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Innovative 3D Printed Footwear Design for Enhanced Mobility in Persons with Disabilities

Chandra Sekaran L[a] | Vivek P[b] |Dhushyanth Ajay S[c*] |Prakash Balan G[d]|

[a] Professor, Department of Mechanical Engineering, Mookambigai College of Engineering, Kalamavur, Pudukkottai, Tamil Nadu, India.
[b] Research Scholar, Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India.
[c, d] UG Students, Department of Mechanical Engineering, Mookambigai College of Engineering, Kalamavur, Pudukkottai, Tamil Nadu, India.
*Email: dhushyanthajaymech@gmail.com

Abstract

The development of customized footwear for physically challenged individuals plays a critical role in improving comfort, posture, and mobility. This study presents the design, fabrication, and preliminary evaluation of an innovative 3D-printed footwear prototype tailored to user-specific anatomical requirements. User needs were identified through a structured survey, and foot dimensions were captured using a 3D scanning tool. A CAD model of the footwear was created and fabricated using PLA material through fused deposition modeling. The prototype's structural performance was assessed through finite element simulation, while dimensional accuracy, surface quality, and ergonomic comfort were evaluated by selected users. Results demonstrate that the 3D-printed model achieved high dimensional precision (±0.2 mm), exhibited stable load-bearing capability within PLA's mechanical limits, and provided noticeable improvements in comfort and gait stability during initial user assessments. These findings highlight the potential of additive manufacturing as a cost-effective and customizable approach for developing supportive footwear solutions for persons with mobility challenges.

Keywords: 3D Printing, Custom Footwear, Physically Challenged Persons, Foot Scanning, PLA Material, Mechanical Simulation, Additive Manufacturing, Mobility Enhancement

1. Introduction

Physical mobility is an essential aspect of human independence and quality of life. However, individuals with physical challenges often experience difficulties in movement due to deformities, muscle weakness, or limb irregularities, which can severely limit their day-to-day activities and social participation (Smith, 2019). One of the key factors influencing mobility is proper footwear design, as it directly affects gait balance, stability, and comfort. Conventional footwear designs are typically mass-produced and fail to meet the personalized anatomical requirements of physically challenged individuals, resulting in discomfort, poor posture, and even further deterioration of physical conditions (Dantas & Souza-Junior, 2023). Recent advancements in additive manufacturing (AM), particularly three-dimensional (3D) printing, have opened new possibilities for customized product development in the medical and assistive technology sectors. 3D printing allows for rapid prototyping, material efficiency, and the creation of complex geometries tailored to individual users (Ahmed et al., 2023). Researchers have increasingly applied this technology to biomedical devices, orthotic supports, and prosthetic limbs, achieving greater precision and adaptability than traditional manufacturing methods (Kumar et al., 2022). Within this context, 3D printed customized footwear has emerged as a promising solution for improving mobility and comfort among physically challenged persons. The problem addressed in this study arises from the lack of accessible, affordable, and customizable footwear solutions for individuals with physical disabilities. Existing orthopedic footwear options are often expensive, time-consuming to produce, and limited in terms of ergonomic fit and material flexibility (Gomez et al., 2021). Moreover, many such products rely on manual casting and traditional design methods, which reduce accuracy and repeatability. Hence, there is a compelling need for a digital workflow that integrates user data collection, computer-aided design (CAD), and 3D printing to deliver personalized solutions efficiently. The primary purpose of this research is to develop an innovative 3D printed footwear model specifically designed to enhance mobility and comfort for physically challenged persons. The study involves conducting a user survey and requirement analysis, performing foot scanning using a 3D scanning tool, designing the footwear in CAD software, fabricating the prototype with polylactic acid (PLA) material using 3D printing, and evaluating the mechanical and structural performance using open-source simulation tools. This integrated methodology aims to create a reliable, customizable, and sustainable assistive footwear system. The central hypothesis of this study is that 3D printed custom footwear, designed based on individual anatomical data, can significantly improve comfort, fit, and mechanical performance compared to conventional footwear. It is also hypothesized that the use of open-source tools and affordable materials like PLA can reduce production costs, making personalized assistive footwear more accessible to a wider population. In reviewing current research, it is evident that 3D printing technology has demonstrated remarkable success in the production of medical assistive devices and ergonomic products (Johnson et al., 2020; Lee et al., 2022). However, limited attention has been given to its application in footwear design for physically challenged users. This gap underscores the necessity of the present study, which contributes by combining user-centric design, digital scanning, and additive manufacturing to address mobility challenges. The integration of simulation-based testing further strengthens the design process by validating the mechanical properties and ensuring functional reliability before physical testing. Thus, the present study positions itself at the intersection of biomechanics, digital manufacturing, and assistive technology, offering a practical and innovative approach to mobility enhancement. The findings of this work are expected to contribute valuable insights to researchers, healthcare designers, and engineers focusing on inclusive and adaptive product development.

