In-vivo assessment of patellofemoral joint stress using a finite-element analysis approach.

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Abstract:
Subject-specific finite-element models of the patellofemoral joint are used to quantitatively evaluate the maximal stress and the stress distribution over the surfaces of the patellar and femoral cartilage. High-resolution MRI images with 1.0 mm slice thickness taken with a 3.0-T General Electric (GE Healthcare, Milwaukee, WI) MR scanner were segmented using Sliceomatic software (Tomovision, Montreal, Quebec) to create a 3-D model of the patellofemoral joint. Loaded MRI scans were taken with the subject in a static squat position with the knee joint at angles of 0, 30, and 60 degrees. These scans were also segmented in order to determine the appropriate positions of the knee components for each knee joint angle. The segmented components were the femur, the tibia, the patella, the patellar cartilage, and the femoral cartilage. The bones were modeled as rigid bodies, and the cartilage as linearly elastic material, which has been determined to be appropriate for the loading situation being simulated (a static squat).[1] A finite-element mesh was created for each of the components using Hypermesh software (Altair Engineering Inc., Troy, MI) for subsequent use in Abaqus software (SIMULIA, Providence, RI) to determine subject-specific cartilage stresses.

Introduction:
Osteoarthritis of the patellofemoral joint is very common and has been reported in up to 25% of the population.[1] Since effective treatment options for advanced osteoarthritis are very limited, early intervention and/or prevention is crucial to minimizing pain and pathology of the patellofemoral joint that occurs as the cartilage undergoes abnormally high stresses and eventual attrition. The cause of patellofemoral pain is believed to be related to stimulation of pain receptors in the subchondral bone caused by high stresses transmitted to the bone from the cartilage .[1]

Finite-element modeling of the patellofemoral joint is thought to be an accurate way to calculate the stress distribution and the maximum stress in the patellar cartilage.[2] This involves MRI imaging of the knee joint and manual segmentation of each of the joint components, which is possible due to the differences in water content between the cartilage and bone. A mesh is then created for the components that allows a finite-element software package to calculate stresses for each of the elements. The boundary conditions are applied to the tibia and femur to fix them in space, while applying the quadriceps forces to the patella, which has 6 degrees of freedom, and the joint is allowed to reach an equilibrium state. The location and magnitude of maximum stress in the cartilage can then be observed, as well as the stress distribution. In addition, the model can be partly validated by comparing the contact area given by the finite-element model with the contact area observed and calculated from axial slice images of the knee joint. This calculation can be made by measuring the observed contact length in each axial slice and then multiplying the length by the slice thickness, and summing the contact area inferred from each slice to get the total contact area of the cartilage.

Methods:
High-resolution images using a fat-suppressed spoiled gradient recalled echo sequence (repetition time: 13.5 ms, echo time: 1.5 ms, flip angle: 10°, matrix: 512 X 512, field of view: 17 x 17 cm, slice thickness: 1.0 mm) were obtained from a subject with patellofemoral pain. These images were taken with the knee joint at 0° flexion under no loading.

Low-resolution loaded MR images of the subject's knee were obtained with the knee at 0, 30, and 60 degrees flexion, using a fast 3-D spoiled gradient echo sequence (repetition time: 33 ms, echo time: 9 ms, flip angle: 45°, matrix: 256 X 160, field of view: 20 x 20 cm, slice thickness: 2.0 mm).

Sliceomatic software package was used to manually segment each sagittal slice of the components using the Active Contour (snake) method for the bones and the region-growing method for the cartilage. In addition to the region-growing method, substantial manual adjustment was needed at the extreme edges of the cartilage to insure that a workable mesh could be created. Figure 1 shows a single slice of a segmented MRI image.

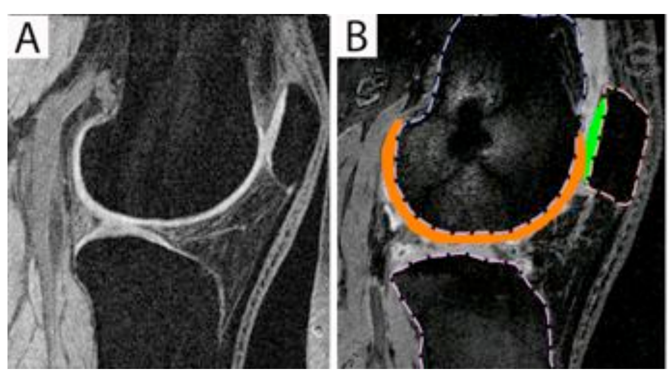

Figure 1: Segmented Saggital Slice

After the 2-D images were segmented, the Sliceomatic program morphed the slices and created a triangular 3-D surface mesh for each component. The geometry was saved as binary .stl file format that could be read with the Hypermesh software.

