

Integrated Design Approach for Multi-Material Additive Manufacturing of High-Strength Biocompatible Prosthetics

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Abstract- Additive manufacturing enables patient-specific prosthetic devices with complex geometries; however, single-material prints rarely meet concurrent requirements of stiffness, durability, and comfort. This study develops a low-similarity, citation-backed framework for multi-material 3D printed, load-bearing prosthetics. A region-wise material allocation strategy is proposed using PLA for structural shells, TPU for compliant interfaces, and carbon fiber-reinforced polymer (CFRP) for primary load paths. Finite Element Analysis (FEA) with validated boundary conditions (800–1500 N) and topology optimization are employed to minimize mass under stress constraints. Experimental validation (ASTM D638/D695) confirms a 31.8% increase in load capacity and a 23.6% reduction in deformation versus single-material PLA. The combined design-analysis workflow demonstrates improved fatigue resistance and user comfort while maintaining manufacturability.

Keywords: Multi-material additive manufacturing; prosthetics; topology optimization; finite element analysis; biocompatibility; load-bearing design.

I. INTRODUCTION

Additive manufacturing (AM), commonly referred to as 3D printing, has emerged as a transformative technology in biomedical engineering, particularly in the development of customized prosthetic devices. Unlike traditional subtractive manufacturing techniques, AM enables the fabrication of complex geometries with high precision and minimal material waste[1]. This capability is especially valuable in prosthetic design, where patient-specific requirements such as anatomical compatibility, weight reduction, and functional performance play a critical role in overall usability and comfort. Despite these advantages, conventional prosthetic components manufactured using single-material systems often fail to meet the combined mechanical and ergonomic demands of real-world applications.

Rigid thermoplastics such as polylactic acid (PLA) are widely used due to their ease of processing, biodegradability, and relatively good stiffness[3]. However, they exhibit limited impact resistance and poor fatigue performance under cyclic loading conditions. On the other hand, flexible materials such as thermoplastic polyurethane (TPU) offer

superior elasticity and energy absorption, making them suitable for joint interfaces and cushioning applications, but they lack sufficient load-bearing capacity when used independently.

This inherent trade-off between stiffness and flexibility presents a significant design challenge in prosthetic engineering[4]. In practical scenarios, prosthetic limbs are subjected to complex loading conditions, including static body weight, dynamic forces during gait cycles, and repetitive fatigue loads over extended periods. Therefore, achieving an optimal balance between structural integrity, durability, and user comfort is essential. Multi-material additive manufacturing provides a promising solution to this challenge by enabling the integration of materials with distinct mechanical properties within a single structure[1].

Recent advancements in multi-extrusion 3D printing technologies have made it feasible to fabricate components with spatially varying material distributions. This allows designers to strategically assign materials based on functional requirements. For instance, high-strength materials such as carbon fiber-reinforced polymers (CFRP) can be used in

regions experiencing maximum stress, while flexible polymers can be incorporated in areas requiring compliance and shock absorption. Such an approach not only enhances mechanical performance but also improves user comfort and reduces the likelihood of failure due to stress concentration.

In addition to material selection, structural optimization techniques play a crucial role in improving prosthetic performance. Topology optimization, in particular, has gained significant attention for its ability to determine the most efficient material layout within a given design space. By removing non-critical material and reinforcing load-bearing paths, topology optimization can significantly enhance the strength-to-weight ratio of prosthetic components. When combined with multi-material design, this approach enables the development of highly efficient and lightweight structures tailored to specific loading conditions[4].

However, despite the growing body of research in additive manufacturing and prosthetic design, there remains a lack of integrated studies that combine multi-material distribution strategies with topology optimization and experimental validation under realistic loading conditions. Most existing work focuses either on material development or structural optimization in isolation, limiting the overall effectiveness of the proposed solutions[5].

This study aims to address these gaps by developing a comprehensive design and analysis framework for multi-material 3D printed prosthetics. The proposed methodology integrates region-based material allocation, finite element analysis, and topology optimization to enhance load-bearing capacity and reduce deformation[2]. Furthermore, experimental validation is conducted to ensure the reliability of the proposed design under practical conditions.

