A General Adhesive Wear Simulation to Predict Long-Term Function of Total Joint Replacements

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Abstract: Wear of ultra-high molecular weight polyethylene (UHMWPE) bearing surfaces is now among the most important problems in total joint replacement. Although physical wear tests are performed routinely, they are time consuming and expensive. The purpose of this study was to develop a general numerical wear simulation applicable to any articulating joint with arbitrary geometry and subject to arbitrary relative motion. Validation of the model was established through application to the patellofemoral joint of a total knee replacement. A 10 year wear simulation was conducted, and a steady volumetric wear rate of 6.5 mm^3/year was observed. Wear depth on the patellar surface reached a peak of 0.63 mm located in the superior-lateral quadrant. As wear increased, peak contact pressure decreased, contact area increased, and gross kinematics exhibited negligible changes.

1. Introduction

Advances in design, materials, and fixation have increased the longevity of total joint replacements and reduced the incidence of mechanical failure of implant components. Wear of ultra-high molecular weight polyethylene (UHMWPE) is now among the most important problems in total joint replacement. Wear tests in joint simulators are the standard means for evaluation of wear resistance and are performed on a routine basis in many laboratories. Physical wear testing, however, is time consuming and expensive. Numerical wear simulations have been developed and applied to the hip joint to evaluate adhesive wear of polyethylene liners (Kurtz, 1999; Maxian, 1996). The purpose of this study was to develop a general adhesive wear simulation applicable to any articulating joint with arbitrary geometry and subject to arbitrary relative motion. Validation of the model was established through application to the patellofemoral joint of a total knee replacement.

2. Materials and Methods

A finite element (FE) model of a left patellofemoral joint (Figure 1) was constructed from the geometry of a contemporary total knee replacement (Petrella, 1997). A mesh convergence study was performed and FE model results for patellar kinematics and contact forces were validated by comparison to experimental data. FE solutions were computed using ABAQUS and accounted for both patellofemoral and tendofemoral contact. The FE model simulated a deep squat with 5° increments of knee flexion from 15° to 100°, and included non-linear UHMWPE properties (DeHeer, 1992) with friction at the sliding interface ($\mu = 0.07$).

Wear depth on the patellar surface was expressed as a function of contact pressure and sliding distance (Marshek, 1989),

$$H = k_w \sigma S \tag{1}$$

where H is wear depth (mm), σ is contact stress (MPa), S is sliding distance (m), and $k_w = 4.25 \times 10^{-7}$ mm^3 N^{-1} m^{-1} is an empirical wear constant (Wang, 1996). The patellofemoral joint contact stress and sliding distance required in Equation 1 were computed using the FE model and a separate computer program was written using the ABAQUS scripting language to calculate linear wear on the patella. Volumetric wear, based on 10^6 flexion cycles per year, was calculated exactly by computing the Jacobian for each element. Wear was calculated at 12-month intervals and the patellar mesh was altered to reflect material loss due to wear. After each wear calculation a new FE solution was obtained with the updated mesh and the process was repeated.

3. Results

A 10 year wear simulation was conducted using the patellofemoral joint FE model, and a steady volumetric wear rate of 6.5 mm^3/year was observed. Wear depth on the patellar surface reached a peak of 0.63 mm located in the superior-lateral quadrant (Figure 2). Wear produced only small changes in patellar kinematics: 1° of medial tilt and 0.5mm of lateral shift. The medially directed shear force on the patella decreased by an average of 30% after 30° of knee flexion and was unchanged at flexion angles less than 30°. Peak contact pressure on the patella decreased by an average of 38% (Figure 3). Patellofemoral joint contact area varied as a function of flexion angle but increased consistently as wear increased (Figure 4).

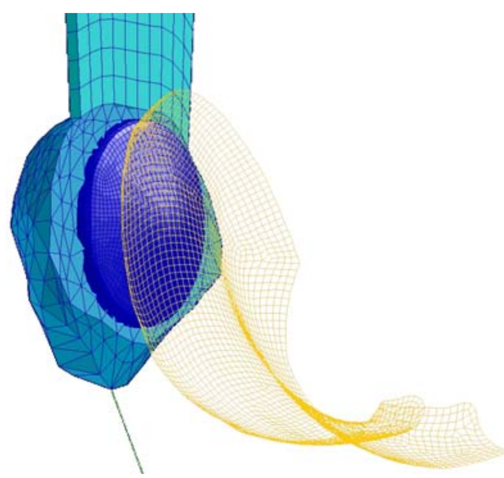

Figure 1. Patellofemoral joint FE mesh used for wear study.

