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The Relationship between Contact Pressure, Insert Thickness, and Mild Wear in Total Knee Replacements

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Abstract: Mild wear of ultra-high molecular weight polyethylene tibial inserts continues to affect the longevity of total knee replacements (TKRs). Using static finite element and elasticity analyses, previous studies have hypothesized that polyethylene wear can be reduced by using a thicker tibial insert to decrease contact pressures. To date, no study has taken this hypothesis to the next step by performing dynamic analyses under *in vivo* functional conditions to quantify the relationship between contact pressures, insert thickness, and mild wear. This study utilizes multibody dynamic simulations incorporating elastic contact to perform such analyses. *In vivo* fluoroscopic gait data from two patients with different implant designs were used to drive dynamic contact simulations. The first design was coronally flat-on-flat while the second was coronally curved-on-curved. Variations in minimum plastic thickness (6, 8, 10, 12, and 14 mm) and applied load profile (corresponding to body masses of 50, 62.5, 75, 87.5. and 100 kg) were used to modify the contact pressures in each of 25 simulations performed with each implant design. Mild wear following five million cycles of gait was calculated from the contact pressure and slip velocity time histories of elements on the tibial insert surfaces. The maximum values of peak and average contact pressure during the gait cycle were found to be poor predictors of wear depth. In contrast, contact pressures were good predictors of wear volume when the pressures were varied by changing the applied load profile. However, when the applied load profile was fixed and the contact pressures varied by changing the insert thickness, no changes in wear volume were predicted. Decreases in contact pressure due to a thicker insert were offset by increases in contact area subjected to sliding in the wear calculations. These findings suggest that use of a thicker tibial insert may not necessarily lead to decreased mild wear in total knee replacements and that further investigation of this issue is warranted.

keyword: Total knee replacement, dynamic simulation, contact pressure, wear prediction.

1 Introduction

Ultra-high molecular weight polyethylene (UHMWPE) debris particles from total knee replacements (TKRs) can produce osteolytic reactions leading to implant loosening and failure. Primary UHMWPE damage modes identified in TKRs include pitting, delamination, and abrasion/adhesion [Harman et al. (2001); Muratoglu et al. (2003)]. Pitting and delamination are influenced by the multiaxial stress state of the UHMWPE at and below the surface [Bartel et al. (1985); Bartel et al. (1986); Bartel et al. (1995); Estupian et al. (1998)]. In contrast, abrasive/adhesive (or mild) wear is influenced primarily by surface topography, contact loads, and surface kinematics [Lancaster et al. (1997); McGloughlin and Kavanagh (2000)]. Early landmark studies using static finite element and elasticity analyses with simplified knee implant geometry demonstrated the important influence of tibial insert thickness and conformity on contact pressures in the polyethylene [Bartel et al. (1985); Bartel et al. (1986); Bartel et al. (1995); Chillag and Barth (1991)]. It was hypothesized that increasing the thickness and conformity of the plastic insert would lead to decreased damage through a reduction in contact pressure and an increase in contact area. However, no study has confirmed the applicability of this hypothesis to mild wear by performing calculations with actual implant geometry under dynamic *in vivo* conditions.

Computational predictions of mild wear derived from dynamic simulations have been reported in several studies. Dinc et al. (1996) coupled dynamic simulations with wear predictions for a gas turbine combustor to identify potential design improvements. Archard's wear law [Archard and Hirst (1956)] with a constant wear factor was used for the wear calculations. Though the wear predictions were imperfect, average lifespan of the ma-

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chines was tripled by implementing design changes identified by the simulations. More recently, Dickrell et al. (2003) performed coupled dynamic and wear analysis of a two-dimensional circular cam mechanism. The cam was made of the polymer polytetrafluoroethylene (PTFE) while the follower was stainless steel. Using Archard's wear law with a constant wear factor, analytical and numerical simulations of the mechanism were able to predict the worn shape of the cam to within 3% of its experimentally measured shape following 1.5 million cycles. The numerical simulations provided general guidelines for when wear predictions from a single cycle can be extrapolated to multiple cycles. Building on this work, Fregly et al. (2004) applied a similar methodology to a total knee replacement for which *in vivo* fluoroscopic data and a postmortem retrieval were available from the same patient. Insert damage was calculated as the sum of wear plus creep. Damage predictions were generated from dynamic simulation of a single cycle of gait and stair activities extrapolated out to the 51 months of implantation. The predictions were able to match medial and lateral damage depths to within 0.1 mm, damage areas to within 15%, and damage volumes to within 20% of the values measured on the retrieval.

