STRUCTURAL AND MECHANICAL ANALYSIS OF CALCANEUS BONE AT THE ACHILLES TENDON INSERTION SITE

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Introduction

Soft tissues such as tendons and ligaments attach to bone thanks to a highly specialized multi-material interface. This complex tissue, called enthesis, enables load transfer between dissimilar materials with a large mismatch in mechanical behavior across a very small region of ca. 500 µm. Previous works have highlighted many strategies to enhance failure resistance at attachment sites including gradual changes in tissue composition and organization [1], unraveling of tendon fibers into smaller interface fibers [2], and interdigitations at the tendon/fibrocartilage and fibrocartilage/bone interfaces [3]. A less investigated aspect is whether the microstructure of bone shows distinctive features to facilitate the force “flow” from tendon to bone. In this context, a detailed analysis of local stresses at the bone-tendon interface based on realistic geometries is still missing. Such knowledge is of high clinical relevance as stresses close to the interface are believed to play a pivotal role in interfaces inflammation and degeneration. Here, we used micro-computed tomography (micro-CT) to characterize the structure of bone close to tendon insertion and microstructural finite element analysis (micro-FE) to calculate the stresses within the bone caused by tendon loading.

Methods

Adult Sprague Dawley rat specimens (n=4) of the calcaneus-Achilles tendon complex were scanned at isotropic voxel size ranging from 5 to 2 µm (SkyScan-1272). Lower resolution scans were used to characterize the structure of the whole calcaneus, including the anatomical landmarks of the attachment site as well as the insertion area. Higher resolution images of the epiphysis encompassing the growth plate and the insertion location were acquired to study surface roughness as well as local porosity. Micro-FE simulations were employed to estimate stress concentrations in the calcaneus caused by the large mismatch in the elastic properties between tendon (0.2 GPa) and bone (15 GPa), assuming different pulling directions. Cubic element meshes were generated with HyperMesh and solved with Abaqus.

Results

At the insertion site, we observed an evident tuberosity protruding up to 660 µm and spanning over 1300 µm (Figure 1). The tuberosity had low porosity (less than 10%) and, on the tendon side, showed high surface roughness (up to 90% greater than adjacent locations). The bone beneath the attachment region contained elongated pores (Figure 1, inset), aligned along the pulling direction of the tendon. Micro-FE simulations underlined a complex and highly heterogeneous stress distribution, with high stresses observed not only at the interface (Figure 1, inset) but also within the underlying bone, even far from tendon insertion.

Discussion

We highlighted a morphological protrusion facilitating load transmission from the Achilles tendon to the plantar ligament through bone in adult rats. The high roughness at the tendon insertion is probably due to mineralization gradients within fibrocartilage and may enhance interface toughness [3]. Despite the low porosity and consequently high rigidity of the tuberosity, this region contains anisotropic pores likely oriented to minimize peak stresses. Our results suggest that not only the interface but also the underlying bone is well-adapted to accommodate tendon loading. Ongoing work focuses on the impact of aging on the structure and mechanical competence of the bone-tendon complex.

References