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Article

Development and Validation of a Wear Model to Predict Polyethylene Wear in a Total Knee Arthroplasty: A Finite Element Analysis

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Abstract: Ultra-high molecular weight polyethylene (UHMWPE) wear in total knee arthroplasty (TKA) components is one of the main reasons of the failure of implants and the consequent necessity of a revision procedure. Experimental wear tests are commonly used to quantify polyethylene wear in an implant, but these procedures are quite expensive and time consuming. On the other hand, numerical models could be used to predict the results of a wear test in less time with less cost. This requires, however, that such a model is not only available, but also validated. Therefore, the aim of this study is to develop and validate a finite element methodology to be used for predicting polyethylene wear in TKAs. Initially, the wear model was calibrated using the results of an experimental roll-on-plane wear test. Afterwards, the developed wear model was applied to predict patello-femoral wear. Finally, the numerical model was validated by comparing the numerically-predicted wear, with experimental results achieving good agreement.

Keywords: wear; TKA; validated model; FEA; patello-femoral joint

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1. Introduction

Total knee arthroplasty (TKA) is a surgical procedure to replace the worn-out, native knee joint. In particular, the cartilage-meniscus-cartilage articular surface is replaced by an ultra-high molecular weight polyethylene (UHMWPE) insert in a metal backing for the lower leg component, which moves against a polished CoCrMo component for the upper leg. This combination of materials has been in use since the early 1960s [1]. Although mechanical failure of the UHMWPE insert has been rare in clinical practice, due to its low wear rate [2], studies have continued to show the adverse effects of wear particles in the joint space surrounding implants, which can lead to clinical failure of the implant (which comes loose) or to pain [2–10] and, ultimately, to a revision of the implant. The number of primary implants is exponentially growing, but unfortunately, also the relative number of the revision implants is increasing [3,4]. With the recent trend of rising numbers of total joint replacements being implanted in younger, more active patients, the wear of the UHMWPE bearings has been a large concern, and understanding the wear mechanism has been of utmost importance to ensuring long-term patient satisfaction and implant survival [11,12].

Hence, it is crucial to be able to pre-clinically evaluate the performance of various implant designs and materials and to provide a better understanding of their wear mechanisms. In order to increase the life of total joints, minimizing the wear of UHWMPE has continued to be a goal of material scientists, engineers and clinicians.

The material properties of UHMWPE have been long studied, and the properties that make this polymer suitable as a bearing material arise from its structural and molecular composition. When the UHMWPE bearing surface is in contact with a metal component, such as in TKAs, the surface-to-surface interaction occurs through microscopic interactions between the opposing surface asperities characterized by plastic deformations [13,14].

In the last few decades, there has been an increasing number of tribology studies to understand the problem of wear in TKA components [15–22]. Experimental testing of UHMWPE wear has been conducted in ever wider arrays of machines, loading conditions and on more types of designs over the years, such as pin on disk/plate, roll-on plane and TKA wear simulators [23,24]. Several developments to reduce wear in TKAs were proposed, such as changing the design of the TKAs, the material properties of the polyethylene for the tibial and the patellar inserts (by cross-linking, for example) and with the use of innovative materials, such as oxidized Zr (Smith & Nephew, Memphis, USA) [25] for femoral components.

Wear testing is a crucial step in the design verification process in the industry, yet it is time consuming and expensive, due to low frequency cycles and testing durations of weeks to months [26,27]. Testing conditions have been prescribed by standards, such as ISO or ASTM, independent of surgical position [28–32], and discrepancies in experimental results exist between testing machines that use force- or displacement-controlled input parameters [33]. To speed the process up, usually pin-on-disk or roll-on-plane [28,34,35] analyses are performed if the research question only concerns the materials that are used for the TKA components. However, if also the design and the position of the TKA components need to be evaluated, dedicated knee wear simulators are used [36–39]. Therefore, each of these devices presents its own advantages and disadvantages; for example, the laboratory evaluation on a simple pin on disk/plate machine is cheap and rapid; however, the results must be viewed with some caution, since the conditions under which the material is tested are drastically simplified. Additionally, knee wear simulators are mainly aimed at analyzing tibio-femoral mechanics and few include also patello-femoral behavior [40,41].