This study uses computational wear prediction methods to quantify the relationship between contact pressures, insert thickness, and mild wear in total knee replacements. To make the results generalizable, knee implants representing two design philosophies were simulated using *in vivo* fluoroscopic gait data. One design was coronally flat-on-flat while the other was coronally curved-on-curved. Contact pressures and areas in the simulations were varied by using all possible combinations of five insert thicknesses (6, 8, 10, 12, and 14 mm) and five axial load profiles corresponding to five body masses (50, 62.5, 75, 87.5, and 100 kg). The hypothesis tested was that quasi-static contact measures (i.e., maximum value of peak pressure, average pressure, and contact area occurring at any point in the gait cycle) are poor predictors of mild wear depth and volume, and in particular, that changes in contact pressure caused by varying the insert thickness have little effect on wear volume.

2 Methods

2.1 Experimental Data Collection

In vivo fluoroscopic data collected from two TKR subjects during treadmill gait were used as inputs to the dynamic contact simulations. All data collection was institutional review board approved and both patients gave written informed consent. The first subject (female, age 65 at time of surgery, height 170 cm, mass 70 kg) received a coronally flat-on-flat cruciate-retaining knee implant design (Design 1), while the second subject (male, age 63 at time of surgery, height 171 cm, mass 73 kg) received a coronally curved-on-curved posterior-stabilized knee design (Design 2). In addition, the second patient performed overground gait during which ground reaction and reflective surface marker data were recorded. The knee flexion angle was used to synchronize the ground reaction data with the fluoroscopic kinematics, and the duration of stance phase was lengthened to 68% of the cycle to account for differences between overground and treadmill gait.

2.2 Dynamic Contact Simulations

Dynamic contact simulations were generated using each subject's fluoroscopically measured kinematics along with ground reaction force data from the second subject. For each knee design, the tibial insert was fixed to ground and the femoral component connected to the tibial insert via a six degree-of-freedom (DOF) joint. The motion of three DOFs was prescribed (i.e., inverse dynamics) to match the fluoroscopically measured flexion, internal-external rotation, and anterior-posterior translation, since contact forces and pressures on the tibial insert are not sensitive to small changes in these motions. The motion of the remaining three DOFs was predicted (i.e., forward dynamics) based on the mass and inertia of the femoral component, a time-varying axial load, and a net force and torque due to elastic contact (see below). Based on data reported for instrumented knee implants [Lu et al. (1997); Taylor et al. (1998); Taylor and Walker (2001)], the axial load profile was assumed to be a scaled version of the vertical ground reaction force curve with a minimum value of 0.25 times body weight and a maximum value of 3.0 times body weight. The load was offset to the medial side to produce a fixed 70% medial-30% lateral load split, consistent with calculations reported in previous studies [Johnson et al. (1981); Schipplein and Andriacchi (1991); Hurwitz et al. (1998)].

Excessive femoral component penetration into the tibial insert was prevented by an elastic foundation contact model incorporated into the multibody dynamic simulation framework. This linear elastic contact model uses a "bed of springs" scattered over the insert contact surfaces to push the femoral and tibial surfaces apart [Johnson (1985); An et al. (1990); Blankevoort et al. (1991)]. The pressure p generated by each spring is proportional to the amount of surface interpenetration δ at the spring's location:

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

In this equation, E is Young's modulus of the polyethylene, ν is Poisson's ratio, and h is the plastic thickness at the spring's location. The values for Young's modulus (463 MPa) and Poisson's ratio (0.46) were taken from the literature [Bartel et al. (1995); Kurtz et al. (2002)]. Multiplying the pressure of each spring element by its area produced a grid of contact forces, each directed along the deformed local surface normal. These forces were replaced with a single force and torque applied to both bodies for purposes of multibody dynamic simulation [Kane and Levinson (1985)].

