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Oral presentation

A finite element foot model for simulating muscle imbalances

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Introduction

To overcome the expense and limitations of cadaveric testing, we developed a finite element (FE) foot model. Previous foot models have included hyperelastic materials, plantar fascia, and extrinsic muscle forces [1]. We also included the plantar fat pad and both distal and proximal cartilage in our model. We validated the model by comparing plantar pressures and joint angles to literature sources and cadaveric testing data.

Methods

High-resolution MRI and CT scans (0.6 mm isometric voxels) were performed on a male cadaveric foot from a 44-year-old, 823 N, non-diabetic subject. An acrylic frame held the foot in the same position between scans. ImageJ was used to segment the plantar fat, proximal and distal cartilage, and outer skin layer from MRI scans. Custom written MATLAB and IDL code was used to create STL files from the XY coordinates exported via ImageJ. Multi-Rigid was used to segment the bones from the CT scans and then register the bones to the MRI scan positions [2]. Rhinoceros was used to perform Boolean operations on the segmented cartilage. The tetrahedral automesher in ANSYS ICEM CFD v10.0.1 was used. LS-DYNA v971d was the non-linear explicit solver. The model includes: foot bones, distal and proximal cartilage of selected joints, plantar fat, with the remaining volume inside the outer skin boundary defined as a general soft tissue (Figure 1). The soft tissue and plantar fat pad were modeled using an Ogden hyper-elastic rubber formulation [3,4], while bones were rigid bodies. Cartilage was considered a linear elastic material and included for the following joints: ankle, subtalar, talonavicular, calcaneocuboid, and metatarsophalangeal and interphalangeal joints of the 1st ray. Ligaments were modeled as 1-D non-linear springs while tendons were included using seatbelt elements and anatomically placed slipring elements. The foot was inclined at 7° to simulate midstance. For a neutral balanced standing simulation, a force of 400 N was applied down on the tibia with 200 N applied up on the calcaneus. Loads were ramped to full amplitude by 0.2 s and the simulation time was 0.4 s. Bone rotations for the calcaneus, talus, navicular, cuboid, and the 1st and 5th metatarsals were compared

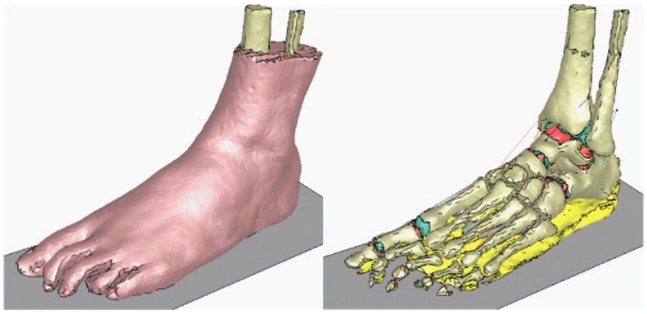

Figure 1
FE foot model: with (left) and without (right) soft tissue. (pink = soft tissue, beige = bone, light blue = proximal cartilage, red = distal cartilage, yellow = plantar fat).

with cadaveric data and pressure data beneath the heel, lateral midfoot, and the 1st and 5th metatarsals to the literature [5].

Results

For the neutral balanced standing simulation, 11 of 18 bone rotation angles fall within two standard deviations of the cadaveric data and all peak plantar pressure values are within one standard deviation.

Conclusion

Our anatomically detailed FE foot model simulated correct plantar pressures, but the bone rotations are not all correct. It is possible that including cartilage at all foot joints and using wider ligament origins and insertions may address these issues. Future simulations include a clawed hallux and a flatfoot model. Future work on the model includes intrinsic muscles, wider ligaments and more cartilage.

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