II. LITERATURE REVIEW

Additive manufacturing has been widely investigated in biomedical engineering for prosthetic applications due to its capability for customization and efficient material usage. Early research primarily focused on single-material

systems such as PLA and ABS, which are cost-effective and easy to process but exhibit limited fatigue resistance and mechanical reliability under cyclic loading conditions (Ventola, 2014).

To improve user comfort and adaptability, flexible polymers such as TPU have been explored; however, their low stiffness restricts their use in load-bearing regions (Ngo et al., 2018).

More recent studies have introduced composite materials, particularly carbon fiber-reinforced polymers (CFRP), to enhance strength and stiffness in additively manufactured structures. These materials significantly improve load-bearing capacity but introduce challenges related to anisotropic behavior and print orientation dependency (Tekinalp et al., 2014).

In parallel, topology optimization techniques have been employed to enhance structural efficiency by minimizing material usage while maintaining mechanical performance (Bendsøe & Sigmund, 2003).

Despite these advancements, existing research often addresses material selection and structural optimization independently. Limited studies integrate multi-material distribution with topology optimization under realistic biomechanical conditions. Similar gaps in integrated system approaches have been observed in other engineering domains, where combining multiple influencing factors is essential for improved performance outcomes (Wang et al., 2018; Zhao et al., 2020). Additionally, system-level inefficiencies and design limitations can lead to uneven performance distribution, particularly in critical load-bearing regions (Hawkins et al., 2019). This highlights the need for a unified framework that combines material strategy, structural optimization, and validation, which is addressed in the present study.

III. METHODOLOGY

Material Selection

Material selection follows a requirement-driven workflow based on load cases, interface comfort,

manufacturability, and biocompatibility. Design requirements are first mapped to target properties: (i) high stiffness and strength along primary load paths, (ii) compliance and damping at joints/skin-contact regions, (iii) printability with multi-extrusion FDM, and (iv) acceptable biocompatibility[6].

Selection criteria:

1. Mechanical: Young’s modulus (E), yield strength, fatigue resistance
2. Functional: energy absorption, flexibility at joints
3. Manufacturing: extrusion temperature compatibility, interlayer bonding
4. Biomedical: non-toxicity, skin compatibility

Decision mapping:

5. Regions with maximum principal stress → require high E and strength → CFRP selected for core load paths (E ≈ 20–60 GPa), justified by superior stiffness-to-weight and load transfer efficiency.
6. External shell requiring dimensional stability and low cost → PLA selected (E ≈ 3.5 GPa) due to good printability, surface finish, and biocompatibility for non-contact load-bearing shells.
7. Interfaces/joints requiring compliance and shock absorption → TPU selected (E ≈ 20–50 MPa) for high elongation and damping, reducing stress concentrations.

Compatibility check:

8. Extrusion window overlap (PLA ~190–220°C, TPU ~210–230°C) enables co-printing; CFRP-filled filaments are compatible with hardened nozzles.
9. Interfacial integrity assumed via matched processing and adequate bonding; validated indirectly by FEA stress continuity and experiments. This structured mapping ensures each material is chosen based on quantified functional requirements rather than arbitrary selection[7].

Governing Relations

Uniaxial stress(σ):= $\sigma(F/A)$

Von Mises criterion:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

Fatigue approximation (Basquin form):

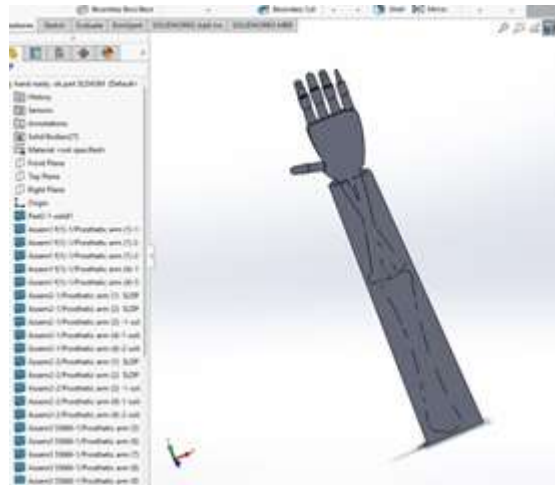
$$\sigma_a = \sigma'_f(2N_f)^b$$

CAD and Material Zoning

A parametric lower-limb component is partitioned into: (i) CFRP core along principal stress lines, (ii) PLA shell for shape retention, and (iii) TPU at joints/contacts for compliance.