To provide a wide range of contact pressures for wear prediction, 25 one-cycle gait simulations were performed with each implant design. The simulations utilized all possible combinations of five minimum tibial insert thicknesses (6, 8, 10, 12, and 14 mm) and five axial load profiles corresponding to five body masses (50, 62.5, 75, 87.5, and 100 kg; Fig. 1a). Since the anthropometry and kinematics of the two experimental subjects were similar, and since vertical ground reaction force profiles are stereotypical during gait, the vertical ground reaction force data from the second subject were also used for the first subject when calculating axial load profiles. Peak contact pressures predicted by the simulations resembled those reported previously by Bartel et al. (1985) for the same range of plastic thicknesses (Fig. 1b).

Each of the 50 dynamic contact simulations was performed on a 2.4 GHz Pentium Xeon workstation and required between 10 and 20 minutes of CPU time. To minimize computation time, the forward dynamic simulations were performed with a coarse element grid of 35 x 20 on each condylar contact surface. In Fregly et al. (2004), this grid density was found to produce contact force and torque results nearly identical to those produced by a finer grid of 50 x 35. Once motion was predicted for the three free DOFs, an inverse dynamics analysis with a fine grid of 50 x 50 was used to generate element contact pressure and slip velocity time histories for input to a subsequent wear analysis.

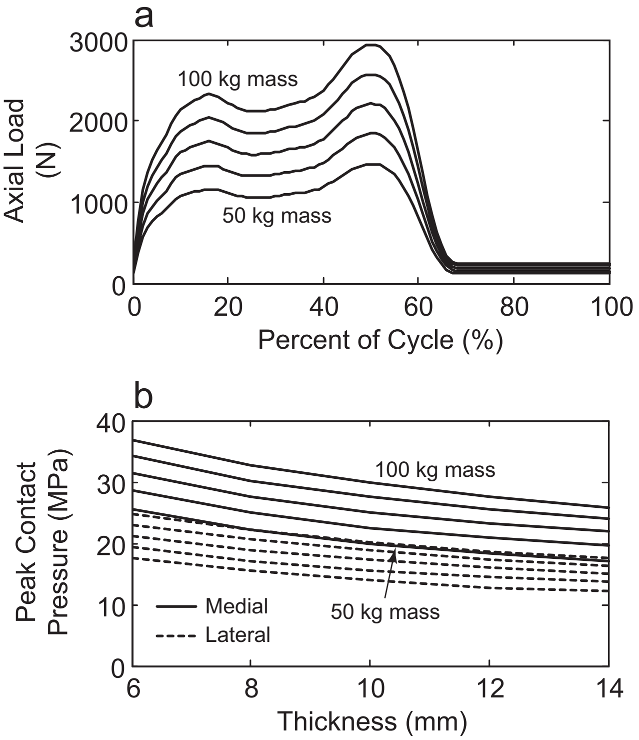

Figure 1 : (a) Axial load profiles for the gait simulations for five assumed values of body mass (50, 62.5, 75, 87.5, and 100 kg). (b) Corresponding variations in the maximum value of peak contact pressure as a function of minimum plastic thickness as predicted by the dynamic contact simulations. Each curve corresponds to an axial load profile in (a).

2.3 Computational Wear Predictions

The wear analysis calculated the depth δ of material removed from each element over one gait cycle based on Archard's wear law [Archard and Hirst (1956)]:

$$\delta = k\sum_{i=1}^{n} p_i d_i = k\sum_{i=1}^{n} p_i\,|v_i|\Delta t \tag{2}$$

Here, k is the material wear factor, i is a discrete time instant in the gait simulation measured at n instants, p_i is the contact pressure on the element at that instant, and d_i is the sliding distance experienced by the element, calculated as the product of slip velocity magnitude v_i and time increment Δt. A constant value of $k = 2.5 \times 10^{-8}$ mm^3 / Nm was calculated from experimental data reported by Lancaster et al. (1997) assuming the femoral component was made of cast, hand polished cobalt chrome alloy with an average surface roughness of 0.058 μm. Wear results for a single cycle were extrapolated out to 5 million cycles, similar to Fregly et al. (2004) (Fig. 2). Wear depth was calculated on an element by element basis, while wear volume was calculated by multiplying each element wear depth by the corresponding element area and then summing over all elements.

