Kinematic Sensitivity Study of Total Knee Replacement FEA Model to Ligament Attachment Site

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INTRODUCTION: The demand for total knee replacements (TKRs) has increased significantly in the past decade as the number of TKR procedures has grown from 402,100 to 1.38 million [1]. As the number of TKRs performed each year increases, long-term failure due to mechanical failure, polyethylene wear, and instability remains a prominent concern [2]. In addition, the influence of ligament properties on knee kinematics is not well understood. Computational modeling and finite element analysis (FEA) can be used to better understand TKR failure and instability. To design such a model, a previously published and validated model of TKR contact was modified to include the LCL, MCL, and PCL ligaments [1]. However, it is important to characterize computational models by performing sensitivity studies to reduce the number of parameters required to be varied in future studies. Therefore, the goal of this study was to determine how changing the ligament attachment sites of the LCL, MCL, and PCL impacts knee translation and rotation during flexion, in a computational model of a TKR with realistic ligament properties. To accomplish this goal, a sensitivity study was performed by varying ligament attachment sites using Latin Hypercube Sampling Design of Experiments (LHS DOE), and linear regression analysis was done to understand the sensitivity of attachment site on the maximum anterior-posterior (AP) translation and internal-external (IE) rotation during flexion.

METHODS: *1) FEA Model:* A previously published and validated FEA cruciate retaining TKR model was modified to include three ligaments that are kept intact after TKR surgery: the LCL, MCL, and PCL. The ISO 14243-1 force control standard was applied as boundary conditions to the FEA model. Flexion was applied to the femur which was otherwise fixed. AP force, axial force, and IE moment was applied to the tibial component. Abduction-adduction and medial-lateral translation of the tibial component were left free. *2) Ligament Properties:* Ligaments were modeled as linear connector elements with a specific stiffness defined according to previous literature: LCL 59 N/mm, MCL 63 N/mm, and PCL 198.9 N/mm [3-4]. The slack length, and attachment site for each ligament was obtained from previous literature, and attachment sites were confirmed by a trained orthopedic surgeon [5-11]. *3) Parametric Study:* The approximate cross-sectional area for each ligament attachment site was used to determine the parameter bounds for a LHS DOE approach [5,8,9,11]. Parameters included the superior and inferior points of each of the 3 ligaments, along 3 translational directions, for a total of 18 parameters. The outputs of the study included the maximum AP translation and minimum IE rotation of the tibial component. Linear regression analysis was performed using MATLAB v2022b on the total AP translation and total IE rotation throughout the gait cycle to determine sensitivity of ligament attachment site on resulting kinematics. A total of 274 jobs were performed in Isight v2019 for this study.

RESULTS: 226 out of 274 FEA simulations successfully converged. Failed jobs had the femoral component fall off the edge of the tibial insert. AP translation was sensitive to six ligament attachment site parameters, five of which were related to the PCL attachment points ($R^2 = 0.794$, $p \ll 0.001$, Figure 1A). IE rotation was sensitive to thirteen attachment site parameters across all ligaments ($R^2 = 0.842$, $p \ll 0.001$, Figure 1B).

DISCUSSION: The purpose of this study was to modify an existing FEA TKR model to incorporate the LCL, MCL, and PCL ligaments with realistic ligament properties, with the long-term goal of understanding the influence of ligament attachment sites, and properties on knee kinematics. It is important to understand the influence of ligament properties on knee kinematics in order to address TKR failure and instability. In this study, LHS DOE techniques followed by linear regression analysis was performed to determine model sensitivity to ligament attachment site parameters. Our results indicate that TKR predicted AP translation is highly sensitive to the location of the PCL ligament. TKR predicted IE rotation was highly sensitive to the location of the attachment points of several ligaments, with the highest effect due to the location of the PCL. A total of 14 out of 18 parameters achieved statistical significance for at least one of the outputs investigated, indicating that not all ligament attachment site degrees of freedom need to be accounted for in future studies. Depending on the needs of future studies, the effect sizes determined here (some of which are small) could be used to reduce this number further. Limitations of this work include the use of tension-only linear connector elements, that do not account for wrapping, and standardized loading. For future work, we will perform additional statistical analysis on the significance of our results using more jobs and with larger parameter bounds. In addition, we will also investigate sensitivity to additional ligament properties (slack length, material properties), and modeling approach (non-linear material definition, inclusion of wrapping, and area of influence). Future studies will also implement population-specific loading and kinematics to increase clinical relevance.

SIGNIFICANCE: The results of this study demonstrate the impact of ligament attachment on predicted knee kinematics in a finite element model of a TKR, which is important for TKR alignment and ultimately understanding TKR surgery outcomes.

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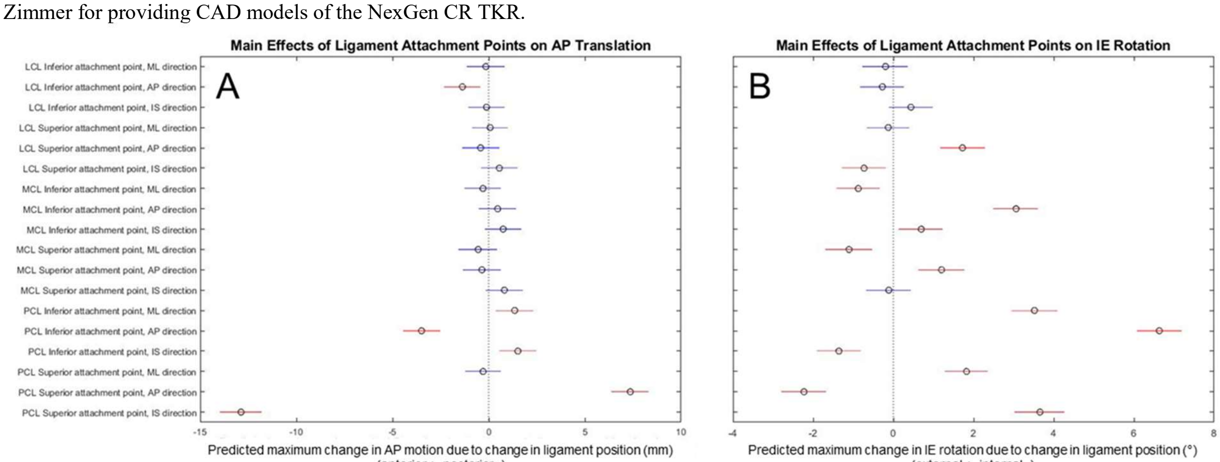

Figure 1: Predicted maximum effect (black circles) on motion due to a change in the corresponding parameter (ligament, location, direction of change). Lines represent 95% confidence intervals for regression models. Figure 1A: AP translation was sensitive to six ligament attachment site parameters (shown in red) ($R^2 = 0.794$, $p \ll 0.001$). Figure 1B: IE rotation was sensitive to thirteen ligament attachment site parameters (shown in red) ($R^2 = 0.842$, $p \ll 0.001$).