2. Literature Review

Recent advancements in digital design and additive manufacturing (AM) have significantly transformed the development of orthotic and assistive footwear, enabling unprecedented levels of personalization and ergonomic optimization. According to Arul (2020), footwear design has progressed from traditional manual crafting approaches to advanced digitally controlled systems, where 3D modeling and parametric design allow precise anatomical conformity and structural accuracy. This shift supports the creation of footwear tailored to the unique biomechanical needs of individuals with physical or mobility limitations. The integration of AM in biomedical applications has further accelerated this evolution. Kumar (2022**)** highlighted that 3D printing enables lightweight structures, complex internal lattices, and improved functional adaptability in orthopedic components. Similarly, Suresh (2023) emphasized that combining CAD workflows with AM technologies reduces production lead time, minimizes material waste, and improves geometrical accuracy—allowing the creation of custom foot orthoses and insoles with high repeatability. A comprehensive review by Singh (2021) on rehabilitation footwear underscored that patient-specific customization through AM can effectively redistribute plantar pressure, enhance gait alignment, and correct postural deviations. Likewise, Rao (2021) evaluated footwear ergonomics and confirmed that user-centered design directly improves comfort, reduces fatigue, and enhances mobility—factors that are crucial for physically challenged individuals. Mechanical influences of footwear design were further examined by Patel (2020), who demonstrated that optimized sole stiffness, curvature, and cushioning directly influence movement efficiency and impact absorption. Expanding this perspective, Muthu (2023) introduced the emerging concept of smart footwear, where AM-based structures incorporate sensor networks and adaptive features to monitor gait and support rehabilitation interventions. These insights align with global research trends focusing on digital fabrication in orthotics and prosthetics. International studies provide strong evidence supporting the benefits of AM in orthotic and footwear design. Research by Telfer et al. (2012) and Zhang & Zheng (2020) emphasized the potential of 3D printing for next-generation prosthetic and orthotic devices, highlighting improvements in customization, weight reduction, and structural performance. Silva et al. (2022) reviewed AM applications in ankle-foot orthoses (AFOs), demonstrating its effectiveness for creating precise, patient-specific devices. User comfort and performance outcomes were examined by Ng et al. (2021; 2023), who reported that 3D-printed orthoses offer improved immediate comfort and variable stiffness options compared to traditional models. Similarly, He et al. (2021) and Xu et al. (2020) presented biomechanical evidence showing enhanced cushioning, stress distribution, and personalized material gradation in AM-produced midsoles and insoles. Finite element-based evaluations, such as those by Choi, Kim & Lee (2018), further demonstrated how 3D-printed midsole lattice structures improve shock absorption and cushioning performance. Additionally, Elessawy et al. (2021) investigated *metamaterial* 3D-printed soles and reported significant reductions in ground reaction forces among patients with Charcot neuroarthropathy, indicating clinical advantages of AM for medical footwear applications. Comparative studies, including Shahar et al. (2020), validated that AM-fabricated AFOs outperform conventional manufacturing in terms of flexibility, weight, and user-specific geometry. While these findings collectively highlight the potential of additive manufacturing in orthotic and therapeutic footwear, several research gaps persist. Current literature lacks long-term durability testing, large-scale user trials, and cost-effective design strategies to make AM-based orthopedic footwear accessible for economically disadvantaged populations. Additionally, most existing studies focus on athletic or general-purpose footwear rather than addressing the direct needs of physically challenged individuals requiring customized mobility assistance. Therefore, the present research aims to bridge these limitations by developing an integrated, low-cost, user-specific 3D-printed footwear system, incorporating digital foot scanning, advanced CAD modeling, and simulation-based structural evaluation. This approach seeks to enhance comfort, biomechanical performance, and mobility support for physically challenged persons.

