Development of a Subject Specific Total Knee Replacement Contact Model using Finite Element Analysis and Marker-Based Gait Analysis

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Introduction: Throughout the course of the day, the knee experiences constant motion and loading/unloading. The interface between the Cobalt-Chromium-Molybdenum (CoCrMo) femoral component and the ultra-high-molecular weight polyethylene (UHMWPE) insert undergoes significant contact interactions, including slipping, tractive rolling and compression. These interactions are directly responsible for wear of the UHMWPE component, which can lead to device failure. To better understand these interactions, and their possible relationship to subject specific gait parameters, we have developed a subject specific total knee replacement (TKR) contact model, utilizing finite element analysis and marker based gait analysis. Utilizing this model our objective is to identify areas of contact, high contact pressure, generate surrogate wear scars, and to identify any relationships between gait parameters and contact parameters. We also compare subject specific results to those obtained from ISO standard simulator testing.

Methods: Gait data was obtained in a previous study from 16 subjects under informed consent and IRB approval [1]. Subject specific knee kinematics including internal/external (IE) rotation, flexion/extension (FE), and anterior/posterior (AP) translation were obtained using the point cluster technique [2]. Axial knee contact forces were calculated [3] using the kinematics and external kinetics measured during gait analysis and a previously developed parametric force model [4]. CAD models of a left sided NexGen Cruciate Retaining TKR (Zimmer, Warsaw, IN) were used to create the finite element model. 53025 quadratic tetrahedral elements were used to model the UHMWPE component. The CoCrMo femoral component was modeled as a rigid surface, utilizing 4627 elements, a mix of quadratic quadrilaterals and quadratic tetrahedrons. The UHMWPE component was modeled as a linear elastic material with an elastic modulus of 930 MPa, a Poisson’s ratio of 0.46, and a density of 9.4E-7 mm/kg. The contact was modeled as penalty contact, with friction coefficient set to 0.04. Movement of the femoral component was applied using velocity boundary conditions applied at a reference point located at the center of rotation as defined during simulator testing. Subject specific IE rotation, FE, and AP translation boundary conditions were applied. AP translation was reduced by a factor of 10 in order to capture relative movement, while preventing the femoral component from sliding off the UHMWPE insert. Medial/Lateral (ML) translation as well as Abduction and Adduction (Ab/Add) were left free. The start and end of the gait cycle was determined, and displacements converted to velocities using a custom written Python script. Axial force was applied to the femoral reference point. Axial force data was available for stance phase only, with force during swing phase being set to a constant 167N as per the ISO standard. ISO standard loads and motions were also applied for comparison to the subject specific results. The backside of the UHMWPE tibial insert was fixed. Analyses were run using ABAQUS v6.13-2 Standard (Dassault Systèmes, Waltham, MA). The completed assembly is depicted in Figure 1(A). A surrogate wear scar based upon the square root of the sum-of-squares of cumulative contact pressure over time
was generated for each subject and compared. A tibio-femoral contact path based on the centroid of contact area for each point in the gait cycle was also generated and compared for the ISO and subject specific inputs. The relationship between the contact variables and IE rotation was also examined.

**Results:** Accuracy of contact pressure was examined based upon the contact pressure contours (example Figure 1(B)) as compared to the contact pressure error indicators (example Figure 1(C)). The max error was generally substantially lower than the max contact pressure, as can be seen in the example, and was considered acceptable. The ISO contact paths showed more movement in the ML direction than the subject specific counterparts. A comparison between ISO wear scars and tibio-femoral contact paths vs. an example subject is depicted in Figure 2. A linear relationship ($R^2 = 0.6$, $p<0.001$) between the length of the wear scar and the magnitude of the range of IE rotation input was found and is depicted in Figure 3.

**Discussion:** Surrogate wear scars were all similar to each other and to the ISO standard. The weak correlation between IE rotation range and the length of the wear scar could indicate higher wear would be experienced with increased IE rotation range (due to higher contact area and sliding distance). While other relationships were explored, such as the maximum angle between the medial and lateral contact points versus IE rotation range, no correlation could be established. It is possible that the modification to AP translation may have affected these results. While AP, as modified, was within the range of the ISO standard, in most cases the peak was a little over half that seen in ISO. This could explain the increased ML movement as seen by ISO in the contact path. The modification was necessary however as the AP range, as recorded, was as high as 3cm in some cases, while the tibial insert itself is only 3cm in length.

In the future, a subject specific contact model could be applied to the development of a subject specific wear model. As such a model will be sensitive to the contact parameters investigated in this study, an accurate and well developed contact model is necessary as a first step. The model described here is hoped to be used in comparison to population specific simulator testing, utilizing the same kinematics and force profiles and TKR design, specifically comparison of a surrogate wear scar. It is also possible to utilize the contact path generated using this model in order to iteratively refine the parametric numeric force model used to generate force input. The force model is highly sensitive to the accuracy of the tibial-femoral contact path, which is used to determine the length of moment arms about the knee.

Limitations to the model include the modification to the AP translation, the lack of subject specific initial implant orientation, and the linear elastic material model. In future iterations of the model, the linear elastic material model will be replaced with a plasticity model [5].

**Significance:** A subject specific TKR contact model could be useful when assessing patient function after TKR surgery, designing and evaluating rehabilitation protocols, and determining the safety of certain activities. In addition, such a model could prove to be a valuable tool for preclinically evaluating new TKR designs under subject specific or TKR population specific activities as a supplement to simulator testing.
Figure 1: A) Completed finite element model of assembly including the femoral component in white and the tibial insert in blue. B) Example of a contact pressure contour with C) corresponding error indicator. Units are in MPa.

Figure 2: Surrogate wear scars (top) and tibio-femoral contact paths (bottom) for ISO (left) and one subject (right). Surrogate wear scars are represented by the square root of the sum-of-squares of contact pressure over time. The x-direction is towards the medial side, the y-direction is towards the anterior side. Red represents higher wear.
Figure 3: Magnitude of IE rotation range vs. the length of the wear scar in the AP direction for all 16 subjects and ISO (green diamond). Linear Regression and corresponding R-squared and p-value also on plot.