SUBJECT-SPECIFIC FINITE ELEMENT MODELS CAN PREDICT STRAIN IN THE HUMAN MEDIAL COLLATERAL LIGAMENT UNDER VALGUS LOADING
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INTRODUCTION: Despite the many investigations of ligament function, the exact role of specific ligaments in maintaining joint stability, the cause and effect of injuries, and the efficacy of various reconstructive procedures remain unclear or unknown. This is partially due to inherent measurement limitations of experimental studies. The finite element (FE) method can predict spatial and temporal variations in stress, strain, and contact area/forces, and provides a standard framework for parameter studies such as evaluation of multiple treatments. This can decrease cost, time, and potentially accommodate intersubject variability that often limits sensitivity of experimental and clinical studies. The objective of this study was to develop and analyze FE models of MCL mechanics using subject-specific material properties, ligament/bone geometry, and in situ strains. Strains in the MCL under valgus knee loading were measured experimentally and predicted using subject-specific FE models with three knee flexion angles. The hypotheses were 1) subject-specific FE models could predict experimental measured MCL strains, and 2) accurate FE predictions of MCL strains could be obtained with average material properties and average in situ strains.

METHODS: Eight male knees (50±7 yrs) were subjected to a detailed experimental and computational protocol to study MCL mechanics during valgus joint loading. All peritalar soft tissues and the patella were removed. The femur and tibia/fibula were secured in mounting tubes. Mounting blocks for an instrumented spatial linkage (ISL, Endura-Tec, Eden Prairie, MN) were secured to the femur and tibia. The blocks allowed spatial registration of experimental and FE coordinate systems [1]. A volumetric CT scan (FOV=140 mm, slice thickness=1.0 mm) was then obtained for each knee at 0° flexion. Each knee was mounted in a kinematic test fixture. Ten cycles of 0, 30, and 60° flexion. Tibial axial rotation, medial-lateral translation, and joint distraction were unconstrained while anterior-posterior tibial displacement was constrained in a neutral position. MCL fiber strain was measured in 12 regions using a 3D marker tracking system (Peak Performance Technologies, Englewood, CO). Kinematic and strain data from the loading phase of the 10° valgus cycle were used for analysis and modeling. The MCL was then dissected free from its attachments, placed on a saline covered glass plate and allowed to assume its stress-free configuration. The marker tracking system was used to determine gauge lengths [5]. These data were used to calculate regional tensile strain between markers. Uniaxial tensile test specimens were harvested from the MCL parallel and transverse to the fiber direction using an established protocol [3]. Stress-strain data were acquired and fit to a transversely isotropic hyperelastic constitutive law [4].

Surface geometry of the femur, MCL, and tibia of each knee was obtained from the CT data. Hexahedral FE meshes (~25k elements) were created from the surfaces (Fig 1B). NIKE3D was used to analyze the FE models. In situ strains measured during passive flexion were applied to the FE models as an initial condition [2]. Experimental kinematics were used to prescribe motion of each FE model. The femur and tibia were represented as rigid. Contact between the MCL and bones was enforced. FE predictions of fiber strain were obtained from locations corresponding to experimental measurement regions.

The necessity of subject-specific modeling was assessed for two inputs that would be difficult to quantify in vivo. All eight models were reanalyzed using average material properties and again using average in situ strains. Regression analyses were used to evaluate the ability of the subject-specific FE models to predict experimental MCL strains, and to compare subject-specific FE model strains with predictions from models that used average material properties and in situ strains.

RESULTS: There was very good agreement between experimental measurements and FE predictions of MCL fiber strain (Fig 2). FE strain predictions significantly correlated with experimental values at all flexion angles (Fig 3A) (p<0.001 at all angles, \( R^2 = 0.83, 0.72, \) and 0.66 at 0, 30, and 60° respectively).

Figure 2 - MCL fiber strain with 10 Nm valgus torque at 0, 30, and 60° for experimental measurements (left) and subject-specific FE models (right) for one of the knees.

Figure 3 - Correlations between experimental and subject-specific FE strains (Left) and avg FE strains and subject-specific FE strains for all knees and flexion angles.

DISCUSSION: The primary goal of this study was to assess the ability of three-dimensional FE models of the human femur-MCL-tibia complex to predict experimentally measured values of MCL strain during valgus loading. FE models with subject-specific geometry, material properties, and boundary conditions (in situ strain and kinematics) resulted in good predictions of experimental MCL strains (Figures 2 and 3A). Despite inter-subject variation in MCL material properties, FE models constructed with average material properties were also able to predict experimental values. However, FE models with average in situ strain values did not provide accurate predictions of experimental values (Figure 3B).

Three-dimensional FE models of the MCL allowed shear, compression, and bending to be represented more accurately than is possible with discrete element ligament models. In addition, the subject-specific approach allowed incorporation of individual material properties, geometry, and boundary conditions. The methodologies developed in this work can be readily adapted to the study of other ligamentous structures and joints. This should provide a solid foundation for further studies of ligament injury, healing, and patient-specific clinical treatment.


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