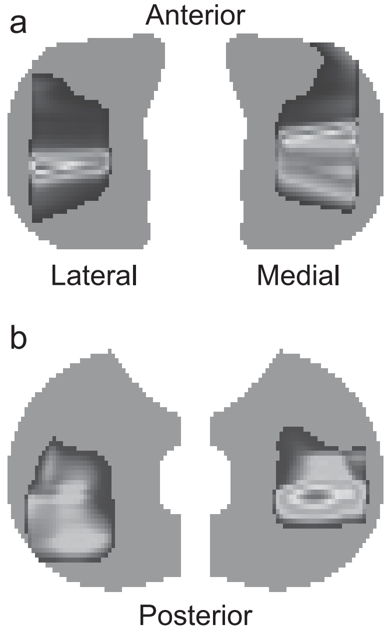

Figure 2 : Visualization of predicted wear contours for the two implant designs using an insert thickness of 10 mm and a body mass of 75 kg. (a) Design 1 - coronally flat-on-flat. (b) Design 2 - coronally curved-on-curved.

For each implant design, wear depth and volume in each compartment were plotted against contact-related quantities (maximum value of peak contact pressure, average contact pressure, and contact area occurring at any point in the gait cycle) to investigate the degree to which contact pressures and areas can be used to predict wear depth and volume. Peak contact pressure at any instant in the simulation was determined by the element with the highest pressure, while average contact pressure was calculated by averaging pressures from all elements with nonzero pressure.

3 Results

Calculated wear depths were poorly predicted by contact-related quantities. When each compartment of each implant design was considered separately, wear depth showed a linear trend with the maximum values of peak and average contact pressure determined over one gait cycle (Fig. 3a and b). However, when both sides of both designs were considered together, no clear relationship between wear depth and contact pressures was evident. Wear depth and maximum contact area also showed no clear relationship (Fig. 3c).

Calculated wear volumes exhibited a linear relationship with maximum peak and average contact pressures when both compartments of both designs were considered simultaneously (Fig. 4a and b). For fixed insert thickness, wear volume showed a linear trend with contact pressures when the pressures were varied by changing the applied load. In contrast, when the applied load was fixed, wear volume remained almost constant as the contact pressures were varied by changing the insert thickness. Wear volume and maximum contact area exhibited a slight nonlinear relationship only when each design was considered separately (Fig. 4c).

4 Discussion

This study used dynamic contact simulations and computational wear predictions of two knee implant designs to investigate the relationship between contact pressures, insert thickness, and mild polyethylene wear. In both dynamic contact models, three DOFs were prescribed using fluoroscopically measured *in vivo* kinematics while the remaining three DOFs were predicted based on a variable axial load profile and elastic contact forces. By systematically varying the insert thickness and axial load profile, 25 simulation cases were generated representing a wide range of contact pressures for quantifying mild wear with each implant design. Overall, contact pressures were poor predictors of wear depth and volume except when they were varied by changing the axial load. When insert thickness was varied in the simulations, little change in predicted wear volume was observed. For a given knee design and side, higher contact pressures with relative motion over a smaller contact area appears to produce equivalent wear volumes to lower contact pressures with relative motion over a larger contact area.

One of the advantages of computational wear predictions is that confounding factors can be easily controlled. In our simulations, insert thickness and axial load profiles could be varied precisely while gross kinematics remained unaltered. This would be impossible to achieve

