Published in final edited form as:

Comput Methods Biomech Biomed Engin. 2014 August ; 17(11): 1227–1236. doi:
10.1080/10255842.2012.739168.

A Novel Formulation for Scratch-Based Wear Modeling in Total Hip Arthroplasty

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Abstract

Damage to the femoral head in total hip arthroplasty often takes the form of discrete scratches, which can lead to dramatic wear acceleration of the polyethylene (PE) liner. Here, a novel formulation is reported for finite element analysis of wear acceleration due to scratch damage. A diffused-light photography technique was used to globally locate areas of damage, providing guidance for usage of high-magnification optical profilometry to determine individual scratch morphology. This multiscale image combination allowed comprehensive input of scratch-based damage patterns to a finite element (FE) Archard wear model, to determine the wear acceleration associated with specific retrieval femoral heads. The wear algorithm imposed correspondingly elevated wear factors on areas of PE incrementally overpassed by individual scratches. Physical validation was provided by agreement with experimental data for custom-ruled scratch patterns. Illustrative wear acceleration results are presented for four retrieval femoral heads.

Keywords

wear; total hip arthroplasty; third body; finite element analysis; retrieval

Introduction

Total hip arthroplasty (THA) has historically enjoyed high rates of clinical success, although aseptic loosening due to osteolysis sometimes limits the longevity, especially for metal-on-polyethylene (PE) implants (Teusink et al. 2012, Ollivere et al. 2012). Given the strong and well-recognized relationship between PE wear and osteolysis (Wilkinson et al. 2005), keeping wear rates low remains an important clinical concern in THA. Highly cross-linked polyethylenes (HXPEs) have shown greatly reduced wear rates compared to conventional polyethylenes (CPEs) (D'Antonio et al. 2011, Laurent et al. 2008), but much of that improvement is lost in situations with damage to the femoral head bearing surface (Sorimachi et al. 2009). A proximate mechanism is that 3rd body particles (e.g. bone, bone cement, metallic particles broken off from porous coatings, particles from the head/trunnion interface, etc.) scratch the femoral head and thus dramatically increase the abrasiveness of this otherwise very-low-roughness counterface. Another proximate mechanism is scraping due to dislocation.

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While 3rd body damage is well understood conceptually, it is poorly defined quantitatively, and no consensus testing standard as yet exists. The various laboratory testing protocols utilized to date have included roughening of all or part of the bearing surface (Bowsher and Shelton 2001), adding particles to simulated joint fluid (Que and Topoleski 2000, Bragdon et al. 2003), ruling discrete scratches at prescribed locations (Lee et al. 2009, Barbour et al. 2000), and working with retrieval implants (Elfick et al. 2000). Despite the obvious differences, advocates of each such protocol have (subjectively) argued physiological relevance. Attempts to quantify 3rd body damage have usually characterized head surface morphology in terms of standard roughness parameters such as average roughness (R_a), peak height (R_p), and maximum depth (R_v) (Minakawa et al. 1998, Hall et al. 1997). While the physical metrology is straightforward, these parameters inherently misrepresent damage as being homogeneous and isotropic, whereas actual scratch damage (Jasty et al. 1994) is discrete and directional. For example, R_a is unable to distinguish between large groups of fine scratches versus small numbers of severe scratches. Similarly, R_p fails to differentiate between a single asperity versus multiple asperities of similar height (Hall et al. 1997). Additionally, for actual scratch damage, the angle at which a given scratch instantaneously traverses the apposing polyethylene is known to play a critical role in wear rate (Glennon et al. 2008).

Physical wear simulators are often used to predict *in vivo* wear. However, such tests are expensive and time-consuming. Computational models have proven to be a useful complementary tool in predicting wear rates, due to their ability to efficiently evaluate a variety of parameters. A sliding-distance-coupled finite element (FE) model implementing the classic Archard-Lancaster wear relationship, first introduced to predict PE wear rates for undamaged femoral heads (Maxian et al. 1997), was subsequently extended to model areas of isotropic roughening, to simulate wear acceleration from damage to the femoral head surface (Brown et al. 2002). While that “patch-roughened” model showed excellent agreement with a physical simulation of the same damage pattern (obtained by grit-blasting) (Brown et al. 2009), it required finite-area roughening zones that were discretizable in terms of surface element facets having elevated Archard wear factors. In contrast, retrieval implants typically show damage in the form of (infinitesimal area) multi-directional scratching, which makes a scratch-based rather than an area-based damage representation a better approximator for actual clinical damage.

