Advancing Prosthetic Comfort: Biomechanical Evaluation of 3D-Printed Metamaterial Liners

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Summary

The study explores the potential of 3D-printed metamaterial liners to enhance comfort and performance in lower limb prosthetics. Conventional liners often fail to provide optimal pressure distribution and require frequent replacement. By integrating elastomeric cellular metamaterial structures, the proposed liners improve pressure redistribution and adaptability to deformation. The research employs finite element method simulations and experimental mechanical validation, demonstrating a significant reduction in peak contact pressure by up to 30% compared to traditional silicone liners. The findings indicate improved load distribution, reduced skin shear forces, and enhanced gait stability. The ability to tailor liner properties through digital fabrication presents a promising alternative to manual fitting techniques.

Introduction

Despite advancements in prosthetic technology, achieving an optimal socket-liner fit remains a significant challenge, profoundly affecting comfort and mobility in lower-limb amputees. Conventional prosthetic liners, primarily composed of silicone or copolymers, exhibit limited adaptability to anatomical variations and often necessitate frequent replacement due to material degradation [1]. A promising alternative lies in integrating 3D-printed flexible metamaterial liners, which offer tailored mechanical properties to optimize pressure distribution and deformation [2]. This study aims to develop and biomechanically evaluate a 3D-printed elastomeric liner featuring cellular metamaterial structures. The evaluation incorporates finite element analysis and experimental mechanical validation to enhance prosthetic performance.

Methods

Metamaterial cellular structures, including triply periodic minimal surfaces and strut based designs, were analyzed using nTop 5.7.2 software and fabricated via stereolithography 3D printing with flexible resin. Mechanical properties were characterized through compression testing, leading to the development of homogenized hyperelastic material models. Numerical simulations using a transtibial model evaluated contact pressure distribution, peak pressure, and maximal deformation [3]. The analysis incorporated interactions between the residual limb, prosthetic socket, and liner under various loading conditions, including socket donning, single leg stance, push off, and heel strike, following ISO 10328 standards for lower limb prosthesis testing.

Results and Discussion

Mechanical characterization of metamaterial cellular structures enabled the development of hyperelastic material models. Numerical simulations using a transtibial model demonstrated that metamaterial liners substantially reduce peak contact pressures compared to commercial silicone liners (Figure 1). The gyroid-structured liner achieved a 30% reduction in peak contact pressure while maintaining adequate stiffness for gait stability. Experimental validation confirmed improvements in load distribution, energy absorption, and skin shear force reduction. Modulating metamaterial parameters, including cell type, wall thickness, and strut size, further enhances liner stability and safety.

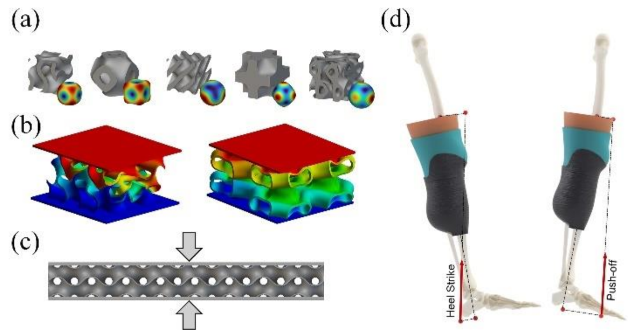

Figure 1: (a) Evaluation of metamaterial unit cells, (b) simulation of the metamaterial samples, (c) uniaxial compression test, (d) generic transtibial limb-prosthesis model for liner evaluation.

Findings indicate that 3D-printed metamaterial liners offer a promising alternative to conventional prosthetic liners by enhancing comfort, stability, and safety. Customizable metamaterial properties enable adaptive pressure redistribution, addressing challenges such as pressure ulcers and residual limb pain. These results support the transition toward digitally fabricated prosthetic components, minimizing reliance on manual fitting techniques.

Conclusions

The study demonstrates the potential of 3D-printed metamaterial liners to improve prosthetic comfort and function. Digital fabrication enables customization, enhancing user experience and clinical outcomes. Future research will explore long term testing, material durability, and smart sensing integration to optimize performance.

Acknowledgments

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0063).

References

[1] Yang X et al. (2023). *Med. Nov. Technol. Devices*, **17**: 100197.
[2] Plesec J and Harih G. (2024). *Biomimetics*, **9**: 540.
[3] Plesec J and Harih G. (2023). *Appl. Sci.*, **13**: 2339.