR Prosthetic foot (or) PP-MCR Foot.

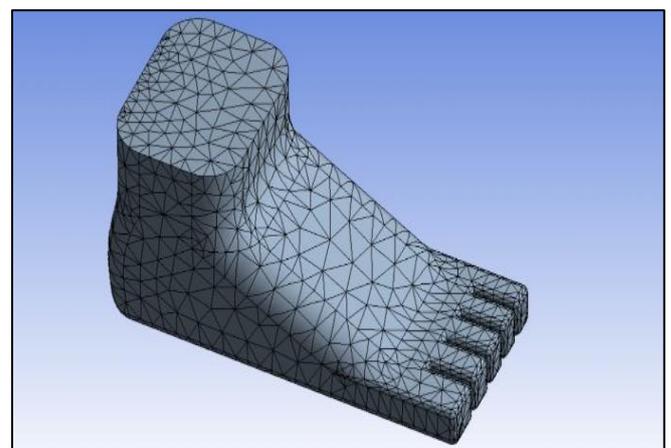
The CAD model is divided into Tetrahedral element type so that the governing equations can be numerically solved. The mesh across the proposed PP-MCR Foot shape in this study is created using an element mesh size of 7 mm.



(a)



(b)



(c)

Fig 3 FEA Model of the Proposed PP-MCR Foot : (a) PP Body; (b). MCR Surface Coating; (c) Finite Element Mesh of the PP-MCR Foot.

➤ *Loading Conditions and Boundary Conditions*

Boundary conditions were generated to accurately imitate the prosthetic foot's load transfer mechanism during the standing phase of gait. The foot's bottom surface, which corresponds to the ground contact region, was confined by a fixed support condition. This constraint limited all translational and rotational degrees of freedom, resulting in firm contact with a stiff ground surface and stable load reactivity during analysis. This assumption is often used in prosthetic foot simulations to assess the worst-case structural response under static loading circumstances.

To simulate force transmission from the residual limb to the foot structure, vertical compressive stresses were applied at the prosthetic model's proximal ankle attachment site. To prevent the effects of localised stress concentration, the load was evenly distributed across the ankle block's upper surface. Three physiological load magnitudes—500 N, 600 N, and 700 N—representing changes in body weight under single-leg stance situations for average adult users were taken into consideration. To replicate downward ground reaction forces, all loads were applied in a negative vertical direction that was parallel to the global gravitational axis. The PP-MCR composite prosthetic foot structure's deformation behaviour and stress distribution were assessed by quasi-static analysis.

➤ *Finite Element Analysis – Types and Setting of Solver*

Numerical studies using finite elements were conducted to assess the prosthetic foot designs' material efficiency, durability, and mechanical performance. To create a direct comparison under the same physiological stress conditions, static structural analysis was carried out on the traditional MCR-based foot and the proposed PP-MCR prosthetic foot. During the standing phase of gait, quasi-static vertical loads between 500 and 700 N were used to simulate single-leg stance. The identification of significant load-bearing regions and evaluation of stiffness and structural stability related to material replacement were made possible by the ensuing stress and deformation responses.

Fatigue research was only performed on the proposed PP-MCR foot model considering the main goal of this study was to find out how polypropylene incorporation could improve durability. In order to forecast cycle life, damage buildup, and safety factor distribution during repeated physiological loading, stress results from static analysis were used as input for stress-life (S-N) based fatigue evaluation. The fatigue results showed homogeneous damage distribution and increased life expectancy, demonstrating polypropylene's potential for long-term prosthetic applications.

Furthermore, the PP-MCR foot underwent topological modification to enhance material utilisation and decrease structural weight without affecting mechanical integrity. Maximising stiffness under specified loads and boundary conditions while limiting material removal to low-stress areas was the optimum focus. The resulting topology contours showed that while maintaining structural continuity in high-stress areas like the heel and ankle attachment, material may be safely decreased in non-critical mid-foot zones. This optimisation result encourages weight loss and cost effectiveness, confirming the viability of a well-designed, long-lasting, and producible prosthetic foot.