FE models have previously been used to study the micromechanics of individual asperities (McNie et al. 1998, Paul et al. 2008) as they relate to local polyethylene damage. Such models have analyzed the stress elevations and elastic/plastic strains caused by individual scratches articulating against polyethylene. To date, however, finite element analysis of scratches has been limited to stress/strain analysis of asperity-apposing sites in polyethylene, rather than providing a basis to directly estimate implant-level wear rate acceleration.

An FE model allowing for scratch-based representation of damage on the global implant level holds the attraction of permitting estimation of wear rates accompanying patient-specific head damage. Providing scratch-specific representations would enable more physiologically relevant wear simulations than are possible with the patch-roughened approach. The present study introduces a novel formulation, allowing wear elevation to be modeled as a function of the morphology and directionality of individual scratches. The central new idea is that instantaneous local wear factors are elevated for counterface nodes being overpassed by individual scratches. This algorithm proved capable of replicating results from a previous physical wear test of femoral heads on which discrete scratches had been ruled (Barbour et al. 2000), and it proved practical for usage for individual retrieval specimens.

Methods

Finite Element Model

A previously experimentally validated FE model for THA wear (Maxian et al. 1997) was implemented in ABAQUS v6.9.1. The model utilized brick continuum elements for the titanium cup backing and PE liner, and used spherical analytical surface representation for the femoral head. Both the titanium backing and the PE liner were assigned linearly elastic material properties, with a Poisson's ratio of 0.3 and elastic moduli of 110 GPa and 1400 MPa (Teoh et al. 2002), respectively.

This model applied the Archard-Lancaster relationship for abrasive/adhesive wear (Archard 1953), which calculates the spatial distribution of wear depth as a function of (i) contact pressure, (ii) sliding distance, and (iii) a wear coefficient based on the tribological properties of the two surfaces in contact. The FE wear model utilized the adaptive meshing capabilities of the ABAQUS UMESHMOTION subroutine, to account for conformity changes associated with wear of the polyethylene surface (Goreham-Voss et al. 2010).

The previous Archard implementation for damaged heads (Brown et al. 2002) was modified to allow for local wear rate elevations to be associated with individual scratches. Individual scratches were modeled using concatenations of discrete, straight-line scratch segments. Each such scratch segment was represented by its two endpoints and its average lip height. The wear coefficient for the undamaged surface ($k_0 = 1.07 \times 10^{-6} \text{mm}^3 \text{N}^{-1} \text{m}^{-3}$ (Maxian et al. 1997)) was locally elevated during a given increment of the duty cycle for acetabular nodes overpassed by a given scratch segment during that cycle increment (Figure 1). A custom FORTRAN algorithm was used to determine the nodal locations incrementally overpassed. To accomplish this, the motion of each scratch segment was tracked throughout the duty cycle. For each increment of the cycle, the coordinates of the scratch segment endpoints from the initiation and termination instants of the increment were used to determine the trapezoidal area overpassed by the segment (Figure 2a). (The incremental overpassage area in general is a trapezoid rather than a parallelogram, due to the femoral head's multi-axial rotation.) The plane of this trapezoidal area was calculated, along with its area. For each acetabular cup node, the vector from the cup center to the node, along with the intersection point between that vector and the trapezoid plane was determined. For each such vector, the area of four triangles was computed, each triangle being formed by one edge of the trapezoidal area and lines connecting the two edge endpoints to the intersection point. When the sum of these four triangle areas was equal to the trapezoidal area, the node necessarily fell with the area overpassed by the scratch segment (and if not, not), and its wear coefficient was correspondingly elevated.

The specific local wear coefficient elevations were based on the scratch segment's lip height and orientation (Glennon et al. 2008). Physical wear test results from the literature (Dowson et al. 1987) were used to determine the relationship between scratch severity and wear acceleration. A series of single-scratch bench studies had shown that wear elevation is dependent primarily on the amount of metal piled up along the lip of the scratch, rather than on the depth or furrow width of the scratch. (This relationship had been confirmed by removing the scratch lips through remedial lapping, and then running further wear tests with only the scratch valleys present.) Using data from those earlier results, a power law curve fit was implemented:

$$k_{\text{inc}} = 58.0985 - 58.0985 \cdot e^{-0.2237 \cdot h_L} \quad (1)$$

where k_{inc} is the incremental wear coefficient scaling factor and h_L is the peak scratch lip height in microns (Figure 3). (This relationship is based on the maximum lip height. A

similar relationship was observed when the average of the scratch's two lip heights was utilized.) This relationship was then used in the FE model to associate incremental wear coefficient elevations with individual overpassing scratch segments, based on their individual lip heights.

