



Micromechanical models of helical superstructures in ligament and tendon fibers predict large Poisson's ratios

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ABSTRACT

Experimental measurements of the Poisson's ratio in tendon and ligament tissue greatly exceed the isotropic limit of 0.5. This is indicative of volume loss during tensile loading. The microstructural origin of the large Poisson's ratios is unknown. It was hypothesized that a helical organization of fibrils within a fiber would result in a large Poisson's ratio in ligaments and tendons, and that this helical organization would be compatible with the crimped nature of these tissues, thus modeling their classic nonlinear stress–strain behavior. Micromechanical finite element models were constructed to represent crimped fibers with a super-helical organization, composed of fibrils embedded within a matrix material. A homogenization procedure was performed to determine both the effective Poisson's ratio and the Poisson function. The results showed that helical fibril organization within a crimped fiber was capable of simultaneously predicting large Poisson's ratios and the nonlinear stress–strain behavior seen experimentally. Parametric studies revealed that the predicted Poisson's ratio was strongly dependent on the helical pitch, crimp angle and the material coefficients. The results indicated that, for physiologically relevant parameters, the models were capable of predicting the large Poisson's ratios seen experimentally. It was concluded that helical organization within a crimped fiber can produce both the characteristic nonlinear stress–strain behavior and large Poisson's ratios, while fiber crimp alone could only account for the nonlinear stress–strain behavior.

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1. Introduction

Tendons and ligaments are fibrous, load bearing tissues that are characterized by a hierarchical organization of collagen microstructures. A basic structural component of ligaments and tendons is the collagen fibril. Fibrils are closely packed within an extrafibrillar proteoglycan rich matrix to form a fiber. Individual fibers are encased in the endotendinous sheath and packed into fascicular units, which then become the constituents of the whole tendon or ligament complex (Kastelic et al., 1978; Kannus, 2000) (Fig. 1).

Although there is a wealth of literature on the elastic and viscoelastic behavior of ligaments and tendons, most studies have focused on uniaxial stress–strain behavior and largely ignore volumetric behavior (e.g. Poisson's ratio). In the biphasic theory, the compressibility of the solid phase is governed by the volumetric material coefficients in the constitutive model

(Mow et al., 1980). For uniaxial tensile loading in linear elasticity, the Poisson's ratio is a measure of volume change and describes the lateral contraction in response to an axial strain. The Poisson's ratio is strictly a kinematic measure, and can be defined both for the kinematically linear and nonlinear cases (generally referred to as the Poisson function in nonlinear theory), and applies to both isotropic and anisotropic materials. In the latter case, more than one Poisson's ratio must be defined.

The reported Poisson's ratios for tendon and ligament subjected to tensile loading along the fiber direction ranged from 0.8 ± 0.3 in rat tail tendon fascicles (Screen and Cheng, 2007) to 2.0 ± 1.9 in capsular ligament (Hewitt et al., 2001) and 2.98 ± 2.59 in bovine flexor tendon (Lynch et al., 2003). Under tensile loading, these large Poisson's ratios are indicative of volume loss, which may result in fluid exudation (Adeeb et al., 2004; Wellen et al., 2004).

The magnitude of volume loss and thus the quantity of fluid exuded during deformation may play an important role in the mechanics and function of these tissues. It has been suggested that biphasic theory may explain some if not all of the viscoelastic behavior of ligament and tendon (Atkinson et al., 1997; Yin and Elliott, 2004). Furthermore, fluid transport resulting from mechanical forces may aid in nutrient delivery within

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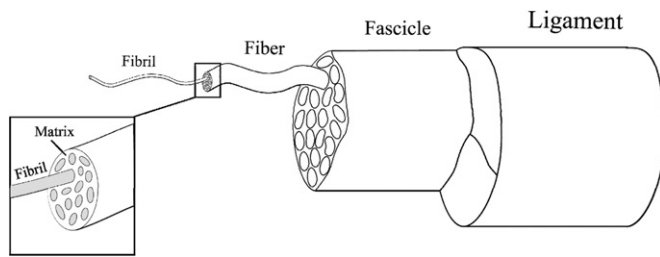


Fig. 1. Schematic of tendon and ligament microstructure, adapted from Kastelic et al. (1978).

these tissues. Finally, shear forces and or cell membrane deformation resulting from pressure driven fluid flux may be an important mechanotransduction signal for tenocytes and fibroblasts (Butler et al., 1997; Chen et al., 1998; Lavagnino et al., 2008). In light of this information, the volumetric behavior, and thus Poisson's ratio, is of fundamental importance in understanding healthy and diseased ligament and tendon tissue.

A number of studies have examined structure–function relationships between the fibrillar microstructure and macroscopic behavior of the “toe region” of ligaments and tendons under tensile loading (Diamant et al., 1972; Lanir, 1978; Ault and Hoffman, 1992; Hurschler, 1997; Freed and Doehring, 2005; Grytz and Meschke, 2009). However, there are no models in the literature that predict or explain the large Poisson's ratio of these tissues. A review of the literature on fiber based composites reveals that at least two microstructural fiber geometries are capable of generating large Poisson's ratios. One possibility is multiple fiber families crossing at non-orthogonal angles (Peel, 2007), but histological studies suggest that fibrils and fibers in most ligaments and tendons are predominantly aligned in a parallel fashion (Provenzano and Vanderby, 2006). The other possibility is the helical arrangement of a fiber family (Marklund, 2007).

