FEB 18, 2016

Anterior Cruciate Ligament and Tibiofemoral Cartilages Characterizations and Modeling, and the Role of Constitutive Model Assumptions on Whole Knee Biomechanics

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ABSTRACT:

Anterior cruciate ligament (or ACL) tears are among the most common injuries in sports, with over 200,000 reconstructions per year in the US alone. Knee cartilage osteoarthritis (OA) is a debilitating disease affecting about 15% of the population in the US, and ACL reconstruction has been linked to OA through associated alterations of knee joint biomechanics. Computational models of whole knee joint biomechanics have the potential to be powerful clinical tools for e.g. preventing ACL injuries or assessing the best approaches to repair cartilage defects to mitigate the progression of OA. In order to be effective in these applications the models must accurately describe the nonlinear, anisotropic, viscoelastic, and heterogeneous properties of soft tissues, and they must be able to account for patient-to-patient variability in mechanical properties, anatomy, and biomechanics. In this work, a patient-specific whole knee computational model was developed using constitutive descriptions of the critical soft tissues involved in the deformation states probed. These descriptions arise from extensive experimental characterization and involve our pioneering efforts to obtain surface and volumetric deformation information in-situ via nano-CT and MR imaging. The focus is on the ACL and the tibial and femoral cartilages, which are all non-linear, anisotropic, viscoelastic, heterogeneous materials. The ACL is comprised of two bundles that spiral around one another and twist approximately 90° as they course from the femur to the tibia. Some portion of the ACL bundles is always under strain in physiologically relevant states. Characterization from an unloaded, reference configuration is an arduous process involving separating the bundles and testing them individually, which will be described. The constitutive descriptions of the bundles are then implemented into a computational framework using the unloaded configuration of the bundles, then the physiological state is restored in silico, primarily by twisting the bundles into the native state. The cartilages on the tibial and femoral surfaces are mechanically heterogeneous across these surfaces. This heterogeneity has been experimentally characterized and also implemented into full knee computational models. The implications of incorporating vs. not incorporating physiologically relevant and mechanically accurate constitutive heterogeneities in both the ACL and tibiofemoral cartilages on both tissue level deformations and macroscopic knee kinematics are investigated. The complex biomechanics of the knee joint lead to large and often anomalous changes in joint motions despite minor alterations in tissue level deformations. The complex interactions among the soft tissues of the knee are examined in the context of altering biomechanics resulting from cartilage defects, cartilage defect repairs, ACL deficiency, and ACL replacement.

BIOGRAPHY:

Ellen Arruda is a Professor of Mechanical Engineering with courtesy appointments in Biomedical Engineering, Macromolecular Science and Engineering, and the Center for Organogenesis at the University of Michigan. She has over 25 years of experience in the theoretical and experimental mechanics of soft materials, including polymers, soft tissues, and proteins. She also has about 10 years of experience in the tissue engineering of soft tissues and tissue interfaces. In her research, she collaborates with physiologists, orthopaedic surgeons, histologists, kinesiologists, biomedical engineers, and other engineers and scientists. She is a past president of the Society of Engineering Science and the current President of the American Academy of Mechanics. She is a Fellow of the ASME, Society of Engineering Science, and the American Academy of Mechanics. She has about 100 papers in peer-reviewed journal with an H-index of 26.