

Creation of a Virtual Cohort of Knees Based on Previously Developed Models

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INTRODUCTION: Computational analysis of knee-specific function continues to play a role in development and evaluation of joint replacements. The benefits of modeling and simulation are well-established and include quantification of internal joint and soft-tissue mechanics (e.g., condyle and ligament reactions) for pre-clinical evaluation of implant designs. As in experimentation, the development of useful models is an involved process, and even well-established simulations fail to capture the range of expected patient characteristics. Development of a means to represent patient populations using simulation, i.e., a “virtual cohort”, would open the door to data-based, large-scale analysis of pre-surgical or pre-clinical implant performance. Such virtual cohorts, however, should reasonably capture the expected in vivo biomechanical behavior. Hence, the goal of this study was to develop an approach to utilize established models as a baseline for the creation of a virtual cohort of knees that capture a range of expected ligament and condyle reactions.

METHODS: Computational Models: Computational models using a custom kinematics driven framework [1,2] were developed for four experimentally tested knee specimens (Fig. 1.a). The experimental procedure included preparation of tibial bone cuts, as in total knee arthroplasty (TKA), and subsequent application of ramped medial and lateral contact loads at 10°, 45° and 90° flexion using a custom-developed distraction device (Fig. 1.b). Measurements were acquired in 5 lbf increments from approximately 5 up to 40 lbf, which were applied equally in both condyles (results reported in Newtons). Ligaments and rigid bones were defined using specimen-specific CT scans. Each ligament was modeled as a set of nonlinear elastic springs (Fig. 1.d). For comparison with the measured values, ligament reactions were summed to represent the condyle specific reactions (Fig 1.b). Optimization-based calibration included data at 10° and 90° knee flexion while 45° was retained for validation. Stiffness values, slack lengths and the nonlinear toe regions for each ligament’s mechanical properties served as the control variables (Fig 1.d). The calibrated models’ root mean square errors (RMSEs) between model-predicted and experimentally measured condylar reactions ranged from 2.8 to 29 N for calibration data and 10 to 58 N for the validation results (45° knee flexion). One thousand **candidate knee models** for each specimen were generated using normal distributions of ligament mechanical properties. Standard deviations of 1, 5 and 10% of the mean values were assigned to the toe, slack and stiffness values, respectively. The means were the calibrated values. As the candidate knee models had the potential to produce unphysiological responses, a filtering approach was adopted to create a **virtual cohort** of biomechanically feasible models. The filter removed candidate knees that did not meet the following criteria: 1) medial and lateral contact forces that ranged from 110 N to 450 N, 2) medial and lateral contact forces within 66 N (15 lbf - 75% of the value in [3]) and 3) maximum ligament forces less than their expected carrying capacity based on their cross-sectional areas. The results were filtered using the experimentally determined kinematics along with perturbations to the internal-external ($\pm 4^\circ$), varus-valgus ($\pm 2^\circ$), inferior-superior (± 1 mm) and anterior-posterior (± 2 mm) degrees of freedom. The use of kinematic perturbations was included to reflect expected changes in joint position with the variability in ligament mechanical properties. The candidate and virtual cohort knee models were generated for two of the four specimens with the remaining forthcoming.

RESULTS: 345 in one specimen and 298 in the second, of the one thousand randomly generated knee models for each, satisfied the outlined filtering criteria. Overall, the virtual cohort retained the expected tibiofemoral joint response while displaying significant variation in ligament reactions (Fig. 2).

