INTRODUCTION: Traumatic injury to the anterior cruciate ligament (ACL) has become a public health epidemic, especially among young athletes, with at least 400,000 documented ACL injuries per year in the United States [1]. Approximately 80% of ACL injuries are non-contact, meaning that the trauma is not caused by physical interactions between individuals. Short-term consequences of ACL injury include pain, joint instability, temporary disability, absence from work or sports, and the financial burdens of treatment and rehabilitation [2]. Even in cases of successful reconstruction, ACL-injured knees develop osteoarthritis (OA) at a rate of 60% and are seven times more likely to need a total knee replacement [3]. Preventative measures, including training programs and knee-braces, are controversial and have not been shown to universally decrease injury risk. This is due in part to a lack of any accepted methodology to evaluate the efficacy of preventative measures in the context of ACL injury scenarios before implementing them into standardized care.

Although computational modeling has historically provided valuable insight into ACL injury, simulation is limited because it assumes that ligaments are straight lines between anchor points, neglects wrapping surfaces, and cannot predict how compliant tissues may interact with external devices such as braces. Cadaveric experiments, on the other hand, uniquely make it possible to i.) directly measure ligament strain, ii.) record reaction loads at the joint, and iii.) observe tissue injury. In theory, all information necessary to reproduce a non-contact ACL injury on a cadaver limb is contained in the 6 degree-of-freedom (DOF) bone kinematics that emerge during injury. Unfortunately, previous cadaver-based models have used oversimplified motions while observing ACL strain during both injurious and non-injurious motions, removing much of the nuance that separates injury from non-injury in the real-world.

The objective of this study is to validate a cadaver-based robotic pipeline capable of reproducing both active non-injurious knee motions and knee motions that cause isolated ACL injury. The non-injurious knee motions are derived from published, scaled, sex-specific dynamic biplane radiography (DBR) data; access to these 6-DOF bone kinematics with sub-millimeter and sub-degree accuracy make it possible to reconstruct these motions with high-fidelity, and avoid the catastrophic bone contact and/or binding that has impeded clamped-kinematic cadaver approaches in the past. We also employ a novel technique to ensure that the subject-specific natural flexion-extension axis (FEA) of the knee is aligned with the primary kinematic axis of the input data, which we credit as being crucial to enforcing knee kinematics without inducing unintended injury.

METHODS: Cadaveric knee specimens (32-66 years of age) were dissected to expose the ACL, and the femur and tibia were potted in polymethyl methacrylate (PMMA). Key anatomical landmarks were digitized (Gage, FARO Technologies Inc.) to identify consistent specimen-specific tibial and femoral coordinate frames. The FEA of each specimen was identified, such that passive flexion of the femur about the FEA resulted in no motion of the tibia in free space. We then instrumented each specimen’s ACL with a 3 mm differential variable reluctance transducer (DVRT) linear displacement sensor (M-DVRT-3, Lord Sensing, Vermont) to directly record ACL strain. Each knee was then fixed to a 6-DOF robotic manipulator (KR210; KUKA Robotics).

The KUKA was programmed to recreate clinical tests of knee stability. During simulated anterior and posterior drawer tests, 134 N force was applied along the tibia’s anterior-posterior axis in the respective direction, and the resultant translational displacement was measured. Varus and valgus tests were performed by applying a 10 Nm torque about the tibia’s anterior-posterior axis, and recording the resultant rotational displacement. These tests were performed immediately after dissection and prior to enforcing any other motions, to ensure that knee stability was not compromised during the dissection.

Published kinematics from active non-injurious motions (walking, running, and drop jump) and ACL injury motions were transformed into specimen-specific and anatomically-relevant frames. We then used the KUKA to enforce the desired kinematics on each knee specimen. We applied 3 cycles of each motion while simultaneously recording ACL strain from the DVRT and femoral reaction forces from the KUKA’s integrated 6-DOF load cell (Omega, ATI).

Stability tests were repeated on the KUKA after the non-injurious motions to ensure the structural integrity of the knee was not unintentionally compromised, and again after the injurious motion to quantitatively assess the extent and appropriateness of the simulated injury.

RESULTS SECTION: Kinematics for walking, running, and drop jump were successfully enforced on the robotic platform, with an average RMS error below 0.05 mm in translation and 0.005 deg in rotation with respect to the published kinematic trajectories. Comparison between pre-experimental and post-non-injurious-motion stability tests shows that the structural integrity of the knee ligaments was not compromised (Fig 1B). Post-injury-motion stability tests showed more than a 3 mm increase in anterior translation, which is considered clinically significant for ACL rupture. Our results also indicate knee instability in varus torque at 0° flexion and valgus torque at 30° flexion, indicating a low-grade collateral ligament injury (LCL, and MCL respectively). All other post-injury stability tests showed consistent deformations with those obtained in the pre-injury conditions, indicating that no other ligaments were damaged by the ACL-injury motion. The average directly-measured ACL strains for walking, running, and drop jump are well below the average strain at rupture (Fig 1C). ACL rupture occurred at a different strain for each knee. The oldest specimen experienced rupture earlier in the injurious trajectory in comparison with younger specimens (Fig 1C).

DISCUSSION: In this study, we validated a cadaver-based robotic pipeline capable of reproducing both active non-injurious and injury-inducing knee motions, as derived from biplanar fluoroscopy data. Importantly, the prescribed non-injurious motions did not injure the knee, and the ACL-injury motion produced clinically-relevant ACL injuries. This pipeline can be used to reproduce any 6DOF motion on anatomically-relevant and specimen-specific frames.

SIGNIFICANCE/CLINICAL RELEVANCE: The proposed robotic cadaver-based pipeline may provide a deeper understanding of injury-inducing kinematic motions, serve as a platform to test current preventative devices, and may inform the development of future artificial and surgical reinforcements aiding in ACL injury prevention.

REFERENCES:

IMAGES:
Fig 1. A) Cadaver fixed to KUKA. B) Stability test results, showing translation along and rotation about the tibial anterior-posterior axis in response to different loads. C) Average ACL strain during each motion. Kinematics used to induce ACL injury. Dashed lines indicate where along the trajectory each specimen’s ACL ruptured, identified by sex and age.

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