Even with the actual application of these experimental techniques, wear issues still persist. For that reason, an increasing number of *in silico* studies have concentrated their research analyses on TKA contact forces and stresses in line with some *in vitro* tests performed to analyze wear. Computational methods can provide a simplified and efficient solution to predict prostheses behavior in the orthopedics field [42,43].

In an effort to provide efficient implant wear evaluation to augment experimental testing procedures, several computational wear models have been developed based on different techniques based on different wear models. Computer simulation can reduce the time and cost of testing, not only for the orthopedic field. Moreover, once validated, numerical wear models can be also applied in other configurations or loading conditions (mal-alignment or activities other than gait, for example) to investigate the performances of a TKA under less than optimal or severe loading conditions.

In any case, numerical wear simulations of total joint replacement require validation to establish their ability to reproduce wear rates and damage profiles from retrievals or experimental simulators [28]. To the authors' best knowledge, very few published papers report on validated wear models. This number even decreases if we focus our research on the analysis of the patello-femoral joint.

For these reasons, the aim of our work was to develop and to validate a finite element model (FEM) to predict polyethylene wear for TKAs. The wear model is based on Archard's wear model [44], and the study is subdivided into two main work packages: the first is the calibration of the FEM wear model based on experimental roll-on-plane tests; once the FEM wear model is validated, the second step is its use to predict patello-femoral wear during walking cycles, as performed in an experimental wear simulator. Finally, the predicted volumetric patello-femoral wear was compared with the experimental results.

