THE DEVELOPMENT AND EVALUATION OF A 3-DIMENSIONAL, IMAGE-BASED, PATIENT-SPECIFIC, DYNAMIC MODEL OF THE HINDFOOT

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INTRODUCTION

A confirmed dynamic model of the hindfoot enables parametric analyses to determine how the following injuries or treatments affect hindfoot mechanics (kinematics, flexibility, contact forces and ligament loads): tearing ligaments and repairing them (tenodesis), changing articulating surface geometry (arthroplasty), and constraining a joint (arthrodesis). The model predictions may provide guidelines for altering existing treatments or designing new ones to more closely restore normal hindfoot mechanics. The objective of this study was to develop and evaluate 3D, subject-specific, dynamic hindfoot models (n = 6 *in vitro*) using 3D stress MRI data [1].

METHODS

Existing software (3DVIEWNIX™ [3], Geomagic Studio™) were used to obtain the subject's bone surface geometry and collateral and subtalar ligament insertion data from MR images. Non-linear load-strain functions described the structural properties of the ligaments [4]. Cartilage's elastic modulus and an exponential term modeled its non-linear compression characteristics [5]. The ADAMS 2003™ software generated and solved the dynamic equations of motion.

Each model (healthy and with ligament injury) was evaluated through subject-specific stress MRI experiments [1] and arthrometer tests [2]. The model used the same forces (inversion, anterior drawer, rotation) and boundary conditions as the experiments. Model output corresponded to the experimental measurements (helical axis parameters, flexibility).

RESULTS AND DISCUSSION

The model with intact ligaments predicted the experimental inversion and anterior drawer kinematic patterns of the ankle joint complex, but under-estimated ankle joint motion and over-estimated subtalar joint motion. Similar to the experimental data, releasing the anterior talofibular ligament and the calcaneofibular ligament caused rotations at the ankle joint complex and at the ankle joint to increase in inversion compared to the intact condition. Unlike the experimental data, the model over-estimated rotations at the subtalar joint.

Similar to experimental data, the modeled ankle joint complex had hysteresis and had high flexibility in the unloaded neutral zone, followed by rapidly decreasing flexibility at the extremes of the range of motion in all directions (Figure 1). The model revealed that hysteresis coincided with low contact forces and with switching contact locations at the articulating surfaces. The low flexibility region coincided with increasing contact forces and with no change in contact location.

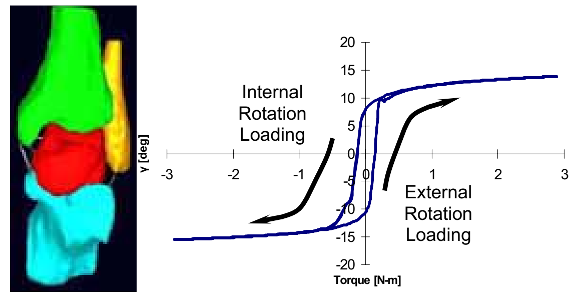

Figure 1: *In vitro* model (left). Predicted load-displacement curve (right).

The ligament strain and loading patterns were sensitive to ligament removal. Sensitivity analyses indicated that rotations caused by altering ligament orientation were smaller than rotations caused by lateral ligament removal; therefore, the model may be sensitive to predicting the changes that occur during ligament rupture. Hindfoot mechanics were sensitive to bone morphology and ligament insertion location.

The results indicate that the structural properties of the subtalar joint's interosseous ligament and cervical ligament must be quantified. The models' assumptions and limitations include differences between the experimental and modeled boundary conditions, exclusion of the cartilage geometry, and estimation of the subtalar ligaments' structural properties.

CONCLUSIONS

Future work will focus on quantifying the structural properties of the subtalar ligaments, developing a larger group of patient-specific models, and performing statistical analysis on output data. Despite the models' assumptions and limitations, they may be a valuable tool to explain fundamental mechanical phenomenon such as joint hysteresis and to do the previously described parametric analyses.

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