### III. RESULTS

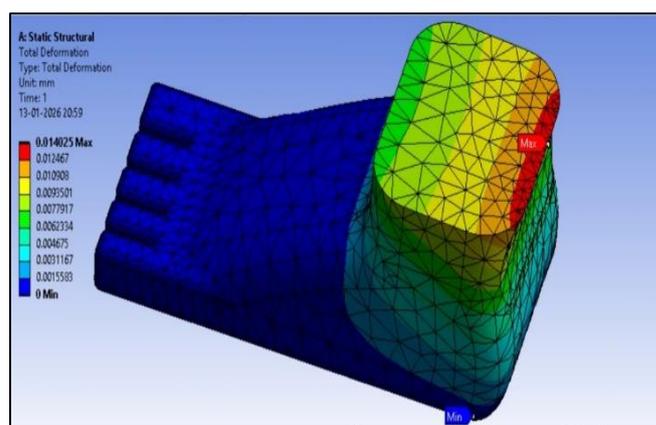
The statistical results from the Jaipur-Foot prosthetic model's finite element simulations are shown in this section. Research results are presented for both microcellular rubber and Polypropylene in terms of fatigue life, stress distribution, deformation response, and safety factor. The comparative performance of the two materials under various loading circumstances is clearly shown in the figures and tables, with additional information given in this section.

➤ *Static Structure Results*

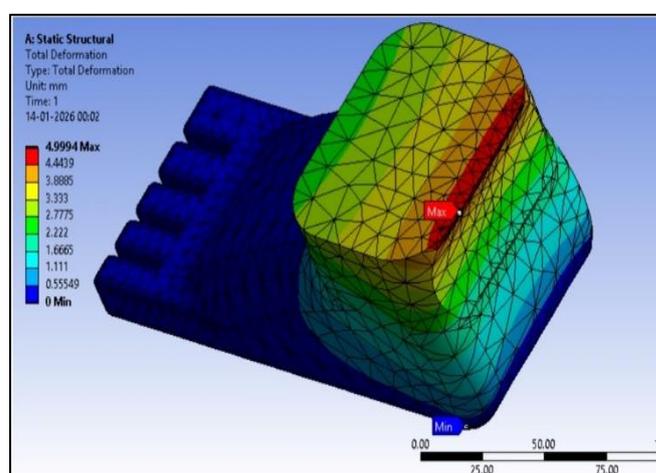
The proposed polypropylene-microcellular rubber (PP-MCR) prosthetic foot and the conventional MCR prosthetic foot's static structural study under 500N to 700 N load presents important data about its load-transfer behaviour and structural dependability. The deformation contour in both material model demonstrates that the heel exhibits the minimal amount of deformation, while the ankle attachment region experiences the most. Although the ankle region acts like a transition zone between the rigid prosthetic shank and the compliant foot structure, this deformation pattern is mechanically constant and produces greater bending and rotational compliance under

load. On the other hand, the heel area limits displacement due to material support and direct ground contact.

The corresponding stress distribution of both material model demonstrates a different pattern, with the forefoot experiencing the least amount of stress and the heel region undergoing the highest level of stress. Although the heel serves as the main load-bearing interface with the ground during the standing phase, concentrated compressive loading is the source of the increased stress at the heel. The microcellular rubber coating's cushioning effect in PP-MCR foot and efficient load distribution over the foot length result in less stress on the forefoot. In general, it is structurally advantageous to separate the regions of peak deformation and peak stress since it minimises the possibility of simultaneous failure brought on by high stress and deformation in one region. These findings demonstrate the PP-MCR configuration's applicability for increased durability and load-bearing performance in prosthetic foot applications by showing that it provides a mechanically balanced response under physiological loads. The amplitude of both the modelled foot's total deformation and equivalent stress gradually increases with increasing load, following a near-linear trend typical of elastic behaviour, even though the crucial locations stay constant.

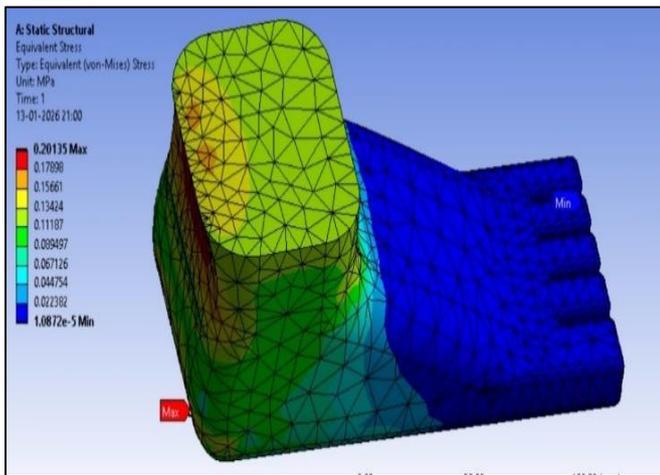


(a)