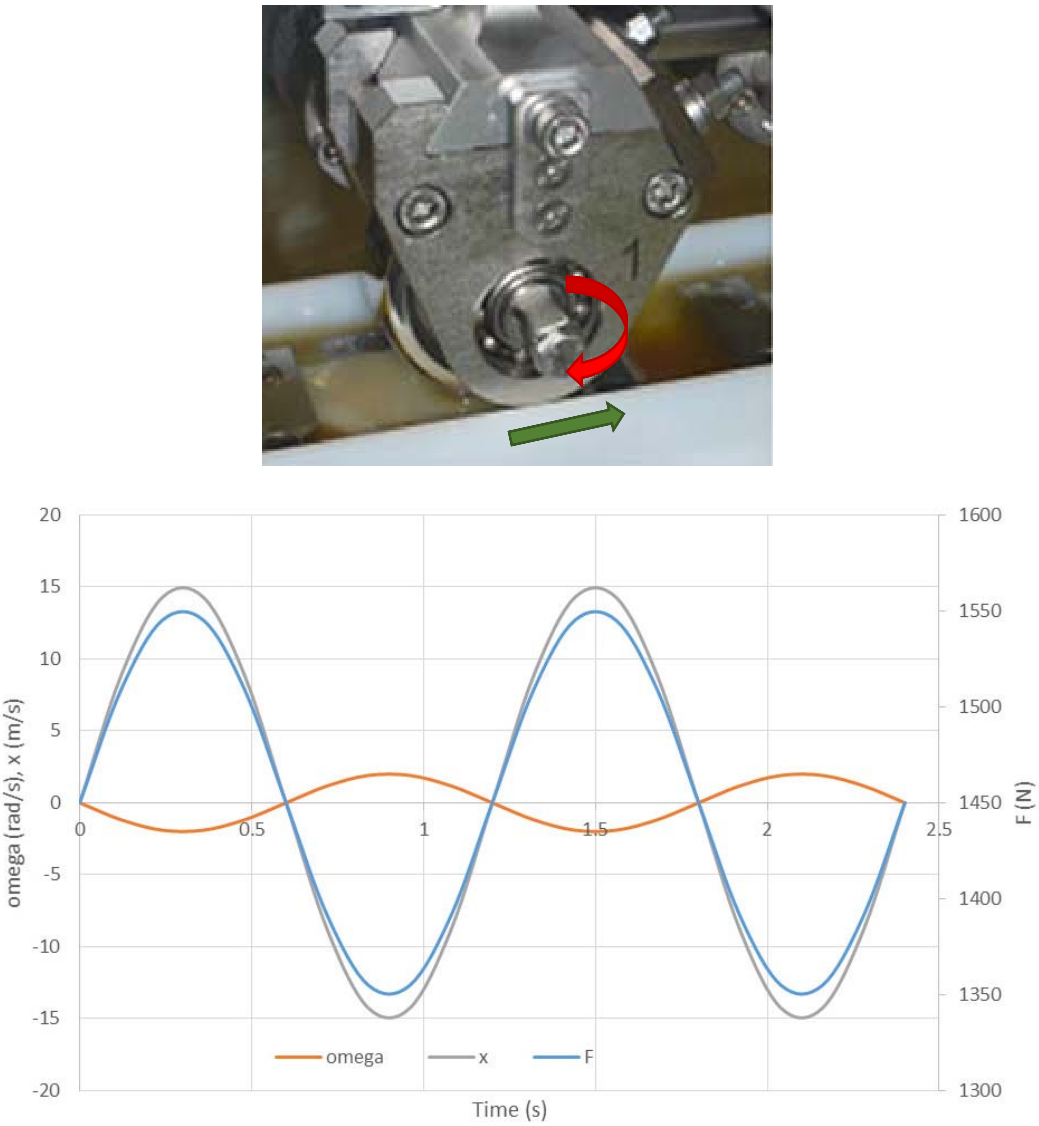
2. Materials and Methods

2.1. Roll-on-Plane: Experimental

Three blocks of UHMWPE (GUR 1020) underwent an experimental roll-on-plane wear test (Figure 1).

The cobalt chromium (CoCr) rolls were sinusoidally loaded with a vertical mean load of 1450 N, a peak-to-peak amplitude of 200 N and a frequency of 1.2 Hz, while they rotated around their symmetry axis with a variable rotation speed (average speed: 0 rad/s; peak amplitude: 0.75 rad; frequency, 1.2 Hz; rotation in phase with the vertical load). Simultaneously, the polyethylene blocks moved back and forth sinusoidally with a peak-to-peak amplitude of 30 mm and a frequency of 1.2 Hz. Their motion was always opposite of the motion of the contact point on the roll. The 6×10^6 cycles were performed while the contact surfaces were immersed in a bovine serum medium simulating human synovial fluid. The wear of each polyethylene block was measured every 500,000 cycles with a profilometer (SURFCOM 1900SD, Zeiss International, Oberkochen, Germany).

Figure 1. Detail of the roll-on-plane experimental machine.



2.2. Roll-on-Plane: Numerical Wear Model

The full experimental roll-on-plane test was reproduced by means of finite element analysis (Figure 2). For the roller, material properties of CoCr were used with $\rho = 8.27 \times 10^{-3}$ g/mm^3, $E = 240$ GPa and $\nu = 0.3$. For this geometry, 4-mm 10-noded tetrahedral elements were chosen. For the polyethylene block, UHMWPE material properties were used with $\rho = 9.4 \times 10^{-4}$ g/mm^3, $E = 666$ MPa and $\nu = 0.46$. For this geometry, 0.83-mm 8-noded hexahedral elements were used. Both materials are considered linear elastic and isotropic, and a friction coefficient $\mu = 0.05$ was simulated to replicate the experimental conditions. The models were loaded and constrained as in the experimental tests.

Figure 2. Numerical roll-on-plane simulation.