At each time step, the angle θ between the scratch segment's orientation and its direction of motion was calculated (Figure 2b). Physical wear tests (Glennon et al. 2008) had shown that when this angle is highly acute, wear increases of up to an order of magnitude are experienced, due to a slicing/shearing mechanism. The wear coefficient was correspondingly elevated based on this relationship between θ and wear elevation. The referenced bench tests had been carried out in 5° increments. Of the various angles tested, only the 5° case showed statistically significant acceleration over other angles. In the present FEA model, when the relative angle (θ) was between 3° and 7° , it was designated as being in this critical range. Successful function of the scratch-based wear formulation was validated (details below) by computational simulation of a previous laboratory simulator experiment (Barbour et al. 2000), in which scratches of specific morphology had been ruled on otherwise-pristine femoral heads.

The capability to simulate wear for individual moving scratches constitutes a significant advancement over the patch-roughened approach, which had implemented wear factor elevation when the roughened patch had overlaid a given node. In its present embodiment, the new scratch-based algorithm has successfully executed simulations involving over 10,000 individual scratch segments, thus allowing for modeling wear acceleration for even relatively severely damaged heads.

Scratch Detection

A goal of the scratch-based FE algorithm was to predict wear acceleration due to damage observed on actual retrieval femoral heads. To gather the necessary input data, a new multi-stage, multi-scale imaging procedure was used for localization and quantification of regions of femoral head damage, on a scratch-wise basis. Identified femoral head damage patterns were imported to the FE model to predict the wear acceleration as a function of the damage present on specific femoral head retrieval specimens. Damage locations were first identified on the femoral head using the novel global-level diffused lighting photographic technique (Heiner et al. 2012), which eliminated extraneous ambient room reflections caused by the highly reflective metallic femoral head surface. This technique involved digitally photographing the femoral head inside of a matte-finish, translucent tube snugly fitted around the camera lens. This dramatically improved the ability to visually observe the apparent physical damage. Photographs were taken at polar and multiple circumferential orientations, such that the entire bearing surface could be captured.

These global-level photographs were then image-analyzed to register individual scratch locations. A Canny edge detector was first used to identify regions of damage (Figure 4a). (The Canny filter (Canny 1986) is a commonly used image processing tool for multi-directional edge detection.) Next, a Hough transform (Duda and Hart 1972) was used to discretize the damage into straight-line segments (Figure 4b). This analysis technique involved a linear transform and the parametric equation of a line to represent each scratch as a series of concatenated straight-line segments. The output of the Hough transform was the polar coordinates of the two endpoints for each scratch segment detected.

The lip heights for thus-identified scratch segments were then determined using optical profilometry (OP). A Veeco Contour GT non-contact profiler (Bruker, Tuscon, AZ), which captured surface features using light interferometry, was used for this analysis. This instrument was capable of scans covering areas up to $5 \text{ mm} \times 5 \text{ mm}$. Scans were taken of all

damaged regions identified in the image analysis of the global-level photographs (Figure 5). Custom-built fixturing (Figure 6) was used to allow for navigation on the surface of the femoral head in the OP setup. The fixturing included a pair of goniometers mounted concentrically, so as to allow for head rotation in two degrees of freedom. OP scan data were then used to assign a specific scratch lip height to each scratch segment detected, based on profiles transverse to the scratch segment axis. A convergence study was conducted to determine the density of sampling profiles needed to reliably approximate the average lip height of each scratch segment. Those results indicated that lip height needed to be measured at least every 10 μm along a given individual scratch segment. The average of those lip height samplings was assigned as the lip height for that scratch segment. Illustratively, wear computations were run for four typical retrieval femoral heads, which had been revised for a variety of clinical indications. Discrete scratch locations and lip heights were mapped using the diffused-lighting photography and OP techniques. Models were run to 10^6 cycles of normal level walking, with adaptive remeshing performed every 41,667 cycles. The adaptive remeshing update interval corresponds to 24 mesh updates over 10^6 duty cycles. This interval was the same update interval used in previous patch roughened work, based on bi-weekly updates over a one year simulation period. This was checked by convergence testing for the scratch-based formation, which showed that the figure of 24 updates per 10^6 cycles was in fact conservative. Linear wear depths and the total volume of PE removed (volumetric wear) were computed.

