AUTOMATICALLY SEGMENTED FOUR-DIMENSIONAL MAGNETIC RESONANCE IMAGING AND BIOMECHANICAL MODELING OF THE MOTION OF THE MENISCUS

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Introduction: The biomechanical importance of the meniscus has become increasingly evident, yet its specific functions in guiding and restraining motion of the knee remain unclear. While the meniscus is now known to support a significant portion of the load transmitted in the knee joint, it is unknown how various injuries to the meniscus may affect this load transmission. An integrated approach to four-dimensional magnetic resonance imaging and biomechanical modeling of the knee joint is being developed to investigate the motion of the normal and injured meniscus. An automatic segmentation algorithm is used to process sequential images of the knee during flexion and quantify the kinematics of the meniscus. A three-dimensional finite element model is constructed from these images to investigate the influence of a circumferential tear on motion and stresses in the meniscus. This model includes poroelasticity and surface-to-surface contact in three dimensions.

Methods: The left knee of a normal 36 yr. old male volunteer was imaged using a T2 weighted 3D gradient recall echo and 3D chemical shift gradient recall echo imaging sequence with optimized parameters. Images were acquired on a 1.5T clinical imaging unit (GE Signa Horizon, Milwaukee, Wisconsin) using specially developed knee phased array coils. Two orthogonal data sets were obtained with the knee in a fully extended position, and 6 additional image sets were collected stepwise as the knee was flexed 40 degrees. An 11 cm FOV with a 256 x 256 matrix was imaged using 1.5 mm slices. The initial orthogonal MRI data sets were then processed using an automatic region-based segmentation algorithm based on voxel-to-voxel connectivity(3). An unsupervised statistical segmentation algorithm was used to separate major structures including bone, cartilage, meniscus, fat, muscles, tendons and ligaments. A motion estimation and tracking algorithm, with registration of selected feature points, was used to follow the segmented images through the flexing motion of the knee. Iris Explorer 2.0 3D visualization software was used to display a movie of surface renderings of the segmented data on a Silicon Graphics Octane workstation. For the finite element (FE) model, Explorer software was used to obtain radial cross sectional images of the knee. A set of nine circumferential surface outlines were captured from the non-segmented image data to define the surface topology of the medial meniscus. These data points were imported into ACIS solid modeling software and connected with B-splines to define a six sided solid model of the meniscus, and custom numerical p.d.e. grid generation algorithms were used to generate a mesh of 510 hexahedral elements. For this preliminary model, the tibia cartilage surface was generated from the lower meniscus surface. All analyses were performed with MARC 7.2 FE analysis software. The bone surface of the tibia cartilage was assumed to be fully fixed, while the articular cartilage was modeled as an isotropic linear elastic material ($E = 10$ MPa, $\nu = 0.3$). The meniscus is modeled as an isotropic poroelastic material and is fully fixed at the anterior and posterior horns. ($E = 20$ MPa, $\nu = 0.3$, $k = 1 \times 10^{-15}$ m^4/Ns, ref. 2) Contact between the meniscus and tibia is assumed frictionless, and a non-uniform pressure is gradually applied to the superior surface of the meniscus approximating the pressure distributions identified by Ahmed and Burke (1). A maximum pressure of 0.31 MPa is reached following a linear ramp of 10 seconds, then this pressure distribution is held for 4 seconds over a total of 35 analysis steps. The FE analysis assumes large displacements in a total Lagrangian formulation. In a second analysis, a full-thickness circumferential tear was introduced into the body of the meniscus model by creating duplicate nodes. The torn surface is also assumed a frictionless contact surface. A comparison is then made between the motion and stress patterns of the normal and torn meniscus

Results: The automatic segmentation algorithm clearly distinguishes the bone, cartilage and meniscus surfaces. Other soft tissues like the cruciate ligaments remain difficult to segment. The motion estimation and tracking algorithm appears to accurately represent the motion of the meniscus relative to the tibia and femur surfaces during normal passive flexion. A surface rendering of the superior tibia surface with the medial and lateral menisci is compared to the FE model of the medial meniscus to demonstrate the similarity of the three-dimensional geometry obtained either from automatic segmentation or manual digitizing of MR images. (Figure 1)

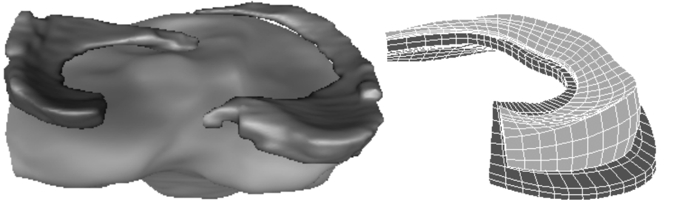

Figure 1.

Results of the FE analysis clearly indicate a large radial displacement of the meniscus which increases with the continued pressure on the meniscus (Figure 2). Only subtle differences were identified between the stress patterns in the normal and torn meniscus for this type of tear, under the prescribed loading conditions.

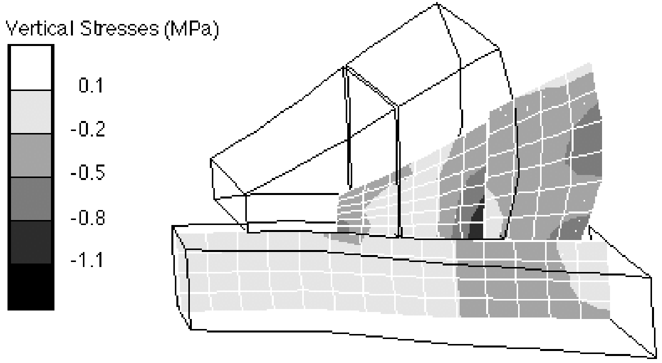

Figure 2. Cross-section of FE model depicting vertical stresses in body of torn meniscus at time = 10 seconds. Original position is outlined in black.

Discussion: The automatic MR image segmentation and motion tracking algorithms provide a powerful tool for visualization of musculoskeletal structures like the knee joint. When coupled with FE analyses, it will also be possible to study alterations in stress and strain patterns due to more complex loading conditions or injuries in the soft tissues. Because the predicted radial displacement of the meniscus in the current model is likely an overestimation due to the assumption of isotropic material properties for the meniscus, future studies will incorporate anisotropy in the solid matrix. In addition, an attempt will be made to validate the FE model using the 4D image sequences of passive flexion prior to further analyses of other loads, motions or injuries. The circumferential tear appears to have a minimal influence on meniscus displacement or stresses in the extended knee. Other knee motions or flexion positions will likely exhibit more significant differences.

References: 1.)Ahmed, A. M., and Burke, D.L.: J. Biomech Eng., 105(3):216-225, 1983. 2.) Schreppers, G.J., et al.: Proc Inst Mech Eng [H], 205(4):233-241, 1991. 3.) Tamez-Pena, J.G., Parker, K.J. and Totterman, S.: IEEE workshop on Biomedical Image Analysis, Santa Barbara, CA, June 1998, pp. 154-163.

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