A THREE-DIMENSIONAL INVERSE FINITE ELEMENT ANALYSIS OF THEHEEL PAD

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INTRODUCTION

Performing vital functions during locomotion and bearing significant loads, the foot is the primary interface between the body and the ground. Heel pad response can be used for biomechanical analysis of plantar tissue, which performs many important functions including shock absorption and distribution of contact loads [1]. To quantify plantar tissue behavior, previous computational studies have generally adopted two-dimensional representations and characterized nonlinear elastic parameters using compression dominant data only [1]. Hence, the goal of this study was to obtain material properties of the heel pad using a three-dimensional (3D) representation of specimen-specific heel pad geometry along with 3D loading response during compression dominated loading. Our follow-up objective was to compare optimized model predictions with data from a separate combined loading scenario including compression and shear. From diabetic foot ulceration to footwear design, the outcome of this work could be used to assess or improve many interventions or preventive treatment options utilizing computational modeling as an evaluation platform [2].

METHODS

Foot experimentation was previously performed on a specimen from a 58 year old male donor [3] (Fig. 1A). Computed tomography (CT) scans (Siemens s5vb20b, Medical Solutions USA, Inc., Malvern, PA) were collected for model development. The mechanical tests were conducted using a six degree of freedom robot (Rotopod R2000, Parallel Robotics Corp., Hampton, NH) using position control. A 25.4 mm diameter spherical indenter was used for compression testing of the heel which was followed by a combined compression and anterior-posterior shear loading [3]. During testing a foot specific coordinate axis was setup to approximately define the anterior axis from the posterior aspect of the heel to the second toe.

Figure 1: Heel pad indentation: (A) experimentation, and (B) 3D model with combined loading directions (B).

A 3D finite element (FE) heel pad model was developed to represent the foot specific geometry (Fig. 1B). The FE package Abaqus (Simulia, Providence, RI) was used to reproduce the experimental test conditions. The heel pad material (plantar soft tissue) was represented as a non-linear elastic material with an effective Poisson ratio of 0.475 to approximate near incompressibility. The strain energy function was defined as a first order Ogden form [4],

\[ U = \frac{2\mu}{\alpha} (\lambda_1^n + \lambda_2^n + \lambda_3^n - 3) \]  

Where, \( \lambda_{1-3} \) are the principal stretches, and \( \mu \) and \( \alpha \) are the material properties representing the hyperelastic behavior. The experimental load-deformation data for the compression only cycle was used for the material parameter (\( \mu \) and \( \alpha \)) optimization and the combined loading (compression and shear) data was used to validate the model response.
For minimization of the sum of squared-errors between model predicted and experimental reaction forces, the Truncated Newton optimization algorithm available in SciPy (http://www.scipy.org) was utilized. Thirteen evenly spaced points along each directional loading curve were defined for the error calculation (anterior-posterior, medial-lateral, superior-inferior). Initial guess values were specified as $\mu = 0.1$ kPa, $\alpha = 11$. The optimized parameter values were then used to simulate the load response during a test in which the heel pad was compressed, and then additionally deformed in anterior and posterior shear. Simulations were compared to measured responses.

RESULTS

A total of 117 iterations were required to reach convergence with a corresponding root mean square error (RMSE) of 0.7136 N (0.61% max force magnitude) between model and experiment (Fig. 2A). Optimized material parameters were found as $\mu= 1.084$ kPa and $\alpha = 9.780$. Using the optimal parameters, it was observed that the overall trends and magnitudes were reproduced during combined loading (Fig 2B). The superior direction loading resulted in an RMSE of 10.54 N (3.0% max force magnitude) with the lateral and anterior directions realizing 21.67 N (6.38% max force magnitude) and 6.52 N (1.9% max force magnitude), respectively.

DISCUSSION

The study was successful in reproducing the 3D geometry and accurately predicted multi-axis response during the compression dominant indentation test (Fig. 1 and 2A). Using the optimized parameters, it was also observed that the model predicted load response was generally comparable in the dominant shear loading direction (anterior) with very good agreement in the superior loading direction (Fig. 2B). It is speculated that deviations in the lateral force behavior could be a result of registration errors between CT image set and experimental setup. Future sensitivity and optimization studies will assess this explanation. Further plantar tissue validation will also be performed for additional loading tools and loading scenarios [3]. Given the availability of data, this study could also be extended to include forefoot passive response, effectively modeling whole foot structural response. To the authors knowledge, this study is the first to optimize nonlinear elastic material parameters using dominant and off-axis loads in a 3D model and including a validation attempt with an additional dataset. The results have important implications for the accurate prediction of shear response in plantar tissue and lend more insight into the biomechanics of this important structure.

![Comparison of experimental reaction forces with the model predicted values using the optimized material properties](image1)

![Comparison of experimental reaction forces with the model predicted values using the optimized material properties](image2)

Figure 2: Comparison of experimental reaction forces with the model predicted values using the optimized material properties A) compression B) combined loading of compression and anterior-posterior shear.

REFERENCES


ACKNOWLEDGEMENTS

This study was funded by NIH R01EB006735.