Direct quantification of errors in ligament tension computed using the superposition technique with a robotic system

Lesley R. Arant[1] and Joshua D. Roth[1]
[1]University of Wisconsin, Madison, WI
larant@wisc.edu

Disclosures: Lesley R. Arant (N), Joshua D. Roth (9: ORS)

INTRODUCTION: The superposition or sequential sectioning technique is a standard method to quantify *in situ* ligament tension using a robotic testing system.[1] This technique has been used for a range of applications including to ascertain healthy ligament mechanics[2, 3] and to determine the effects of injury[4, 5] and surgical interventions[6, 7] on ligament mechanics. In this technique, the same kinematics are prescribed to a joint with the ligament of interest intact and then resected. The tension in that ligament is computed as the vector difference in the joint reaction forces between the intact and resected states.[1] To date, joint kinematics have typically been measured and controlled using the position and orientation of the robot end effector. However, compliance in any structure in the testing system except the ligament of interest (e.g., robot, fixtures, bones) may introduce errors in superposition-computed tensions. These errors will vary from system to system and thus, must be reported for proper interpretation of superposition-computed tensions from a particular system. Accordingly, using the lateral collateral ligament (LCL) of the knee as a representative ligament, the ***objectives of this study*** were to (1) directly quantify the errors in superposition-computed tensions when robot-determined kinematics are used for robot control, (2) determine whether the errors in superposition-computed tensions decrease when motion capture-determined kinematics, which account for system compliance, are used for robot control, and (3) develop a surrogate joint model that the biomechanics community can use to conveniently quantify superposition tension errors for testing systems and applications.

METHODS: ***Robotic testing****:* We prepared three cadaveric knees for robotic testing as previously described.[8] To provide a gold-standard measure of LCL tension, we potted the distal end of the proximal fibula of each knee in an aluminum tube and attached it in-series with a single-axis load cell (Futek LSB210, reported nonlinearity = 0.9 N) to the fixed tibial bone tube (***Figure 1a***). Then, we resected the articular surfaces of the tibiofibular joint to free the fibula from the tibia such that the single-axis load cell directly measured LCL tension. We controlled our robotic testing system (KR300 2700-2, KUKA) using an algorithm[9] (simVITRO eXactoPOSE®) that allowed joint kinematics to be controlled using either the robot's kinematics or the kinematics of optical motion capture marker sets fixed to the femur and tibia (***Figure 1a***). After defining a functional coordinate system[10] and performing preconditioning, we prescribed varus (15 Nm) and external rotation (5 Nm) ramp load-unload torque trajectories, each at 0°, 25°, 45°, and 90° flexion. Then, we prescribed the kinematics measured during these kinetic-control trajectories to the intact joint and to the joint with the LCL attachment removed (***Figure 1a***). We repeated this process for the two control modes (i.e., robot-determined kinematics and motion capture-determined kinematics). We also performed superposition testing of a surrogate knee model that consisted of two rigid bodies connected by compression springs to provide comparable stiffness to a typical knee (***Figure 1c***). The surrogate knee model has a phantom LCL[11] attached in series to a single-axis load cell (Futek LCM300, reported nonlinearity = 2.8 N) to directly measure ligament tension. We determined superposition-computed tensions in the phantom LCL during a 15 Nm varus torque ramp load-unload at 0° flexion. ***Statistical analysis:*** We used the principle of superposition[1] to compute the *in situ* tension in the LCL and phantom LCL for each trajectory and control mode. We calculated the errors in all measured tensions and in peak tensions between the superposition-computed and load-cell-measured tensions. We pooled these errors across all specimens and trajectory types (varus or external rotation) and computed the bias and precision errors.[12]

RESULTS SECTION: When we used robot-determined kinematics for control, superposition-computed LCL tensions consistently underestimated true LCL tensions in the cadaver knees (***Figure 1b***). Although using motion capture-determined kinematics for robot control decreased the bias errors in the superposition-computed tensions for the varus trajectories, it increased the precision errors for both varus and external rotation trajectories (***Figure 1b***). We found that our surrogate knee model replicated the same trend of reduced bias errors when using the motion capture-determined kinematics, but also showed a reduction in the precision errors unlike that of the cadaver knees (***Figure 1d***).