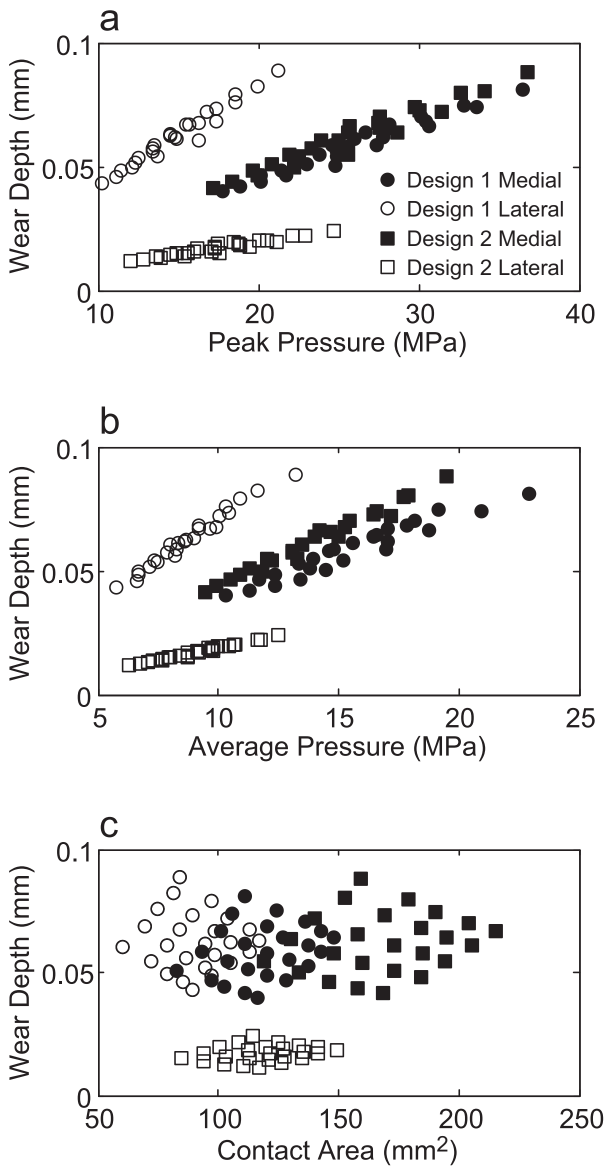

Figure 3 : Variation in maximum wear depth as a function of maximum value of (a) peak contact pressure, (b) average contact pressure, and (c) contact area predicted at any single time frame during one cycle of simulated gait.

under *in vivo* conditions. While the repeatability of *in vitro* wear testing is improving, significantly greater time and cost would be incurred to perform the same experiments with a knee simulator machine compared to the computational approach used here.

One of the disadvantages of computational wear predictions is that no computational model is ever 100% accurate. For example, our model does not account for plastic deformation of the polyethylene [Glaessgen et al. (2002); Sainsot et al. (2002)]. Nonetheless, as shown by Dinc et al. (1996), the ability to predict trends accurately, even when absolute values are less accurate, is extremely valuable for understanding design issues. While several key approximations were made to facilitate generation of our wear predictions, we do not believe that the use of a more accurate model would alter the general trends of our results.

One of the most significant approximations was the use of a constant wear factor in Archard's wear law. Critical factors that can influence the wear factor include surface roughness [Lancaster et al. (1997)], contact pressure [Barbour et al. (1997)], and time-varying loading [Barbour et al. (1997)]. Of these three, variations with contact pressure and time-varying load are the least significant. Work by Fisher and colleagues [Barbour et al. (1997)] indicates that the wear factor for UHMWPE is approximately constant for contact pressures above 5 MPa and increases at lower pressures. In the same study, the wear factor for UHMWPE was shown to increase by 50% for cyclic compared to constant loads. In contrast, changes in counterface surface roughness can change the wear factor by two orders of magnitude [Fisher et al. (1994); Lancaster et al. (1997)], making surface roughness the most important determinant of the wear factor. This may explain why in recent *in vitro* tests of three total knees, Muratoglu et al. (2003) found that the rate of change of wear depth and volume was linear with the number of simulated gait cycles as the number was increased from one to five million. This may also explain why Dickrell et al. (2003) could obtain such a close prediction of the worn PTFE cam shape after 1.5 million cycles using a constant wear factor, even though the load, geometry, and contact pressures changed dramatically. Selection of a different constant wear factor to account for a different assumed femoral component surface roughness would scale all of our wear predictions linearly but would not change the trends.

The other significant approximation in our study was the use of a linear elastic contact model. Use of this model, and the associated low value of Young's modulus, was based on comparison with Tekscan pressure measurements made on a moderately conformal knee design [Fregly et al. (2003)]. That study demonstrated that a linear elastic foundation model was able to reproduce

