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Computational wear simulation of patellofemoral articular cartilage during *in vitro* testing

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ABSTRACT

Though changes in normal joint motions and loads (e.g., following anterior cruciate ligament injury) contribute to the development of knee osteoarthritis, the precise mechanism by which these changes induce osteoarthritis remains unknown. As a first step toward identifying this mechanism, this study evaluates computational wear simulations of a patellofemoral joint specimen wear tested on a knee simulator machine. A multibody dynamic model of the specimen mounted in the simulator machine was constructed in commercial computer-aided engineering software. A custom elastic foundation contact model was used to calculate contact pressures and wear on the femoral and patellar articular surfaces using geometry created from laser scan and MR data. Two different wear simulation approaches were investigated—one that wore the surface geometries gradually over a sequence of 10 one-cycle dynamic simulations (termed the "progressive" approach), and one that wore the surface geometries abruptly using results from a single one-cycle dynamic simulation (termed the "non-progressive" approach). The progressive approach with laser scan geometry reproduced the experimentally measured wear depths and areas for both the femur and patella. The less costly non-progressive approach predicted deeper wear depths, especially on the patella, but had little influence on predicted wear areas. Use of MR data for creating the articular and subchondral bone geometry altered wear depth and area predictions by at most 13%. These results suggest that MR-derived geometry may be sufficient for simulating articular cartilage wear *in vivo* and that a progressive simulation approach may be needed for the patella and tibia since both remain in continuous contact with the femur.

1. Introduction

According to recent data from the US Centers for Disease Control and Prevention, arthritis costs the US economy close to $128 billion annually and remains the leading cause of disability (CDC, 2007). The most common form, osteoarthritis (OA), disables about 10% of the population above age 60, with the knee being the joint most commonly affected (Buckwalter et al., 2004).

Despite the growing burden of knee OA to society, researchers have made little progress at developing treatments that modify the course of the disease. One reason is the difficulty of performing experimental knee OA studies in human subjects. Consequently, much of the experimental OA research has involved animal or *in vitro* studies (Setton et al., 1999; Herzog et al., 2004; Griffin and Guilak, 2005). Coupled with clinical observations, such studies have led to viable hypotheses for how biomechanical factors affect the initiation and progression of the disease. One hypothesis proposed by several researchers is that altered joint kinematics (e.g., due to anterior cruciate ligament injury) cause previously unloaded regions of the joint to become overloaded, creating damage that eventually spreads to neighboring regions as well (Wu et al., 2000; Carter et al., 2004; Andriacchi and Mundermann, 2006).

Since contact stresses and strains across the knee's articular cartilage surfaces cannot be measured accurately *in vivo* (Winby et al., 2009), a computational approach could be valuable for evaluating such hypotheses and ultimately predicting the outcome of proposed treatment scenarios. Numerous finite element (Li et al., 1999; Donahue et al., 2002; Pena et al., 2006; Papaioannou et al., 2008; Yao et al., 2008b; Yang et al., 2010) and elastic foundation (Blankevoort et al., 1991; Cohen et al., 2003; Bei and Fregly, 2004;

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Caruntu and Hefzy, 2004; Elias et al., 2004) models of natural knees have been published that are capable of analyzing contact areas, stresses, strains, and/or forces. These models typically use cartilage/bone geometries derived from MR data, with relative bone poses measured using bi-plane fluoroscopy (Papaioannou et al., 2008; Van de Velde et al., 2009a, 2009b; Liu et al., 2010) or MR imaging (Salsich et al., 2003; Gold et al., 2004; Yao et al., 2008a; Connolly et al., 2009). Despite this breadth of models, to the best of the authors' knowledge, only two studies have predicted articular cartilage wear in the knee computationally, both under approximated *in vivo* conditions (Andriacchi et al., 2006; Pena et al., 2008). No study has compared articular cartilage wear predictions with cartilage wear measured in the same knee, either under *in vivo* or *in vitro* conditions as performed for artificial knees (Fregly et al., 2005; Knight et al., 2007; Zhao et al., 2008; Willing and Kim, 2009; Strickland et al., 2010).

This study evaluated the ability of a cadaver-specific computational model of the patellofemoral joint to reproduce articular cartilage wear depths and areas measured from the same specimen following testing in a knee simulator machine. Computational simulation of an *in vitro* situation with no menisci and well-controlled motion and loads inputs provides a valuable first step toward computational simulation of the more complex *in vivo* situation. The three specific goals of the study were as follows: (1) to evaluate whether the model can reproduce experimentally measured wear depths and areas for both the femur and patella, (2) to assess whether a progressive simulation approach that wears the articular surface geometry gradually over a sequence of simulations significantly alters the wear predictions, and (3) to determine whether the source of imaging data (i.e., laser scan or MR) used to construct articular surface geometry significantly affects the predicted wear.

