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BIOMECHANICAL MECHANISMS FOR DAMAGE: RETRIEVAL ANALYSIS AND COMPUTATIONAL WEAR PREDICTIONS IN TOTAL KNEE REPLACEMENTS

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Damage patterns on the articular surface of the proximal tibia, including cartilage degeneration in osteoarthritic knees and damage of polyethylene knee prostheses after total knee replacement, provide information related to knee joint biomechanics and damage mechanisms at the articular surface. This study reports articular damage patterns and knee kinematics assessed in the knees of older subjects, before and after total knee replacement. The damage patterns are used to evaluate computational dynamic contact and tribological models that predict polyethylene damage in a patient-specific total knee replacement model.

Keywords: Fluoroscopy; polyethylene wear; dynamic contact; total knee replacement.

1. Introduction

Knee motion, tibial-femoral contact mechanics and loading conditions contribute to cartilage degeneration in osteoarthritic knees and polyethylene damage after

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total knee replacement (TKR). Therefore, evaluation of damage patterns occurring on the articular surface of the proximal tibia can provide insight into the biomechanical function of the knee and mechanisms by which damage occurs. This study reports articular damage and knee kinematics assessed in the knees of older subjects before and after TKR. The goal is to understand the relationships between tibial articular damage and ligament laxity, knee kinematics, and tibial-femoral contact. Damage patterns are used to evaluate computational dynamic contact and tribological models that predict polyethylene damage in a patient-specific TKR model (Fig. 1)

2. Methods

All portions of this study involving human subjects were approved by an Institutional Review Board.

2.1. *Cartilage damage measurements*[1]

Cartilage degeneration on the proximal tibia was measured in 143 osteoarthritic knees of patients undergoing TKR, of which 106 are knees with varus and 37 are knees with valgus malalignment. The anterior cruciate ligament (ACL) was assessed intraoperatively and was intact in 42% and ruptured in 25% of the knees. Resected tibial plateaus were preserved after TKR and articular cartilage damage patterns were measured using calibrated digital images and image analysis programs.[1] The circumference of the medial and lateral tibial plateau and regions of cartilage fibrillation and eburnated bone were digitized, and the area and location of damage were calculated as well.
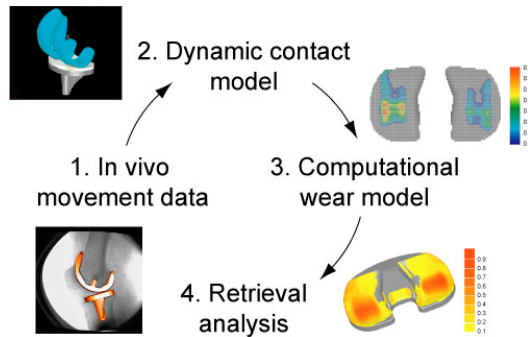

Fig. 1. Overview of the experimental and computer modeling methods.[4] Wear predicted by the computational methods was compared to the autopsy-retrieved polyethylene tibial insert, from the same patient whose *in vivo* kinematics were used as model inputs.

2.2. *Knee kinematics and polyethylene damage measurements*[2]

Knee kinematics and tibial-femoral contact locations after TKR were evaluated in six subjects (eight knees) over an average follow-up period of 18 months. All subjects had the same cemented posterior cruciate ligament retaining knee prosthesis with >6 mm thick machined polyethylene tibial inserts. The multi-radius femoral component had three sagittal plane radii and the tibial inserts were essentially flat in the sagittal and coronal planes. Two-dimensional fluoroscopic images were recorded during stair rise/descent and treadmill gait activities. Kinematic data were measured using published shape-matching techniques[3] and the locations of tibial-femoral contact were determined in each patient. Polyethylene tibial inserts from these eight subjects and 29 other inserts of the same design were retrieved after an average of 31 ± 22 months *in situ*. Medial and lateral articular damage were evaluated using optical microscopy and image analysis programs.[1]

2.3. *Dynamic contact model and computational wear model*

A multi-body dynamic contact model was constructed from CAD models of the same prosthesis used in the fluoroscopy and retrieval studies.[4] The contact model utilized elastic foundation theory which scatters a "bed of springs" over the three-dimensional surfaces to push them apart,[5] with *in vivo* fluoroscopic measurements (e.g., translation, rotation, and flexion) as inputs. Contact forces, kinematics, contact pressures, and slip velocities were generated for two activities, gait and stair, with a 70–30 medial-lateral load split and input into a computational damage model. The damage model produced element-by-element damage predictions, given the time history of contact pressures and slip velocities during the stair and gait activities. Total damage depth for each element was the sum of material removal due to surface wear, calculated using Archard's wear law, and surface deformation due to compressive creep.[4] Damage calculated from a single cycle simulation was used to extrapolate over the total time of implantation.

The predicted total damage depth was used to create a "worn" polygonal surface model. Three-dimensional laser scans of the worn polyethylene insert retrieved at autopsy from the same patient, whose fluoroscopic data were used as model inputs, and a size-matched unworn insert were converted to polygonal surface models. Contour plots of the predicted damage and *in vivo* retrieval damage, measured as deviations between the original and worn surfaces, were generated.