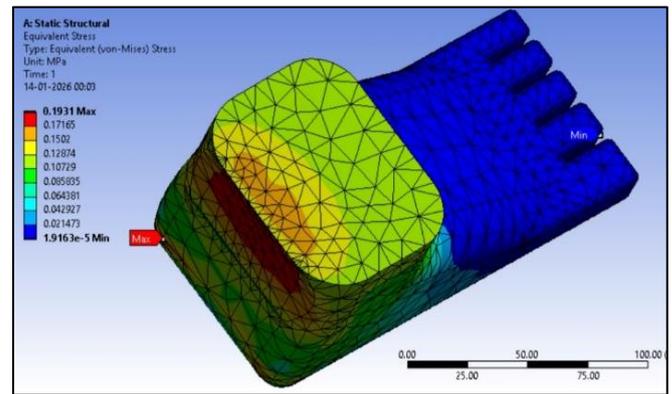


(b)

Fig 4 Total Deformation of the Prosthetic Foot at Maximum Load 700N; (a) PP-MCR Prosthetic Foot; (b) Conventional MCR Prosthetic Foot.



(a)



(b)

Fig 5 Equivalent Von Mises Stress Distribution at Maximum Load 700N; (a) PP-MCR Prosthetic Foot; (b) Conventional MCR Prosthetic Foot.

Table 3 Maximum Total Deformation of the PP-MCR Foot and MCR Foot Under Different Static Loading Conditions

Load (N)	PP-MCR Foot Maximum Deformation (mm)	MCR Foot Maximum Deformation (mm)
500	0.010018	3.571
600	0.012021	4.2852
700	0.014025	4.9994

Table 4 Maximum Equivalent Von Mises Stress of PP-MCR Foot and MCR Foot Under Different Loading Conditions

Load (N)	PP-MCR Foot Maximum Stress (MPa)	MCR Foot Maximum Stress (MPa)
500	0.14382	0.13793
600	0.17259	0.16552
700	0.20135	0.1931

➤ *Response to Strain and Principal Stress*

The strain response of the proposed Polypropylene-Microcellular Rubber (PP-MCR) prosthetic foot was examined to determine concentrated deformation behaviour and identify fatigue-critical regions under physiological loading. The zone of maximal deformation observed in the static analysis corresponds to the increased strain concentrations in the ankle attachment region, as demonstrated by the strain contours under the 700 N load. In addition to the load transfer from the prosthetic shank to the foot body, this region undergoes excessive bending and constraint-induced deformation, which raises the requirement for elastic strain within the PP core.

The heel region, on the contrary contrast, demonstrates comparatively lower strain levels because of compressive load dominance and geometric support from ground contact, even if it represents higher equivalent stress. This pattern is additionally demonstrated by the main stress response, demonstrating that the ankle attachment region experiences alternating tensile and compressive principal stresses related to bending, whereas the heel region is primarily driven by compressive principal stresses. The forefoot region has minimal strain and primary stress participation, indicating that structural demand is low during static stance. Overall, the lower fatigue life anticipated for the PP core is explained by the strain-dominated reaction at the ankle attachment, confirming strain-controlled fatigue as the primary failure mode.