DISCUSSION: Results indicate that a virtual cohort of knees can be readily created using the outlined approach. The virtual cohort retained the typical joint

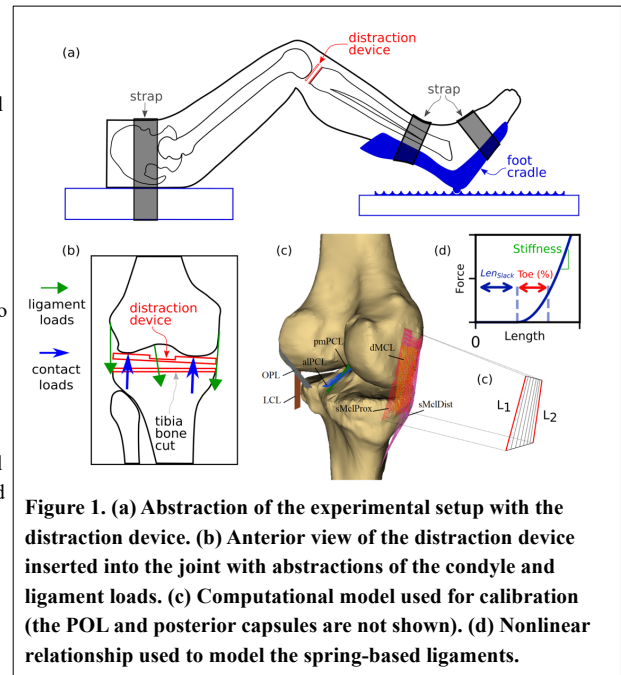


Figure 1. (a) Abstraction of the experimental setup with the distraction device. (b) Anterior view of the distraction device inserted into the joint with abstractions of the condyle and ligament loads. (c) Computational model used for calibration (the POL and posterior capsules are not shown). (d) Nonlinear relationship used to model the spring-based ligaments.

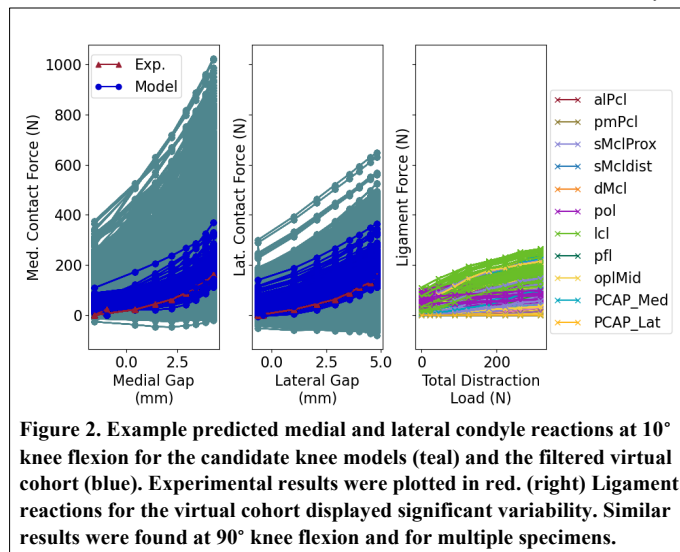


Figure 2. Example predicted medial and lateral condyle reactions at 10° knee flexion for the candidate knee models (teal) and the filtered virtual cohort (blue). Experimental results were plotted in red. (right) Ligament reactions for the virtual cohort displayed significant variability. Similar results were found at 90° knee flexion and for multiple specimens.

response while, presumably, minimizing the likelihood of producing unphysiological models. The creation of the candidate and virtual cohorts can be easily updated to capture the desired range of condylar or ligament reactions. Areas to address in future work include capturing anatomical, possibly implemented through morphing techniques, and kinematic variability within the expected patient population. Near-term, we will develop additional virtual knees to support complementary machine learning models to establish relationships between measured TKA joint gaps and condylar and ligament reactions.

SIGNIFICANCE/CLINICAL RELEVANCE: This work provides a preliminary assessment of a virtual cohort of knee models able to capture expected biomechanical response. These findings also have implications for development of a tool to complement clinical assessment of passive knee behavior during TKA, which in turn can impact decisions regarding implant type and/or placement.

REFERENCES: [1] Zaylor, et al., *J Biomech* (2019) [2] Zaylor & Halloran, *J Biomech Eng* (2021). [3] Gustke et al., *Bone & Joint* (2014).

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