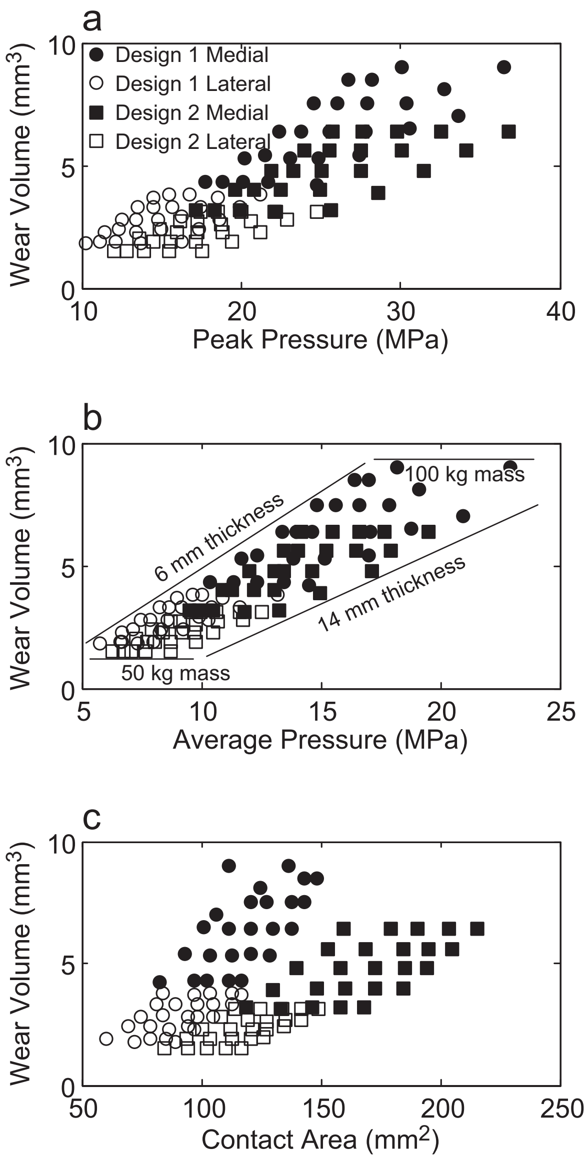

Figure 4 : Variation in predicted wear volume as a function of maximum value of (a) peak contact pressure, (b) average contact pressure, and (c) contact area predicted at any point during one cycle of simulated gait. For each design and side, data points along a horizontal line correspond to changes in insert thickness for a fixed body mass, while data points along a slanted line upward and to the right correspond to changes in body mass for a fixed insert thickness.

peak and average contact pressure measurements simultaneously over a wide range of flexion angles and applied static loads. The excellent agreement was likely due to low experimental contact pressures (peak values of about 30 MPa) that avoided significant yielding of the polyethylene. In the present simulations, peak pressures reached about 38 MPa, which is still well below the contact pressure required to achieve full subsurface yielding [Johnson (1985); McGloughlin and Kavanagh (2000)]. Subsequent comparisons with a linearly elastic finite element (FE) model (unpublished) have shown that the elastic foundation model matches average pressures and contact areas but overpredicts peak pressures from FE analysis. However, even if the peak pressures are overestimates, the average pressures from the elastic foundation model are consistent with both experimental measurements and FE analysis. Since the relationship between wear quantities and maximum average pressures was similar to that between wear quantities and maximum peak pressures, inaccuracies in the predicted peak contact pressures would not significantly change the reported trends.

A final important approximation was that the tibial insert geometry did not need to be progressively modified as the wear evolved. For some systems, accurate wear prediction requires accounting for the coupled evolution of wear, kinematics, and load. Such coupling would require geometry updating after every cycle along with simulation over millions of cycles, which is not practical computationally. One trade-off would be to update the geometry a limited number of times. For example, the first simulation could be used to extrapolate wear out to half the total number of cycles. After updating, the geometry would reflect the new worn state, and a second simulation could be performed for the remaining cycles. Validated theoretical studies have been performed for cam-follower mechanisms [Dickrell et al. (2003)] to determine the number of cycles that can be extrapolated from a single simulation before geometry updating is necessary. Updating frequency was a function of changes in the applied load and surface geometry. In knee implants, the applied loads are not expected to change significantly as the polyethylene wears, while changes in the surface geometry due to mild wear are typically small over 5 million cycles. Thus, the system is expected to be weakly coupled [Fregly et al. (2004)] so that omission of geometry updating should not significantly affect the predictions.

Though increased insert thickness and conformity are valuable for reducing the risk of pitting and delamination [Bartel et al. (1985); Bartel et al. (1986); Bartel et al. (1995); Estupian et al. (1998)], they may not provide much reduction in mild wear. Rather, strategies aimed at decreasing the loads to which the insert is subjected are likely to be more beneficial. Such strategies are not limited to encouraging patients to lose weight. Joint instability can lead to high levels of muscle co-contraction [Akjaer et al. (2000)], significantly increasing the contact forces. Thus, implant stability, muscle strength and coordination, proper ligament balancing, and surgical component positioning may all be critical for minimizing contact forces.

