PREDICTING IN VITRO ARTICULAR CARTILAGE WEAR IN THE PATELLOFEMORAL JOINT USING FINITE ELEMENT MODELING

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INTRODUCTION

The mechanism by which altered knee joint motions and loads (e.g., following anterior cruciate ligament injury) contribute to the development of knee osteoarthritis (OA) is not well understood. One hypothesis is that articular cartilage degradation is initiated when altered knee kinematics increase loading on certain regions of the articular surfaces and decrease loading on other regions [1]. As a step toward computational simulation of the *in vivo* mechanobiological process of knee OA development, this study uses a finite element model to simulate *in vitro* patellofemoral (PF) articular cartilage wear observed for a cadaver specimen tested in a knee simulator machine. The goal was to evaluate a specimen-specific model of the experimentally worn PF joint.

METHODS

A single cadaveric PF joint specimen was wear tested in an AMTI multi-axial knee simulator machine (Figure 1, left). Experimental cartilage damage was visualized using India ink and measured using pre- and post-test laser scans. Experimental details have been previously reported in Li et al. [2].

A computational model of the specimen in the knee simulator machine was constructed using customized FEBio finite element code [3]. Geometry for the model was provided by CAD models of the machine components and laser scan data of the femur and patella before and after testing. Elements were generated using TrueGrid and a mesh density converging study was performed. Articular cartilage on the femur and patella was modeled as deformable. The femur bone was modeled as a rigid body with prescribed motion. The patella bone and most machine components were modeled as rigid. Interacting machine components were modeled as deformable with contact between them. A Young's modulus 15 MPa and Poisson's ratio of 0.46 for the cartilage layers was chosen by reproducing Tekscan static pressure mesurements with the model. Resulting errors in predicted contact force and area on the medial and lateral sides were less than 5%.

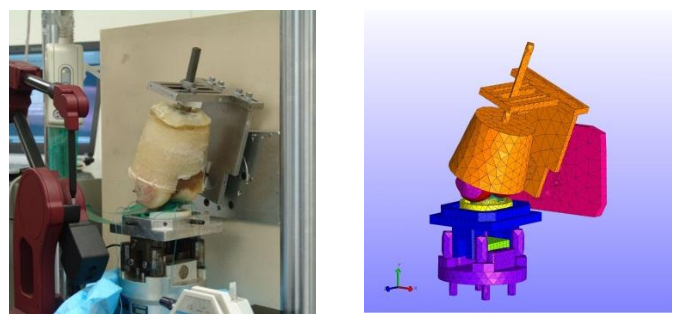

Figure 1: Experimental set-up for *in vitro* PF wear testing on an AMTI Force 5 machine (left), and computational model of the specimen and knee simulator machine (right).

The finite element model was used to predict the articular cartilage wear observed on the femur and patella over the 375,000 cycles of simulated gait. The wear predictions were based on Archard's wear law and were implemented using two approaches. The first approach (i.e., "non-progressive") involved a single one-cycle dynamic simulation. Wear depth at each surface location due to one loading cycle was calculated and extrapolated to 375,000 cycles. The second approach (i.e., "progressive") involved a sequence of 10 dynamic simulations. Wear depth at each surface location due to one loading cycle was calculated and extrapolated to 37,500 cycles. The nodes of each surface element on the femur and patella were offset by these wear depths, and the process was repeated for 9 additoinal simulations. For both approaches, a constant wear factor was chosen that provided the best match of the progressive results to the experimentally measured maximum wear depths on both bones.

RESULTS AND DISCUSSION

Predicted wear areas and locations of maximum of wear showed good qualitative agreement with the experimental wear areas visualized by removal of India ink (Figure 2). In both the non-progressive and the progressive simulation, a hen-shaped wear band was observed on the central region of patella, and a butterfly-shaped wear region was observed on the trochlear groove of the femur.

Predicted wear depths also showed good quantitative agreement with experimental wear depths measured using the pre- and post-test laser scans. For the experiment and both wear simulation approaches, the patella exhibited more wear than the femur did, and the ratio of patellar to femoral maximum wear depth was similar in all cases (Figure 2). The progressive approach reproduced the experimental wear depths the best, though the less costly non-progressive approach predicted wear areas almost as well. Each dynamic simulation required only 20 minutes of CPU time.

Compared to the elastic foundation contact model [2], the finite element modeling approach can simulate more complex contact situations such as the tibiofemoral joint with menisci, and it provides additional information beyond normal surface pressure (e.g., subsurface normal and shear stress/strain) that may be useful for developing an appropriate *in vivo* cartilage adaptation law [4].

Compared to elastic material properties, biphasic cartilage properties can introduce beneficial damping behavior. However, biphasic materials significantly increase computation time for dynamic simulations. Furthermore, studies have reported that for dynamic loading at physiological frequencies, articular cartilage responds roughly as an elastic material [5].

CONCLUSIONS

Finite element simulation of *in vitro* articular cartilage wear of the PF joint provides a good foundation for extending the work to simulations of other joints, both *in vitro* and *in vivo*. This step will involve additional challenges such as *in vivo* measurement of knee kinematics, estimation of *in vivo* contact loads, modeling of the menisci, and identification of an appropriate *in vivo* cartilage adaptation law.

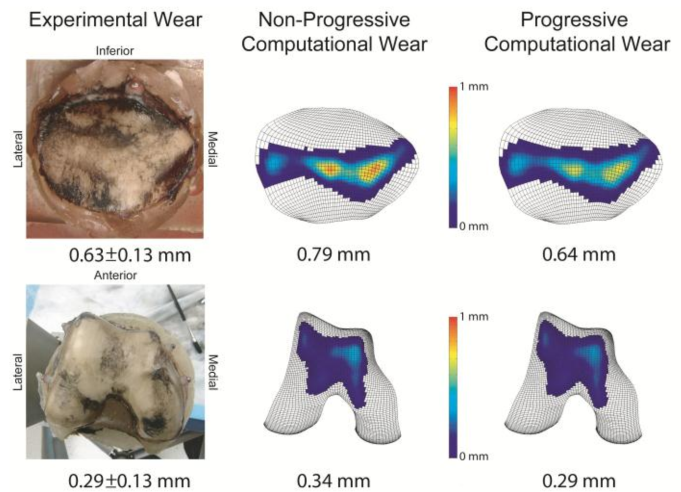

Figure 2: Wear results for the patella (top row) and femur (bottom row). Left column is experimental wear areas (white areas are worn regions) and depths. Middle column is predicted wear areas and depths from the non-progressive approach. Right column is predicted wear areas and depths from the progressive approach.

REFERENCES

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