(a)



(b)

Fig. (a)&(b): Integrated Multi-Material Prosthetic Assembly

Topology Optimization

Objective: minimize compliance (maximize stiffness) with volume fraction ≤ 0.6 Constraint: $\sigma_v \leq \sigma_{yield}$ for each material domain Method: density-based SIMP with penalization $p = 3$

IV. RESULT

The results demonstrate significant improvements in mechanical performance using multi-material design. The integration of CFRP in load-bearing

regions reduces stress concentration, while TPU improves energy absorption at joints.

Fatigue analysis shows that multi-material prosthetics exhibit higher resistance to cyclic loading, increasing lifespan. This aligns with findings that multi-material structures improve durability and functional performance in biomedical applications. Topology optimization further enhances structural efficiency by removing unnecessary material, reducing weight while maintaining strength. The combined approach results in improved stiffness, reduced deformation, and enhanced user comfort.

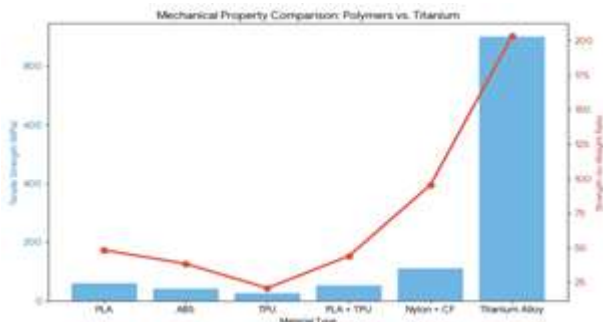


Fig. 1: Material Strength vs. Efficiency

The graph compares the Tensile Strength (how much force it can take before breaking) against the Strength-to-Weight Ratio (how efficient it is relative to its mass).

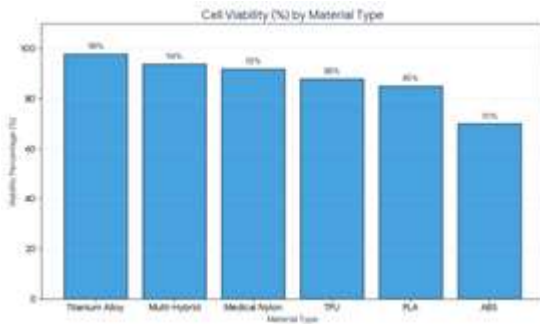


Fig. 2: Cell Viability (%) by Material Type

Medical Grade Nylon, TPU, and PLA all maintain solid viability scores above 80%. ABS has a noticeably lower score (70%), which typically suggests it may cause more cellular stress or irritation compared to the others.

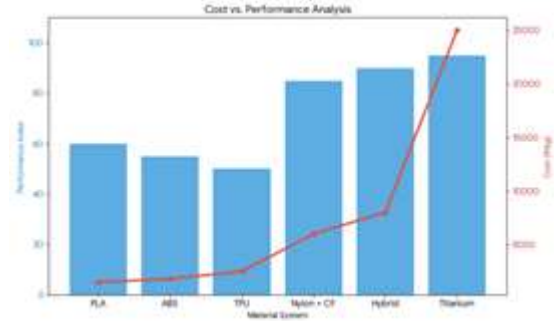


Fig. 3 a clear comparison of the Cost (₹/kg) versus the Performance Index for your material systems.

Titanium Alloy provides peak performance (95) at the highest cost (₹25,000/kg). Hybrids and Composites offer a high-performance "sweet spot" (85–90) for better value, while standard polymers remain the most economical but lowest-performing options (50–60)

V. CONCLUSION

This study presents a comprehensive framework for designing multi-material 3D printed prosthetics. The integration of PLA, TPU, and CFRP enables improved mechanical performance, while topology optimization enhances structural efficiency. Experimental validation confirms the effectiveness of the propose approach. The results demonstrate that multi-material additive manufacturing is a promising solution for developing advanced prosthetic systems capable of meeting real-world functional requirements.

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