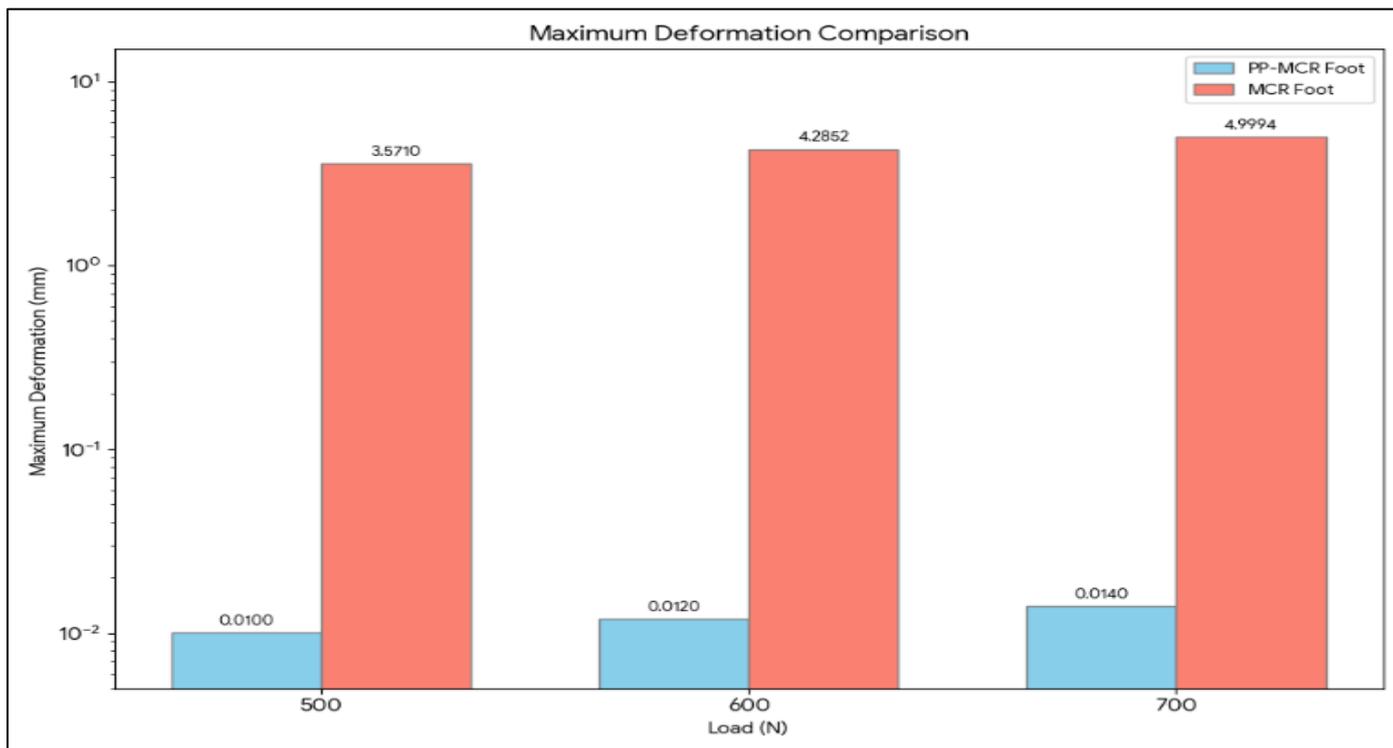


Fig 6 Illustration of Maximum Deformation Response of PP-MCR Foot and MCR Foot.

