A COMPUTATIONAL INVESTIGATION OF THE TENDON-TO-BONE INSERTION: THE ROLE OF TISSUE ANISOTROPY

A. Malerba (1,2), A. Tits (2), T. Volders (2), P. Vena (1), D. Ruffoni (2).

(1) Politecnico di Milano, Italy. (2) University of Liege, Belgium.

Introduction

Understanding the mechanics of tendon-to-bone insertion is a challenging task, owing to the strong tissue dissimilarities occurring at this anatomical site: tendon is compliant and anisotropic, whereas bone is not only much stiffer but also much less anisotropic. At bimaterial attachments, differences in elastic properties can lead to peak stresses and failure. The insertion of the Achilles tendon (AT) into calcaneus bone (CB) occurs through a transitional tissue called fibrocartilage (FC). Some joints have two FC: enthesis FC anchoring tendon to bone and periosteal FC facilitating tendon sliding. Both FCs exhibit specific structure, composition and material properties, including a strong microstructural anisotropy at enthesis FC [1]. Little is known about the influence of FC properties on the force transmission from tendon to bone. Yet, such knowledge is of high clinical relevance as local stresses play a crucial role in enthesis pathologies and injuries such as enthesopathies and avulsion fractures. Here, we propose a two-dimensional (2D) finite element (FE) approach exploiting two idealized geometries of increasing complexity, to characterize the impact of enthesis FC on stresses at the tendon-bone interface.

Methods

Two FE models were developed and solved using Abaqus/CAE. The first model (Fig. 1) consisted in two regions with specific material properties, representing tendon and mineralized FC (mFC), with a load applied on the tendon extremity. In the second model (Fig. 2), we implemented a simplified geometry of AT attachment to CB, based on rat micro-computed tomography scans from a previous study [1]. The local stresses (extracted at the interface between AT and mFC) were investigated as a function of enthesis FC anisotropy and elastic properties. In both models, quadrilateral plane stress linear full integration elements were used. Bone and periosteal FC were considered isotropic, with an elastic modulus of 22 GPa and 17 GPa, respectively, based on previous nanoindentation measurements. Tendon and enthesis mFC were considered transversally isotropic with a principal modulus (E_t) of 500 MPa and 17 GPa, respectively. Other parameters ($E_p, \nu_{tp}, \nu_p, G_t, G_p$) were computed through suitable relationships proportional to E_t [2].

Results

Simulations based on the first model revealed strong variations in the stress level at the interface as a function of mFC anisotropy (Fig. 1). Such bi-material configuration is known to generate a stress concentration at the interface [3]. If both materials are isotropic, an interfacial stress 2.5 times higher than the applied boundary traction is generated. Here, we show that increasing the degree of anisotropy (expresses by the transversal component of the Poisson's ratio ν_{tp}) reduced stress concentration.

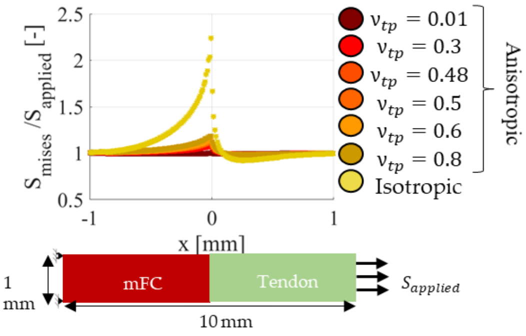

Fig. 1: Spatial variations of Von Mises stress at the tendon-mFC interface, normalized by the applied boundary traction, as a function of the degree of anisotropy ν_{tp}.

The same occurred in a more realistic setting (Fig. 2): using an anisotropic model for enthesis FC causes a reduction in interfaces stresses. Decreasing the elastic modulus mismatch between AT and FC also leads to a decrease in interfacial stresses but of a smaller extent than observed when changing the elastic anisotropy.

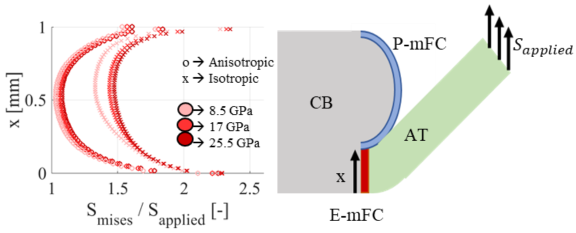

Fig. 2: Normalized von Mises stress at the interface between AT and enthesis mFC (E-mFC) as a function of mFC elastic properties and anisotropy.

Discussion

Models accounting for tissue anisotropy resulted in lower interface stress compared to isotropic tissue models. Despite the idealized geometry, this result suggests the critical contribution of the mechanical anisotropy of FC, based on high aligned collagen fibers at the enthesis. Our findings should provide guidelines for bimaterial attachments and enthesis reattachment surgeries.

References

1. Tits et al., Sci rep, 11:1–17, 2021.
2. Thomopoulos et al., J. Biomech, 1842-1851, 2006.
3. Uzan et al., Acta Biomater, 153:320-330, 2022.