New Approaches to Pedestrian Knee Joint Biomechanics

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I. INTRODUCTION

Injury epidemiologic data suggests that tibia fractures are far more common than knee ligament injuries in pedestrians impacted by vehicles [1]. However, studies using post mortem human subjects (PMHS) [2] and computational models [3] (whose responses are based on PMHS testing) predict a much higher ratio of knee ligament injuries than tibia fractures. Vehicle pedestrian impacts with PMHS have shown that when the tibia is fractured, loading across the soft-tissues of the knee joint is reduced, thereby preventing injury [4]. While the absence of the stiffening effect of musculature may play a role in this difference in observed injury, another potential reason may be related to how the knee joint has been characterized biomechanically. Specifically, knee joint response data that are used to inform computational models have been performed solely with the knee in full extension, and only in the valgus loading direction [5]. This setup is potentially problematic, given that full extension of the knee joint occurs only during standing and rarely during gait. Further, laterally impacted pedestrians typically have one knee joint that is loaded in valgus bending while the other is loaded in varus bending. This difference in boundaries is exacerbated in computational knee joint models that include knee ligaments typically use ligament material property data derived from tests on PMHS bone-ligament-bone (BLB) samples [6]. Since specimens are extracted from intact knee joints, the neutral loading state of the ligament in vivo cannot be identified, and the resulting data, as well as the derivative models, assume that a zero load state as the initial condition within the knee joint. This study aims to describe a new methodology for determining the biomechanical response of a knee joint and its ligaments for pedestrian injury modelling. To that end, knee joints are tested in varus and valgus bending, at a variety of flexion angles, in order to assess strains in the medial collateral ligament are measured to determine strains in the neutral joint.

II. METHODS

A six degree-of-freedom (DOF) position and force/torque controlled serial robotic test system was used to characterize varus/valgus (VV) response as well as the natural flexion path for a matched pair of knees in increments of 15° between 0 to 90° flexion. The specimens were harvested from two PMHS donors (Male, 84 years, 65.3 kg, 167.6 cm; Male, 76 years, 76.2 kg, 182.9 cm). The donations were obtained and treated in accordance with the ethical guidelines established by the United States National Highway Traffic Safety Administration (NHTSA), and all testing and handling procedures were reviewed and approved by an institutional review board for human surrogate use at the University of Virginia.

In VV range of motion (ROM) tests, a 12 Nm torque was applied in both directions while minimizing all forces and torques, except for axial compression, over a 62s period. Additionally, ROM tests were performed, for Internal External (IE) rotation to ±6Nm, anterior-posterior (AP) drawer, medial-lateral (ML) drawer, and distraction/compression (DC) to ±100 N. To ensure the femoral condyles remained seated within the tibial plateau, a constant 44 N compressive load was applied throughout the test. Additionally, to assess ultimate strength of the joint, failure tests were performed with the knee at 0° flexion with a constant 20 N compressive load using a matched pair of specimens to assess MCL versus LCL response. For these final tests, position control was used to drive each joint in the desired direction until failure at a dynamic rate (around 0.5s before failure). Surface (Lagrangian or Green) strains of the MCL were captured by an optical system employing digital image correlation (Aramis, OM mbH, Braunschweig, Germany). Visualization of the ligament complex was facilitated by a longitudinal incision in the medial knee (approximately 20mm x 100mm) to expose the MCL. The ligament was then died and speckled in order to maximize contrast for the optical strain measurement. Kinetic and kinematic data were low pass filtered using a 1Hz Butterworth phaseless filter.

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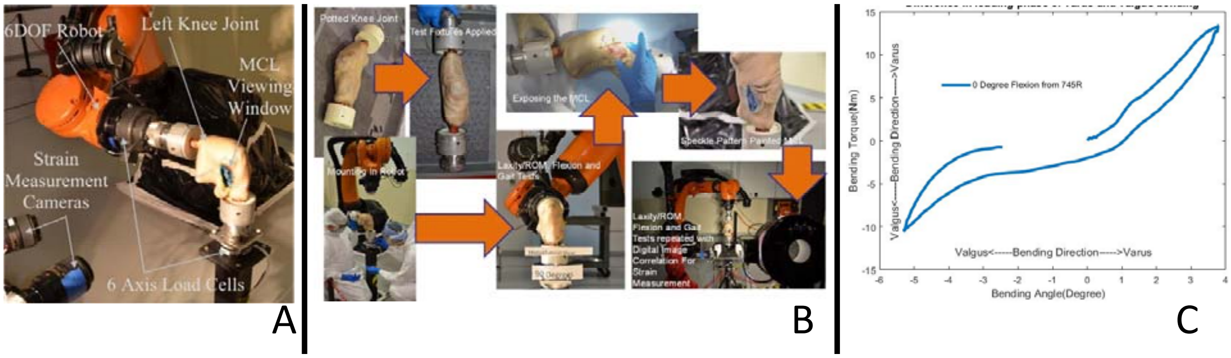

Figure 1. (A) Six DOF testing device, (B) testing procedure, and (C) sample input vs output for the VV bending test.