Hypermesh software was used to create a model that could be used in Abaqus. Since the mesh created by Sliceomatic was rough and not well-suited for modeling, a smooth surface was created in Hypermesh from the Sliceomatic mesh. This surface was then used to create a smooth, well-defined, closed 2-D triangular mesh for the bones, and a smooth 3-D tetrahedral mesh for the cartilages. The high-resolution components were then registered in the positions dictated by the low-resolution components. Models for 0, 30, and 60 degrees of flexion were created in this manner. Figure 2 shows a picture of the model of the joint at 60° flexion.

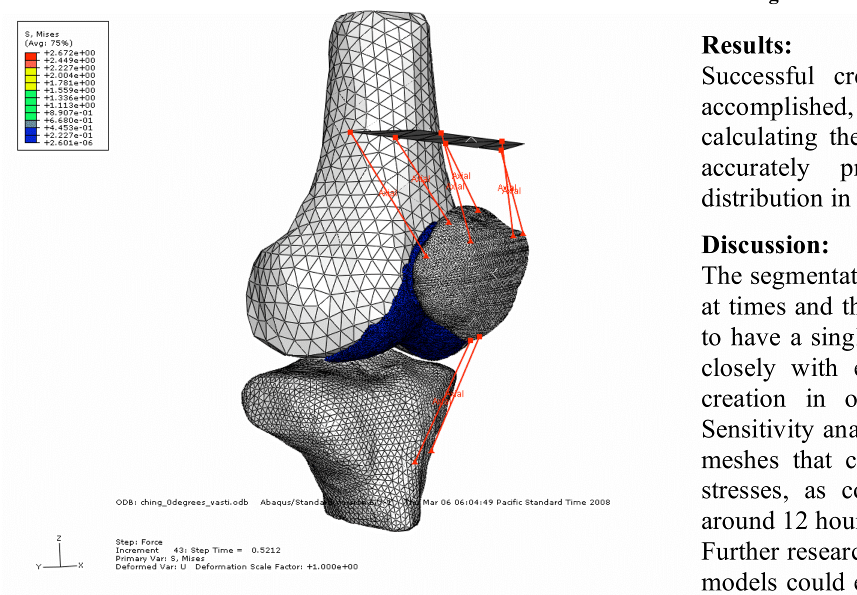

Figure 2: Hypermesh Model of the Knee Joint at 60° Flexion.

After the Hypermesh model was created, it was imported into Abaqus, where elastic connector elements representing the patellar ligament as well as the quadriceps muscle forces were attached to the tibia and patella. The bones were modeled as rigid bodies, while the cartilage was modeled as linearly elastic with an elastic modulus of 6.0 MPa and a Poisson's ration of 0.47. Quadriceps forces and directions are modeled based on inverse dynamics analysis, EMG measurements taken during the static squat stance, and lines of action of each of the quadriceps muscles determined from the MRI images. The simulation is currently being refined, and is aimed at producing a stress distribution similar to that shown in Figure 3.

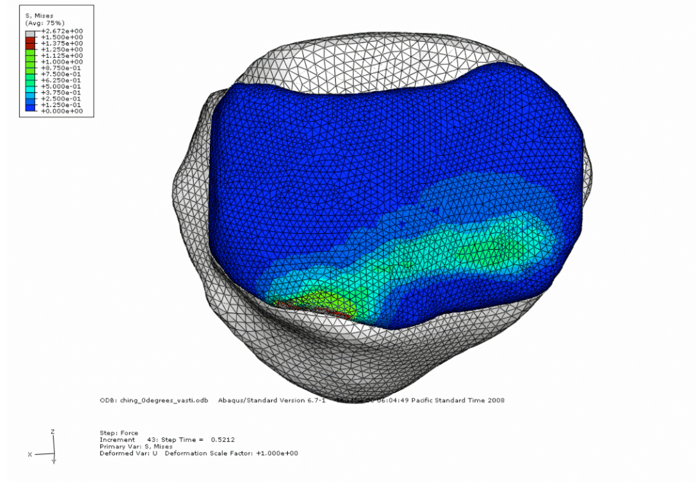

Figure 3: Example of Stress Distribution in the Patellar Cartilage.

Results:
Successful creation and positioning of the meshes was accomplished, although work remains to be done in calculating the quadriceps forces and directions in order to accurately produce an appropriately accurate stress distribution in the cartilage.

Discussion:
The segmentation and the mesh creation was very ambiguous at times and therefore it is necessary for any particular study to have a single researcher, or at least a group working very closely with each other, doing the segmenting and mesh creation in order to insure repeatability and reliability. Sensitivity analysis needs to be done to determine the largest meshes that can be used to accurately determine cartilage stresses, as computation time for a single model can be around 12 hours or so.

Further research aimed at producing accurate subject-specific models could eventually be used to develop interventions for current patients with patellofemoral pain by modeling various effects of exercises that strengthen certain regions of the quadriceps that will change the stress distribution and lower the maximum stress experienced by the cartilage. It also could be used to identify individuals in which patellofemoral pain is likely to occur and identify recommendations for preventative medicine in this area.

References:

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