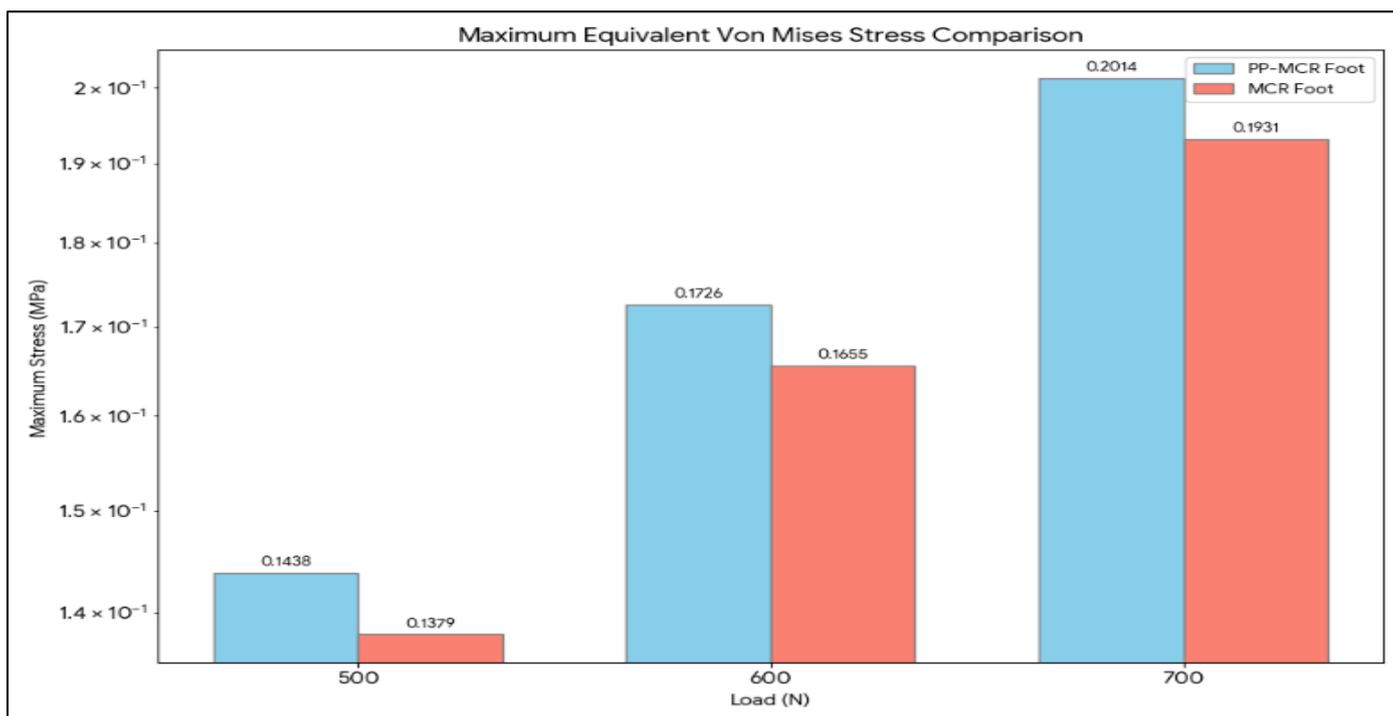


Fig 7 Illustration of Equivalent von Mises Stress Response of PP-MCR Foot and MCR Foot

➤ *Fatigue Analysis Results*

• *Life Range and Damage*

To determine the number of load cycles sustained under repetitive physiological loading, a stress–life (S–N) based fatigue study was performed to assess the fatigue performance of the proposed PP–MCR Jaipur Foot prosthetic model. The study utilised fatigue life and damage contours to investigate the regional distribution of fatigue resistance and to determine

regions that might be dependent to damage accumulation. Analyses of representative fatigue life maps for the PP–MCR composite structure were conducted in accordance with the highest applied loading condition. It is possible to evaluate the prosthetic foot's long-term durability by expressing the fatigue life curves in terms of cycles to failure. The entire model showed a consistent fatigue life distribution of  $1 \times 10^7$  cycles, demonstrating that there were no concentrated fatigue-critical regions.

Furthermore, fatigue damage contours verified stable stress redistribution within the structure and demonstrated the full application of the predetermined design life without premature failure. These findings show that the PP-MCR

Jaipur Foot is appropriate for long-term daily prosthetic usage since it functions in a high-cycle, low-damage fatigue condition.

Table 5 Estimated S–N Curve Data Collected from Peer-Reviewed Journals.

Cycles (N)	Alternating Stress (MPa)
1000	26.94
10000	23.90
$1 \times 10^5$	21.20
$1 \times 10^6$	18.81
$1 \times 10^7$	16.68

• *Safety Factor*

The safety factor distribution of the PP-MCR Jaipur Foot has a constant maximum value of 15 across the structure, demonstrating that stresses caused by the loading conditions are substantially within safe limits. The constantly high safety factor demonstrates that the Polypropylene core and Microcellular Rubber layer effectively distribute stress, with no concentrated regions approaching material failure. The absence of poor safety factor zones emphasises the design's structural robustness and reliability. The actual safety margin is probably higher because the reported value in ANSYS indicates the highest limit, indicating a conservative design approach. The results presented support the prosthetic foot's capacity to tolerate repetitive walking pressures over time.