2.4. *Statistical approach*

Articular damage and femoral contact data were analyzed using analysis of variance and appropriate post-hoc multiple comparisons, Spearman's correlation and linear regression with $\alpha = 0.05$.

3. Results

Patterns of cartilage degeneration were significantly different on tibial plateaus resected from ACL intact and ACL deficient knees (Fig. 2).[1] With varus alignment, ACL deficient knees had significantly larger damage areas located posteriorly on the medial plateau, compared to ACL intact knees. With valgus alignment, both ACL intact and ACL deficient knees had centrally located damage patterns on the lateral plateau, independent of the ACL status.

After TKR, there was a significant correlation between damage locations on the retrieved polyethylene inserts and femoral contact locations measured during dynamic activities on the same patients before retrieval (Fig. 3). Femoral contact and damage occurred predominantly on the posteriorly articular surface and the damage area was largest in the compartment with the greatest range of *in vivo* femoral contact. Adhesive-abrasive damage, such as scratching, burnishing and tractive striations, were the most common damage modes, occurring in more than
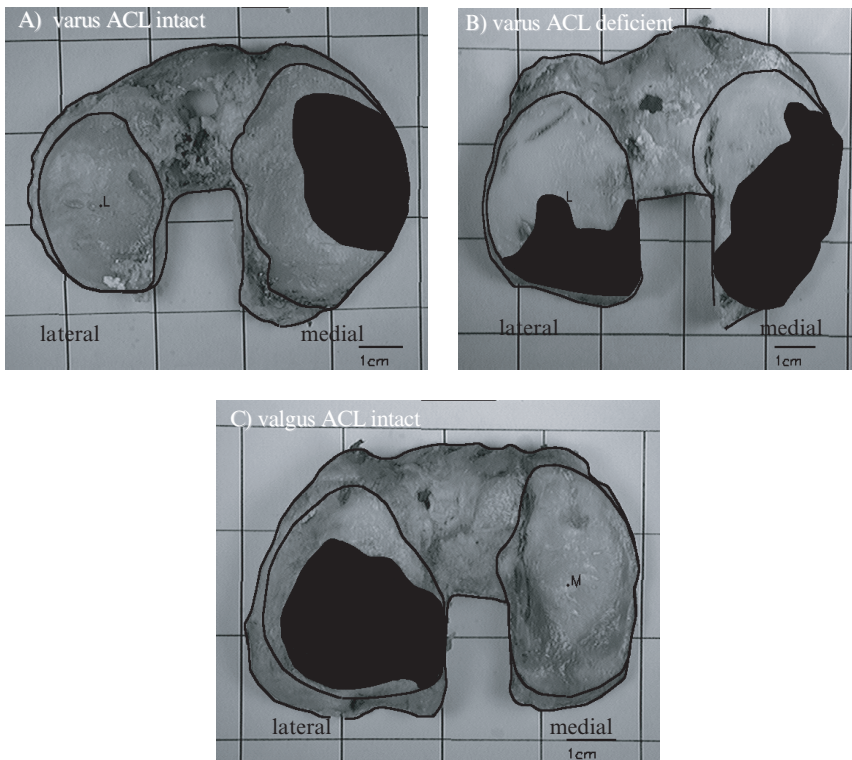

Fig. 2. Proximal tibial plateaus resected from left knees during total knee replacement. Anterior cruciate ligament laxity affects the location of cartilage degeneration in varus osteoarthritic knees (A, B). Typically, valgus osteoarthritic knees have concave damage regions centrally located on the lateral plateau (C), independent of ACL status.
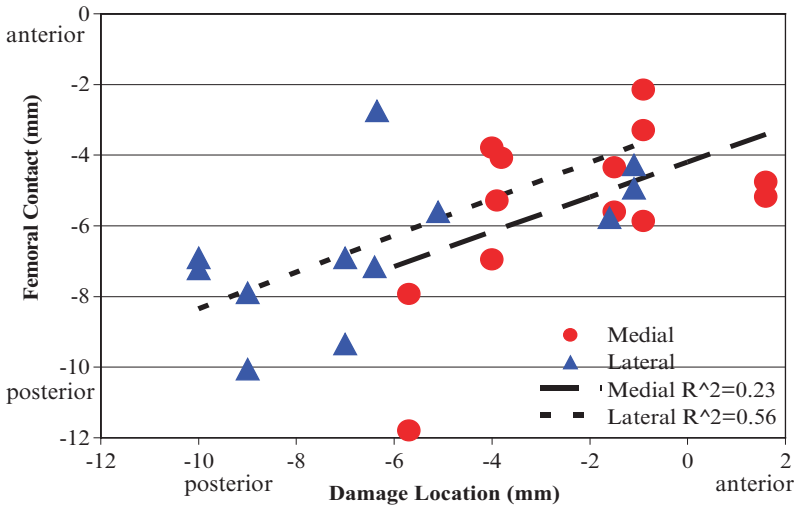
Fig. 3. There was a positive linear relationship between femoral contact location during the knee extension phases of gait and stair activities as well as the damage location.[2] Locations were computed relative to an axis at the anteroposterior midpoint of the tibial component.