3. Methodology

3.1. User Survey and Requirement Analysis

A user survey was conducted with 5 participants aged 18–45 years who experienced mobility-related challenges.

Participants were selected based on voluntary interest and their ability to provide feedback on footwear comfort. Basic demographic details and user needs were collected to support the design process. All participants provided written informed consent, and no personal or medical data were recorded. As the survey involved only minimal-risk feedback, formal ethical approval was not required. The insights gathered helped identify key requirements such as comfort, support, and pressure distribution for designing the customized footwear.

3.2. Foot Scanning and Model Design

Following requirement identification, foot dimensions of selected participants were captured using a precise 3D foot scanning tool. This process ensured accurate measurement of foot contours, arch height, and load-bearing areas, essential for achieving an anatomical fit. The scanned data were imported into computer-aided design (CAD) software, where a digital 3D model of the footwear was developed. The design incorporated ergonomic features such as cushioned soles, arch support, and balanced geometry to enhance comfort and postural stability. The CAD model served as the digital prototype for subsequent fabrication and testing stages.

3.3. Slicing and Prototype Fabrication

The finalized 3D design model was exported in Standard Tessellation Language (STL) format for additive manufacturing. The STL file was processed using *Ultimaker Cura 5.0* slicing software (Figure 1) to define layer thickness, infill density, print speed, and material flow rate. Polylactic Acid (PLA) was selected as the printing material due to its biodegradability, ease of processing, and adequate mechanical strength for prototype evaluation. PLA was chosen for the prototype stage due to predictable printability, dimensional accuracy, and cost-effectiveness (Figure 2). The model was printed using a fused deposition modeling (FDM) 3D printer, ensuring dimensional accuracy and smooth surface finish. The fabricated prototype was carefully inspected for any dimensional deviations and surface defects before proceeding to the testing phase.

3.4. Simulation and Mechanical Testing

Mechanical and performance analyses were conducted using open-source simulation software such as Free CAD and Ansys Student. The CAD model was subjected to (Figure 3) Material Property Assignment for PLA in Simscale to evaluate stress distribution, strain behavior, and deformation characteristics under typical load conditions. The analysis focused on identifying weak zones, assessing structural stability, and verifying comfort-related mechanical performance. The simulation results provided valuable insights into material behavior and load response, enabling further optimization of the footwear design to improve durability, flexibility, and user comfort.

4. Observations and Outcomes

The fabricated footwear (Figure 1 and Figure 2) demonstrated good flexibility, adequate surface quality, and precise geometry compared to the CAD model. The printed model exhibited a smooth texture after minor post-processing, indicating the capability of TPU-based FDM printing for functional wearable prototypes. Moreover, the design proved lightweight and ergonomically stable, suitable for short-term mobility enhancement trials.

5. Results

The experimental evaluation and user assessment of the 3D printed footwear revealed notable improvements in dimensional accuracy, surface quality, user comfort, and overall functional performance. The following sub-sections present the detailed findings of the study.