Results

The new scratch-based wear algorithm was validated by successfully simulating *in vitro* wear tests of otherwise-pristine femoral heads that had been modified by stylus ruling of discrete scratches (Barbour et al. 2000). Those physical tests had involved three equally-spaced scratches extending 180° from the equator, through the pole, and back down to the equator, to form a stellate pattern (Figure 7a). Two series had been run (each with three replicate specimens), one with scratch lip heights of 0.3 μm and the other with heights of 2.9 μm . FE models which replicated this stellate pattern were run to one million cycles. The wear elevation (relative to the results for an undamaged femoral head) was compared between the physical tests and the computational simulations (Figure 7b). The baseline wear rate for the physical wear test was 47 mm^3 while the baseline model for the FE model was 28 mm^3 . The FE model was able to predict relative wear acceleration to within approximately 4% for the 0.3 μm lip height case, and to within 10% for the 2.9 μm lip height case.

To illustrate the algorithm's capacity to estimate wear from actual *in vivo* damage, four representative specimens were selected (Figure 8) from an existing collection of 199 retrieval femoral heads. These implants had been revised for various reasons including aseptic loosening, septic loosening, dislocation, and wear. These four illustrative retrievals had been implanted for between 5.1 and 14.8 years. Acetabular anteversion, femoral lateral opening, and femoral anteversion were known for all cases. The global-level photographic image analysis detected 101 individual scratch segments on sample A, 172 on sample B, 430 on sample C, and 62 on sample D. The corresponding microscopic-level scratch lip height determinants required twenty $2 \times 2 \text{ mm}$ scans at $20\times$ magnification for each sample, requiring an average of twenty hours of OP scanning time per specimen. Scratches were found to have lip heights ranging from 0.1 μm to 10.0 μm . The maximum wear depth and volume of PE removal were calculated for each of the retrieval FE models for 10^6 duty cycles (Figure 9). The spatial distributions of wear were also determined. These results underscore that even relatively few isolated scratches visible at the global level can lead to dramatic increases in wear volume.

Discussion

The present report introduces a novel computational wear formulation to allow for modeling wear increase due to scratching of the femoral component in THA. The model utilizes an experimentally-based relationship between wear acceleration and scratch location, orientation and lip height, to allow wear acceleration assessments on an individual-scratch basis. Reasonably accurate replication of results from laboratory hip simulator wear tests provides confidence in the validity of the model. Modeling of damage using this scratch-based representation allowed for first-ever computational simulation of wear from damage observed on patient-specific retrieval femoral heads.

The physical simulation and FE model showed different baseline wear values. Determination of baseline wear coefficients is a longstanding challenge in FEA wear simulations. Most k data are ultimately sourced from reciprocal motions tests (commonly pin-on-plate), and tend to under-predict whole-implant wear behavior. The FE model behaves nearly linearly with k (Maxian et al. 1997), so it would have been possible to achieve absolute wear increases comparably similar to those that occurred physically, by starting with a correspondingly higher baseline wear coefficient.

The optical profilometer used was capable of scans at nanometer resolution. Scratches with lip heights as small as $0.2\text{ }\mu\text{m}$ have been shown to cause detectable increases in wear (Dowson et al. 1987). The present analysis included scratches with lip heights as small as $0.1\text{ }\mu\text{m}$. Information is as yet lacking as to a threshold of lip height below which scratches can reasonably be ignored. Presumably, formal convergence testing could be used to identify such a threshold. In the current embodiment of the image analysis, determination of scratch lip heights from OP scans (based on locations in global photographs) involved a manual user intervention step to register the global versus microscopic datasets. In principle, this step could be automated to further improve overall processing speed.

In most retrieval series the femoral heads are removed from the neck of the femoral component, and oftentimes data on the circumferential orientation of the head on the trunnion are lacking. This orientation has a large influence on computed wear acceleration. Differing assumed head/trunnions orientations for Sample A, for example, led to computed wear increases ranging from 0 to 15.8 mm^3 after 10^6 cycles. Going forward, this underscores the importance of recording head orientation information of retrieval specimens being collected for scientific purposes, given head orientation's strong influence in the level of wear acceleration. Another limitation of working with retrieval specimens is that the damage apparent on retrieval femoral heads constitutes only a snapshot of damage at the time of the revision surgery. Obviously, no information is available regarding how long the detected scratches may have been present, or to what extent initially higher lips may have been worn down with articulation over time. These limitations, however, are clearly intrinsic to the physical specimens being simulated, rather than to the scratch-based wear algorithm per se.

