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Computational Wear Prediction of UHMWPE in Knee Replacements

ABSTRACT: A multibody dynamic contact model predicted the damage sustained by two tibial inserts tested under different conditions on an AMTI knee simulator machine. The model required a wear factor of 7.7×10^{-7} mm^3/Nm to match the wear volume measured from the first insert after 0.86 million cycles of simulated gait. The model matched the medial and lateral damage depths measured from the second insert to within 0.3 mm after 5 million cycles of simulated gait and stair (10:1 ratio). Computational models may be valuable for screening new knee implant designs rapidly and performing sensitivity studies of component positioning issues.

KEYWORDS: computational wear prediction, dynamic contact simulation, knee simulator, total knee replacement

Introduction

Wear of ultrahigh molecular weight polyethylene remains a primary limitation in extending the longevity of total knee replacements (TKRs) [1]. Consequently, knee simulator machines are commonly used to evaluate wear performance of new knee implant designs and materials [2]. These machines typically have multiple stations, each providing multiaxial motion and load control of the TKR components in a physiological environment. Wear testing on a simulator machine is time consuming and expensive due to the large number of low-frequency cycles that must be run [3]. Moreover, different stations on the same test machine sometimes produce different wear results.

In contrast, computer simulation can be a fast and reproducible method for predicting TKR performance [4]. For example, computer simulations have been used to predict tibial insert damage under in vivo conditions [5]. These simulations required between 10 and 20 min of CPU time on a typical PC workstation to predict tibial insert wear, creep, and damage (=wear+creep) for a specified number of loading cycles of gait and stair activities. While fluoroscopic measurements can provide accurate in vivo motion inputs to such simulations [6,7], accurate in vivo load inputs are difficult to obtain and an estimated number of motion cycles must be used for each simulated activity. Simulation of a simulator machine overcomes these limitations since the motion and load inputs as well as number of loading cycles are known accurately for each simulated activity, as is the sequence of simulated activities. Thus, simulator machines provide a well-controlled test bed for evaluating computational approaches to TKR damage prediction.

This study evaluates the ability of a multibody dynamic contact model of an AMTI knee simulator machine to predict tibial insert damage in two knee implants of the same design. Wear volume was measured gravimetrically for one insert after 0.86 million cycles of simulated gait while damage depths were estimated via laser scanning for another insert after 5 million cycles of simulated gait and stair. Computer simulations were used to predict wear volume for the first insert and damage depths for the second. Sensitivity studies were also performed for the second insert to evaluate the extent to which predicted damage depths varied with changes in femoral component position and orientation in the AMTI machine.

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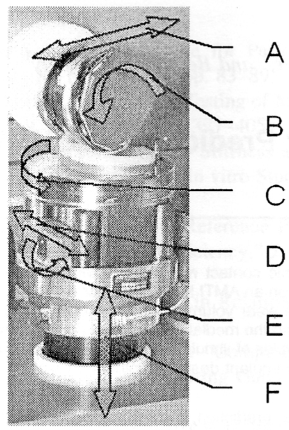

FIG. 1—*Degrees of freedom for one station of the AMTI knee simulator machine. A=anterior/posterior translation, B=flexion/extension, C=internal/external rotation, D=medial/lateral translation, E=varus/valgus rotation, and F=vertical translation.*

Multibody Dynamic Contact Model

The AMTI simulator studied in this paper has six stations. On each station, the implant components are mounted and immersed in a sealed, temperature controlled, fluid bath. Loads and motions are programmed through the control system in order to simulate walking, stair climbing, or other physiologic motions. The machine has displacement control for anterior/posterior translation, flexion extension, and internal/external rotation and force control for superior/inferior translation (Fig. 1).

A multibody dynamic contact model of one station of an AMTI knee simulator machine was constructed to predict TKR damage in a single cruciate-retaining knee implant design (Genesis II, Smith & Nephew, Inc., Memphis, TN). The multibody model was implemented within the Pro/MECHANICA MOTION simulation environment (PTC, Waltham, MA) (Fig. 2). The femoral component was connected to the ground via a planar joint, the tibial tray to the machine base via another planar joint, and the

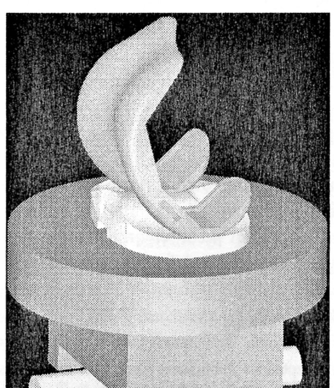

FIG. 2—*Multibody dynamic contact model of the AMTI knee simulator developed within the Pro/MECHANICA MOTION simulation environment.*

machine base to the ground via a 6 degree-of-freedom (DOF) joint. The joint between the femur and insert possessed 6 DOFs and was utilized to measure relative (i.e., joint) kinematics for contact calculations. Each DOF in the model was either motion or load controlled to mimic the function of each DOF in the AMTI machine. Femoral component and tibial insert contact surfaces were extracted from the Genesis II CAD models and refitted with single-surface representations using commercial software (Geomagic Studio, Research Triangle Park, NC) to improve computational efficiency.

