MENISCAL MODELING IN A DISCRETE ELEMENT ANALYSIS OF THE KNEE

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INTRODUCTION

Discrete element analysis (DEA) is a means for estimating articular joint contact stress, using bone surface geometries derived from CT or MRI [1]. The utility of DEA in studying knee joint contact stress from a cohort of 60 subjects from the Multicenter Osteoarthritis (MOST) study, an investigation of the incidence and progression of knee osteoarthritis in a cohort of 3026 men and women, was previously established [2] (Figure 1).

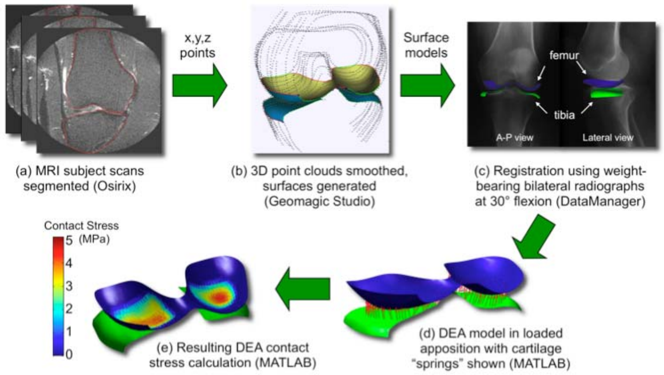

Figure 1. This schematic outlines the approach implemented for population-wide investigations of habitual contact stress exposure.

In that previous work, the meniscus was not included in the knee models.

The meniscus plays an important role in stress transfer across the knee joint. DEA models, as conventionally implemented, have not incorporated intervening tissues between contacting cartilage surfaces. However, in principle, the meniscus can reasonably be treated as simply another deformable in-line structure, using the same DEA concepts. This of course requires meniscal geometry (available from MR images) and appropriate modification to the underlying formulation of DEA equations being solved.

In the present study, the feasibility of incorporating a meniscus in a knee DEA model was evaluated in a group of MOST subjects for whom the meniscal geometry was amenable to segmentation from MR images. Computed contact stress distributions with the meniscus included were compared to those computed without a meniscus.

METHODS

The basic DEA implementation constructs a system of linear compressive elements at closest-point vertex pairings between the tibia and the femur, with the spring constants reflecting local effective stiffness, based upon the elastic modulus, Poisson's ratio, and thickness of the cartilage. When menisci are included, the local effective stiffness can instead be taken as a series composite of the local meniscus and local cartilage stiffnesses, with deformations distributed between the two tissues according to their respective individual stiffness values.

$$(1/k_{composite}) = (1/k_{cartilage}) + (1/k_{meniscus})$$

The local meniscus stiffness can be derived from its material properties and its thickness ($h_{meniscus}$) at any given point in the structure.

$$k_{meniscus} = \frac{E_{meniscus}\,(1-\nu_{meniscus})}{(1+\nu_{meniscus})\,(1-2\nu_{meniscus})\,h_{meniscus}}$$

The meniscal thickness distribution was computed first, using a closest point algorithm between superior and inferior meniscal surfaces. Those tibia-femur vertex pairings having an intervening meniscus segment were next identified. The meniscus was assumed to not move with respect to the tibia during a simple quasistatic loading at a fixed knee flexion angle. The meniscal thickness to be associated with a given tibiofemoral vertex pairing was obtained by then indexing the closest point on the inferior surface of the meniscus with the tibia. A combined stiffness matrix was then constructed using the paired meniscal and cartilage thicknesses, and the correspondingly modified DEA equations are solved to calculate contact stress.

In order to assess the feasibility of meniscus inclusion in a knee DEA model, the menisci were subsequently segmented for twenty-four of the MOST study knees for which the menisci could be reasonably discriminated on MR images. Linear elastic compressive material properties ($E_{cartilage}$ = 12MPa, $\nu_{cartilage}$ = 0.42; $E_{meniscus}$ = 80MPa, $\nu_{meniscus}$ = 0.3) were assigned for the materials. The meniscal DEA formulation was then applied, with the same displacements applied as for the models without menisci, yielding alternative contact stress values for comparison.

RESULTS AND DISCUSSION

The computed contact stress distributions extended over a larger area, as expected, when the knee DEA formulation was modified to include a meniscus (Figure 2). There were only minor reductions in the computed maximum contact stress values, which still occurred centrally on the joint surfaces. Given that the model was run in displacement control, this result was not totally unexpected. The inclusion of menisci resulted in model run times similar to those without menisci.

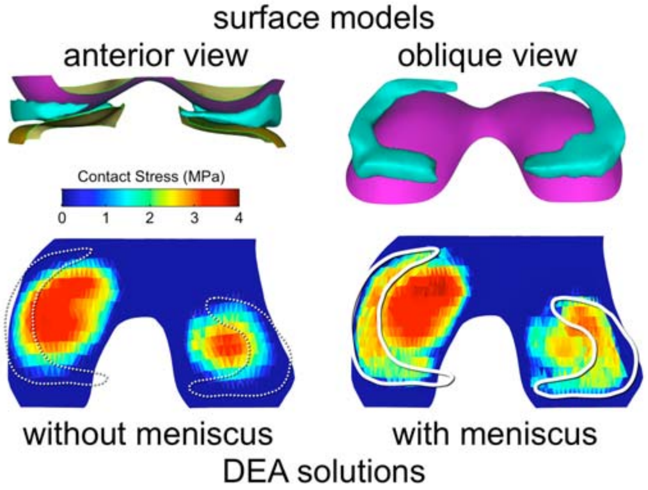

Figure 2. The inclusion of a meniscus resulted in a broader distribution of contact stress over the articular surface, but the maximum computed values were comparable, and still centrally located.

This exploration of feasibility assumed that the menisci do not move relative to the tibia when loaded. The implementation remains to be validated experimentally. These limitations clearly must be addressed in future (ongoing) work.

CONCLUSIONS

Based upon pilot work aimed at identifying local mechanical risk for incident symptomatic knee OA, the presented subject-specific implementation of DEA has shown itself as a feasible method for exploring the associated articular joint mechano-pathology. A viable approach to including a meniscus in knee joint DEA models has been developed and implemented. These methods open the way for more widespread use of subject-specific determination of risk for OA attributable to habitual contact stress exposure.

REFERENCES

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2. Anderson, D, Segal N, Torner J, Brown T. *Am. Soc Biomech Conf*, California, 2007.

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