Adaptable customised orthotic insole: optimisation, simulation and experimental validation of 3D printed solid-liquid composite insole

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Summary

This study introduces a 3D printed solid-liquid composite orthotic insole, featuring fluid-impregnated gyroid lattices optimised for tailored stiffness and graded permeability. Using finite element modeling and a gradient-based algorithm, the design reduces peak plantar pressures and improves pressure distribution dynamically. Experimental validation confirms enhanced comfort and injury prevention, showcasing a transformative advancement in orthotic design.

Introduction

Plantar foot pain often results from uneven pressure distribution, causing localized stress, tissue strain, and potential ulceration [1]. Conventional orthotics aim to reduce peak stresses by ensuring full plantar surface contact but fail to address dynamic effects or active pressure redistribution. This paper presents a novel solid-liquid composite (SLC) orthotic design featuring fluid-impregnated cellular structures [2]. The SLC combines tailored stiffness and graded permeability to enable passive, responsive pressure redistribution over the foot's irregular topology, both statically and dynamically, enhancing comfort and mitigating stress. Regional tailoring of cell size and thickness optimizes permeability, flow resistance, and energy absorption for superior orthotic performance.

Optimisation and Computational Modelling

The insole geometry was derived from authors previously developed gait-driven computational simulations [2], accounting for plantar pressure distributions and biomechanical loading conditions as shown in Figure 1. A gradient-based optimisation algorithm along with MRI-based FE modelling of foot (Figure 1) was employed to minimise peak plantar pressures by iteratively adjusting the insole's regional material properties. The algorithm balanced factors such as stiffness, energy absorption, and pressure redistribution, incorporating constraints for biomechanical compatibility and manufacturability. The computational model was developed using FE, integrating subject-specific loading scenarios and material definitions for the solid-liquid composite. The gyroid lattice structures were modelled to mimic viscoelastic responses under dynamic gait conditions. The model accounted for fluid-structure interactions, using homogenization techniques to simplify complex behaviours while maintaining accuracy [2].

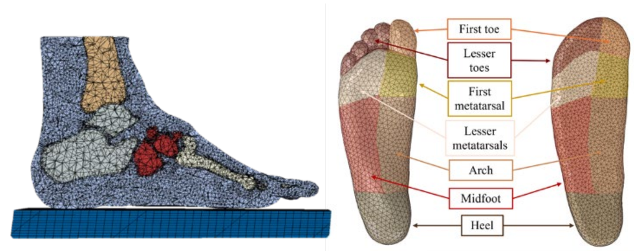

Figure 1: FE simulation model (left), optimisation regions (right)

Results and Discussion

The results show the effectiveness of a customised orthotic insole designed using a solid-liquid composite material and optimised through a gradient-based approach. As shown in Figure 2, the dynamic optimisations significantly reduced peak plantar pressures and enhanced pressure redistribution during gait compared to initial insole. The magnitude of peak pressures through each stage of gait is visibly clear, particularly in heel strike, foot flat, heel off, and toe off. This may be due to the significant reduction in insole stiffness in the high-pressure regions. The findings highlight the potential of the optimised insole to mitigate foot discomfort and prevent injuries, offering a transformative approach to orthotic design.

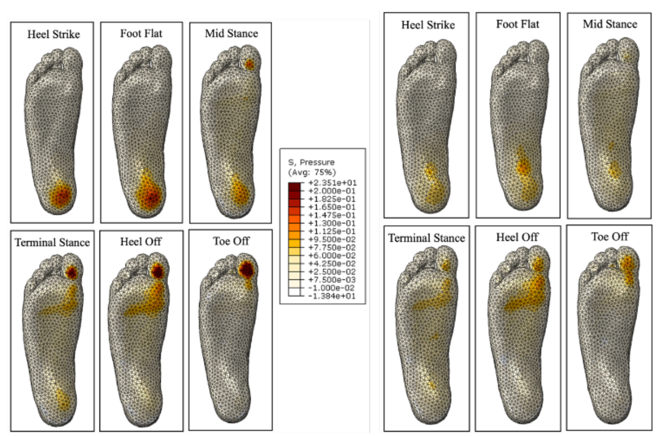

Figure 2: Plantar pressure through gait with initial insole (left) and optimised insole geometry (right)

References

[1] K. B. Landorf, "Plantar heel pain and plantar fasciitis, " BMJ Clinical Evidence, vol. 2015, Nov. 2015, issn: 1752-8526.

[2] Cracknell, D., Battley, M., Fernandez, J., & Amirpour, M. (2024). Fluid-filled lattices for responsive orthotic insoles. Smart Materials and Structures, 33(11), 115034.