Sensitivity of Local Male and Female Ankle Geometries on Soft Tissue Injury Prediction Metrics in Morphed Finite Element Models

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I. INTRODUCTION

The field of injury biomechanics has increasingly used geometric morphing techniques in finite element human body models in attempts to include greater biological variance in injury prediction tools [1-2]. In theory, increasing the number of geometries represented by biomechanical tools should improve response prediction at a population-level, however, little is currently known about how advantageous morphed models are in representing population variance in injury prediction. Frequently, the results of morphed models are not compared to subject-specific experimental data of the target geometries, and therefore the accuracy and amount of injury risk variation that is captured by geometry alone is unquantified [1]. It is possible that morphing techniques might not provide an advantage in injury prediction for some load conditions or body regions, or that this advantage is negligible relative to using a single geometry model with an injury prediction metric created with population-level injury tolerance or injury risk data. Therefore, it is pertinent to evaluate the sensitivity of injury prediction metrics to geometric morphing in models representing different body regions and different loading conditions. This study aims to determine the sensitivity of local injury prediction metrics resulting from three male and three female ankle geometries under inversion and eversion loading.

II. METHODS

Six lower extremity models were generated by geometrically morphing a base finite element model [3-4]. These models were assigned the same soft tissue material properties [5-8], had subject-specific bone mass from computed tomography scans [9], and were scaled to the same gross size; this allowed the effect of local geometry on injury prediction metrics to be isolated. Models were simulated in ankle inversion and eversion (up to 50 degrees) with a constant 2000 N axial load similar to previous experiment inputs [10-11]. The maximum principal strains in soft tissues were evaluated across morphed models of different local geometries.

Model Development

The lower extremity bones of three male and three female donor CT scans were segmented, and used as the input to a morphing algorithm that included automatic implementation of cartilage and ligaments based on bone geometry [3]. The models included 26 rigid bones, 111 deformable ligaments, and 96 deformable pieces of cartilage inferior to the knee joint [4]. Assigned soft tissue material properties were shown to be reasonable by determining simulation ankle bone kinematics fit within experimentally derived corridors [11]. All node positions and subject-specific bone masses were scaled to the same gross size using equal-stress equal-velocity scaling with scale factors created from donor total height. This resulted in six morphed models of the same total size and material properties, but with different local ankle geometries, which can be visualized in Figure 1.

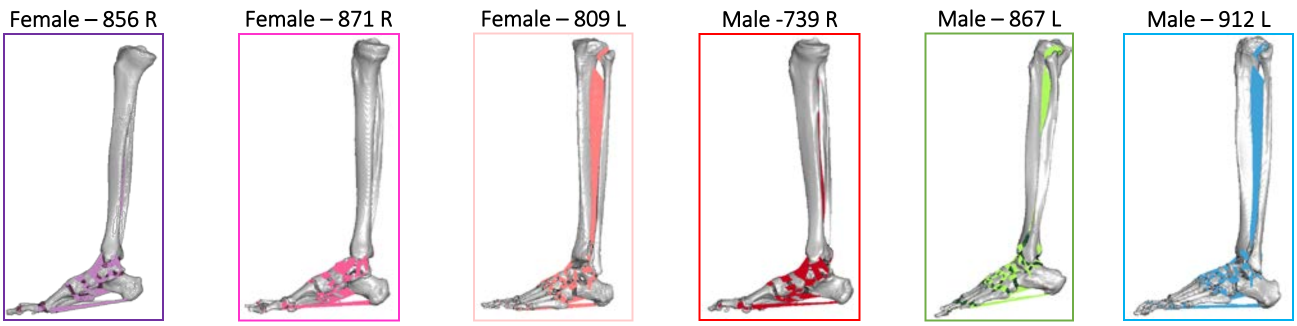

Fig 1. Local ankle geometry variation for the three male and three female finite element models.

