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# Nonlinear viscous behavior of the tendon's fascicles from the homogenization of viscoelastic collagen fibers

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ABSTRACT

The level of the fascicle including collagen fibers, membranes and interstitial fluid is quite representative of the structure of tendons. We presently investigate the effect of the rheology of the components of the tendon fascicles in a multiscale analysis starting from the level of individual collagen fibers organized into bundles, and then into fascicles at the next scale. ~~A~~ configuration of a collagen bundle is conceived in terms of a representative unit cell including a collagen fiber surrounded by a viscous membrane and a physiological fluid. The mixing of solid and fluid components gives rise to an equivalent stress-strain response in tensor format highlighting a long term memory, in addition to instantaneous viscous effects. The kernel function of the hereditary response is determined thanks to the theory of homogenization, relying on the solution of the localization problem over the selected unit cell. Homogenization is the principal factor responsible for both the relaxation phenomena and the nonlinearity due to recruitment of fibrils observed at the fascicle level, although none of the components present at the lower scales is endowed with these properties. The nature of the matrix surrounding the collagen fiber – described as either viscous solid or a biological fluid - is shown to strongly influence the transverse response, but it has a weaker influence on the tensile response of fascicles. The initial waviness and progressive recruitment of the collagen fibers under the effect of the local strain has been integrated in the expression of the elastic and viscous stresses at the scale of the collagen fiber bundle, allowing simulating the nonlinear response of a fascicle. The computed response is able to reproduce the measured physiological response of a real tendon to a uniaxial tensile test for a proper choice of the parameters of the recruitment statistical function.

## 1. Introduction

Tendon exhibits a hierarchical structure with each level comprising the assembly of many finer structures at lower scales. The mechanical behavior at each level thus depends on the immediate lower level, but also on the nature of the assembly. This behavior can therefore vary from one level to the next one, and as a corollary, the whole set of responses of the inherent entities govern the tendon response itself. It is accordingly necessary to provide context for this work in relation to the structure and behavior of tendon at its different hierarchical levels.

Tendons are natural fibrous composite materials; their complex structure has been widely described (e.g. Wang, 2006; Cowin, 2000): it can be modeled as a composite tissue, with a complex hierarchical arrangement going from collagen molecules (nanoscale) to fibrils (hundreds of nanometers), fibers (tens of micrometers), and different levels of fascicles (hundreds of micrometers) up to the macrolevel of the tendon. At the different levels of this hierarchy, discontinuous aligned structures are embedded in a hydrated matrix, and some levels (from subfascicles to the whole tendon) are surrounded by a thin membrane called the endotenon. Understanding the role and impact of the mechanics of the constituents at the separate scales on the behavior of the structure at the ultimate scale of the whole tendon is a very challenging problem, due to the combination of time-dependent (viscous) responses and geometrical as well as material nonlinear effects. Moreover, the proposition of accurate biomechanical constitutive theory accounting for the dynamic description of the tendinous microstructure is crucial for the development of novel healing methods in tissue engineering (Lin et al., 2004), technical applications in biomedical and (further) improvements of surgical techniques in tissue repair (Matheson et al., 2005), or for the finite element

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modeling of joints within the human body (Weed et al., 2009).

Tendons display high tensile strength and complex viscoelastic and anisotropic characteristics (Jozsa and Kannus, 1997), enabling elastic strain transfer with a capacity for shock absorption. From a physiological point of view, tendons are hierarchical structures consisting of the assembly of fibrils – principally collagen, with a content higher than 95% -, physiological liquid and little elastin. The collagen portion is made up of 97–98% type I collagen, with small amounts of other types of collagen, including essentially heterotypic collagens of type I, III, V, and a smaller fraction of collagens of type II, IX, XI+ and XII (Woo et al., 2006).

This type of structure and behavior grossly appears at each level, without being the same from one scale to the next one, since a given scale level is not the mere copy of the immediately preceding one. At the fiber level, each fiber is made almost exclusively of fibrils of collagen I. Fibers are assembled to form fascicles maintained by a membrane called the endotenon, similar to a perforated net-like structure serving as an insertion site for the collagen fibers. The endotenon includes blood vessels, nerves and lymphatic canals; moreover, it adheres to the tendon fibers. According to (Ritty et al., 2002), the mesh of this network consists principally of elastin with a Young modulus close to 0.6 MPa. The whole set of constituents is immersed into an extracellular matrix made of 70% water and tenocytes.

Contrary to fibers and fascicles, fibrils are not enclosed by a membrane; they are moreover linked together only by a few proteoglycan bridges (Silver et al., 2003). It makes therefore sense to make the approximation that fibrils are nearly mutually free, also assuming they have the same geometry and mechanical properties; the mechanical behavior of fibers can then be assimilated to that of fibrils (Franchetti and col. 2002; Silver et al., 2003). We presently adopt the simple Kelvin-Voigt model introduced in Shen (2010), which allows to bring to the fore the reasons of the difference of behavior at two consecutive scales. In our opinion, homogenization applied to a model with two relaxation times like the one lay down in the more recent works of Shen et al. (2011), cannot alter the nature of our results. In both cases, a complementary long range memory emerges, which however can only be determined with great difficulty.