➤ *Topology Optimization*

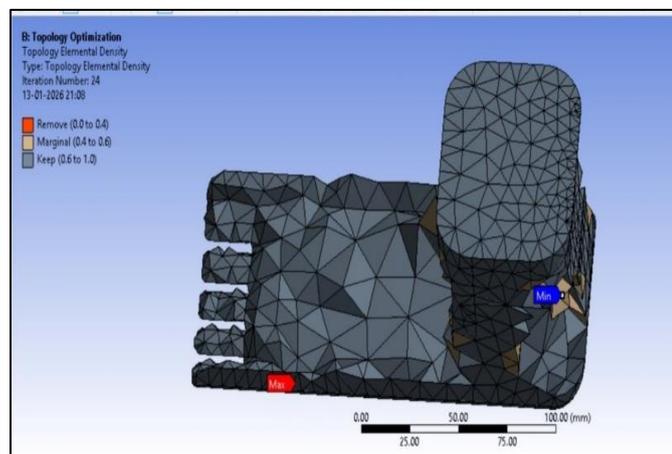


Fig 8 Topology Optimization Results of PP-MCR Foot

The PP-MCR Jaipur foot's topology optimisation elemental density plot demonstrates that stiffness-driven material retention is determined by predetermined density thresholds. The primary load-transmission methods and the ankle attachment are surrounded by regions with density values in the 0.6–1.0 range (retain), indicating their essential function to withstand compressive and bending loads. The midfoot has zones with intermediate density (0.4–0.6) where regulated material reduction is possible, implying partial structural engagement. Regions with low density  $< 0.4$  (remove) are those that contribute very little to load resistance because they are mechanically inactive. The optimisation process' convergence is confirmed by the stabilised density distribution throughout several iterations, which also permits

a focused, lightweight redesign without impacting structural performance.

IV. DISCUSSION

➤ *Comparative Assessment of PP-MCR Foot and MCR Foot*

A mechanical comparison among the proposed PP-MCR hybrid prosthetic foot and a traditional solid MCR (Jaipur) foot was carried out under physiological loading conditions with a range of 500–700 N. While the Jaipur foot is made entirely of MCR composite, the proposed structure includes a Polypropylene (PP) core with an exterior MCR coating. Long-term structural integrity, deformation response, and load transfer are all significantly impacted by this variation in material configuration. According to finite element study, the PP-MCR foot has a significantly lower maximum deformation (0.010–0.014 mm) than the traditional MCR foot (3.57–4.99 mm), which translates to a deformation reduction of around 99%. This significant enhancement demonstrates the increased structural rigidity and load-bearing capacity offered by the PP core. Furthermore, the equivalent von Mises stress levels for the two designs stay in the same range (about 0.14–0.20 MPa), demonstrating that the hybrid configuration's higher stiffness does not result in the formation of new stress concentrations. This demonstrates that stress safety limits are maintained while structural reinforcement is carried out.

Additionally, the PP-MCR foot exhibits a more consistent distribution of stress across the foot structure, which minimises strain caused by bending and optimises constant load transfer. The MCR foot, on the opposing alternative, experiences significant elastic deformation despite being extremely compliant and capable of absorbing shock. This might have a detrimental effect on dimensional stability and gait efficiency during the stance and push-off phases. In accordance with durability, the PP-MCR design provides better fatigue resistance and less creep susceptibility due to polypropylene's higher Young's modulus and time-dependent stability. In contrast, MCR-based designs are more prone to long-term creep under repeated pressure. When compared to traditional MCR prosthetic feet, the hybrid PP-MCR prosthetic foot offers better mechanical reliability, gait stability, and long-term functional performance by offering the ideal balance between stiffness and compliance.

➤ *Critical Evaluation with Earlier Peer-Reviewed Studies*

Previous research on low-cost prosthetic feet has been concentrated on entirely elastomeric designs, specifically

MCR-based configurations like the Jaipur foot, due to their price, shock absorption capability, and ease of production. According to published research, MCR has good compliance and energy dissipation, which enhances user comfort, particularly when operating on uneven terrain. The intrinsic drawbacks of solid MCR feet, such as excessive elastic deformation, poor dimensional stability under body-weight loading, and sensitivity to long-term creep and fatigue under cyclic gait conditions, have been brought to light by a number of studies. Numerous researchers have tried using material mixing, reinforcing layers, or geometric changes to enhance prosthetic foot function. Although these methods slightly increase stiffness or durability, they frequently compromise manufacturability or shock absorption. Furthermore, the majority of documented designs depend on uniform material distribution, which leads to a contradiction between comfort and load-bearing capability that is still mostly unresolved in the literature. The proposed PP–MCR prosthetic foot, on the alternative aspect, offers a functionally hybrid material architecture in which the functions of shock absorption and load carrying are clearly different. The Polypropylene core solves the excessive deformation and creep problems frequently mentioned for entirely MCR-based feet by improving structural stiffness, fatigue resistance, and dimensional stability. In order to retain functional comfort, the exterior MCR coating simultaneously maintains the compliant interface needed for impact reduction and ground adaptation.