2.3. Wear Model

The adhesive/abrasive wear process of UHMWPE was numerically formulated based on the Archard wear model (Archard, 1953) [42]. In 1953, Archard [42] published an equation to estimate the linear wear depth perpendicular to the wear surface of two contacting metal surfaces sliding relative to one another. The equation was known as Archard's wear law and is shown below in Equation 1, in which the linear wear h is determined using the following equation:

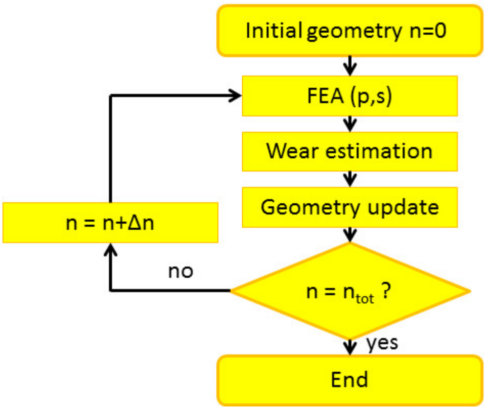
$$h = k_W \cdot p \cdot s \tag{1}$$

Where k_W is the wear factor, p is the contact pressure and s is the sliding distance. When contact forces are in the range of those experienced *in vivo*, Archard's law has been shown to reasonably calculate wear depths due to linear sliding of UHMWPE on metal or ceramic [45]. However, the kinematics displayed in total joint replacements are often nonlinear, so the applicability of Archard's law to total joint replacements has been questioned. Moreover, in this expression, delamination, pitting and third body wear are not included, as literature studies report that for UHMWPE, these effects are negligible [46]. To include the friction parameter μ in the model, we adopt the Sakar modification [47] to the Archard model:

$$h = k_W \cdot p \cdot s \cdot (1 + 3\mu^2)^{0.5} \tag{2}$$

The adapted Archard model was used to estimate, after the deformation under a period of cycles, wear and to predict polyethylene geometry modifications due to the wear after a certain number of cycles (CoCr is assumed without modifications). The wear is considered constant for a certain number of cycles (Figure 3).

Figure 3. Flow chart of the wear estimation during the FEM modeling.



2.4. Roll-on-Plane Calibration

The wear model is implemented by means of FEM. The simulations were performed with ABAQUS Explicit v6.10 in 3 h 10-min computation time. A Python code was written to implement the wear algorithm in Abaqus, as explained in Figure 3. The geometry of the block was updated every step of 500,000 cycles to reflect the experimental loss of PE material due to wear.

The wear factor was calibrated to fit the numerical prediction to the experimental wear.

2.5. Experimental Patello-Femoral Wear Tests

Three CoCr Genesis II femoral components, Size 5 (Genesis II, Smith & Nephew, Memphis, TN, USA), and the corresponding polyethylene patellar components (32 mm in diameter) underwent experimental tests on a knee wear simulator machine (Figure 4) with simulated 5 × 10^6 cycles of walking, as reported by Vanbiervliet *et al.* [25]. Patellar flexion, patellar rotation and proximal-distal displacement were derived from the literature on patello-femoral kinematics as a function of the angle of the flexion of the knee. We began the investigation by applying the knee flexion curve from the international standard for wear-testing machines with displacement control (ISO 14243-312); the corresponding patellar flexion, patellar rotation and proximal-distal displacement were then calculated *versus* the cycle time (Figure 5), as reported by Vanbiervliet *et al.* [25].

Figure 4. Experimental patello-femoral test setting.

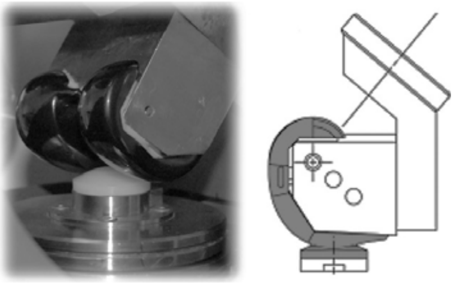
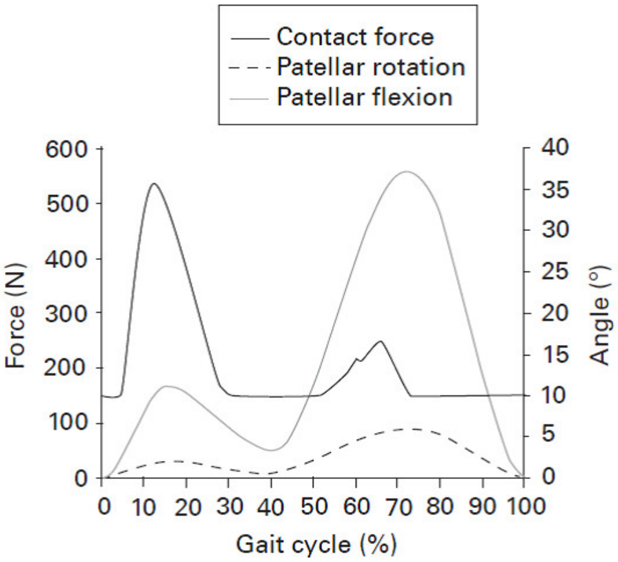


