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Anterior cruciate ligament biomechanics: characterization and computational modeling within a full knee model

Mallett, Kaitlyn, kmallett@umich.edu; Arruda, Ellen, University of Michigan, United States

ABSTRACT

Anterior cruciate ligament (ACL) replacements are among the most common knee ligament invasive procedures. Over 60% of sports-related surgeries in high school students are knee-related [1]. Many patients who have undergone ACL replacement surgeries have experienced long-term detrimental effects, including ruptures of the replacement tissue and the development of early onset osteoarthritis [2]. It is estimated that the combination of ACL and meniscal injuries can lead to the development of osteoarthritis in up to 48% of patients with replacements [3]. These complications pose a major challenge to health care professionals, and there is a pressing need to understand the mechanics of the ACL in physiologically relevant loading states to develop accurate constitutive models and select appropriate replacement options. The dynamic model of the knee is highly complex and difficult to describe. This intricate structure has made characterization of the mechanical properties of the components of the knee, including the ACL, difficult. The ACL is primarily responsible for preventing anterior translation of the tibia with respect to the femur and is particularly challenging to experimentally characterize. In its anatomically relevant state, it is twisted and partially extended regardless of knee flexion angle [4–7]. The material properties of the ACL include nonlinearity, anisotropy, and viscoelasticity. The tissue structures that make up the ACL also exhibit mechanical heterogeneity. The ACL is primarily comprised of two sections of tissue, the anteromedial and the posterolateral bundles (AMB and PLB, respectively). These bundles are not simultaneously unloaded under any configuration and are oriented so that regardless of the angle of extension of the knee, one bundle is always in a state of tension, further complicating the overall tissue structure [8,9]. Our experimental methods involve mechanically testing in uniaxial loading as well as anatomical positions and using digital image correlation (DIC) analysis to accurately describe the strain fields arising from mechanical heterogeneity in each experimental condition. Using DIC and traditional tension testing techniques, we are able to obtain quantitative global stress and time data, as well as average and region-specific strain information over the surface of the test specimens. We demonstrate that the anteromedial bundle of the ACL is functionally graded, whereas the posterolateral bundle is mechanically homogeneous in uniaxial tension. We also perform anterior tibial translation loading experiments; this motion is relevant to ACL injury as the ACL tears when the tibia anteriorly translates excessively relative to the femur. We have developed a nonlinear, viscoelastic, and anisotropic mathematical model of the ACL and implemented it into a finite element framework for computational analysis of the ACL during physiologically relevant loading conditions. This framework contains relevant bone and soft tissue structures, including the femur, tibia, patella, tibial–femoral cartilage, medial and lateral collateral ligaments, and anterior and posterior cruciate ligaments. The material response of the ACL within the full knee model is governed by the experimentally developed constitutive models. This full knee model is used to simulate physiologically relevant loading conditions, and the resulting ACL strains are compared to experimentally obtained tissue strains. Computational comparisons are made between the use of linearity and nonlinearity, homogeneity versus heterogeneity, isotropy versus anisotropy, and elasticity versus viscoelasticity. We investigate the difference between models and probable errors in those that do not incorporate nonlinearity, anisotropy and viscoelasticity into ACL mechanical properties. Our computational model is able to predict the location of ACL tears in the proximal third of the tissue and simulate the ACL tissue response to diverse knee injury situations.

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