Introduction: Predicting and measuring the mechanical response of tendon is important in the development and assessment of various orthopaedic reconstruction techniques. Understanding the mechanical implications of the collagen structures and extracellular matrix in tendon may provide insight into tendon healing and optimal graft choice for Anterior Cruciate Ligament (ACL) reconstruction. At the microscopic and molecular level, the strength and elastic properties of tendon are thought to be the result of the interaction of the collagen microstructure and interstitial fluid. The collagen microstructure of tendon has been described as being composed of fascicles which in turn are composed of subfascicles (1,2). The subfascicles are the smallest repeating structural element of the tissue and their structure in the patellar tendon has been documented by Yahia and Drouin (2). Atkinson et al. (3) suggested that the collagen subfascicle might be the functional structural unit within the tendon. They devised a finite element method (FEM) model of the structure, based on descriptions by Yahia and Drouin (2), where a band of collagen was helically oriented about a central core. This model suggested that the helical orientation causes the collagen to compress the interstitial matrix causing fluid motion and relaxation. The response of the model compared well with whole tendon and ligament responses, however no data was available to describe the mechanical response of the subfascicle itself.

In the current study tendon specimens with both large and small cross sectional areas were tested to provide a comparison between mechanical responses at a subfascicular and whole tendon level. Finite element models of a subfascicle and a fascicle were constructed to examine how the collagen structures and matrix portions of tendon might interact to produce the mechanical responses observed in the experimental study.

Methods: The subfascicle finite element model utilized in the current study was a modification of the previously described subfascicle model (3). Briefly, the model represents Yahia and Drouin’s (2) description of a subfascicle in patellar tendon using a representative 3-D section with a 100 µm radius. Helically oriented collagen fibers were wrapped around the periphery of the model and the matrix within the subfascicle was collected in the center. The top and bottom surfaces of the model were sealed (as the subfascicle is a long thin structure) and the outer boundaries were assumed to be perfectly draining. The bottom plane of the model was constrained in plane motions with 4 nodes, 90° apart, additionally constrained to radial motion. The top plane was assumed to deform uniformly in the z direction with x and y free. The matrix portion, in the center of the model, was assumed to be linear isotropic poroelastic material. An orthotropic poroelastic material simulated the helically oriented fibers within the fibrous rings, where the E-direction represented the fiber modulus. The properties of the orthotropic material were selected to achieve a nearly incompressible material which was weak in shear. These properties allowed the fiber portion to helically twist in a nearly rigid body fashion. The fiber direction of the orthotropic outer ring was a 20° declination from vertical, the approximate fiber orientation scaled from SEM images presented by Yahia and Drouin (2) and the crimp angle exhibited in young rat tail tendon (4). Fluid flow was assumed to obey Darcy’s law and the permeability was assumed to be constant.

A simple fascicle model was constructed from two subfascicle models. In ligament, fascicles are covered by a connective tissue sheath termed epitenon (5,6). These areolar tissues bind the fasciculi into functionally independent units (5). In collagen the epitenon is “tissue situated in a coiled manner along the long axis of the fasciculi” (5). In the fascicle model a thin epitenon layer surrounds the subfascicles and was assumed to be perfectly bonded to the subfascicles, based on early observations of binding fibers between the structures (6,2). The thickness of the epitenon layer (1/12 of the fascicle major axis) was taken from average thicknesses measured in connective tissue micrographs of human anterior cruciate ligament (7). Danylechuk et al. (5) suggested that only the orientation of the collagen fibers in the epitenon distinguished it from the fasciculi. The epitenon was therefore simulated using the collagen fiber material model. Fiber orientations from 0° (horizontal, transverse to the length of the tendon) to -60° from horizontal were investigated in the fascicle model. The relaxation response of the fascicle was compared to that of two subfascicles without epitenon.

The experimental portion of the study involved four pairs of human cadaver knees. The patellar tendons were separated into quadrants with bone blocks maintained at each end. One quadrant sized specimen was selected from each cadaver to serve as a “large” sized specimen. The contralateral quadrant specimen was then subdivided to create two “small” specimens. This protocol helped reduce the influence of spacial variations in tendon. A total of 4 “large” and 8 “small” specimens were tested. The specimens were inspected under a dissecting microscope. Atkinson et al. (5) suggested that the collagen subfascicle might be the functional structural unit within the tendon. They devised a finite element method (FEM) model of the structure, based on descriptions by Yahia and Drouin (2), where a band of collagen was helically oriented about a central core. This model suggested that the helical orientation causes the collagen to compress the interstitial matrix causing fluid motion and relaxation. The response of the model compared well with whole tendon and ligament responses, however no data was available to describe the mechanical response of the subfascicle itself. In the current study tendon specimens with both large and small cross sectional areas were tested to provide a comparison between mechanical responses at a subfascicular and whole tendon level. Finite element models of a subfascicle and a fascicle were constructed to examine how the collagen structures and matrix portions of tendon might interact to produce the mechanical responses observed in the experimental study.

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