The present study's finite element results show that the PP–MCR design significantly reduces deformation under physiological loading without raising stress concentrations when compared to deformation values often reported for solid MCR feet in previous research. Furthermore, stress levels stay within ranges that are similar to those reported in previous research on MCR prosthetic feet, implying that the stiffness improvement does not result in excessive stress concentration, a problem that is sometimes observed in reinforced or metallic prosthetic designs. In addition, in contrast to earlier research that focuses on either strength or flexibility, the proposed structure produces a balanced mechanical response, providing increased long-term durability, decreased bending-induced strain, and greater gait stability. The PP–MCR foot is a technically robust and practically feasible improvement over traditionally researched prosthetic foot designs because to this hybrid material strategy, which immediately fills in gaps found in previous literature by combining structural integrity with functional compliance.

#### ➤ *Limitations of the Proposed Work*

Although a thorough numerical analysis of a Polypropylene–Microcellular rubber (PP–MCR) prosthetic foot is presented in this thesis, the results cannot be directly applied to clinical applications due to a number of presumptions and controlled simplifications. In the structural analyses, idealised boundary conditions are used, representing ground interaction through simplified support conditions under static physiological stress and the ankle attachment as a constrained interface. Transient heel-strike impacts, toe-off bending, and multidirectional stresses associated with dynamic gait are not captured by this method, which may result in greater local strain amplitudes, especially at the ankle

transition region, even if it is suitable for evaluating comparable designs.

To allow for consistent comparison across configurations, linear elastic constitutive models are used to represent the material behaviour of both microcellular rubber and polypropylene. As a result, factors that are particularly important to polymer-based prosthetic components, such as temperature sensitivity, creep behaviour, time-dependent viscoelastic effects, and long-term material degradation, are not specifically taken into consideration.

The estimation of fatigue life is predicated on anticipated fatigue parameters for Polypropylene and numerically determined stress–strain responses. This methodology does not replace experimental fatigue testing under realistic cyclic loading conditions, but it is appropriate for identifying fatigue-critical regions and evaluate designs in comparison. Predictions of fatigue life should therefore be regarded as indicative rather than definitive.

Additionally, the topology optimisation study does not completely incorporate manufacturability limitations such production tolerances, interfacial bonding between PP and MCR, or moulding feasibility, thereby emphasising stiffness-driven material distribution. Finally, the analysis is mostly based on numerical simulations; real-world performance confirmation requires experimental validation using physical prototypes, which is beyond the boundaries of this work.

## V. CONCLUSION

- According to the thesis, a hybrid Polypropylene–Microcellular Rubber (PP–MCR) prosthetic foot configuration has a higher mechanical efficiency than a completely MCR-based design due to the fact that it fundamentally changes load transfer by separating structural stiffness and shock absorption functions.
- According to static structural analysis conducted under physiological loading, the PP–MCR configuration exhibits stiffness enhancement without stress amplification, exhibiting a deformation reduction of approximately 99% in comparison to the conventional MCR foot while maintaining comparable equivalent stress levels.
- A strain-controlled fatigue mechanism for the PP core has been identified by strain and primary stress analyses, which show that strain concentration at geometrically limited regions—specifically, the ankle attachment—rather than peak equivalent stress governs fatigue-critical behaviour.
- The significance of deformation control in polymer-based prosthetic components is further supported by fatigue life estimation, which demonstrates that the heel and other compressive stress-dominated regions have relatively lower fatigue susceptibility, while the ankle transition region is the dominant damage initiation zone.
- A structurally efficient and lightweight redesign without affecting stiffness is made possible by the results of topology optimisation, which confirm the viability of targeted material reduction in mechanically inactive

regions while maintaining high-density material along load-transmission modes.

- Comparative analysis demonstrates that the PP–MCR foot achieves a balanced compromise between strength and user comfort by offering greater dimensional stability, fatigue resistance, and long-term durability while maintaining functional compliance through the MCR coating.
- Overall, the thesis demonstrates that a feasible approach to enhancing prosthetic foot performance—particularly for long-term structural integrity under physiological loading conditions—is provided by purposeful material hybridisation when combined with numerical analysis and optimisation.

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