Several studies have reported the presence of helical structures within fibers and fascicles of ligament and tendon. Yahia and Drouin (1989) presented histological evidence that suggests the presence of a super-helical organization of fibrils in canine patellofemoral tendon and ACL. An organizational scheme was suggested in which a helical twist was superimposed on top of crimp structures. The scale of this twist was suggested as being an order of magnitude larger than that of the crimp. Studies by Vidal et al. have also presented histological evidence suggesting a super-helical arrangement of fibrils (Vidal Bde, 1995; Vidal, 2003; Vidal Bde and Mello, 2009). It was suggested that this helical arrangement is difficult to see in standard preparations, which may account for their absence in past histological studies.

It was hypothesized that a micromechanical model with super-helical fibril organization in the presence of crimp would predict the large Poisson's ratios seen experimentally while simultaneously predicting the nonlinear stress–strain behavior of these tissues. The objective of this study was to use homogenization methods and finite element micromechanical models to test this hypothesis, as well as to assess the influence of material coefficients and geometric characteristics of the micromechanical model on the predicted Poisson's ratio.

2. Methods

2.1. Fiber geometry and unit cell

It was assumed that a fiber is the fundamental repeating structural unit within a tendon and ligament. For the purposes of homogenization, a single fiber unit was considered to be a periodic unit cell. Unit cells were modeled by embedding

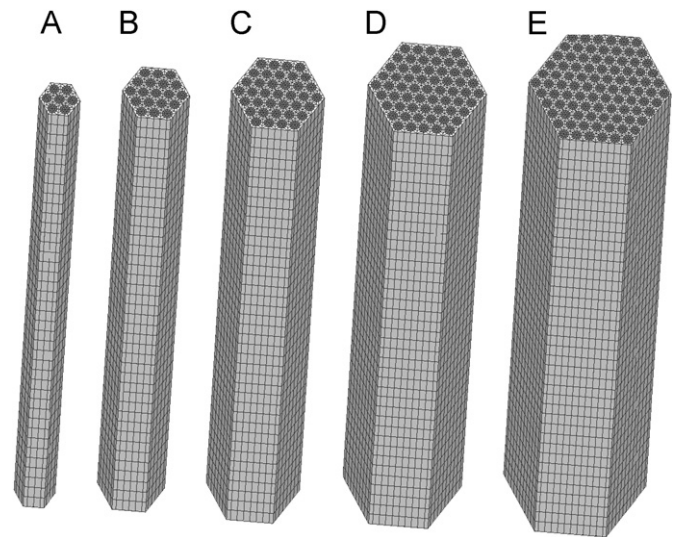


Fig. 2. Separate models were constructed with 7, 19, 37, 61 and 91 discrete fibrils. Model C, which had 37 fibrils, was considered to be the base model and was used for most simulations.

discrete fibrils within a more compliant matrix material and were assumed to be hexagonally packed within the fiber (Chen et al., 1998). It was assumed that the matrix material modeled both the inter-fibrillar and inter-fiber space. The number of fibrils embedded within the fiber was varied as part of the study, with models featuring 7–91 discrete fibrils (Fig. 2). The fibril diameter was set to 100 nm, based on values reported in the literature for ligament and tendon (Baek et al., 1998). The inter-fibrillar spacing was set to 25 nm (Baek et al., 1998), which generated a fibril volume fraction of 57%. The baseline model contained 37 fibrils (based on a convergence study described later in the text), had a diameter of 0.769 μm and a height of 8.0 μm . Transformations were applied to the baseline model in order to generate models with planar crimp, helical twisting and planar crimp models with a super-helical twist (Fig. 3).

2.2. Sinusoidal and helical transformation of unit cells

The most accepted geometric model of fiber crimp is planar crimp, in which the crimp plane is constant throughout the fiber and fascicle (Rowe, 1985; Gathercole and Keller, 1991; Hansen et al., 2002). Planar crimp models were generated by applying a sinusoidal transformation of the following form along the fiber axis:

$$y' = y + A_0 \sin\left(2\pi \frac{z}{\lambda}\right); \quad A_0 = \frac{\lambda}{4} \tan(\theta_{\text{crimp}}), \quad (1)$$

where λ is the crimp period and θ_{crimp} is the crimp angle (Fig. 4A). To accurately represent the crimp structures observed in histological studies (Hansen et al., 2002; Hurschler et al., 2003; Jarvinen et al., 2004), the models were scaled such that the ratio of the crimp period to fiber diameter was similar to that seen experimentally

$$\frac{\lambda_{\text{experiment}}}{D_{\text{experiment}}} = \frac{\lambda_{\text{model}}}{D_{\text{model}}}, \quad (2)$$

where $\lambda_{\text{experiment}}$ and $D_{\text{experiment}}$ are the experimentally measured crimp period and fiber diameter and λ_{model} and D_{model} are the model crimp period and model fiber diameter, respectively. Histologically measured values for the crimp period and fiber diameter vary between tendons and ligaments, as well as between studies. Table 1 provides values from the literature for rat tail tendon, rat MCL, human Achilles tendon and for the baseline model used in this study (Gathercole and Keller, 1991; Hansen et al., 2002; Hurschler et al., 2003; Jarvinen et al., 2004; Franchi et al., 2007).

Helical models were generated with a mean fibril pitch (averaged over all fibrils) ranging from 0° to 60° (Fig. 4B). To generate the helical models, the mesh nodes were rotated by an angle θ about the fiber axis such that a complete rotation was generated. Since the diameter of a given fiber model was constant, the helical pitch was altered by changing the height of the model such that

$$\theta_{\text{pitch}} = \frac{2\pi r}{H} \quad (3)$$

These models were then modified to include planar crimp superimposed with helical twist. The scaling of the models required that the length was a multiple of the crimp period, which restricted the possible model lengths and thus the helical pitch.

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