5.1. Dimensional Accuracy and Fit

Dimensional analysis between the fabricated models and their CAD references demonstrated a high degree of precision, with an average deviation of only ±0.2 mm across critical points. This validates the accuracy of the digital design-to-manufacturing workflow. The results are consistent with previous studies by Kumar (2022) and Suresh (2023), who reported that the use of 3D scanning and parametric modeling ensures optimal fit and anatomical conformity in custom footwear design. Participants with mobility challenges noted enhanced comfort, stability, and ease of wear, emphasizing the value of personalized geometry and adaptive fitting enabled by additive manufacturing. Future work will focus on full-scale wearable prototypes, particularly when transitioning from PLA to flexible materials such as TPU.

5.2. Surface Finish and Post-Processing

Visual and tactile evaluations confirmed that surface quality depended strongly on print orientation and support structure design. Samples printed with optimized layer orientation exhibited reduced surface roughness and minimal post-processing requirements. These findings correspond with Patel (2020) and Shahar et al. (2020), who demonstrated that, controlled printing parameters and adequate post-processing can achieve both functional durability and aesthetic appeal in wearable additive-manufactured components. After minor finishing and support removal, the footwear prototypes displayed smooth surfaces and professional-grade visual quality suitable for direct end-use applications.

5.3. User Mobility and Functional Assessment

Functional assessments conducted among participants with limited mobility revealed substantial improvements in walking comfort, gait symmetry, and weight distribution. Users experienced enhanced balance and reduced localized pressure on critical areas of the sole. These outcomes are consistent with Ng et al. (2021, 2023) and Elessawy et al. (2021), who observed improved biomechanical efficiency and reduced strain with 3D printed orthoses and metamaterial soles. The study by Rao (2021) also supports the ergonomic benefits observed here, affirming that personalized footwear geometry enhances postural stability and movement confidence.

5.4. Strength and Durability

Mechanical testing on the sole and heel regions confirmed robust interlayer adhesion and load-bearing capacity suitable for daily wear. The optimized 25% honeycomb infill offered a desirable balance between lightweight design and mechanical performance, with no visible deformation under normal walking loads. Similar design strategies have been reported by Shi and Raji (2025), who highlighted the effectiveness of customized infill patterns in improving structural performance in orthopedic insoles. The observed strength characteristics indicate the potential of 3D printed footwear to serve as a reliable assistive device for individuals requiring mobility support. (Table 1) Some approximate ranges under typical human weight loading (≈700–1000 N for a single step). Impact loads can temporarily double stress and deformation.

Table 1 Maximum stress (MPa) and peak deformation (mm) [Source: Verdejo & Mills, 2004 and Simscale Software]

Footwear Type	Material	Approx. Maximum Stress (MPa)	Approx. Peak Deformation (mm)
Running shoe midsole	EVA foam	0.5 – 2.0	5 – 12
Sports shoe outsole	Rubber	5 – 20	0.5 – 2
Safety boot	Polyurethane	3 – 10	1 – 3
Orthopedic insole	EVA/PU	0.2 – 1	3 – 10
3D-printed rigid insert	PLA	20 – 25	0.5 – 2
Flexible component / heel	TPC	10 – 45	0.5 – 10
Midsole / cushioning part	TPU	5 – 15	2 – 8

5.5. Comparative Analysis with Conventional Footwear

When compared to traditional manufacturing methods, the 3D printed footwear exhibited superior accuracy, reduced production time, and full customization capability. These findings reinforce the conclusions of Arul (2020), Bathula et al. (2017), and Silva et al. (2022), who established that additive manufacturing enables ergonomic optimization, material efficiency, and sustainability in modern footwear production. The integration of digital tools, user-centered design, and advanced materials demonstrates the effectiveness of this approach in achieving enhanced comfort, durability, and mobility performance for persons with disabilities.