Figure 5. Graphs showing the input curves for the wear simulator.



The volumetric wear was measured, using the weight loss of the components by means of an analytical balance XP205, with an integrated antistatic kit from Mettler-Toledo (Mettler-Toledo International Inc., Greifensee 8606, Zürich, Switzerland).

2.6. Numerical Patello-Femoral Wear Test

Based on the numerical FEM patello-femoral wear analyses performed by Halloran [48] by means of an explicit analysis, the same total knee arthroplasty components have been reproduced in geometries and material properties in FEM (Figure 6) with the same boundary conditions as applied in the wear simulator.

Figure 6. Patello-femoral numerical model.

The material properties of the two components in analysis are the same used for the roll-on-plane simulation, but for this FEM, 1-mm shell elements were adapted for the femoral component and 1-mm hexahedral elements for the patellar component. The applied wear model (Figure 3) is the calibrated one by the roll-on-plane calibration work package.

The predicted volumetric wear volume was compared to the experimental measurements.

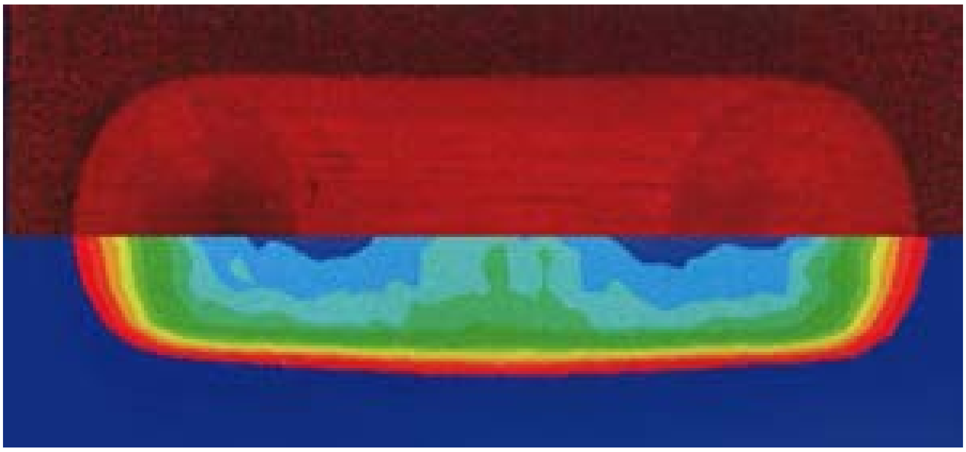
3. Results

3.1. Roll-on-Plane

Calibration of the wear model showed that a wear factor of $k_W = 1.83 \times 10^{-8}$ mm^3/Nm gave the best correspondence with the experimental results.

With that wear factor, the wear print for roll-on-plane simulation is in agreement with the experimental one, as shown in Figure 7.

Figure 7. Comparison between experimental and numerical polyethylene wear.



Moreover, with that wear factor value, the FEM results show a maximum linear wear of 0.127 mm, very close to the average maximum depth of the wear track compared to the calculated maximum depth of the wear track (0.125 mm, ±0.01 mm).

3.2. Patello-femoral Test

Results from the experimental test for CoCr femoral components are fully described in Vanbiervliet *et al.* [25].

FEM results show a total volume wear of 0.39 mm^3 after 2×10^6 cycles, in agreement with the mean volume wear measured experimentally for the same number of cycles for three samples, 0.38 ± 0.326.

