A Combined Experimental and Computational Approach to Measure Knee Ligament Tensions After TKR

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April 14th, 2022, at 3:30pm in 111 Rhodes Annex

Introduction: During total knee replacement (TKR) procedures, surgeons conduct intraoperative assessments of passive (non-weight bearing) range of motion (ROM) to assess for proper TKR component alignment and ligament tension. This provides the surgeons with manual feedback perceived as tension in ligaments and other soft tissues [1]. Evaluation of ligament tension is judged subjectively based on the surgeon's perception of balance, and not by quantitative objective means [2, 3]. These assessments show poor inter-rater reliability and are based on surgeon experience [4,5]. Clinical assessments of knee laxity are challenging to interpret because they do not provide direct measures of tension in ligaments, which are the primary passive stabilizers in the knee.

Previously developed assessments provided methods to objectify laxity, but they are unable to calculate ligament tensions from the loading applied by a surgeon [2,6,7,8]. Due to the challenges of directly measuring ligament tensions *in vivo* in patients and *in vitro* in cadavers, computational modeling is a common approach to predict ligament tensions from experimentally measured joint kinematics or applied loads. Here, computational modeling can fit and take the results of such experiments and calculate ligament tensions. Previous lab studies have done this using kinematic modeling, but the applied loading was unknown [9]. Measured applied loads from passive ROM assessments are included in the computational model to calculate the ligament tensions during such assessments.

Experimental Design: This study included: 1) an experimental phase involving an orthopaedic surgeon apply passive flexion/extension external loading conditions to 3 cadaver knees after TKR; and 2) a computational phase involving use of a validated computational knee model modified to be specimen-specific for the implanted cadaver limbs and actuated with the passive flexion kinematics and loads collected during the experimental phase. The computational model calculated tensile loads for 8 knee ligaments under the passive flexion/extension loading conditions.

Hypothesis: It is hypothesized that ligament tension would be linearly correlated with external load magnitudes throughout the range of motion.

Specific Aims

Aim 1: Develop skills in finite element modeling combined with experimental validation.

Aim 2: Experimentally measure surgeon-applied loads during passive ROM of cadaver limbs implanted with TKR.

Aim 3: Modify a previously validated computational model of a knee with a virtually implanted TKR to input surgeon-applied loads and measure ligament tension during knee flexion.

Methods

Experimental Phase: Three left cadaveric lower limbs were acquired from a tissue bank and radiographed to confirm the absence of any gross deformities. The limbs were implanted with a cemented mobile-bearing cruciate-retaining TKR (Scorpio PCS, Stryker) by an experienced orthopaedic surgeon. Each limb was instrumented with reflective markers arrays attached to the femur and tibia to support measurement of knee kinematics during testing. Each limb was mounted onto a custom test rig and fitted with a six degree of freedom load cell (MC3A 1000, AMTI) attached at the distal tibia (**Figure 1)**. One orthopaedic surgeon maneuvered the limbs through a passive flexion and extension ROM, with 5 repeated trials per limb. Limb motion was optically tracked using a 2-camera motion capture system (Polaris Vicra, NDI Medical). Following testing, each cadaver was manually digitized to register the bone axes, major ligament attachment points, and the alignment position of the tibial and femoral TKR components.

Computational Phase: A finite element (FE) model of an unimplanted left knee was acquired from an open-source model repository (SinTK.org). The model was previously developed in Abaqus/Explicit (Simulia) and rigorously validated using controlled mechanical testing on the cadaver limb used to create the specimen-specific model [10]. The unimplanted knee model was validated against specimen-specific laxity tests. Data from those tests, which were part of the initial validation during model development, were provided by the model developer to ensure the model was behaving correctly following transfer from the repository. The unimplanted knee model was then virtually implanted with the same cruciate-retaining mobile-bearing TKR having specimen-specific component alignments to match those measured in the experimental study (**Figure 2)**. The modeled behavior of the mobile-bearing tibial insert was calibrated against experimental rotation constraint testing previously performed specifically for this study [11].

Results: External loads applied during passive ROM were determined at four flexion angles (30, 50, 70, and 90 degrees) for all trials (n=25). External loads (varus-valgus, anterior-posterior, axial compression) and moments (internal-external) acting at the distal tibia were assessed during the extension to flexion phase of each ROM cycle (**Table 1**).

References: [1] Schroer et al. 2013 J Arthrop [2] Sasanuma et al. 2010 J Ortho Surg [3] Smith et al. 2016 J of Clinical Ortho [4] Mears et al. 2022 J Arthrop [5] Hargett et al. 2022 ORS 2022 [6] Sharma et al. 1999 J Arth Rheum [7] van Der Esch et al. 2005 Rheumatology [8] Clarke et al. 2012 Proc Inst Mech Eng [9] Snethen et al. 2018 ProQuest [10] Harris et al. 2016 J Biomech Eng [11] Bebler et al. 2018 ProQuest.

Images and Tables:

Figure 1. Implanted knee on the test rig being assessed in passive ROM

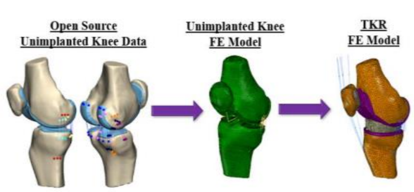

Figure 2. Schematic of the modeling workflow starting with open-source knee and ending with the final adaptation TKR FE knee

Anatomic Direction	Load Range (min to max)
varus-valgus	-5.6 N to 4.7 N
anterior posterior	-12.9 N to 12.4 N
axial compression	7.6 N to 53.1 N
internal-external rotation	-1.62 Nm to 1.34 Nm

Table 1. Load and moments applied at the distal tibia