COMPUTATIONAL PREDICTION OF IN VIVO WEAR IN TOTAL KNEE REPLACEMENTS

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INTRODUCTION

Wear of ultra-high molecular weight polyethylene (UHMWPE) in total knee replacements remains a major limitation to the longevity of these clinically successful devices [1]. Improvements in sterilization techniques over the past decade have reduced oxidative degradation of the UHMWPE bearing, with potentially dramatic long-term reductions in fatigue-related pitting and delamination wear. However, abrasive-adhesive or “mild” wear mechanisms remain, with the potential to generate large numbers of submicron debris particles of osteolytic potential [2].

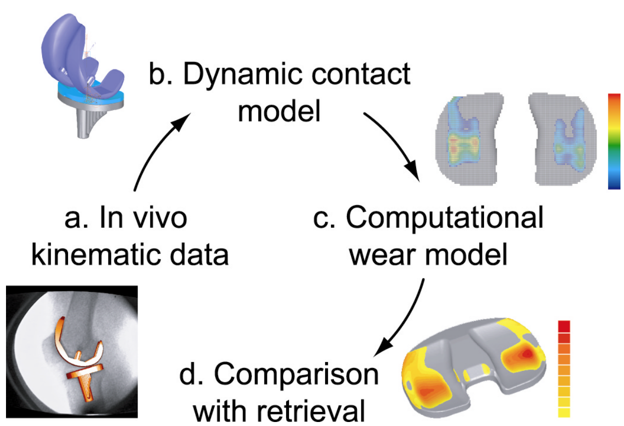

Figure 1. Four-step process used to develop and evaluate in vivo computational wear predictions.

This study presents a novel computational approach for predicting patient-specific mild wear from *in vivo* knee kinematics (Fig. 1a), dynamic contact simulations (Fig 1b), and tribological modeling (Fig 1c). The effort was guided by the concept that no tuning of model parameters would be done, and only previously published values for material properties and other input parameters would be used. The approach was evaluated by predicting wear in a knee for which an autopsy-retrieved tibial insert was available (Fig. 1d).

METHODS

Fluoroscopic kinematic data previously collected from one total knee arthroplasty patient (female, age 65 at surgery, height 170 cm, mass 70 kg) were used in this study [3]. The patient received a cemented posterior cruciate ligament retaining prosthesis (Series 7000, Stryker Howmedica Osteonics, Allendale, NJ) with a 6.8 mm thick tibial insert. The patient gave written informed consent to participate as described previously [3]. The patient performed treadmill gait and stair rise/descent activities during fluoroscopic motion analysis [4] 21 months after surgery (Fig. 1a). Kinematic data from one representative cycle of each activity were averaged in 5° increments of knee flexion for stair and 1% increments for gait including stance and swing phases. Cycle duration was 1.22 sec for gait and 4.6 sec for stair.

Dynamic simulations to predict *in vivo* tibial insert contact pressures and slip velocities were created by incorporating an elastic contact model into the commercial multibody dynamics code Pro/MECHANICA MOTION (Parametric Technology, Waltham, MA). The contact model treats the tibial insert as an elastic foundation [5,6] contacting a rigid femoral component, where contact pressures are calculated on a grid of mutually-independent elements covering the insert surfaces [5]. For any element, given the interpenetration δ between the undeformed surfaces, the contact pressure p acting on the element can be calculated from [5,6]

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

where E is Young’s modulus of the elastic layer, ν is Poisson’s ratio of the elastic layer, and h is the layer thickness. The interpenetration δ for each element is calculated using the ACIS 3D Toolkit (Spatial Corporation, Westminster, CO). The resulting element pressures are replaced with a single equivalent force and torque applied to both bodies for purposes of multibody dynamic simulation.

The dynamic simulations were driven with a combination of the *in vivo* fluoroscopic data and assumed loading conditions. Three DOFs (anterior-posterior translation, internal-external rotation, and flexion) were prescribed to match fluoroscopically measured gait and stair kinematics. The remaining three DOFs (axial translation, varus-valgus rotation, and medial-lateral translation) were numerically integrated to predict their motion. An axial force was applied vertically downward to the femoral component to produce a 70% medial-30% lateral load split at 0º flexion [7]. The force magnitude for each activity was defined by scaling a vertical ground reaction force curve from a patient of similar age, height, weight, and knee flexion characteristics to be between 0.25 and 3.0 BW [8]. Each dynamic simulation required less then 15 minutes of CPU time on a 2.4 GHz Pentium IV workstation.

A computational wear model was developed to produce element-by-element damage predictions given the predicted time history of contact pressures and slip velocities experienced by each element. The model computes total damage depth for each element as the sum of material removal due to mild wear and surface deformation due to compressive creep:

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

The number of cycles per year N was assumed to be 1 million for gait or stair. Mild wear depth per cycle was calculated from Archard's classic wear law while total creep was estimated from data in the literature [9]. To account for a varying spectrum of activities, a linear rules-of-mixture model was used to predict the total damage produced by any combination of gait and stair activities. The predicted damage depths and patterns were compared with a retrieval obtained from the same patient after 51 months of implantation.

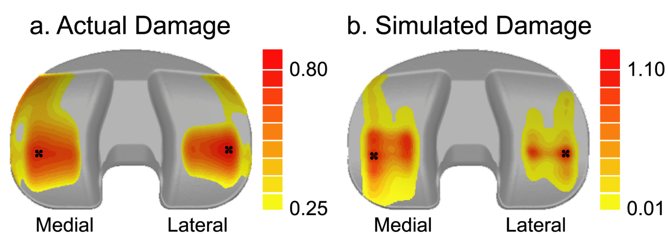

Figure 2. Comparison between (a) actual and (b) simulated damage for the same patient. x indicates max damage.

RESULTS

Using an assumed partitioning of 70% gait, 30% stair, the damage regions predicted by the computer simulations (Fig. 2b) were in good qualitative agreement with the clinical damage regions (Fig. 2a). The predicted damage area was a combination of the gait and stair damage areas (not shown). On the medial side, gait produced anterior damage while stair produced posterior damage. On the lateral side, gait and stair produced more focalized damage regions similar to the retrieval. The predicted maximum damage location on the medial and lateral sides was consistent with the retrieval, as were the maximum damage depths and total damage areas (Table 1).

DISCUSSION

The computational approach utilized a number of important modeling assumptions. Linear material properties were used since they provided the best match to static contact pressure experiments simulated with the same contact model [10]. The large percentage of stair activity (30%) provides an approximation to other activities involving the flexed knee under high load, such as sitting and rising from a chair or bed. Simulation of one cycle of gait and stair were extrapolated out to millions of cycles. Nonetheless, the approach produces damage predictions that capture the important features observed in the retrieval.

	Retrieval		Simulation	
Damage	Medial	Lateral	Medial	Lateral
Depth (mm)	0.7	0.8	1.0	1.1
Area (mm^2)	422	305	354	277

Table 1. Comparison between retrieval and simulation damage depths and areas.

In summary, this study used a novel combination of *in vivo* measurements, post mortem observations, and computational tools to predict patient-specific damage in a total knee replacement. The approach allows researchers to "close the loop" on damage predictions by validating them against the tibial insert retrieved from the same patient whose *in vivo* kinematics were used as model inputs. With continuing refinements, this methodology may be useful for improving implant designs through virtual prototyping prior to clinical use.

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