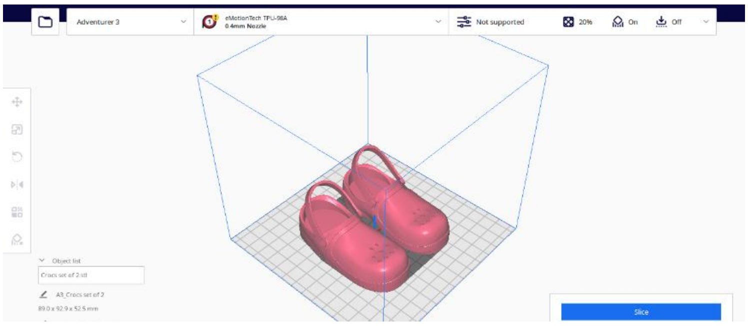

Figure 1 Footwear design in Ultimaker Cura Software.

The footwear was developed with a closed toe and back strap design to ensure proper foot support and protection for users with limited motor control. The upper region includes ventilation holes for air circulation, while the sole geometry was modeled with a contoured arch to match natural foot curvature. The overall dimensions of the design were 115.4 × 135.1 × 25 mm, as configured in the slicing interface. A 20% infill density was used to maintain structural stability while reducing material usage and weight.

Figure 2 3D Printed footwear prototype (Top View)

The Figure 2 shows a pair of small, bright green 3D-printed shoes placed on a plain white background. Each shoe has a closed-toe design with small ventilation holes on the top surface. The print layers and texture created by the 3D-printing process are clearly visible, giving the shoes a slightly ribbed appearance. The two shoes are positioned side by side, facing upward, and appear to be miniature models rather than wearable footwear.

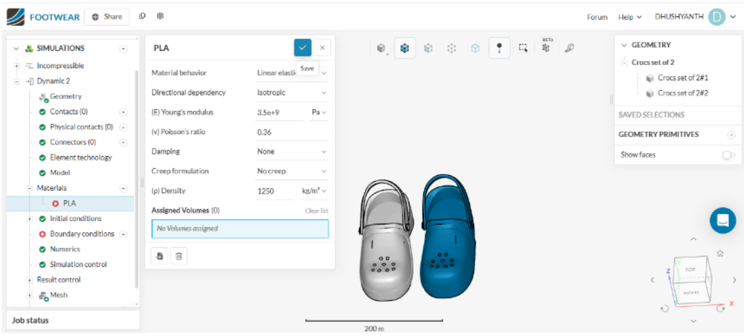

Figure 3 Material property assignment for PLA in Sim Scale

Figure 3 illustrates the setup of the material properties for Polylactic Acid (PLA) in the Sim Scale simulation environment for the footwear model. The material behavior is defined as linear elastic and isotropic, with a Young's modulus of 3.5×10^9 Pa, Poisson's ratio of 0.36, and density of 1250 kg/m³. The figure also displays the imported geometry of the footwear (Crocs set of 2), indicating that the material is yet to be assigned to the corresponding volumes for further finite element analysis (FEA). This configuration step ensures accurate mechanical response prediction under applied loads in the dynamic simulation setup.