In the present study, the organization of tendinous structure is simplified as illustrated on Fig. 1.

Numerous morphological observations (e.g. Kahn et al., 2010) have reported that collagen fibers have undulated structure and mainly arrange in plane with preferred orientations, which entails that fibers become only progressively active during a mechanical loading in the direction parallel or transverse to the fibers axis.

The typical uniaxial stress-strain relationship for tendon under quasi-static loading conditions is anisotropic and nonlinear like other soft connective tissues. Three regions can be distinguished (Fig. 2): an initial zone of low stress in the range of very small strains (the toe region), the linear region in which collagen fibers straighten under the effect of the local stresses, and the failure zone. These distinct parts of the stress-strain curve are correlated to the different structural changes occurring within the tissue during uniaxial loading (Wang, 2006).

The time-dependent behavior of tendons is important for the damping of transient stresses and optimization of tissue stiffness under different loading regimes (Woo, 1982; Kubo et al., 2002; Lynch et al., 2003). From a practical point of view, their viscoelastic properties make tendons act as mechanical buffers to protect the muscle fibers. The mechanisms of force transmission of the muscle-tendon unit are dependent on the structural arrangement between individual collagen fibers and the interstitial fluid (Kjaer, 2004; Butler et al., 1997). This fluid - also called the ground substance - consists of an amorphous gel-like structure containing proteoglycan, glycosaminoglycan and glycoproteins (Chen et al., 2013), which are hydrophilic macromolecules present in water-filled compartments. It has been clearly reported that this ground substance has an impact on the overall mechanical behavior of soft tissues (Minns et al., 1973).

Without explaining the very mechanisms and their contribution at each scale, tendon viscoelasticity has been explained either by sliding between collagen fibers (Gupta et al., 2010; Screen, 2008; Screen et al., 2013), by interactions at the molecular level (Usha et al., 2001; Puxkandl et al., 2002), or by interstitial fluid flow during loading (Swedberg et al., 2014). These mechanisms remain however poorly understood, and may differ between tendon types. A hysteretic behavior is observed in the range of 5%–10% strains, as revealed by loading unloading sequences, and many studies attempted to quantify the viscoelastic response of such tissues based on either relaxation tests, creep tests or by tensile testing at different rates (Peltonen et al., 2013; Shepherd et al., 2014; Wan et al., 2013; Wren et al., 2003). It has been emphasized that the underlying mechanisms of creep and relaxation may be different (Sopakayang et al., 2012), and that the tertiary creep is a damage mechanism leading to the rupture of tendon (Wang, 2006; Wren et al., 2003). Mechanical hysteresis in tendons has been traditionally quantified from tensile testing of isolated specimens (Ker, 1981; Shadwick, 1990; Devkota and Weinhold, 2003). Many contributions in soft tissue biomechanics focused on modeling the stress softening associated with cyclic loading (De Zee et al., 2000; Elliott et al., 2003; Natali et al., 2005). These are mainly rate and time-independent constitutive theories, based on phenomenological equations or rheological models like pseudo-hyperelastic models

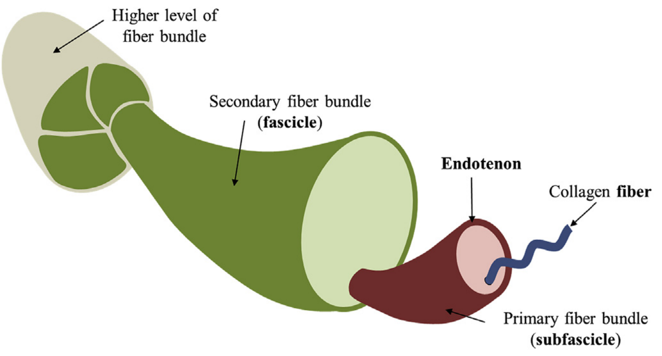

**Fig. 1.** Simplified hierarchical structure of a tendon considered in the present study.

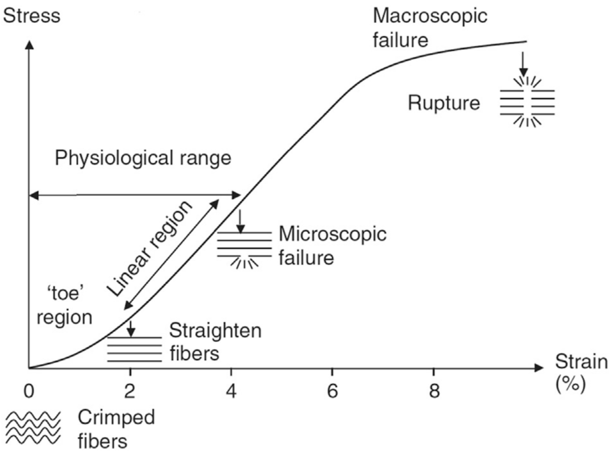

**Fig. 2.** Typical stress-strain response of tendon (Wang, 2006).