A deformable contact model based on elastic foundation theory was incorporated into the multibody dynamic model to predict contact forces and pressures between the implant surfaces. The contact model utilizes springs distributed over the articulating surfaces of the tibial insert to prevent excessive interpenetration. The contact pressure p for any spring was calculated from

$$p = \frac{(1-\nu)E(p)}{(1+\nu)(1-2\nu)}\frac{d}{h} \tag{1}$$

where $E(p)$ is Young's modulus of the elastic layer, which was either constant or a nonlinear function of p, ν is Poisson's ratio of the elastic layer, h is the layer thickness at the spring location, and d is the spring deflection, defined as the interpenetration of the undeformed surfaces in the direction of the local surface normal (see [8] for further details). The distance d was computed each time instant given the current position and orientation of the tibial insert and femoral component obtained from the 6 DOF joint in the multibody dynamic model.

Computational Wear and Creep Model

The time history of contact pressures and slip velocities experienced by each element were input into a computational wear model to develop element-by-element damage predictions. The total damage depth for each element was the combination of the material lost due to mild wear and the surface deformation due to compressive creep.

$$\delta_{Damage} = N\delta_{Wear} + \delta_{Creep}(N) \tag{2}$$

where δ_{Damage} is the total damage depth, N is the total number of cycles, δ_{Wear} is the wear depth per cycle, and $\delta_{Creep}(N)$ is the creep depth for N cycles.

The depth of material removed from an element over one cycle due to mild wear was predicted using Archard's classic law for mild wear [9]. The model predicts the wear depth of an element on the contact surface based on the wear rate, contact pressure and sliding distance.

$$\delta_{Wear} = k\sum_{i=1}^{n} p_i d_i = k\sum_{i=1}^{n} p_i |v_i| \Delta t_i \tag{3}$$

where k is the wear rate, p_i is the contact pressure and the sliding distance is calculated as the product of the slip velocity magnitude $|v_i|$ multiplied by the time increment Δt_i.

UHMWPE creep is the time dependent deformation of a loaded viscoelastic material. UHMWPE that experiences creep deformation will have some elastic recovery when the load is removed. Based on the research of Lee and Pienkowski [10], creep of each element in a UHMWPE can be estimated as a function of contact pressure and compression time.

$$\delta_{Creep} = \left[C1 + C2\left(Log\left(N\sum_{i=1}^{n}\Delta t_{ci}\right) - 4\right)\right]\frac{\sum_{i=1}^{n} p_i \Delta t_{ci}}{\sum_{i=1}^{n}\Delta t_{ci}} h \tag{4}$$

where R is the relaxation rate, $C1 = 3.491 \times 10^{-3}$ and $C2 = 7.966 \times 10^{-4}$ are constants, N is the total number of cycles, Δt_{ci} is the time increment when the contact pressure p_i is nonzero, and h is the initial thickness. The unit for pressure is MPa, the unit for time minutes, and the unit for thickness mm.

Comparison with Worn Inserts

Two sets of simulations were performed with the model to emulate the conditions experienced by the two Genesis II implants tested on the AMTI machine. The first set was configured to mimic component

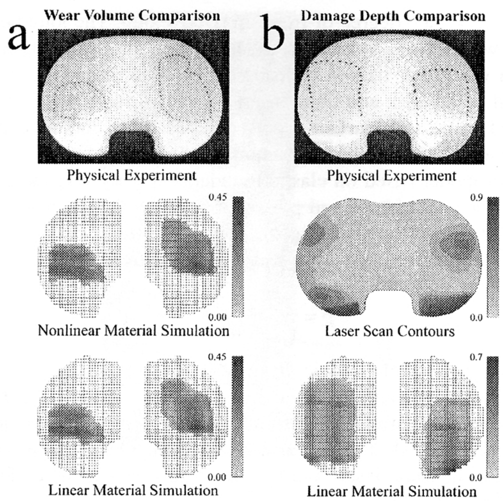

FIG. 3—*Visualization of experimental and simulated damage of a commercial knee implant tested on an AMTI simulator machine under two test configurations. (a) First test where experimental wear volume was measured gravimetrically after 0.86 million cycles of simulated gait. (b) Second test where experimental damage depths were measured via laser scanning after 5 million cycles of simulated gait and stair.*

