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Bayesian identification of the tendon fascicle's structural composition using finite element models for helical geometries

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Highlights

- Bayesian inference of the structural composition of tendon fascicles.
- Mechanical modeling of the fascicle's geometric and material properties with an optimized model for helical geometries.
- Direct link between the compatible material and geometric properties between the fascicle and the fiber tendon scale.
- Design framework for biocompatible, artificial tendons.

Abstract

Despite extensive experimental and computational investigations, the accurate determination of the structural composition of biological tendons remains elusive. Here we infer the structural compositions of tendons by coupling a finite element model with fascicle experimental data through a Bayesian uncertainty quantification framework. We present a mechanical model of the fascicle's geometric and material properties based on its constituents and employ the Bayesian framework to infer its parameters. The finite element model is optimized for helical geometries to reduce the computational cost associated with the Bayesian inference. We establish a link between the fiber and the fascicle tendon scale and identify an appropriate range of mechanically compatible material and geometric properties to quantify the tendon properties. These findings could serve as a basis for the design of artificial tendons.

Keywords: Tendon; Fascicle; Bayesian inference; Finite elements; Helix

1. Introduction

Tendons are natural fibrous tissues transferring loads between the muscles and the skeleton. They exhibit a natural spatial and size hierarchy [1] and their composition and the structural arrangement of their constituents reflect their functional role (e.g. positional or energy storing [2], age [3,4] as well as health state [5] (Fig. 1)). The material

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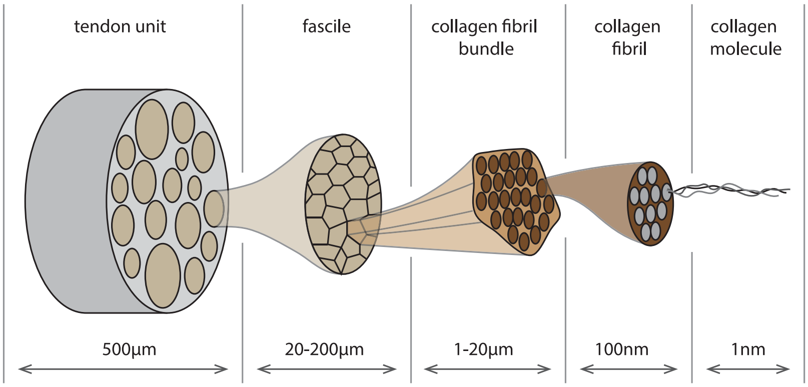

Fig. 1. Hierarchical decomposition of Tendons into structural multi-scale subunits.

properties of the tendon building blocks affect its functionality, as well as its efficiency on load transfer. A thorough structural quantification of the tendon's constituents is essential for its characterization and the understanding of its properties. Such knowledge can assist the selection of bespoke materials for any repair and restoration method [6] involving biocompatible solutions mimicking the physiological functionality of the native tissue [7,8].

The material properties of the tendon are linked to the structure of its constituents and more specifically to their helical patterns. Helices are a persistent pattern across several tendon scales. Orgel et al. [9] established that the fibrous content of the tendons is immersed in a matrix with a crimped and helically undulating pattern. The lowest hierarchical tendon level, fibrils, also exhibit a helical pattern. Yahia et al. [10] and De Campos Vidal et al. [11] visualized the helical structure of the collagen fibril bundles (fibers) and fascicles by using interference and polarized microscopy in bovine and rat tail tendon specimens. Visual observations postulated the helical structuring of fibrils. This was further corroborated by measurements of their mechanical response. Tendon fascicle specimens were shown to deform both axially and torsionally upon axial straining, a response characteristic of helical formations [2]. The reported fiber angles (θ) of ruptured human tendons do not exhibit a large scatter (see Ref. [12] and references therein), but their exact value remains uncertain, and greatly influences the tendon properties.

The material moduli of the tendon constituents (Fig. 1) are commonly measured using uniaxial strain experiments. In particular, for fibrils, the reported Young's moduli mean values may differ by more than 3 times (from $E_{fibril} = 0.86 \pm 0.45$ GPa [13] up to $E_{fibril} = 2.89 \pm 0.23$ GPa) [14]. As for fibers, Kato et al. [15] reported mechanical moduli as low as $E_{fiber} = 0.57 \pm 0.08$ GPa and as high as $E_{fiber} = 2.69 \pm 0.42$ GPa for wet and dry rat tail tendon specimens respectively. Gentleman et al. [16] computed a modulus value of $E_{fiber} = 0.36 \pm 0.03$ GPa for extruded fibers and reported a value of $E_{fiber} = 1.17 \pm 0.28$ GPa. These values are about two times the ones reported by Kato et al. [15] for rat tail tendon fibers. Finally, at the top hierarchical level of fascicles, experiments report a mechanical modulus of $E_{fascicle} = 0.64 \pm 0.03$ GPa [17] and $E_{fascicle} = 0.48 \pm 0.07$ GPa [18] for rat tail tendon specimens. Human fascicle specimens yielded an estimate of $E_{fascicle} = 0.55 \pm 0.14$ GPa [14]. Despite the importance of the fascicle matrix properties in the mechanical response and in the tendon functionality [19], little is known about its mechanical attributes. Since no direct experimental results are available, Ault [20] developed analytical micro-mechanical models to provide a matrix modulus estimate of $E_{matrix} = 0.25$ MPa, 3 orders of magnitude smaller than the fiber modulus.

In order to quantify the mechanical properties of the tendon hierarchical constituents, numerous studies measured their volumetric response subject to axial straining. Both experimental and numerical studies, yielded lateral contraction values that exceed significantly the ones predicted by the assumption that the tendon is an isotropic composite material. More specifically, Lynch et al. [21] measured the Poisson's ratio of bovine flexor tendons and reported values up to an order of magnitude greater than the ones predicted assuming an isotropic material. Cheng et al. [22] measured an effective fascicle Poisson's ratio of 0.8 ± 0.3 for rat tail tendon specimens. Similar values were also reported for horse tendon fascicles [2]. Complementing the experimental studies, Reese et al. [23] used a finite element model and found that the lateral contraction of embedded helical fibers exhibits a non-linear, structure dependent behavior with values exceeding the isotropic Poisson's ratio limit of $\upsilon_{eff} = 0.5$. The same conclusion is reached using analytical models by Swedberg et al. [24].