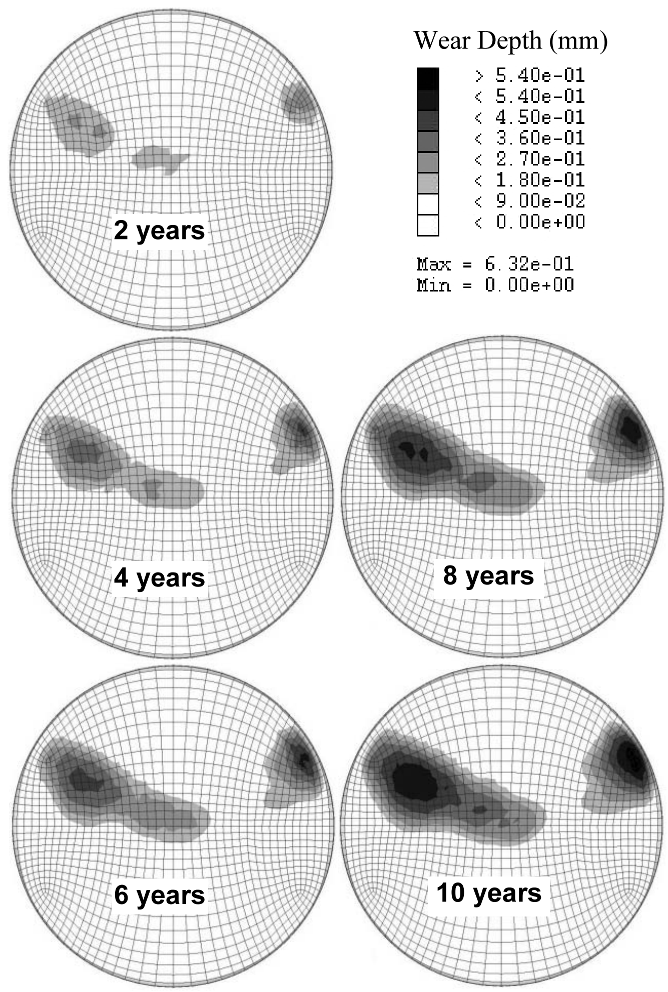

Figure 2. Wear depth on the patellar surface.

Figure 3. Peak contact pressure on patella.

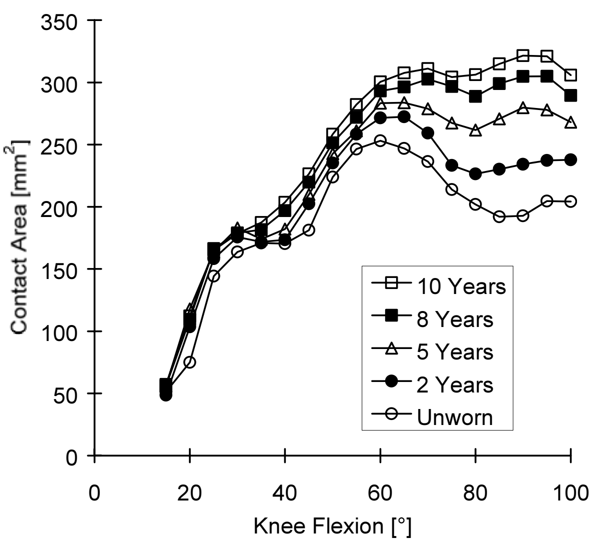

Figure 4. Change in contact area with flexion and wear.

4. Discussion

Patellofemoral joint wear data are not well documented in the literature, but a wear rate of 6.5 mm^3/year is reasonable compared to typical rates ranging from 5 to 200 mm^3/year in the hip and tibiofemoral joint. Also, the loading in this model was based on a sub-physiologic body weight load required by cadaver specimens tested experimentally for FE model validation. Wear rate and wear volume would be higher in a system subjected to a normal body weight load.

Volumetric wear rate did not increase noticeably over the 10 year duration of this wear study. This observation contrasts with results reported in the hip joint, in which wear rate increased asymptotically to a steady state value during the simulation (Maxian, 1996). This disagreement may be explained by the difference in conformity between the patellofemoral joint and the hip joint, the latter being much more conforming.

The kinematic results indicate that patellar tracking was not significantly affected by changes in implant geometry associated with polyethylene wear. In light of the consistent patellar tracking, the 30% decrease in mediolateral force on the patella suggests that the implant exhibited more stable articulation with the femoral trochlea and a decreased propensity for subluxation. The decrease in contact pressures supports the idea that the patella developed increasing conformity to the femoral component through a combination of wear and plastic deformation.

The model developed in this study is capable of simulating adhesive wear in any interface subject to complex multidirectional sliding motion. Adhesion is a dominant wear mechanism in the patellofemoral joint, but other forms of wear such as delamination and pitting have been observed upon retrieval. Adhesive wear has also been shown to depend on the history of counterface sliding, suggesting that the wear coefficient in Equation 1 is neither constant nor isotropic. The findings of this study suggest that moderate adhesive wear has a stabilizing effect on patellofemoral tracking. However, more aggressive wear mechanisms and factors that exacerbate adhesive wear must also be considered.

5. References

1. DeHeer, D. C. and B. M. Hillberry, "The Effect of Thickness and Nonlinear Material Behavior on Contact Stresses in Polyethylene Tibial Components," 38th Annual Meeting of the ORS, p. 327, 1992.
2. Kurtz, S. M., J. A. Ochoa, C. B. Hovey and C. V. White, "Frontside vs. Backside Wear in an Acetabular Component with Multiple Screw Holes," 45th Annual Meeting of the ORS, p. 54, 1999.
3. Marshek, K. M. and H. H. Chen, "Discretization Pressure-Wear Theory for Bodies in Sliding Contact," Journal of Tribology, vol. 111, pp. 95-100, 1989.
4. Maxian, T. A., T. D. Brown, D. R. Pederson and J. J. Callaghan, "A Sliding-Distance-Coupled Finite Element Formulation for Polyethylene Wear in Total Hip Arthroplasty," Journal of Biomechanics, vol. 29, pp. 687-692, 1996.
5. Petrella, A. J., H. E. Rubash and M. C. Miller, "The Effect of Femoral Component Rotation on the Stresses in an UHMWPE Patellar Prosthesis - A Finite Element Study," Advances in Bioengineering, vol. 36, pp. 309-310, 1997.

6. Wang, A., C. Stark and J. H. Dumbleton, “Mechanistic and Morphological Origins of Ultra-High Molecular Weight Polyethylene Wear Debris in Total Joint Replacement Prostheses,” Journal of Engineering in Medicine, vol. 210, pp. 141-155, 1996.

6. Acknowledgment

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