III. INITIAL FINDINGS

Peak tensile MCL strains (blue) and maximum changes in tensile strain (orange) for each ROM test at 0° flexion are shown in Figure 1. No laxity or buckling of the MCL was observed in any test, so negative strains do not indicate compression of the ligament, but simply reduced tension relative to the unloaded state. VV responses are plotted in Figure 2, where difference in peak value, slope for loading/unloading and area under the curve varies with flexion angle. Also, varus response differs from valgus response both in failure tolerance and in loading/unloading responses. Across all flexion angles, varus loading response appears to be almost linear, while valgus loading demonstrates strong nonlinearity behavior. Failure responses are capped where initial failure of the corresponding ligament is identified. Failure from varus and valgus happened at almost the same load level and angle. Pre-failure loading response is also similar.

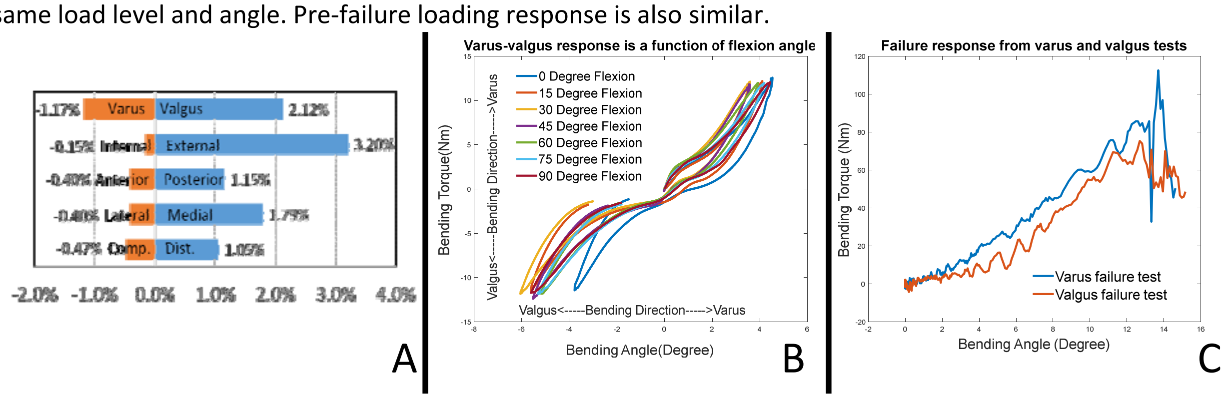

Figure 2. (A) Delta strain observed in the MCL across the VV ROM. (B) VV torque-angle curve for ROM tests. (C) VV torque-angle curve for failure tests.

IV. DISCUSSION

These results suggest that the MCL in the fully extended knee joint is under tensile strains exceeding 1% relative to a zero-stress state. Additionally, they describe how the MCL is loaded relative to the unloaded state for VV bending at a range of flexion angles. These relationships may be useful for interpreting the failure properties in studies where BLB specimens are extracted and tested. Moreover, these data show that the knee joint has a flexion angle sensitivity to both varus and valgus bending, and that valgus and varus responses do not have equivalent stiffnesses or ultimate strengths. This finding suggests that future investigations in both varus and valgus bending are needed to provide sufficiently complete response data to inform human body pedestrian models, with the hope that better response data could improve human body model prediction of pedestrian injury risk. This study described a new methodology that can be used to characterize knee joint response, and how ligament strain as a function of knee orientation can be measured by digital image correlation.

V. REFERENCES

[1] Chidester *et al.*, ESV, 2001. [2] Kerrigan *et al.*, IRCOBI, 2012. [3] Tang *et al.*, SAE, 2016. [4] Kerrigan *et al.*, SAE, 2008. [5] Bose *et al.*, *J Biomech Eng*, 2008. [6] van Dommelen *et al.*, *Traf Inj Prev*, 2005.