VALIDATION OF SUBJECT-SPECIFIC MODELS OF THE ANKLE JOINT COMPLEX

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INTRODUCTION

Three-dimensional (3D) image based, subject specific models of the ankle complex can be useful predictive and planning tools in clinical applications such as diagnosis of ligament injuries, planning personalized surgical reconstructive procedures, and evaluation of Total Ankle Replacements. However, few subject-specific computational models exist that produce the complex 3D properties of the ankle complex [1]. Using a computational modelling framework introduced by us in the past [1], we developed in the present study several such subject-specific models and compared their simulated mechanical behaviour against the experimental data on a subject-by-subject basis. This comparison providing the necessary testing of the validity and reliability of our ankle complex models. It also allowed us to test the validity of the hypothesis that the source of the inter-subject variability in joint mechanical properties is the inherent inter-subject variability in the morphology of the ankle's articulating bones.

METHODS

Cadaver leg specimens (n=9) were scanned both on CT and MRI and then tested on a special linkage where they were loaded in three planes (Figure 1). The applied loads and displacement in 3D of the calcaneus, talus and tibia were recorded [2].

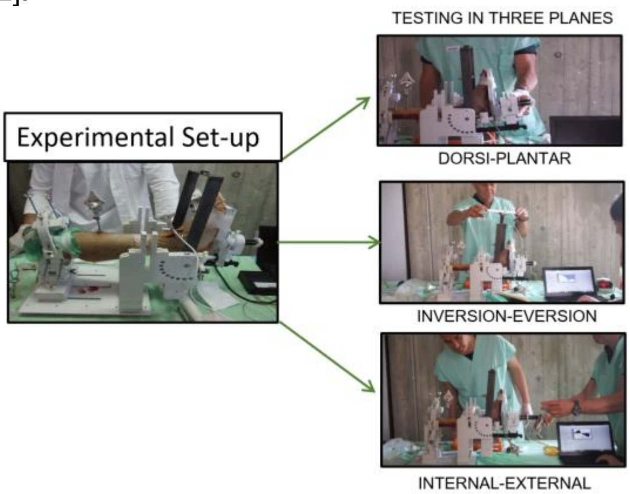

Figure 1 – Experimental set-up for testing the cadaver legs in three planes. The applied torque and the displacement of hindfoot bones (calcaneus, talus, tibia) were recorded.

Using the image data, 3D models of the ankle complex were produced for each specimen. The models included bone morphology, ligament attachments, articular cartilage thickness distribution. Cartilage-based contact mechanics and mechanical properties, ligaments pre-strains, and ligament mechanical properties were based on literature (Figure 2) [3,4].

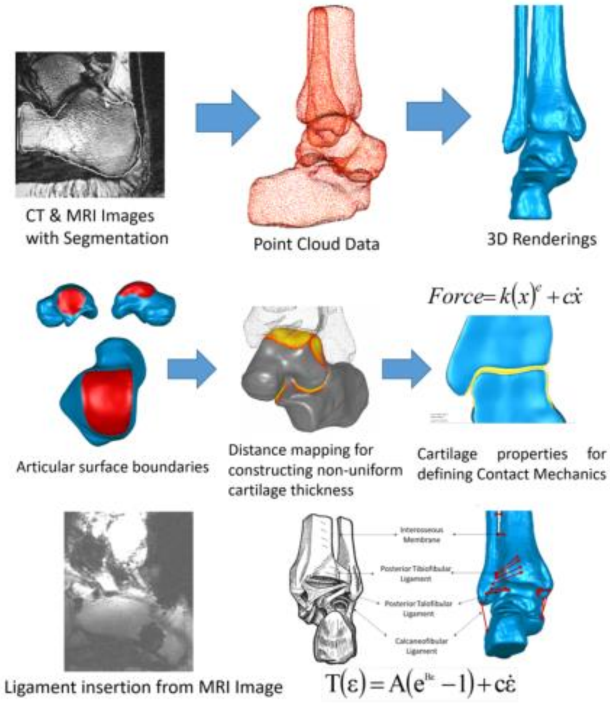

Figure 2 – The process of producing the subject-specific ankle complex models

Simulations, using experimental loading and boundary conditions, were performed with ADAMS™ [1].

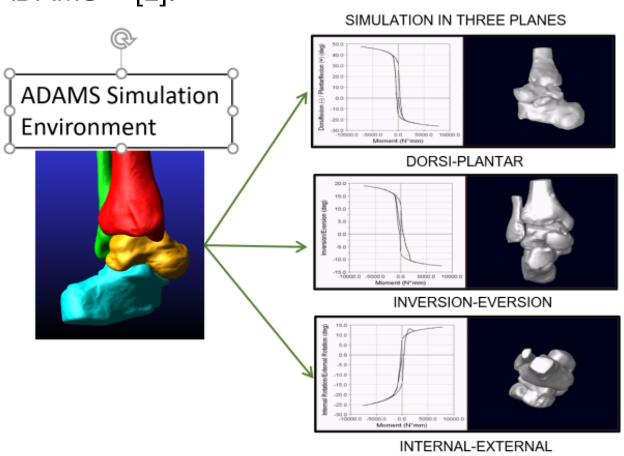

Figure 3 – ADAMS simulation environment for simulating Ankle behaviour in three planes.

