TRABECULAR ARCHITECTURE IN HUMAN CALCANEUS BONE AND FUNCTIONAL ADAPTATION TO TENDON INSERTION

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Introduction

More than a century ago, Wolff's law defined bone as a highly adaptive tissue responding to its mechanical environment. Yet, relating bone microstructure to external loading is not straightforward, given the unknowns on loading history and on several aspects of mechanoregulation. Most of the studies investigating mechanical adaptation have considered the proximal femur [1].The femoral head is directly loaded by external forces (through the hip), whereas the femoral neck transmits internal stresses to the shaft. An alternative location to investigate bone adaptation is below the enthesis, where tensile forces applied by the muscle-tendon complex are distributed to the bone. In this work, we exploited natural differences in loading conditions found in the human calcaneus to investigate microstructural adaptation. Employing high-resolution peripheral quantitative computed tomography (HR-pQCT), we conducted a position-resolved analysis of trabecular bone in human calcanei, focusing on regions subjected to different loading coming from body weight (BW) and Achilles tendon (AT) (Fig. 1a). A specific emphasis is given on bone adjacent to the Achilles tendon insertion, which was analyzed at high resolution with micro-computed tomography (micro-CT).

Methods

Eight samples were collected from four female donors aged 88 to 94 years, considering both right and left calcanei [2]. HR-pQCT (82 µm voxel size) was used to scan the whole calcanei. Morphological parameters were assessed in a central region delimited by two sagittal sections and having a thickness of 1.8 cm, corresponding approximately to the width of the enthesis in the transversal plane (Fig. 1b). We performed a spatially resolved analysis within a 3x3x3 mm cubic volume of interest (VOI), which was moved through the calcaneus. Within each cube, we computed bone volume fraction (BV/TV), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp) and trabecular number (Tb.N). A spherical VOI inscribed in the cube was used to evaluate the degree of anisotropy (DA) and the preferred orientation of the trabeculae. Results were grouped into 3 regions, based on loading conditions and dominant trabecular patterns [3]. Smaller samples were obtained by trimming the calcanei at the posterior region around the enthesis, and were scanned with micro-CT (17.4 µm voxel size). Individual trabecular analysis was performed after skeletonizing the trabecular network.

Results

Higher BV/TV and Tb.Th were found in regions below the enthesis (loaded in tension) and below the talus (loaded in compression). The distal portion of the calcaneus showed the lowest BV/TV and highest Tb.Sp (Fig. 1c). Trabeculae prevalently loaded in tension had higher BV/TV, Tb.Th and DA, with their prevalent orientation being towards the enthesis (Fig 2b). Local trabecular analysis confirmed high trabecular orientation beneath the enthesis, and further highlights that longer the trabecula, higher is its alignment (Fig 2a).

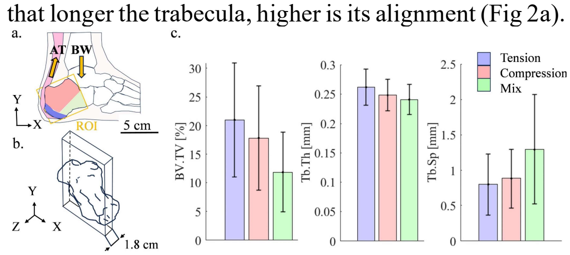

Fig. 1 (a) Illustration of extracted regions based on anatomical landmarks and loading conditions (b) Illustration of the central region studied (c) Bar plots display mean values and standard deviations of morphological parameters for the entire dataset (n=8).

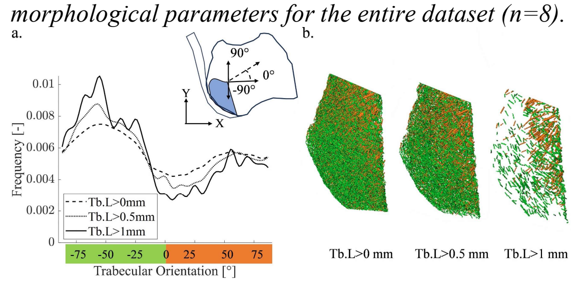

Fig. 2 (a) Frequency plot of trabecular orientation (sagittal plane) beneath the enthesis (blue region) for varying trabecular lengths across the micro-CT dataset. (b) Skeletonized trabecular network beneath the enthesis highlighting orientations of green (-90° to 0°) and orange trabeculae (0° to 90°) for different lengths.

Discussion

This study emphasized the consequences of Wolff's law on trabecular microstructure at calcaneus bone. The morphology and the orientation of the trabeculae below the enthesis should reflect the mechanical needs: the correlation between trabecular length and alignment may indicate that this region maximize rigidity and strength, while minimizing bending. The trabeculae under predominant compression were slightly thinner and more spaced than those under tension, perhaps to provide some compliance and energy absorption ability at the bone region below the talus. Future work may use exploit finite element analysis to correlated microstructure with local mechanical behavior.

References

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2. Metcalf et al., Bone, 106:69-77, 2018
3. Gefen et al., Med Eng Phys., 26:119-129, 2004