Knee Kinematics and MCL Strains During Gait, Passive Flexion, and Laxity Tests

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ABSTRACT INTRODUCTION: Recently there have been an increasing number of studies investigating the effects of changing total knee arthroplasty (TKA) component sizes and orientations in an effort to evaluate how the changes effect the resulting joint kinematics and range of motion [5]. In particular, attempts to improve joint stability have resulted in attempts to increase the thickness of the polyethylene inserts. While this results in a tighter complex, it can pre-stress knee ligaments, which results in a reduced injury tolerance. While numerous studies have been performed to determine ligament strains resulting in disruption/injury using of bone-ligament-bone (BLB) specimens extracted from cadavers [4], fewer studies have examined ligament strains *in vivo,* or at least *in situ*. Since extracted BLB specimens do not retain the native stress, or native strain, of the *in vivo* knee joint, failure strains are usually presented relative to a completely unloaded, and potentially unnatural, state. There is a paucity of information in the literature defining ligament strain levels *in vivo* in typical activities, and it appears that such information may only be available for the anterior cruciate ligament [1]. This is largely because it is too difficult to instrument knee ligaments in volunteers. This study aims to measure strains on the medial collateral ligament (MCL) in cadavers via a non-contact technique during motions and loads that are representative of *in vivo* dynamics.

METHODS: A 6 degree-of-freedom position and force/torque controlled serial robotic test system was used to identify the natural flexion path to the left knee joint of a human cadaver (Male, 76 years, 76.2 kg, 182.9 cm) from 0 to 120 deg flexion (Fig. 1). The donor was obtained and treated in accordance with the ethical guidelines established by the United States National Highway Traffic Safety Administration, and all testing and handling procedures were reviewed and approved by an institutional review board for human surrogate use at the University of Virginia. The natural flexion path, as defined by the joint morphology, was found by applying flexion about a hypothesized axis that was free to translate and rotate, while minimizing all forces and the varus/valgus (VV) and internal/external (IE) torques. The natural flexion path was used to apply a combination of compressive loading, which was defined by the combination of body weight and muscle force [2], and flexion angle [6] to emulate gait dynamics. To assess the repeatability and sensitivity of the loading time, this test was performed first over a 60 sec duration (60s) and then over a 10 sec duration (10s). Additionally, to assess laxity of the joint, range of motion (ROM) tests were performed, with the knee at 0 deg flexion followed by repeats at 30 deg and 90 deg flexion, in VV bending to +/-12 Nm, IE rotation to +/- 6Nm, and in anterior-posterior (AP) drawer, medial-lateral (ML) drawer, and distraction/compression (DC) to +/- 100 N. All of the ROM/laxity tests were performed with a constant 44 N compressive load, to ensure the femoral condyles remained seated in the tibial plateau. In the gait, flexion, and ROM tests, medial surface (Lagrangian or Green) strains of the MCL were captured by an optical system employing digital image correlation (Aramis, GOM mbH, Braunschweig, Germany). MCL viewing by the system was facilitated by cutting through the medial superficial tissues, and the effect this cut had on joint stability was evaluated by performing the ROM/laxity tests both before and after the cutdown.

RESULTS SECTION: While strains across a large portion of the MCL were recorded in each test, strains measured near the mid-substance at the femoral/tibial interface were compared across tests (Fig 3). Strains during the tests were repeatable, and reached as high as 1.85% above strains at full extension (with 400 N axial load) at approximately 70 deg flexion (Fig. 2). However, negative strains between -1.14% to -1.33% were recorded when the unloaded knee reached flexion angles approaching extension (5.9-7.9 deg). No laxity or buckling of the ligament was observed in any test (like that in [3]), which suggests that the MCL in the extended knee joint, even with 400 N axial load, is under tensile strains exceeding 1%. The largest negative strains (-1.2%) recorded in the 0 deg flexion tests were recorded at peak varus loading, while peak valgus loading generated 2.1% strain. The largest positive strain in any test of the study was 3.2%, which was recorded at peak external rotation and 0 deg flexion. In repeated passive flexion/extension (FE) tests, the difference between the peak tensile and peak negative strains were 2.42-2.48%, with negative strains as high as -1.36% (recorded at 110 deg flexion). As a result, when the knee was positioned at 90 deg flexion, and loaded in Anterior drawer, peak negative strains of -1.9% at 100 N of load indicate that anterior motion of the tibia relative to the femur will unload the MCL, but the 1.73% peak tensile strain recorded at peak posterior drawer indicates that the MCL stiffens the knee in posterior drawer at 90 deg flexion. Lastly, it should be noted that a Lachman test (anterior drawer at 30 deg flexion to 100 N) does strain the MCL to 1%, suggesting that some of the resistance in the test is borne by the MCL.

DISCUSSION: The results indicate the level of loading experienced by the MCL during gait, passive FE, and various ROM/laxity tests. More importantly, they begin to describe how the MCL is loaded relative to the unloaded state used as the baseline to describe the failure properties in studies where BLB specimens are extracted and tested. These results indicate that the natural knee, under low (44N) compression, places the MCL in at least 1.3% of tensile strain, which should be considered when increasing TKA polyethylene thickness.

SIGNIFICANCE: This study contributes to a better understanding of the structure/function relationship of the MCL, and how it supports the knee joint under various loading regimes. Further, this study could be used to guide future studies aimed at identifying particular TKA procedures aiming to restore knee ligaments to the level of loading experienced in the pre-implanted knee. Lastly, it demonstrates that non-contact strain measurement methods can be used to quantify ligament strain when cadaveric knee joints are loaded *in situ* to mimic the loading conditions in the human knee.

REFERENCES: [1]Beynnon B Fleming BC, J Biomech, 31, 1998. [2]Harrington IJ Biomed Eng 11(5), 1976; [3]Lujan TJ et al. J Biomech Eng 129, 2007; [4]Kennedy JC et al. JBJS 58(3), 1976; [5]Mueller JKP et al. Knee Surg Sprts Traumatol Arthrosc, 22, 2014; [6] Winters DA, University of Waterloo Press, 1991.

Figure 1. Test setup showing knee, robot, instrumentation, and imaging.

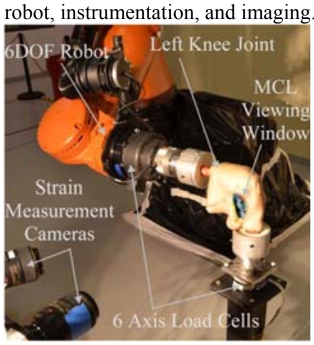

Figure 2. MCL strain, flexion angle, and compressive load in repeated gait tests.

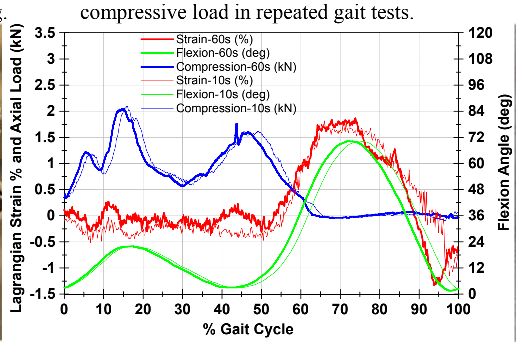

Figure 3. MCL strain maps under passive flexion at two different angles.