A Scratch-Based Formulation for Finite Element Wear Simulation of Total Hip Arthroplasty

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Introduction

Aseptic loosening due to polyethylene wear remains a leading cause of failure in total hip arthroplasty (THA), particularly in the late term. Physical lab tests have historically been used in order to predict wear rates, but they are slow (requiring weeks to months) and expensive. In the last several years, computational simulations [1] have come into widespread use.

Retrieval studies have shown that third body damage, especially scratching of the femoral head, can lead to dramatic wear acceleration. However, studies of wear due to third body scratching have previously been limited to physical testing.

A sliding-distance-coupled finite element (FE) model has been successful in predicating wear rates for undamaged femoral heads and for heads with areas of homogenous roughening [1]. The damaged wear model shows strong correlation with corresponding physical simulations. However, homogeneous roughening fails to replicate the manner by which damage occurs *in vivo*, which is by scratching. Bench studies have shown the presence of even a few isolated scratches can cause order-of-magnitude wear acceleration [2]. The level of wear acceleration was found to be related to the amount of piled-up metal along the edge of the scratch. Other wear tests have shown wear elevation to be dependent on the orientation of the scratch relative to its direction of motion [3]. The present model utilizes a novel algorithm to allow for local wear acceleration to be dependent on the properties of individual scratches overpassing a given site on the polyethylene liner.

Materials and Methods

An experimentally validated finite element model for THA wear was implemented in ABAQUS v6.9.1, using the adaptive meshing capabilities of the UMESHMOTION subroutine. Damage to the femoral head was simulated by postulating three equally spaced scratches extending 180° from the equator, through the pole and back down to the equator, to form an “asterisk” shape (Figure 1) , for which corresponding physical wear simulator data were available. Various cases were run allowing for these scratches to be represented at a variety of severity levels.

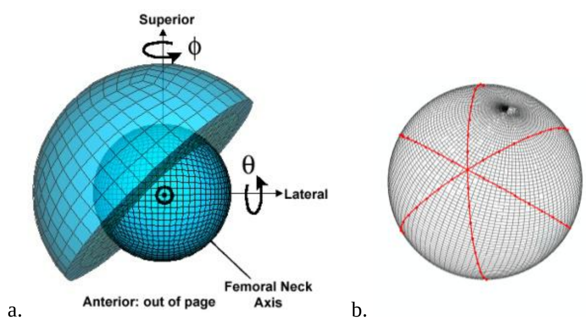

Figure 1: a. THA Finite Element Model
b. Scratches to Femoral Head

Wear was determined using the Archard wear formula, which calculates the spatial distribution of wear depth as a function of contact pressure, sliding distance, and a wear coefficient based on the tribological properties of the surfaces in contact. When an area of the acetabular cup was overpassed by a femoral head scratch, the wear coefficient was elevated based on the severity of the scratch and its directionality. At each increment of the gait cycle, the angle between the orientation of the scratch and its direction of motion was calculated. When this angle was highly acute, the wear was correspondingly elevated, as reported in physical wear tests [3].

Simulations of this model were run to one million standard gait cycles, with linear and volumetric wear calculated. A parametric series was conducted with this model for lip heights from 0.5 µm to 10 µm, to study wear acceleration due to individual scratches.

Results

Compared to the baseline simulation for a non-roughened femoral head (k_0=1.07x10^{-6} mm^{3}N^{-1}m^{-1}), the scratched femoral head model experienced up to a 3-fold increase in wear for the most severely damaged head. The wear increases were compared to two corresponding physical wear tests [4] of the same damage pattern, with scratch lip heights of 0.278 µm and 2.909 µm. The results showed that the FE model is able to predict wear increases due to discrete scratches, within 10% error (Table 1).

For the case of damage severity equal to 2.909 µm, the average surface roughness increased from 0.007 µm to 0.011 µm. The corresponding wear increase was much larger than would be suggested from this R_a increase.

Table 1: Wear rate increases from physical and computational simulations of one million gait cycles

Scratch Severity	Wear Increase: Physical Test	Wear Increase: FE Model	Error
0.278 µm	1.19-fold	1.24-fold	4.03%
2.909 µm	2.38-fold	2.14-fold	10.08%

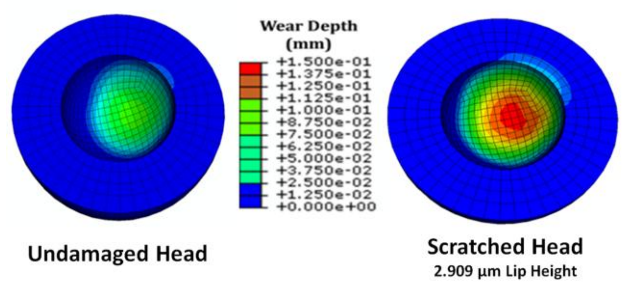

Figure 2: Wear depth of undamaged and damaged model

Discussion and Conclusion

This study represents the first demonstration of modeling of scratch-specific damage on a global implant level. Previous finite element models of global level 3rd body wear have only allowed for damage representation in terms of average zonal roughness. Representation of damage on a scratch-specific basis will allow for physiologically significant predictions of wear elevation due to 3rd body damage. This new formulation allows for accurate representation of damage observed on retrieval femoral heads, in order to gain further understanding of femoral head damage as it relates to wear acceleration. The approach is tractable for very large numbers of scratches (we have run simulations with up to 12,000 discrete scratches), and thus, applicable to even severe third-body damage situations.

References

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