5 Conclusions

In summary, this study presented computational wear predictions for two knee implant designs as a function of changing insert thickness and applied load profile. These changes were used as a convenient way to modify contact pressures in 50 dynamic simulations of gait derived from *in vivo* fluoroscopic measurements. The wear prediction methodology has been evaluated in previous studies and found to reproduce *in vitro* and *in vivo* measurements well when applied to polymers. The current simulations demonstrate the weak ability of contact pressures alone to predict wear depth and volume in the two designs analyzed. Though the predictions were based on a variety of modeling assumptions, the general trends should be relatively insensitive to modeling errors. At a minimum, our results show that if these conditions existed *in vivo*, it would be possible to vary the insert thickness without changing the mild wear volume. This finding suggests that changes in insert conformity with a fixed axial load profile may also produce little change in wear volume. Further investigation of the relationship between insert thickness and mild wear appears to be warranted, either by analytic wear prediction methods, *in vitro* mechanical testing, or even state-of-the-art *in vivo* motion measurement methods [Alexander et al. (2003)].

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References

Akjaer, T.; Simonsen, E. B.; Jørgensen, U.; Dyhre-Poulsen, P. (2003): Evaluation of the walking pattern in two types of patients with anterior cruciate ligament deficiency: copers and non-copers. *Eur J Appl Physiol*, vol. 89, pp. 301-308.

Alexander, E. J.; Bregler, C.; Andriacchi, T. P. (2003): Non-rigid modeling of body segments for improved skeletal motion estimation. *CMES: Computer Modeling in Engineering & Sciences*, vol. 4, no. 3&4, pp. 351-364.

An, K. N.; Himenso, S.; Tsumura, H.; Kawai, T.; Chao, E. Y. S. (1990): Pressure distribution on articular surfaces: application to joint stability analysis. *J Biomech*, vol. 23, pp. 1013-1020.

Archard, J. F.; Hirst W. (1956): The wear of metals under unlubricated conditions. *Proceedings of the Royal Society*, vol. 236, pp. 397-410.

Barbour, P. S. M.; Barton, D. C.; Fisher, J. (1997): The influence of stress conditions on the wear of UHMWPE for total joint replacements. *J Matls Sci: Matls Med*, vol. 8, pp. 603-611.

Bartel, D. L.; Bicknell, V. L.; Weight, T. M. (1986): The effect of conformity, thickness, and material on stresses in ultra-high molecular weight components for total joint replacement. *J Bone Joint Surg [Am]*, vol. 68, pp. 1041-1051.

Bartel, D. L.; Burstein, A. H.; Edwards, D. L. (1985): The effect of conformity and plastic thickness on contact stress in metal-backed plastic implants. *J Biomech Eng*, vol. 107, pp. 193-199.

Bartel, D. L.; Rawlinson, J. J.; Burstein, A. H.; Ranawat, C. S.; Flynn, F. W. (1995): Stresses in polyethylene components of contemporary total knee replacements. *Clin Orthop Rel Res*, vol. 317, pp. 76-82.

Blankevoort, L.; Kuiper, J. H.; Huiskes, R.; Grootenboer, H. J. (1991): Articular contact in a three-dimensional model of the knee. *J Biomech*, vol. 24, pp. 1019-1031.

Chillag, K. J.; Barth, E. (1991): An analysis of polyethylene thickness in modular total knee components. *Clin Orthop Rel Res*, vol. 273, pp. 261-263.

Dickrell, D. J.; Dooner, D. B.; Sawyer, W. G. (2003): The evolution of geometry for a wearing circular cam: analytical and computer simulation with comparison with experiment. *J Tribology*, vol. 125, pp. 187-192.

Dinc, O. S.; Cromer, R.; Clabrese, S. J. (1996): Redesigning mechanical systems for low wear using system dynamics modeling. *J Tribology*, vol. 118, pp. 415-422.

Estupian, J. A.; Bartel, D. L.; Wright, T. M. (1998): Residual stresses in utra-high molecular weight polyethylene loaded cyclically by a rigid moving indenter in nonconforming geometries. *J Orthop Res*, vol. 16, pp. 80-88.

