Fiber Orientation and Structural Model of Tendon-to-Bone Insertion

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Introduction: Tendon-to-bone insertions are functionally-graded connective tissues whose anisotropic biomechanical functions depend intimately on the regional biochemical composition and structure [1]. The insertion site provides a gradual transition from soft tendon tissue to hard bone tissue, functioning to alleviate stress concentration at the junction of these tissues [2]. In this study, we examine the collagen fiber distribution through two-dimensional fast Fourier transformation (FFT) of histological imaging data from fluorescent microscopy [3]. To better understand how tendon-to-bone insertion performs its function, the fiber distribution results are incorporated with the structure- and constituent-based computational models under super-physiological loading conditions.

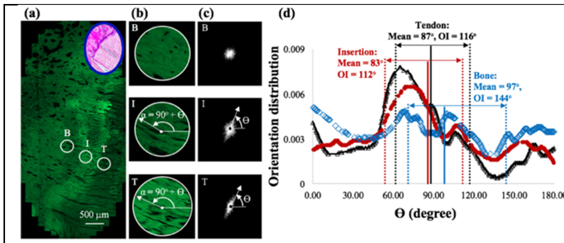

Figure 1: **(a)** H&E stained section was used for measurement of collagen fiber orientation in the bone (B), insertion (I), and tendon (T) regions. **(b)** Mean fiber orientation α **(c)** FFT was applied to images. Angle of orientation Θ on the FFT. **(d)** Orientation index decreases from bone to tendon.

Materials and Methods: Collagen orientation distribution are obtained through two-dimensional FFT (**Fig. 1a**). The FFT is converted to a log spectrum of its magnitude to eliminate its imaginary component. The mean fiber orientation α is calculated (**Fig. 1b**) and the angle of orientation of white pixels on the FFT image is represented by Θ (**Fig. 1c**). By fitting the FFT image pixel data onto a circular distribution, the number of pixels oriented along each incremental angle from 0 to π is obtained. Each FFT individual pixel count is normalized by the total area to obtain the unit area orientation distribution (**Fig. 1d**). Mean angles of orientation associated with each region are calculated as the angles corresponding to the centroids of the respective distributions. Hence, the peak angle in each distribution corresponds to the direction of highest frequency content and is presumably 90° out of phase with the orientation of the fibers (**Fig. 1b**). Orientation index (OI), used as a measure of fiber dispersion, is calculated as the difference between the angles bounding the middle 50% area under the orientation distribution curve. Hence, an increase in randomization of fiber direction would correspond to shorter peaks and wider orientation indices. Further, we developed a computational model of tendon-to-bone insertion implemented in commercial finite element software ABAQUS. We adopted nonlinear anisotropic Hozlapfel-Gasser-Ogden (HGO) model [4] to incorporate collagen fiber dispersion and mineralization concentration. A python script was developed to alter the tapered tendon-bone transition zone and to provide spatial grading of material properties, which may be rather complex as experiments suggest. A simple linear interpolation between tendon and bone material properties was first used to describe the graded property within the insertion region.

Results and Discussion: Fiber orientation gradation across insertion regions is studied quantitatively through image analyses of histological data and FFT was performed. Results of FFT clearly indicate gradation in the directionality of fiber orientation from the bone to the tendon region. Furthermore, stress distributions from the structural model are obtained and compared for spatially graded and various piece-wise materials properties. It was observed that spatial grading results in more smooth stress distributions and significantly reduces maximum stresses. The geometry of the tissue model could be optimized by minimizing the peak stress to mimic in-vivo tissue remodeling. The in-silico elastic models constructed in this work are verified and modified by comparing to our in-situ biaxial mechanical testing results, thereby serving as translational tools for accurately predicting the material behavior of the tendon-to-bone insertions.

Conclusions: The insertion forms a functionally-graded interface between tendon and bone. This study addresses quantification of gradual changes in the orientation distribution of collagen fibers on two orthogonal planes and provide stress distribution from a structural-based computational model. The merit of this study lies in the image-based simplified approach to fiber distribution quantification. The develop structural computational model will be useful for understanding how tendon-to-bone insertion functions and may be also useful to planning surgical interventions and developing orthopedic implants.

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