60% of the retrieved inserts. Plastic deformation on the anterior tibial eminence occurred on 24 or 65% of the retrieved tibial inserts, consistent with the impingement of the femoral intercodylar notch. Mechanisms for this damage include tibialfemoral hyperextension and the femoral component rotation and/or posterior translation during dynamic activities.[6]

Predicted medial and lateral damage regions were in good agreement with the retrieved polyethylene tibial insert (Fig. 4). On the medial plateau, damage was anterior during gait simulations and posterior during stair simulations, compared to a more central location in the anteroposterior direction for the lateral plateau for each activity. Simulation of the gait and stair activities separately predicted the location of maximum damage on the lateral side, while combining damage predictions from the two activities (85% gait, 15% stair) using linear rule of mixtures also predicted the correct location on the medial side. Predicted locations of maximum surface deformation for the combined activities (85% gait, 15% stair) were the same as those on the retrieved insert. Maximum damage depth for the retrieved insert was 0.7 mm medially and 0.8 mm laterally versus 0.8 mm and 0.9 mm, respectively, for the simulation. The combined activities predicted 108% (lateral) to 114% (medial) of the total damage area on the retrieved insert.

4. Discussion

These studies demonstrate that ligament laxity, knee motion, tibial-femoral contact mechanics and loading conditions affect articular damage patterns before and
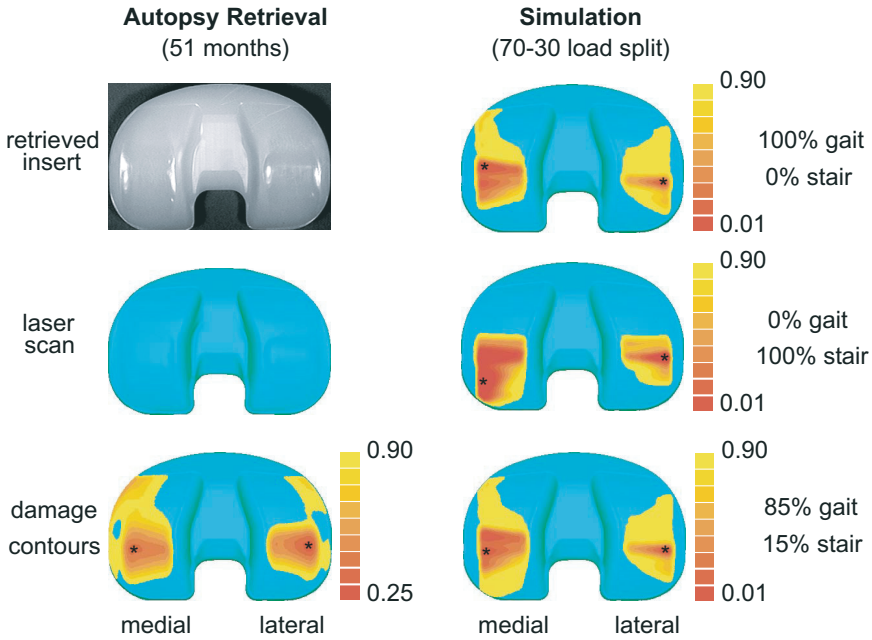
Fig. 4. Laser scan and damage contour maps measured from the autopsy retrieved insert (left) and predicted by the computer simulations (right) with gait, stair and combined gait and stair activities.[4] The symbol (∗) indicates the location of maximum surface deformation.

after TKR. In osteoarthritic knees, the condition of the ACL strongly influences the patterns of tibial articular cartilage degeneration. ACL deficient damage patterns are consistent with posterior femoral subluxation and posterior tibiofemoral contact. After TKR, tibiofemoral contact locations measured fluoroscopically during dynamic activities, significantly predict damage locations on retrieved polyethylene inserts. During knee extension, posterior femoral contact places high compressive joint loads on the posterior polyethylene insert. These joint loads are combined with substantial medial condylar translations, consistent with adhesive-abrasive damage modes observed in the retrieved polyethylene inserts.

Using *in vivo* knee kinematics from two activities (85% gait, 15% stair) to drive a dynamic contact model, it was possible to simulate articular damage similar to that of the retrieved polyethylene insert (Fig. 4). There was greater damage under the lateral femoral condyle for both simulation and retrieval, explained by the measured *in vivo* kinematics, where minimal translation of the lateral femoral condyle focused contact and damage to a smaller area. The medial femoral condyle showed greater translations for both activities, creating greater damage areas but shallower damage depths, both in simulation and *in vivo*. This novel approach allows damage predictions to be evaluated against actual damage observed in polyethylene tibial inserts retrieved after *in vivo* function.

Acknowledgments

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