4. Discussion

The increasing number of tribology studies to analyze polyethylene wear in total knee arthroplasties confirms the need for improved understanding and to find new solutions to avoid the failure of an implant due to polyethylene wear.

Experimental studies are often used, but they are quite expensive and time consuming, and usually, they can analyze only limited configurations and load conditions. For that reason, the use of computational modeling is expanding also in this field, but unfortunately, very few published papers present validated wear models to be used.

Using an FEM analysis, in this study, a model to predict polyethylene wear was developed, calibrated and validated for the wear surface and for the total volumetric wear. The wear model has been applied to predict patello-femoral wear after simulated walking cycles.

The wear model calibration has been performed using data from roll-on-plane experimental tests. Once the model was calibrated, it was applied to predict patello-femoral wear. The results from simulations were compared with some experimental results presenting the same boundary conditions. FEM computational prediction is in good agreement with the experimental results [25], so the model was validated.

The loading conditions and kinematics were different in the patella-femoral test compared to the roll-on-plane test. While the kinematics in the roll-on-plane test essentially lead to a unidirectional reciprocal motion of the contact between the roll and the plane, this is certainly not true in the patella-femoral experiment [49–52]. Because of the fact that also the rotation of the patellar button is included, there will most certainly occur some cross-shearing in this situation. It has been shown before (although in tibio-femoral testing) that this usually leads to 4–10 times more polyethylene wear [22]. Therefore, in fact, it is rather surprising that the FE model calibrated with the help of the relatively simple roll-on-plane test (without cross-shearing of the polyethylene) does predict also the wear quite well in the more complicated and more realistic patello-femoral wear test, where cross-shearing is present. The reason for this is not entirely clear. One might think that not enough cross-shear was present in our experiment, as Maiti *et al.* have shown that the amount of cross-shear also plays a role in the wear of the replaced patello-femoral joint [41]. In their experiments, wear increased from 8.6 mm^3/MC to 12.3 mm^3/MC, after the amount of patella rotation was increased from 1° to 4°. However, in our experiment, the rotational range of motion was already 5°. Another reason may be that the contact forces and pressures in this set-up are relatively low. The question remains whether the correspondence would still be true in the tibio-femoral articulation, where larger contact forces and pressures are present, but this is the subject of further research.

From the authors' best knowledge, this is the first example of a validated wear model to predict patello-femoral wear. This wear model could also potentially be used for the analysis of wear for tibio-femoral articulations and the analysis of wear for mal-positioned components, such as patellar maltracking. Moreover, this wear model could be implemented in a musculoskeletal system to be able to predict TKA long-term performance for a specific patient. The outputs can be used both for surgeons to better understand the effects of the design and component alignment on wear and for engineers to optimize and improve implant designs.

5. Conclusions

In this study, a numerical procedure to predict polyethylene wear for patello-femoral interactions, after a TKA, by means of finite element analysis was developed and validated. To achieve this, the model was first calibrated on a generic roll-on-plane experimental set up that considers the same material used for TKA. Once the calibration has been performed, the wear model has been used to predict patello-femoral wear under the same boundary conditions of experimental tests. Numerically predicted data have been then compared with experimental outputs founding good agreement. Also comparing with the literature, the developed model assume significance for its use in developing more close-to-real finite elements models that could be used in the orthopaedic clinical and industrial fields in order to help in predicting patients follow-up after a TKA and to improve materials coupled for knee prostheses or TKA designs.

Author Contributions

Bernardo Innocenti designed and performed numerical test, analyzed numerical and experimental data and wrote the paper; Luc Labey and Amir Kamali designed and performed experimental tests, Walter Pascale gave clinical support and conceptual advice and Silvia Pianigiani analyzed numerical and experimental data and wrote the paper. All authors discussed the results and implications and commented on the manuscript at all stages.

Conflicts of Interest

Bernardo Innocenti and Luc Labey were employees of Smith & Nephew. Amir Kamali is an employee of Smith & Nephew. The other authors declare no conflict of interest.

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