Subject specific comparison included Range of Motion, Load-Displacement characteristics, and surface-to-surface interaction based on distance mapping which quantified the distance distributions between the articular surfaces.

RESULTS AND DISCUSSION

The results show good agreement in ROM, in all three planes of motion (Figure 4). The load-displacement characteristics obtained with the models were similar to the experimental results and produced the non-linear behaviour with the typical hysteresis characteristics (Figure 5).

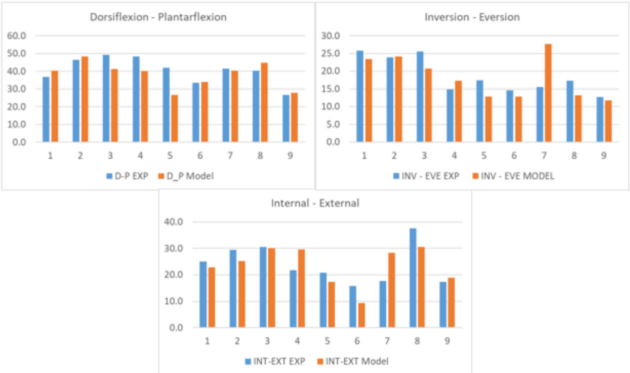

Figure 4 – Comparison of total range of motion in the three planes of motion between experimental data and models.

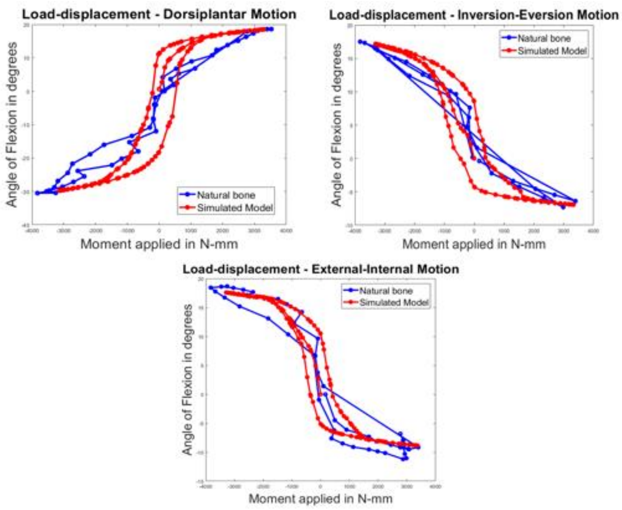

Figure 5 – Comparison of displacement-load in three planes between experimental data and model for one specimen.

The surface to surface interaction at the ankle joint [5] described by the distance maps, produced in the neutral position and at the extreme of the ROM in all direction showed good agreement between the simulations and the experiments (Figure 6).

CONCLUSIONS

Data obtained from image-based, subject-specific computational models were compared to experimental data from cadaver specimens on a specimen-by-specimen basis and produced

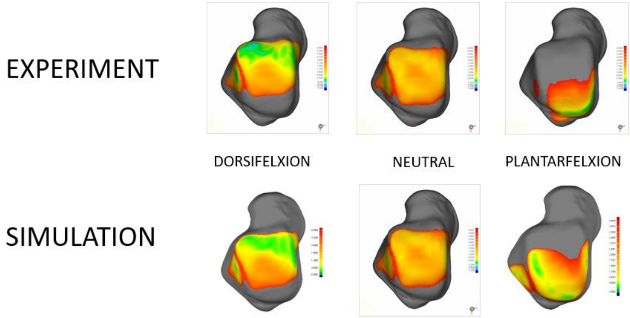

Figure 6 – Comparison of distance maps at the ankle joint in neutral and in extreme dorsiflexion and plantarflexion position, between the experimental data and the results of the simulation for one specimen.

similar results over a wide range of biomechanical parameters, confirming the reliability of these models. Such models may be used in the future as an important aid in personalized treatment planning such as design of patient specific surgical planning for ligament reconstructions and design of patient specific Total Ankle Replacements. In addition, both the experimental and corresponding simulation results demonstrate large inter-specimen and inter-model variability in mechanical properties of the ankle complex (see for example Figure 4). Such large inter-subject variability was observed and documented in many earlier experimental studies. The correspondence between the models results and the experimental results and the large inter-subject variability strongly suggest that this inter-subject variability is to a great extent the results of inter-subject variations in the morphology of the articulating bones. In addition, the large inter-model variations in mechanical properties suggests that, unlike the common practice used in many modelling studies, one single "representative" model may not be adequate to understand and characterize a variety of ankle joint mechanical phenomena. A more reliable approach would require a multitude of models so that the inter-model variability could be described.

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