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Mechanical Property Characterization of the Rotator Cuff Tendon via MR-Based Full-Volume Measurements and Variational System Identification

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ABSTRACT:

Partial-thickness rotator cuff tendon tears constitute a common pathology and a leading cause of pain and disability, affecting between 13% and 32% of the general population. Despite their high prevalence, the natural history of these tears remains unclear. Surgical repair is recommended when more than 50% of the tendon's thickness has been compromised. However, this threshold mostly relies on anecdotal evidence. Additionally, re-tear rates as high as 35% have been reported for repaired partial-thickness tears. My lab has pioneered a method for soft material characterization involving a full-field method we created to collect the kinematic variables and force boundary conditions and inverse methods to determine the material constants. We have previously demonstrated success with this approach on soft tissues and elastomers. Here we describe our development of a custom displacement encoded MRI protocol in which the phase of each voxel, modulo 2π, is proportional to the displacement which that voxel sees when the tendon is stretched from a reference state to a stretched state. This protocol provides access to the entire three-dimensional displacement field throughout the volume of the rotator cuff tendon with sub-millimeter resolution. We combine this with an inverse method developed by our collaborators and used for the first time for soft tissue characterization. This variational system identification (VSI) approach seeks the parsimonious representation of the material physics. We apply this unique approach to intact and partially torn rotator cuff tendons. The displacement fields are converted to strain fields and their maps show significant differences in shear strains between the two populations, and the highest shear strains in the interiors of the tendons. All previous measurements on rotator cuff tendons, limited to measurements on bursal and articular surfaces, are incapable of detecting these strains. The high shear strain patterns in the partially torn tendons suggest delamination (mode II) failure as a mechanism of tear progression, and could have implications for the surgical management of high-grade partial thickness tears. Anatomical differences are found to influence the strain patterns in both intact and torn tendons. High resolution images of the tendons are obtained from the magnitude portion of the MRI signal. These are used to create the model geometry for the VSI computational framework. The rotator cuff tendon is a non-linear, visco-elastic, anisotropic material. If viscous effects are neglected, the governing material physics relating stresses and strains is a strain energy density function. One approach to VSI is to assume a number of isotropic and anisotropic polynomial terms that are functions of the strain invariants (I1, I2, I3, and I4). The success of this VSI approach in characterizing the rotator cuff tendon material parameters will be discussed.

BIOGRAPHY:

Professor Ellen M Arruda is the Tim Manganello / BorgWarner Department Chair and Maria Comninou Collegiate Professor of Mechanical Engineering at the University of Michigan. She also holds appointments in Biomedical Engineering and in Macromolecular Science and Engineering. Professor Arruda earned her B.S. degree in Engineering Science and her M.S. degree in Engineering Mechanics from The Pennsylvania State University, and her Ph.D. degree in Mechanical Engineering from the Massachusetts Institute of Technology. Under her leadership the Mechanical Engineering department earned the Inaugural Mechanical Engineering Department Heads Executive Committee's Diversity, Equity, and Inclusion Award from the American Society of Mechanical Engineers in 2022 and the Rhetaugh G. Dumas Progress in Diversifying Award, from the University of Michigan, also in 2022. For her research accomplishments Professor Arruda has been recognized with the 2023 Borelli award from the American Society of Biomechanics (the highest award given), the 2021 Eringen medal from the Society of Engineering Science, the 2019 Nadai medal from the American Society of Mechanical Engineers, and the 2018 Rice medal from the Society of Engineering Science.Professor Arruda teaches and conducts research in the areas of theoretical and experimental mechanics of macromolecular materials, including polymers, elastomers, composites, soft tissues and proteins. Her research programs include experimental characterization and analytical and computational modeling of soft materials, including native and engineered tissues. She has pioneered a novel inverse method to characterize the non-linear, anisotropic response of soft tissues such as the anterior cruciate ligament (ACL) of the knee and the supraspinatus (rotator cuff) tendon of the shoulder. Professor Arruda has over 120 papers in scientific journals with over 16,500 citations. Her H-index is 50 (Google Scholar), and she holds 16 US patents. She is a Fellow of the American Society of Mechanical Engineers, the American Academy of Mechanics, the Society of Engineering Science, and the American Institute for Medical and Biological Engineering. Professor Arruda was elected to the National Academy of Engineering in 2017.