Microstructural and micromechanical investigation of the tendon-bone attachment

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Introduction
Tendons anchor to bone through a specialized multi-material region called enthesis. Multiple strategies are present at attachment sites to enhance failure resistance, including gradual changes in tissue composition, unraveling of tendon fibers into smaller fibrils, and interdigitations [1]. Less understood is whether bone microstructure shows features to facilitate force transmission from tendon to bone. In this context, a detailed analysis of the micromechanical environment at the bone-tendon interface is missing. Such knowledge is of clinical relevance as interfacial stresses play a role in interface inflammation and degeneration. We used micro-computed tomography (micro-CT) to characterize the microstructure of bone close to tendon insertion and image-based fine element analysis (micro-FE) to calculate stresses within the bone induced by tendon loading.

Methods
Adult Sprague Dawley rat specimens (n=5) of the calcaneus bone-tendon complex were scanned at isotropic voxel size ranging from 5 to 1.2 µm (SkyScan, Bruker). Lower resolution scans were used to investigate whole bone microstructure. Higher resolution images were acquired to study canal network and surface roughness at the insertion site. With micro-FE simulations we characterized stress distributions assuming different pulling directions.

Results
After aligning the virtual bones along the main axes of inertia, we observed an evident bony tuberosity connecting the Achilles tendon with the plantar fascia ligament. We performed a spatially resolved analysis of trabecular microstructure, suggesting that trabecular network was not significantly influenced by the tendon insertion. Conversely, bone beneath the attachment region showed a highly oriented canal network, aligned along the pulling direction of the tendon. Surface roughness was significantly higher at the tendon insertion with respect to nearby locations. Micro-FE simulations clarified the contributions of these different microstructural features to local stresses.

Discussion
Our work suggests that not only the interface but also the underlying bone is well-adapted to accommodate tendon loading.