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Simulations

For each model, the tibia ridge was oriented perpendicular to a footplate, and a 2000N axial load on the tibia plateau was applied in a pre-simulation. The tibia was then rigidly constrained to its preloaded position. Automatic surface-to-surface contacts were applied between the midfoot and forefoot and the footplate and medial and lateral blocks, which were placed to ensure the foot rotated with the footplate. The calcaneus was then rigidly constrained to the foot plate, where rotations were applied. Models were simulated in both ankle inversion and eversion (1000 deg/s up to 50 degrees) with a 2000 N constant axial load. Centre of rotation was determined anatomically as two-thirds of the z-direction height from the most inferior point on the calcaneus to the midpoint of the malleoli. Maximum principal strain of each ligament and piece of cartilage were output.

III. INITIAL FINDINGS

Simulation results showed the six local geometry finite element models demonstrated negligible difference in soft tissue strain with respect to ankle angle. The maximum principal strain of a selection of soft tissues for inversion and eversion rotations can be seen in Table I. Qualitatively, the strain distributions in the ankle ligaments and cartilage were similar across models, i.e., the calcaneofibular ligament consistently had the highest strain value in the inversion simulations, and the tibiocalcaneal ligament had the highest strain in all the eversion simulations. Results show these injury prediction metrics are not sensitive to local geometry variance (sex-related or inter-individual) for inversion and eversion about the anatomic centre of rotation of the ankle.

TABLE I

MAXIMUM PRINCIPAL STRAIN IN SOFT TISSUES THE FINITE ELEMENT MODELS WITH SIX DIFFERENT LOCAL GEOMETRIES

Model Local Geometry→	F – 856 R	F – 871 R	F – 809 L	M – 739 R	M – 867 L	M – 912 L	VARIANCE
Ankle Inversion Simulations: *calcaneofibular ligament strain*	0.412	0.424	0.411	0.424	0.415	0.433	5.76e-5
Ankle Inversion Simulations: *inferior talus cartilage strain*	0.064	0.061	0.065	0.067	0.061	0.063	4.00e-6
Ankle Eversion Simulations: *tibiocalcaneal ligament strain*	0.376	0.387	0.393	0.385	0.37.8	0.391	3.90e-5
Ankle Eversion Simulation: *inferior talus cartilage strain*	0.079	0.083	0.81	0.085	0.077	0.077	8.89e-6

IV. DISCUSSION

In this study, different local geometries had minimal differences in soft tissue strain when the foot was driven by a defined rotation input; this is contrary to experiments under the same load condition, where different types of soft tissue injury occurred across same-size donors [10-11]. This suggests that increasing the number of geometries represented in human body models might not capture variance in injury risk for some loadings. Rather, it is likely important to also capture inter-individual variance in material stiffness and failure properties to improve population-level injury prediction for some injury types and/or load conditions. Additionally, previous morphing studies have shown that morphed models improve subject-specific kinematics when subjected to external load, but these studies note that morphed models did not necessarily improve injury prediction [12-14]. The results of this study and previous studies suggest that increasing geometric accuracy via morphing methodologies should not be assumed to definitively improve injury prediction capability, especially when material or failure properties of tissue of the morphed model are anticipated to deviate from the baseline model's material properties, i.e., male baseline model morphed to a female geometry) [15-16].

V. REFERENCES

[1] Hwang E et al, SAE Tech Paper, 2016.
[2] Hu J et al, J Automot Saf Energy, 2012.
[3] O'Cain C et al, OSU Inj Biomech Symp, 2019.
[4] Nie B et al, Comput Method Biomec, 2016.
[5] Siegler S et al, Foot & Ankle, 1988.
[6] Attarian D et al, Foot & Ankle, 1985.
[7] Funk J et al, J Biomech, 2000.
[8] Ding M et al, Clin Biomech, 1998.
[9] Taylor Wet al, J Biomech, 2002.
[10] Roberts C et al, IRCOBI, 2018.
[11] Funk J et al, SAE Tech Paper, 2000.
[12] Iraeus J et al, Traffic Inj Prev, 2019.
[13] Beillas P and Berthet F, Traffic Inj Prev, 2017.
[14] Larsson KJ et al, IRCOBI, 2019.
[15] Chandrashekar N et al, J Biomech, 2006.
[16] Jiao K et al, Arch Oral Biol, 2010.