Proceedings of BIO2006
2006 Summer Bioengineering Conference
June 21-25, Amelia Island Plantation, Amelia Island, Florida, USA

BIO2006-157865

CAN PIN-ON-PLATE TESTS BE USED TO PREDICT JOINT-LEVEL WEAR IN KNEE REPLACEMENTS?

**Dong Zhao(1), Hideyuki Sakoda(2), W. Gregory Sawyer(1),
Scott A. Banks(1,3), and Benjamin J. Fregly(1,3)**

(1) Department of Mechanical & Aerospace
Engineering
University of Florida
Gainesville, FL, 32611

(2) Nakashima Medical Division
Nakashima Propeller Co., Ltd.
Japan

(3) Department of Biomedical Engineering
University of Florida
Gainesville, FL 32611
USA

INTRODUCTION

Wear of ultra-high molecular weight polyethylene (UHMWPE) remains a primary factor limiting 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]. 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]. In contrast, pin-on-plate wear tests using the same material pairs are faster and cheaper to perform, though they do not provide the joint-level evaluation desired for design purposes.

This study evaluates whether a wear factor found from a pin-on-plate test can be incorporated into differential elements of a joint-level computational simulation to predict wear in a total knee replacement [4]. The evaluation is performed using a multibody dynamic contact model of an AMTI knee simulator machine constructed to match physical wear tests performed on the same implant.

MATERIALS AND METHODS

A multibody dynamic contact model of one station of an AMTI knee simulator machine was constructed to predict TKR damage in a knee implant design (HTK-II, Nakashima Medical Division, Nakashima Propeller Co., Ltd. Japan). The multibody model was implemented within the Pro/MECHANICA MOTION simulation environment (PTC, Waltham, MA) (Figure 1). 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 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. The force and displacement outputs from the machine were used as inputs to the dynamic simulation. The surfaces of the manufactured femoral component were digitized using a coordinate measurement machine (CMM) and the resulting point clouds were fitted with single-surface representations using commercial software (Geomagic, Research Triangle Park, N.C.) to improve computational efficiency.

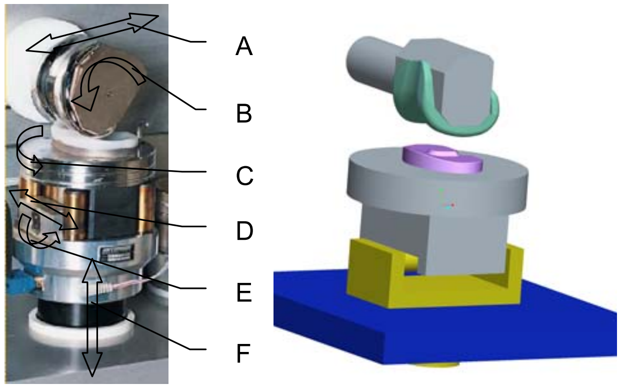

Figure 1: Degrees of freedom for one station of AMTI simulator machine (left, A = anterior/posterior translation, B = flexion/extension, C = internal/external rotation, D = medial/lateral translation, E = varus/valgus rotation, F = vertical translation) and multibody dynamic contact model of the AMTI knee simulator developed within the Pro/MECHANICA MOTION simulation environment (right).

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 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 [4] for further details). The distance 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.

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. 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. The model predicts the wear depth of an element on the contact surface based on the wear rate, contact pressure, and sliding distance, and it predicts creep of each element based on contact pressure and compression time [4].

Multidirectional pin-on-plate wear tests were performed to determine the wear factor for the material pairs used in the implant tested on an AMTI simulator machine. Wear volumes of three inserts of the same design were measured gravimetrically after every 1 million cycles of simulated gait and damage depths were estimated via CMM after 5 million cycles.