Fisher, J.; Dowson, D.; Hamdzah, H.; Lee, H. L. (1994): The effect of sliding velocity on the friction and wear of UHMWPE for use in total artificial joints. *Wear*, vol. 175, pp. 219-225.

Fregly B. J.; Sawyer W. G.; Harman M. K.; Banks S. A. (2004): Computational wear prediction of a total knee replacement from in vivo kinematics. *J Biomech* (in press).

Fregly, B. J.; Bei, Y.; Sylvester, M. E. (2003): Experimental evaluation of an elastic foundation model to predict contact pressures in knee replacements. *J Biomech*, vol. 36, pp. 1659-1668.

Glaessgen, E. H.; Riddell, W. T.; Raju, L. S. (2002): Nodal constraint, shear deformation and continuity effects related to the modeling of debonding of laminates, using plate elements. *CMES: Computer Modeling in Engineering & Sciences*, vol. 3, no. 1, pp. 103-116.

Harman, M. K.; Banks, S. A.; Hodge, W. A. (2001): Polyethylene damage and knee kinematics after total knee arthroplasty. *Clin Orthop Rel Res*, vol. 392, pp. 383-393.

Hurwitz, D. E.; Sumer, D. R.; Andriacchi, T. P.; Sugar, D. A. (1998): Dynamic knee loads during gait predict proximal tibial bone distribution. *J Biomech*, vol. 31, pp. 423-430.

Johnson, F.; Scarrow, P.; Waugh, W. (1981): Assessments of loads in the knee joint. *Med Biol Eng Comp*, vol. 19, pp. 237-243.

Johnson, K. L. (1985): *Contact Mechanics*, Cambridge University Press, Cambridge.

Kane, T. R.; Levinson, D. A. (1985): *Dynamics: Theory and Applications*. McGraw-Hill Book Company, New York.

Kurtz, S. M.; Jewett, C. W.; Bergström, J. S.; Foulds, J. R.; Edidin, A. A. (2002): Miniature specimen shear punch test for UHMWPE used in total joint replacements. *Biomatierals*, vol. 23, pp. 1907-1919.

Lancaster, J. G.; Dowson, D.; Isaac, G. H.; Fisher, J. (1997): The wear of ultra-high molecular weight polyethylene sliding on metallic and ceramic counterfaces representative of current femoral surfaces in joint replacement. *Proc Instn Mech Engrs H*, vol. 211, pp. 17-24.

Lu, T.-W.; Taylor, S. J. G.; O'Connor, J. J.; Walker, P. S. (1997): Influence of muscle activity on the forces in the femur: an in vivo study. *J Biomech*, vol. 30, pp. 1101-1106.

McGloughlin, T. M.; Kavanagh, A. G. (2000): Wear of ultra-high molecular weight polyethylene (UHMWPE): in total knee prostheses: a review of key influences. *Proc Instn Mech Engrs H*, vol. 214, pp. 349-359.

Muratoglu, O. K.; Ruberti, J.; Melotti, S.; Spiegelberg, S. H.; Greenbaum, E. S.; Harris, W. A. (2003): Optical analysis of surface changes on early retrievals of highly corss-linked and conventional polyethylene tibial inserts. *J Arthroplasty*, vol. 7 suppl. 1, pp. 42-47.

Muratoglu, O.; Perincheif, R. S.; Bragdon, C. R.; O'Connor, D. O.; Konrad, R.; Harris, W. H. (2003): Metrology to quantify wear and creep of polyethylene tibial knee inserts. *Clin Orthop Rel Res*, vol. 410, pp. 155-164.

Sainsot, P.; Jacq, C.; N ' e lias, D. (2002): A numerical model for elastoplastic rough contact. *CMES: Computer Modeling in Engineering & Sciences*, vol. 3, no. 4, pp. 497-506.

Schipplein, O. D.; Andriacchi, T. P. (1991): Interaction between active and passive knee stabilizers during level walking. *J Orthop Res*, vol. 9, pp. 113-119.

Taylor, S. J. G.; Walker, P. S. (2001): Force and moments telemetered from two distal femoral replacements during various activities. *J Biomech*, vol. 34, pp. 839-848.

Taylor, S. J. G.; Walker, P. S.; Perry, J. S.; Cannon, S. R.; Woledge, R. (1998): The forces in the distal femur and the knee during walking and other activities measured by telemetry. *J Arthroplasty*, vol. 13, pp. 428-437.