Sensitivity Study of Knee Ligament Properties in a Computer Simulation of a Total Knee Arthroplasty

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Disclosures:

Introduction: It is widely believed that surgical technique has a large influence on postoperative function after total knee arthroplasty (TKA) [1]. Computer simulation of TKA is a valuable tool for establishing an objective connection between surgical technique and postoperative function. However, in these simulations, ligaments surrounding the knee are frequently modeled based on small samples of (typically) healthy (non-OA) cadaver knees [2], adapted from previous models [3], or arbitrary chosen [4]. There is little consensus on how to accurately model ligaments and a lack of understanding of how ligament modeling choices influence simulated TKA kinematics and forces. The purpose of this study is to systematically investigate the sensitivity of variations in ligament modeling parameters on simulated TKA kinematics.

Methods: Experimental data were collected from a fresh frozen cadaveric specimen using a custom knee stability device and navigation system [5] to develop and validate a musculoskeletal model of TKA kinematics. An orthopaedic surgeon performed a posterior-stabilizing TKA and used an instrumented force handle to apply a load in the varus-valgus direction (±40N) below the ankle at both full knee extension and 20⁰ degrees of flexion. The surgical navigation system measured and recorded the tibio-femoral kinematics over three trials. Our musculoskeletal model included the femur as one segment and all other bony structures as one segment and the size, mass, and inertia of each segment were scaled based on anatomical measurements. The LCL and MCL were each represented by two fibers and the posterior capsule was represented by four fibers, and all soft tissues were modeled as tensile springs with quadratic force-strain relationships. TKA component models were obtained from the manufacturer (Zimmer, Warsaw, IN) and the tibio-femoral contact was modeled using a previously established method [6,7]. Forward dynamic simulations of the experimental varus-valgus motions were created using the SIMM Dynamics Pipeline (MusculoGraphics, Inc.; Santa Rosa, CA, USA) and SD/FAST (Parametric Technologies; Needham, MA, USA).

We ran 212 simulations with the knee in full extension to investigate the sensitivity of varus-valgus laxity characteristics to the following modeling choices: increasing and decreasing slack length and stiffness by 2.5 and 5%, varying insertion points of the ligaments by translating 1 cm in two anatomical directions (collaterals were translated in the superior-inferior and anterior-posterior directions, and posterior capsule was translated in the superior-inferior and medial-lateral directions), and increasing the number of fibers from two to four (LCL and MCL) and from four to eight (posterior capsule). A force versus varus-valgus angle curve (as seen in Figures 1 and 2) was calculated from the output of each simulation. From this curve, we calculated the amount of varus-valgus rotation (laxity) under ±15N loads. We compared the laxity for each altered simulation to the baseline (unaltered) curve (black).

Results: Slack length had the greatest effect on the varus-valgus force-displacement curves (Figure 1). Altering the slack length of the MCL and LCL independently highlighted different ligament behavior. While the LCL disengaged under a valgus load, the MCL remained engaged over the entire range of motion for this knee. The anterior fiber of the MCL dominated the behavior of the MCL while the two fibers of the LCL more equally contributed to the behavior of the LCL. The four fibers of the posterior capsule did not contribute equally. Changing ligament stiffness values did not affect VV motion until increased and decreased by 10%, and then only affected the MCL. Increasing the number of fibers representing the MCL caused more valgus rotation under a given valgus load when fibers were added more anteriorly and less valgus rotation when fibers were added more posteriorly (Figure 2). Increasing the number of fibers to the LCL had no effect on VV laxity. Translating the insertion sites of ligament fibers did not affect the LCL or posterior capsule but caused less valgus rotation when fibers of the MCL were moved posteriorly or proximally.

Discussion: Our subject-specific simulation of TKA motion showed clear differences in the varus-valgus behavior of the knee when performed with varying ligament modeling choices. Our results suggest that ligament slack length has the greatest impact on varus-valgus laxity and should receive special attention in any ligament modeling effort. Increasing the number fibers of the MCL affected the VV laxity and indicated sensitivity to the anterior/posterior location of the additional fibers. However, increasing the number of fibers of the LCL did not affect VV laxity. The LCL and MCL were found to engage differently, demonstrating differences in their contributions to VV rotation in this model.

Significance: Understanding the sensitivity of ligament modeling choices informs the creation of computer simulations of TKA motions that can provide reliable insight of how surgical technique influences knee function. By understanding how ligament
modeling choices impact knee motion and forces, researchers can more easily create more biofidelic and patient-specific simulations to predict postoperative function based on surgical technique.

**Acknowledgments:** This project was supported by Award Number R21AR061085 from the National Institute of Arthritis and Musculoskeletal and Skin Diseases.

**References:**

**Figure 1:** Varus-valgus forces versus angle curves produced by our model as slack length of all the ligaments is varied. Laxity increases with increased slack length and decreases with decreased slack length.

**Figure 2:** Varus-valgus forces versus angle curves produced by our model as the number of fibers of the MCL and their location is varied. Four fibers placed more anteriorly produced more valgus rotation while four fibers placed more posteriorly produced less valgus rotation in full extension.

**ORS 2014 Annual Meeting**
*Poster No: 1729*