RESULTS AND DISCUSSION

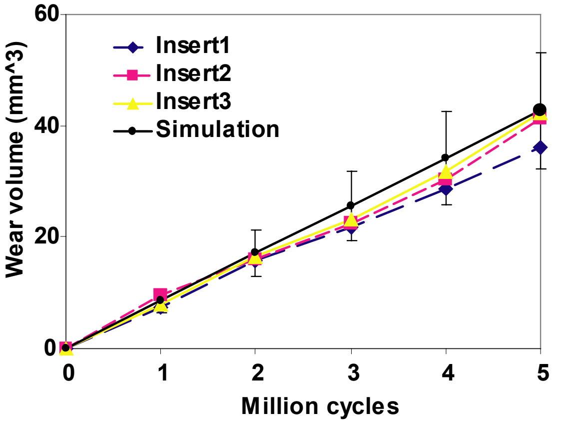

Figure 2: Simulated and gravimetrically measured volume loss due to mild wear. Simulation error bars indicate ± 1 SD in wear factor measurement.

The wear volume prediction using the wear factor from the pin-on-plate tests matched the experimental measurements well for all three inserts. The wear factor of the UHMWPE was $2.59 \pm 0.63 \times 10^{-7}$ mm^3/Nm. The average of the gravimetrically measured wear volumes after 5 million cycles of simulated gait was 39.9 mm^3 while the model prediction was 42.8 ± 10.3 mm^3 using this wear factor and its error bounds. The wear volume predicted with the computational model is proportional to the number of motion cycles. All the experimental measurements fell in the bounds of the predicted wear volumes using the wear factor error bounds.

The models over predicted the maximum damage depth (mm) and under predicted wear areas (Figure 3). The most likely explanation is that the tibial contact surfaces were not modified progressively like during the physical tests. Incorporation of surface updating into the dynamic contact model should make the wear area prediction more realistic and reduce the maximum damage depth without changing the wear volume [5]. Lack of creep recovery also contributes to the over prediction of damage depth.

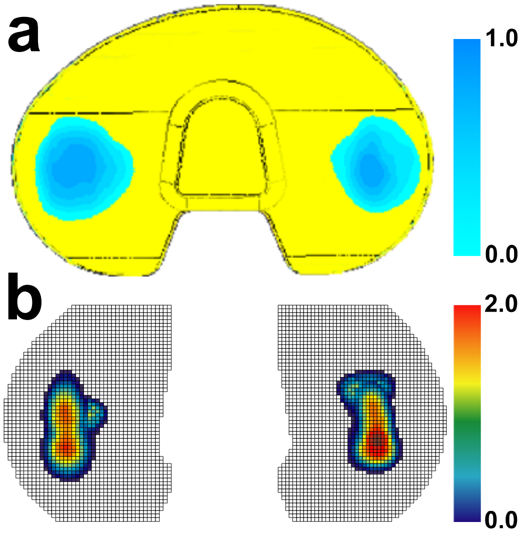

Figure 3: (a) Contour plot of a tibial insert tested on AMTI simulator machine. (b) Predicted tibial insert damage (=creep+wear) with linear material properties (*E* = 463MPa, *v* = 0.46).

The wear volume results suggest that a multibody dynamic model using a wear factor from pin-on-plate tests 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.

REFERENCES

1. Sharkey, P.F., *et al.*, 2002, "Why are knee replacements failing today?" In Proceedings of the Knee Society, Dallas, TX.
2. Walker, P.S., Blunn, G.W., Broome, D.R., Perry, J., Watkins, A., Sathasivam, S., Dewar, M.E., Paul, J.P., 1997, "Knee simulating machine for performance evaluation of total knee replacements," J Biomech, **30**, pp. 83-89.
3. Godest, A.C., Beaugonin, M., Haug, E., Taylor, M., Gregson, P.J., 2002, "Simulation of a knee joint replacement during a gait cycle using explicit finite element analysis," J Biomech, **35**, pp. 267–276.
4. Fregly, B.J., Sawyer, W.G., Harman, M.K., Banks, S.A,. 2005, "Computational wear prediction of a total knee replacement from in vivo kinematics," J Biomech, **38**, pp. 305–314.
5. Knight, L.A., Bronson, F., Pal, S., Haider, H., Coleman, J., Levine, D. Toylor, M., and Rullkoetter, P., 2005, "Comparison of Numerical and Experimental total Knee Replacement Wear Simualtion," Knee Arthroplasty: Engineering Functionality, London, UK, pp. 245-248.