Contribution from Collateral Ligaments to Overall Knee Joint Constraint

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Introduction: As ligaments strain and become taught, their individual stiffness increases thus increasing their contribution to total joint constraint (TJC). The roles of the collateral ligaments to TJC are of particular interest due to their contributions to constraint for multiple degrees of freedom (DOF). The existing data on the collateral ligaments supports an integral role in TJC for a variety of DOF. However, previous studies have been isolated to specific loads and flexion angles, leaving a detailed mapping of their TJC contribution over a range of loads and flexion angles is unavailable. Demanding dynamic activities, such as those experienced in many sporting activities, push the boundaries of joint constraint and produce complex joint loads at an array of flexion angles [1]. By mapping the contribution of specific structures in a unified passive constraint, a relationship between joint loads and orientations with ligament contribution can be made and applied to many applications. The objective of this work was to utilize a unified passive constraint envelope and experimental measurement of ligament recruitment to map the contribution of the collateral ligaments over a broad range of flexion angles and compound joint loads.

Methods: Cadaveric knees from 9 specimens (8 male, 61.7 ±14.2 years, BMI 26.9 ±7.9) were acquired. Cylindrical aluminum fixtures were fixed to the femur and tibia, and the fibula was fastened to the tibial fixture. Specimens were instrumented with an implantable pressure transducer (IPT) (Model 060, Precision Measurement Company) within the superficial fibers at the joint line for either the MCL, LCL, or both (Figure 1). Of the nine specimens, eight had instrumented MCLs and six had instrumented LCLs. The transverse pressure in the ligament is not a direct measurement of load or strain, but rather a qualitative measurement of ligament contribution magnitude as a function of joint positions [2]. Laxity evaluations were performed from 0 to 120 degrees flexion while varus-valgus (VrVl) and internal-external (IE) torques were applied to the distal tibia up to ±10 N-m and ±8 N-m, respectively. An Optotrak 3020 camera system (NDI) was used to track femoral and tibial positions during the experiment, and a 6-DOF tri-axial load cell (JR3 Inc.) fixed to the distal tibia measured applied loads. Bony landmarks on the tibia and femur were digitized and used to calculate tibiofemoral kinematics according to Grood and Suntay [3]. The voltages from the IPTs were conditioned by normalizing the signal voltage for each specimen by the maximum voltage. Data were then used to develop a unified envelope (UE) for each specimen [4]. The UE creates a single model of joint laxity in multiple degrees of freedom by calculating tibiofemoral orientation as a function of flexion angle, VrVl and IE torques distributed over a uniform grid space. For this study, IPT data were also used as a dependent variable along joint orientation to create a map of MCL and LCL tensioning over the entire range of flexion angles, pure axial loads, and compound loads. The resulting UEs for each specimen were used to calculate mean ligament tensioning and statistically significant ligament activity for each joint position.
Results: Envelopes were separated into quadrants to interpret the data (Figure 2). The planes separating each quadrant were established by the joint position under a pure VrVI (horizontal plane) and IE (vertical plane) load across the flexion range. The most prominent occurrence of MCL contribution was in Quadrant 1 throughout the flexion range (Figure 3A). MCL contribution was highest from 60° to 120° flexion, with increasing contribution under larger valgus rotations. Quadrant 2 showed moderate MCL contribution under low internal rotation, and decreasing contribution with increasing internal rotation. Quadrant 1 had the most prominent occurrences of MCL contribution (Figure 3B). The most prominent occurrences of LCL contribution occurred under high internal rotation at the border of Quadrant 2 and 3 between 60° and 110° flexion, as well as in Quadrant 4 at maximum external rotation from 0° to 30° flexion and near maximum varus rotation from 30° to 60° flexion (Figure 3C). Quadrant 2 showed increasing LCL contribution with increasing internal rotation, though to less of an extent between 0° and 60° flexion. Quadrant 3 had moderate LCL contribution throughout the flexion range, with exception to an increase near maximum internal rotation from 60° to 110° flexion. Quadrant 4 had moderate to high LCL contribution until 70° flexion where the contribution decreased to nearly 0%. Quadrant 2 had significant MCL contribution from 70° to 110° flexion near peak internal rotation (Figure 3D). Quadrant 3 had a small region of significant contribution from 20° to 50° flexion under internal and varus rotation.

Discussion: Studies have reported ligament properties under various in vitro and in vivo conditions [5, 6], although there has not been a comprehensive analysis of joint orientations and loading conditions that induce ligament response, and thus become a constituent of overall TJC. The current study addresses this through a measurement of relative contribution of the collaterals related to a broad range of external loads and excursions. Mapping individual ligaments over the UE presents a novel method for predicting how individual structures are working in concert to create the net constraint of the joint. Additionally, the data presented here quantifies the complex nature of passive constraint and the contribution from the collateral ligaments. This work may be applicable to total knee arthroplasty, injury diagnosis, and preventative intervention, aiding clinicians to identify joint orientations that require significant recruitment from one or several ligaments. There are several limitations to this study. The experiments were manually performed, which may lead to variation in the application of loads. As mentioned previously, the IPTs were used for a qualitative measurement of relative ligament recruitment, and were not used to extract absolute ligament strain or force. Future work will seek to incorporate subset populations, such as ligament deficiencies or total joint replacements.

Significance: Quantifying collateral ligament response provides insight into the functional behavior of passive structures under applied loading of the knee. This information can be used for identifying soft-tissue injuries, predicting ligament recruitment in dynamic activities, and quantifying the contribution of individual structures to total joint constraint.
Figure 1: (A) Photo of the IPT and relative size (dimensions in mm, obtained with permission from Precision Measurement Company (www.pmctransducers.com)). (B) Example placement of an IPT in the superficial fibers of the anterior MCL.

Figure 2: UE quadrants in knee position space as defined by pure peak loads in VvV (red horizontal plane) and IE (green vertical plane) across all flexion angles. The quadrants are defined as follows: (1) varus/external, (2) valgus/internal, (3) varus/internal, (4) varus/external.
Figure 3: UE in joint orientation space for 100% magnitude isosurface, colored with mean and significant collateral contribution. Mean colors represent average level or normalized MCL or LCL constraint. For significance figures, red regions correspond with statistically significant collateral contribution greater than 0% ($H_0: 0$, $p < 0.05$).