2. Methods

2.1. Experimental wear testing

A single cadaveric patellofemoral joint specimen was wear tested in a multi-axial knee simulator machine (Force 5, AMTI, Watertown, MA). The specimen exhibited no visible signs of articular cartilage degeneration in the anticipated regions of contact. The femur was cut approximately 10 cm above the joint line, and titanium beads were embedded around the edges of the patella and distal femur for subsequent surface model registration purposes. The specimen and titanium beads were laser and MR scanned prior to wear testing and laser scanned again after wear testing. The patella and femur were mounted in the Force 5 knee simulator machine with the patellar articulating surface facing upward (Fig. 1(a)). Prior to wear testing, the specimen was contact pressure tested to estimate an effective Young's modulus for the subsequent computational wear simulations (Fig. 2(a)). Details of specimen scanning and subsequent surface model creation, specimen mounting, and specimen contact pressure testing are included as Supplementary Material.

Following contact pressure testing, the specimen was wear tested for 375,000 motion cycles of simulated gait (approximately 2 months *in vivo*; Schmalzried et al., 2000). The applied flexion angle and axial load profiles were taken from the literature (Ward and Powers, 2004). The patella was mounted in a new fixture that allowed the entire specimen to remain bathed in a solution of phosphate buffered saline with proteinase inhibitors (Frank et al., 1987). This solution was used to minimize cartilage enzymatic degradation so that experimental cartilage damage, as visualized using India ink (Fig. 3) and measured using the aligned pre- and post-test laser scan geometry, would be due primarily to mechanical wear.

2.2. Computational wear simulation

A computational model of the cadaver knee specimen mounted in the simulator machine was constructed using Pro/MECHANICA MOTION (PTC, Waltham, MA) (Fig. 1(b)). The degrees of freedom in the multibody dynamic model matched those of the simulator machine. Geometric models of the machine components and aluminum fixtures were created in CAD software based on the measured dimensions of each component. Digitized titanium bead locations were used to align the femur and patella cartilage/bone geometries with the geometric models of their respective fixtures. The laser scan geometry was the more accurate representation of the articular cartilage and subchondral bone geometry and was therefore used as the starting point for all wear simulations.

A previously published computational methodology was used to simulate progressive cartilage wear on both articular surfaces over multiple loading cycles (Fig. 4) (Knight et al., 2007; Zhao et al., 2008). The methodology employs a modified version of an elastic foundation model (Bei and Fregly, 2004) to simulate deformable contact between the patellar and femoral articular surfaces. Both bones were treated as layered elastic bodies with non-uniform thickness, where the thickness at any articular surface location was defined as the distance to the closest point on the subchondral bone. A uniform grid of contact elements was placed on the patella, and the contact pressure p on each element was calculated

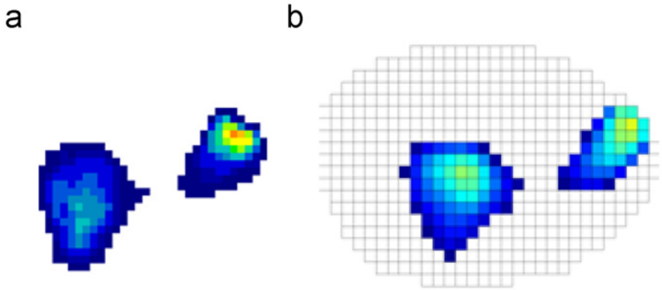

Fig. 2. Contact pressures and areas (a) measured by a Tekscan K-scan sensor and (b) predicted by the elastic foundation contact model when the model of the simulator machine was placed in the same configuration as the actual machine during pressure testing.

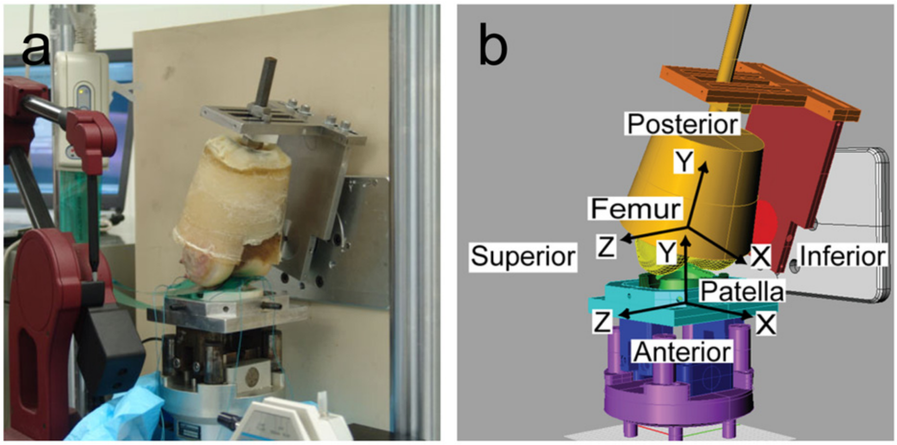

Fig. 1. (a) Cadaveric patellofemoral joint specimen mounted in an AMTI Force 5 knee simulator machine for Tekscan contact pressure testing and subsequent wear testing. (b) Geometric model of the same specimen mounted in an identical manner in a multibody dynamic model of the simulator machine. Deformable contact between the femoral and patellar articular cartilage was modeled using an elastic foundation model. Bone-fixed coordinate systems are as indicated in the figure.