positioning and loading during 0.86 million cycles of simulated gait. Linear (E=463 MPa) and nonlinear (ε_0=0.0257, σ_0=15.9, n=3) material models (ν=0.46 for both models) were used in the elastic foundation contact model to investigate the influence of material properties on wear area and volume predictions. The predicted wear volume for a range of wear factors was compared to the actual wear volume measured gravimetrically. The second set of simulations was configured to mimic different component positioning and loading during 5 million cycles of simulated gait and stair (10:1 ratio). Only the linear material model was used and the wear factor was set to 1×10^{-7} mm^3/Nm based on measurements of the average femoral component surface roughness (not available for the first implant) and data reported in [11]. The predicted damage depths for this one wear factor were compared to actual damage depths estimated by laser scanning the worn and a matched unworn insert and measuring the deviation between the two sets of contact surfaces with commercial software (Geomagic Studio, Research Triangle Park, NC). Changes in wear, creep, and damage depths for variations in femoral component position and orientation in the AMTI machine (±3 mm or ±3° in each direction) were also predicted. All simulations used a contact element grid of 40×30 in both compartments and required less than 20 min of CPU time on 2.0 GHz Xeon work station.

Results and Discussion

For the first insert, a wear factor of 7.7×10^{-7} mm^3/Nm was needed in the wear model to match the gravimetrically measured wear volume of 21.7 mm^3 (Fig. 3(*a*)). This value corresponds to an average femoral component surface roughness of approximately 0.1 μm which is likely higher than that of the component used in the test. Wear areas and volumes predicted using the two material models (linear and nonlinear) were nearly identical, indicating that choice of material model had little influence on these quantities. Damage regions predicted by the simulations were in excellent agreement with those observed on the central portion of each insert contact surface. However, small posterior damage regions observed experimentally were not reproduced by the simulation, possibly because the feedback control system of the simulator machine did not follow the commanded load waveform closely during portions of the cycle. Posterior damage would have increased the predicted wear volume and caused a corresponding decrease in the wear factor necessary to match the experimentally measured wear volume.

For the second insert, the predicted damage depths of 0.6 and 0.8 mm on the medial and lateral sides,

TABLE 1—*Sensitivity of predicted wear, creep, and damage (=creep+wear) depths to, variations in femoral component position (±3 mm or ±3° in each direction).*

	Wear Depth (mm)		Creep Depth (mm)		Damage Depth (mm)	
	medial	Lateral	Medial	Lateral	Medial	Lateral
Nominal	0.11	0.17	0.45	0.59	0.56	0.76
+Xtrans	0.10	0.36	0.54	0.89	0.64	1.14
−Xtrans	0.12	0.15	0.46	0.51	0.54	0.66
+Ytrans	0.12	0.18	0.48	0.59	0.60	0.76
−Ytrans	0.09	0.16	0.49	0.56	0.58	0.69
+Ztrans	0.11	0.17	0.47	0.57	0.58	0.70
−Ztrans	0.11	0.18	0.47	0.58	0.57	0.75
+Xrot	0.10	0.19	0.47	0.59	0.52	076
−Xrot	0.12	0.16	0.57	0.55	0.69	0.68
+Yrot	0.09	0.16	0.52	0.53	0.54	0.66
−Yrot	0.15	0.17	0.51	0.58	0.66	0.75
+Zrot	0.12	0.19	0.47	0.61	0.58	0.74
−Zrot	0.11	0.16	0.45	0.51	0.56	0.64
Experiment	...	...	...	...	0.92	0.92

respectively, were within 0.3 mm of the measured depths of 0.9 and 0.9 mm (Fig 3(*b*)). Increasing the wear factor to 2×10^{-7} mm^3/Nm, consistent with the roughest regions on the femoral component, increased the predicted damage depths to 0.7 and 0.9 mm. The predicated damage regions were in good agreement with the actual damage regions, though the predicted locations of maximum damage did not correspond well with reality. Modifying the femoral component position by ±3 mm or orientation by ±3° created a standard deviation of at most ±0.06 mm in predicted wear depth, ±0.10 mm in predicted creep depth, and ±0.13 mm in predicted damage depth on either side, indicating that predicted damage depth was not highly sensitive to femoral component malalignment in the simulator machine (Table 1). The most likely explanation for poor prediction of maximum damage locations was observed changes over time of the motion and load outputs produced by the simulator machine.

These results suggest that a multibody dynamic model can produce reasonable predictions of TKR damage generated in a knee simulator machine. Such models may prove valuable in the future for screening new knee implant designs rapidly or performing sensitivity studies that would be too time consuming to complete with physical simulator machines.

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