While much/most femoral head damage takes the form of discrete scratches, a number of the femoral heads in retrieval collections show global regions of roughening/darkening due to bearing-foreign material transfer (typically titanium). Damage of this type can be caused by dislocations or subluxations of the head such that it contacts the acetabular cup (Bowsher et al. 2008). Retrievals displaying this type of damage sometimes show such darkening over a large percentage of the bearing surface (Figure 10), with the deposits having maximum profile heights (R_p) approaching $10\text{ }\mu\text{m}$, and with average roughness (R_a) values up to $0.5\text{ }\mu\text{m}$ (Tikekar et al. 2012). (By comparison, typical R_a values of undamaged femoral heads are on the order of $0.007\text{ }\mu\text{m}$ (Barbour et al. 2000).) Such diffusely damaged regions do not

lend themselves well to being discretized into individual scratch segments. Nevertheless, the high average roughness values of these regions suggest that there would be substantial wear elevations associated with these damage features. Retrieval studies have shown that there can be preferential orientations of damage in these roughened regions (Mai et al. 2010). Since retrieval heads can exhibit both discrete scratching and regional diffuse roughening, an inviting avenue for future work is to combine the directional capabilities of this new algorithm with those of the previously developed patch-roughening wear model (Brown et al. 2002).

In conclusion, the ability to map microscopic-level implant damage over the entire femoral head offers new possibilities for quantifying 3rd body effects. Determination of damage patterns and severities observed on specific retrieval femoral heads can serve as a maximally clinically grounded basis for modeling 3rd body damage in laboratory wear simulations. The present scratch-based FE formulation expands upon the capabilities of previous computational wear models, by allowing simulation of wear acceleration due to actual *in vivo* scratch damage patterns.

Acknowledgments

This research was funded by NIH AR057780. Dr. Steve Liu provided invaluable assistance in our institution's implant retrieval program.

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Figure 1.
Flowchart of scratch-based FE wear model.

Figure 2.

(a) Identification of acetabular cup nodes overpassed by a scratch segment during a given time increment. The delimit points of the scratch segment at time t_n and time t_{n+1} were used to define the vertices of the trapezoidal area (shaded) overpassed by the scratch. Each node of the acetabular cup surface was tested to determine if it fell into this overpassed area. (b) Scratch segment orientation and direction-of-motion vectors used to calculate the angle θ between the two vectors. The endpoints of the segment at time t_n were used to define the scratch segment orientation vector. The direction-of-motion vector was calculated using the midpoints of the scratch segment at time t_n and time t_{n+1} .

Figure 3.

Single-scratch bench study data (Dowson et al. 1987) were used to generate a power law relationship between wear coefficient elevation (k_{inc}) and scratch lip height in microns.

Figure 4.

(a) Canny edge detection of scratch damage to femoral head. (b) Hough transform discretising this damage into straight-line scratch segments (red).

Figure 5.

Global (a) and close-up (b) diffused-lighting photographs of the damaged head surfaces. (The circle at the centre of the femoral head delineates the area of camera lens reflection. Photographs taken at two different angles were digitally combined to eliminate this reflection.) (c) OP scan of a specific scratch revealing the characteristic lip-and-valley morphology. The colour modulation depicts height relative to the undamaged spherical surface. (d) OP scan profiles used to determine scratch lip height.

Figure 6.

(a) Diffused-lighting photography set-up. The rotary table allows for global navigation of the femoral head. (b) Optical profilometry set-up with custom-built test stand to allow for global femoral head navigation. (The OP objective lens is retracted, for clarity of visualization of the mounting fixture.)

Figure 7.

(a) Scratches to femoral head for physical validation simulation. (b) Computed distribution of linear wear. Results were compared to a baseline condition of an undamaged femoral head ($R_a = 0.007$) (Barbour et al. 2000).

Femoral Head A

Revised at 5.1 years
Septic Loosening

Femoral Head B

Revised at 13.5 years
Aseptic Loosening

Femoral Head C

Revised at 14.8 years
Wear

Femoral Head D

Revised at 6.2 years
Dislocation

Figure 8.

Retrieval femoral heads used in analysis (Heads A, B and C – equatorial views, Head D – polar view).

Figure 9.
Computed wear depths for undamaged versus retrieval femoral heads.

Figure 10.
Retrieval femoral head with bearing-foreign material transfer.