Finite Element Modeling and Gaussian Process Regression for Heel Pad Visco-Hyperelastic Properties and Thickness Estimation from Indentation Tests

Olamide R. Hassan[1,2], Youngbin Lim[3], Luca Quagliato[1], Bogyoung Kang[1], Siwoo Jung[1], Sewon Kim[1,2], Jeicheong Ryu[1], Taeyong Lee[1,2]
[1]Division of Mechanical and Biomedical Engineering, Ewha Womans University, Seoul 03760, Republic of Korea
[2]Graduate Program in System Health Science and Engineering, Division of Mechanical and Biomedical Engineering, Ewha Womans University, Seoul 03760, Republic of Korea
[3]SIMULIA, Dassault Systèmes Korea, Seoul 06164, Republic of Korea
Email: tlee@ewha.ac.kr

Summary

Assessing the mechanical response of the plantar foot is crucial in biomechanics; however, traditional methods are often complex and time-consuming. To address this, a combined finite element analysis (FEA) and Gaussian Process Regression (GPR) approach is presented to model both the loading and relaxation phases of an indentation test, predicting visco-hyperelastic properties along with heel pad thickness. This approach effectively integrates experimental methods and computational modeling, with GPR enabling real-time estimation of material properties (within 10 seconds), offering accuracy comparable to analytical methods for reliable biomechanical analyses.

Introduction

Plantar soft tissue is essential for foot function and overall biomechanics, acting as a natural shock absorber during weight-bearing activities. The heel pad, in particular, is vital for distributing plantar pressure, making its properties key to understanding foot biomechanics. To evaluate these properties, relaxation tests were chosen for their ability to simulate the foot's daily mechanical effects through consistent deformation over time. While numerous studies have focused on plantar surface modeling using hyperelastic or viscoelastic models [1, 2], few have combined these methodologies to characterize foot properties fully. This study demonstrates the feasibility of incorporating hyperelastic and viscoelastic models into FEA, further enhanced by a trained GPR model to improve computational efficiency while maintaining accuracy.

Methods

The relaxation test was conducted using a spherical indenter with a diameter of 32mm, attached to a load cell with 1% accuracy. The test involved a 4mm indentation depth at a velocity of 5mm/s for 30 seconds on six subjects (Figure 1a). Heel pad thicknesses were measured using the portable MyLab Six (Esaote, Italy) ultrasound platform (Figure 1b).

FEA was used to replicate the indentation test, incorporating heel pad thickness in a simplified 2D model (Figure 1c). A total of 1,000 training data points were generated by randomly varying hyperelastic constants (C_{10}, C_{01}, C_{11}) and viscoelastic constants (g_0, t_0, β) (Figure 1c). Viscoelastic properties were directly obtained from the relaxation graph from the indentation test, while hyperelastic properties were estimated using GPR. The trained GPR model was validated by comparing predictions with six subjects' parameters.

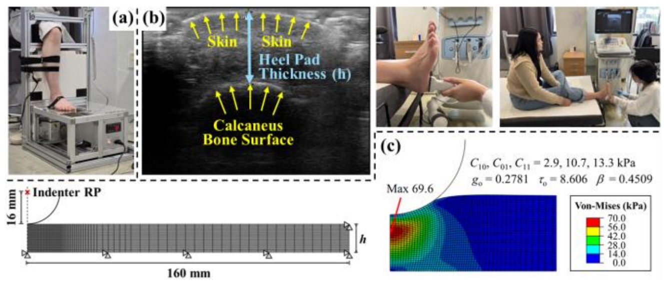

Figure 1: (a) Indentation test setup; (b) Ultrasonography for heel pad thickness measurement; (c) FEA model showing 2D geometry, von Mises stress distribution, and material parameters.

Results and Discussion

The indentation test results, analytical model, FE model, and GPR estimations were compared using R^2 and the identifiability index. For visco-hyperelastic modeling, the lowest R^2 was 0.95, and the I-index stayed below 2 in all cases, confirming that the parameters were identifiable and robustly estimated [3]. GPR-estimated heel pad thicknesses had an average error of 0.067mm, further validating the model's performance and reliability for the proposed applications.

Conclusions

This study introduces an FEA-driven GPR approach for the prompt and accurate estimation of visco-hyperelastic properties and heel pad thickness. Despite simplifications, the model demonstrates promising accuracy and potential for clinical and personalized healthcare applications, though fixation methods should be improved for better repeatability.

Acknowledgments

This research was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 2710000375, RS-2022-00164554).

References

[1] Suzuki R et al. (2017). *J Mech Behav Biomed Mater*, **65**: 753-760.
[2] Richard F et al. (2013). *J Mech Behav Biomed Mater*, **24**: 41-52.
[3] Renner E et al. (2020). *J Mech Phys Solids*, **138**: 103916.