DISCUSSION: Our ***first key finding*** was that the traditional control mode of performing superposition testing using robot-determined kinematics can result in large errors in ligament tensions (***Figure 1b***). The errors in tension may differ when testing different ligaments using other robotic testing systems, with higher errors expected in less stiff systems. Our ***second key finding*** was that using motion capture-determined kinematics for robot control is a promising, but currently imprecise method for determining superposition-computed tensions (***Figure 1b***). We hypothesize that noise in our motion capture data introduces kinematic tracking errors in robot control, which in turn contributes to high precision errors in superposition-computed tensions. Our ***third key finding*** was that our surrogate knee model provides a convenient and accessible method to quantify errors in superposition testing (***Figure 1d***). However, the lower errors in tension using our surrogate model compared to those using the cadaver knees suggest that surrogate models need to be designed to match the stiffness of a worst-case joint to yield more representative errors. Our ongoing work is focused on leveraging the benefits of each control mode (robot = low precision errors, motion capture = low bias errors) to develop a true gold standard method of superposition testing to determine ligament tensions.

SIGNIFICANCE/CLINICAL RELEVANCE: These results suggest that superposition-computed ligament tensions reported without system-specific errors should be interpreted with caution. A surrogate model is a convenient and accessible method to quantify the errors in superposition-computed tensions for a particular system. With proper reporting of these errors, superposition-computed tensions will continue to provide valuable insights into ligament mechanics.

REFERENCES: **1.** Fujie, J Biomech Eng, 1995. **2.** Dalmau-Pastor, Am J Sports Med, 2023. **3.** Imhauser, J Biomech, 2017. **4.** Battaglia, Am J Sports Med, 2009. **5.** Debski, JBJS, 2001. **6.** Mae, Arthroscopy, 2001. **7.** Okada, JBJS, 2018. **8.** Arant. in *ORS*. 2023. **9.** Gillespie. in *SB3C*. 2023. **10.** Nagle, Journal of Biomechanics, 2021. **11.** Arant, J Mech Behav Biomed Mater, 2022. **12.** ASTM E177-13, 2020.
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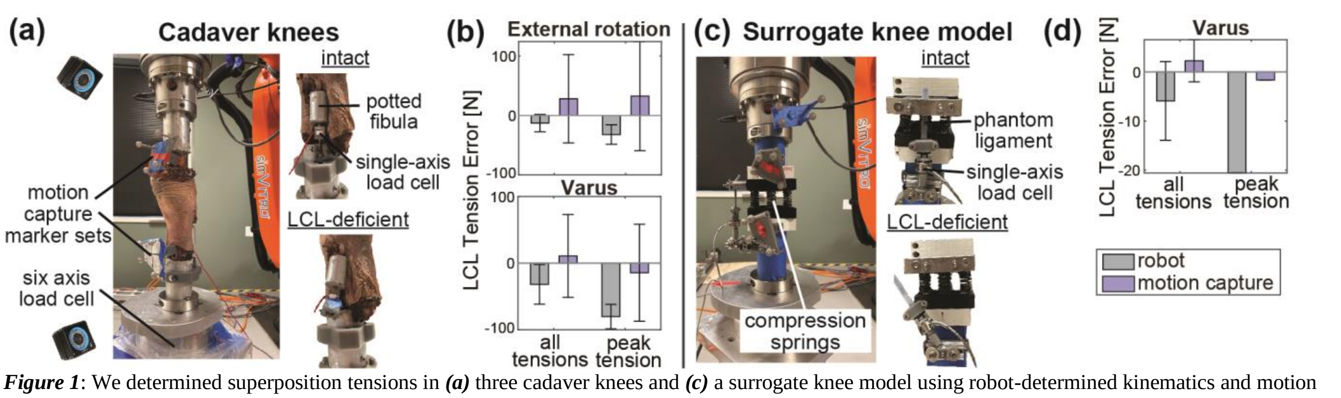

Figure 1: We determined superposition tensions in ***(a)*** three cadaver knees and ***(c)*** a surrogate knee model using robot-determined kinematics and motion capture-determined kinematics for control. ***(b)*** Neither control mode resulted in small errors in superposition-computed tensions in the cadaver knees. ***(d)*** The errors were smaller in the surrogate knee model than in the cadaver knees.