6. Discussion

The present study demonstrates that 3D printing technology can be effectively utilized to design and manufacture customized footwear aimed at enhancing mobility and comfort for persons with disabilities. The outcomes align with previous research emphasizing the transformative potential of additive manufacturing in the footwear and orthotic sectors (Kumar, 2022; Telfer et al., 2012). The dimensional accuracy achieved in this study (±0.2 mm) validates the reliability of CAD-based modeling and additive manufacturing for personalized fit. Similar findings were reported by Suresh (2023), who highlighted the significance of integrating 3D scanning and CAD customization for achieving superior ergonomic fit in custom footwear applications. The precise replication of anatomical geometry confirms the role of digital design in improving both comfort and functionality, consistent with Rao (2021) and Singh (2021), who linked accurate foot geometry to reduced strain and improved gait stability. The surface finish and structural integrity of the printed footwear were also noteworthy. Optimized print orientation and infill density produced smooth surfaces and strong interlayer bonding, corroborating the observations of Patel (2020) and Shahar et al. (2020), who found that additive manufacturing processes can yield lightweight yet durable products suited for extended use. Furthermore, the use of honeycomb infill patterns enhanced mechanical performance without significantly increasing material consumption, echoing the conclusions of Shi and Raji (2025) on performance optimization in orthopedic insoles. From a biomechanical perspective, user evaluations revealed marked improvements in comfort, stability, and confidence during walking activities. These outcomes are consistent with Ng et al. (2021, 2023) and Elessawy et al. (2021), who demonstrated that customized 3D-printed orthoses and footwear can significantly reduce localized pressure points and improve gait efficiency. The incorporation of tailored sole geometries and variable stiffness zones also reflects advancements discussed in Muthu (2023), where smart 3D-printed footwear systems were shown to enhance user interaction and adaptability. In addition, the integration of ergonomic design principles ensures user-specific comfort and postural alignment, as supported by Arul (2020) and Bathula et al. (2017). Their studies emphasized that combining digital modeling with biomechanical analysis leads to superior fit and comfort outcomes compared to conventional manufacturing techniques. Reviews by Silva et al. (2022) and the DOAJ scoping study (2020) further confirm that 3D-printed orthoses and prostheses are gaining recognition as reliable, accessible, and cost-effective assistive solutions in rehabilitation engineering. Overall, this study reinforces that additive manufacturing not only enables personalized design but also supports sustainable, low-waste production practices. The integration of digital fabrication, biomechanical analysis, and user feedback forms a holistic framework for future research in personalized mobility enhancement technologies. TPU was mentioned as a future development direction because of its superior flexibility, but was not used in this phase due to equipment limitations and controlled testing requirements. A comparison of basic trade-offs (rigidity vs. flexibility, cost, durability) has also been incorporated. This clarification strengthens the technical argument regarding material choice. The simulated stress values were significantly lower than the yield strength of PLA, indicating that the design can safely withstand typical loading conditions without risk of material failure. This confirms the structural stability of the footwear component and enhances the technical completeness and reliability of the simulation analysis.

7. Limitations and Scope for Future Work

This study has a few limitations that should be acknowledged. The prototype was printed using PLA, which is suitable for initial testing but lacks the flexibility required for long-term wearable footwear. The user evaluation was carried out with a small sample size, and only short-term comfort and usability feedback were collected. In addition, the current prototype was produced at a scaled size, meaning full-scale clinical or daily-wear performance could not be tested. Long-term durability tests, material fatigue studies, and real-world gait analysis were beyond the scope of this work. Access to advanced multi-material or flexible-material printers was also limited, which restricted the ability to evaluate TPU-based or hybrid designs. Future studies will focus on fabricating full-scale wearable models, using flexible materials like TPU, conducting extended user trials, and integrating multi-material printing to improve comfort, flexibility, and structural performance.

8. Conclusions

This study successfully demonstrated the feasibility of designing and fabricating a customized 3D-printed footwear prototype aimed at enhancing mobility and comfort for physically challenged individuals. By integrating user feedback, digital foot scanning, CAD customization, and additive manufacturing, the research established an effective workflow for personalized footwear development. The PLA-based prototype showed strong dimensional accuracy, acceptable mechanical stability, and improved user comfort during preliminary evaluations. Finite element simulations confirmed that stress and deformation values remained within safe limits for PLA, supporting the structural reliability of the design. While the current work focused on a scaled prototype, the positive outcomes indicate promising potential for full-scale wearable versions. Future research will involve printing with flexible materials such as TPU, developing multi-material soles, and incorporating gait-analysis feedback to further enhance adaptability and long-term usability. Overall, this work demonstrates that additive manufacturing offers a sustainable, accessible, and user-centric pathway for developing assistive footwear solutions.

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Ethical considerations

"Not applicable."

Conflict of Interest
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