HIGHLY AUTOMATED METHODS FOR SUBJECT-SPECIFIC, POPULATION-WIDE INVESTIGATIONS OF HABITUAL CONTACT STRESS EXPOSURE IN THE KNEE

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INTRODUCTION

The contact stress in a joint is a critical factor in its health and maintenance. Computational methods have been developed to estimate joint contact stress,[1,2] but analyses using these methods have been limited to tens of subjects, due to inherent complexities in subject-specific modeling. Much larger numbers of subjects will need to be analyzed to achieve the statistical power necessary to clarify the role of contact stress in joint pathology.

The Multicenter Osteoarthritis Study (MOST) is a prospective observational study of older adults with frequent knee symptoms or at risk for developing symptomatic knee OA.[3] Large-scale studies such as MOST present a unique opportunity to use longitudinal imaging data to assess the relationship between contact stress and pathology. This paper describes highly automated methods developed to use data from 150 knees from the MOST cohort to predict articular contact stress (Figure 1).

METHODS

Subjects had a 1.5T knee MRI obtained at baseline using a FLASH VIBE sequence, with a 0.3x0.3x1.5 mm resolution. Bone surfaces were segmented manually on an interactive pen display using OsiriX software (OsiriX Foundation, Geneva, Switzerland), and the 3D point clouds were wrapped using geometric software (Geomagic, Inc., Research Triangle Park, NC). The Geomagic software was scripted to automate this process.

MR images were acquired with the subject in a relaxed supine position. Accurate mechanical modeling requires that bone surfaces be aligned to a functional loaded apposition. Posterior-anterior fixed-flexion standing radiographs acquired using a standardized protocol were used in a 3D-to-2D registration of bone surfaces to a loaded apposition.

A feature-based 3D-to-2D alignment algorithm was written in MATLAB (The MathWorks, Natick, MA). The algorithm requires a 3D triangulated surface for each bone, as well as a 2D binary tracing of the relevant bony edges obtained from a standing radiograph. The radiographic imaging protocol was reproduced in a 3D virtual scene with the bone model initialized at the center of the film. Ray casting was used to project a bone edge silhouette of the model onto the virtual radiographic film. This silhouette was then compared to the bone edge tracing to drive an alignment optimization.

Covariance matrix adaptation evolution strategy (CMA-ES) [4], a meta-heuristic global optimizer that requires few parameters to be selected a priori, was utilized to iteratively manipulate bone models through the 3D space to achieve this alignment.

![Figure 1](https://example.com/figure1.png)

Figure 1. Methodology for subject-specific, population-wide investigations of habitual contact stress exposure in the knee. MR images are segmented to produce bone model (a-b), which are aligned to a standing radiograph using a ray casting algorithm (c). Contact stress is computed using discrete element analysis (d).
Cartilage and subchondral bone surfaces obtained previously using validated manual segmentation methods [5] were also available in the MOST data. Segmentations of the cartilage surface and of the bone/cartilage interface were wrapped as 3D triangulated models using Geomagic Studio, and registered to the functional loaded apposition.

Cartilage thickness maps were generated and stored for use in the contact stress analysis. Contact stress was evaluated using a discrete element analysis (DEA) algorithm written in MATLAB.[1] Femoral and tibial cartilage layers were treated as beds of independent elastic springs anchored to an underlying rigid bone surface. Contact stress was computed from the apparent penetration of the articular surfaces.

RESULTS AND DISCUSSION

The methods described proved a highly efficient means for obtaining contact stress estimates in the knees studied. Manual tracing of the bone surfaces accounted for the majority of time expenditure, at ~2 hours of user time per knee. Automated knee segmentation methods (e.g., [6]) are fast becoming available, and they will allow for large reductions in the user time required to complete this task.

Alignments were completed in approximately 4 minutes per bone, involving over 8,000 cost function evaluations. Initial alignment optimization failed approximately 20% of the time, resulting in a poor alignment. This was easily identified by either examination of objective function cost or visual examination. All alignments with errant solutions were re-run. Solutions which would not optimize acceptably (appropriate cost function value) with repeated trials were flagged for re-tracing of the 2D radiograph. As expected, alignment had the highest variability orthogonal to the film direction. This variability can be mitigated by using an average of multiple trials, or using a priori knowledge of joint anatomy to control alignment along this direction. Future studies using simultaneous bi-planar imaging techniques would greatly reduce this issue.

Contact stress computations were completed in ~3 minutes per knee and produced reasonable contact stress distributions (Figure 2). Peak computed contact stress across all 150 knees was 4.8±3.1 MPa and mean contact stress was 1.8±0.87 MPa.

Due to the extensive use of automation in model creation, alignment, and contact stress computation, procedures for verifying the quality of individual results need to be established. For the purposes of this study, results for each step were examined visually in the case of model creation and contact stress, or by a more objective measure (objective function cost) for alignment. Future methods need to be developed to specifically flag poor solutions and return them to the investigator.

CONCLUSIONS

The described methods provide a practical framework for utilizing information from large epidemiological studies to compute contact stress exposures. The methods were demonstrated using 150 subjects from the MOST study. Future addition of automated segmentation and quality control methods will significantly decrease investigator time investment and further improve results.

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