Trabecular Bone has the Capacity for Hemiosteonal Collagen/Lamellar “Morphotype” Adaptation: Implications for Advancing Understanding of the Emergence of Skeletal Fragility in the Elderly

John G. Skedros, MD, Chad S. Mears, Richard T. Epperson, Roy D. Bloebaum, PhD
University of Utah, Salt Lake City, Utah, USA

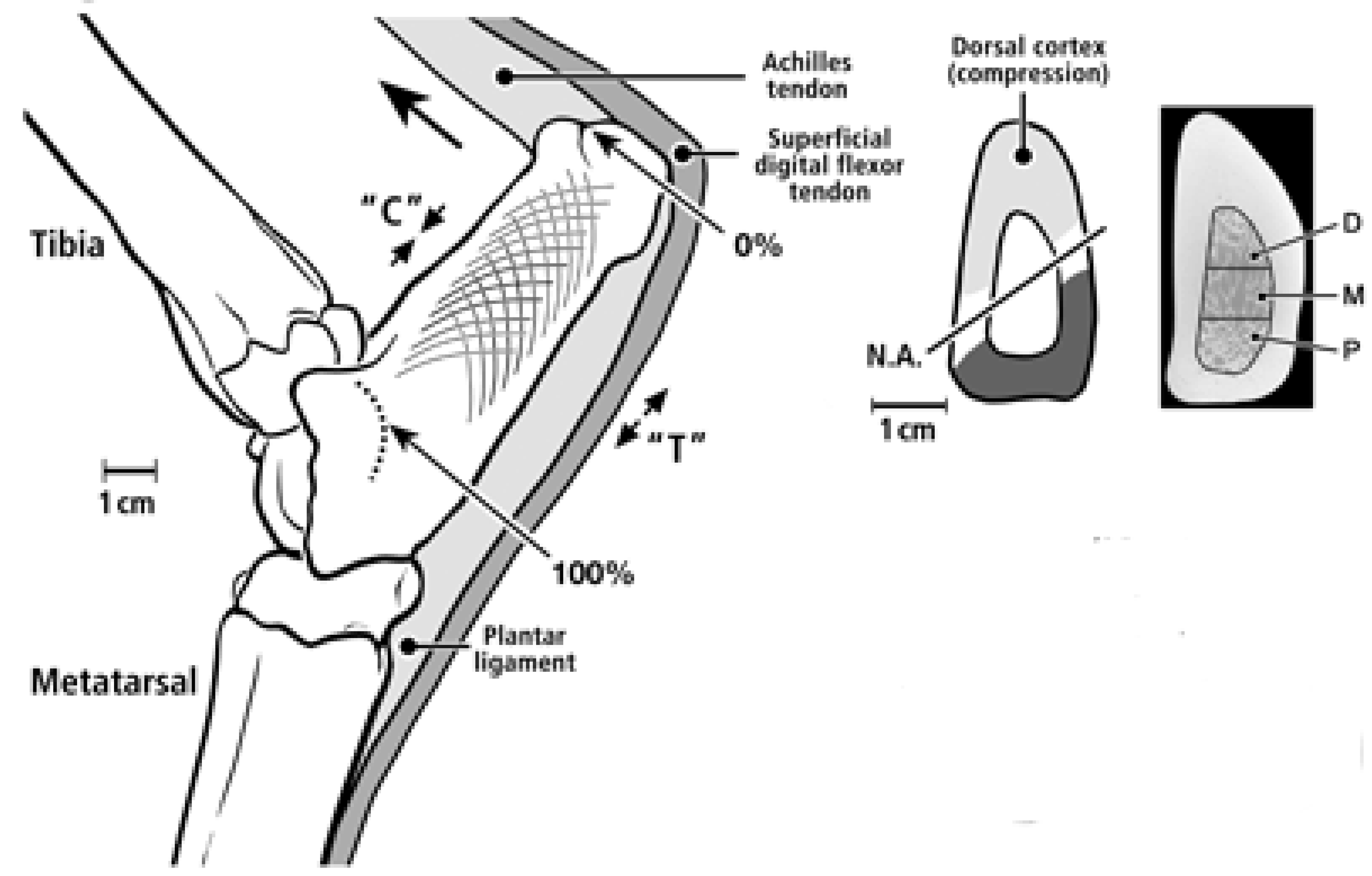
Introduction

There is substantial interest in determining how trabecular (cancellous) bone adapts to mechanical loads. Most studies have focused on the adaptability of trabecular bone in the context of structural (architectural) variations. The reasons for this focus are clear: the majority of variance in conventional mechanical tests of bulk specimens can be explained by variations in a few of these trabecular architectural characteristics. However, there is evidence that trabecular bone can also exhibit phenotypic plasticity of its material organization, which could have important influences in mechanical properties including toughness and fatigue resistance at the bulk and local trabecular levels. These variations include: (1) bone tissue mineral density, (2) bone tissue mineral density distribution (BMDD), (3) hemiosteonal packet prevalence, (4) lamellation differences in hemiosteonal packets, and (5) nanoscale mineral grain patterns [7-10]. One characteristic that has not been studied is the possibility that trabecular bone can exhibit mechanically adaptive variations in the collagen/lamellar organization of the hemiosteons that form the “packets”. It is well known that cortical (compact) bone has the capacity to adapt in terms of the collagen/lamellar organization of secondary osteons (i.e., Haversian systems). These are called secondary osteon “morphotypes”, which are important toughening mechanisms in cortical bone. We hypothesized that trabecular bone has the capacity for similar adaptations between regions that are habitually subject to tension vs. compression strains.

Methods

To determine the potential for the adaptive plasticity of trabecular bone, the simply loaded model of a deer calcaneus was used because it is known to have significant differences in hemiosteonal packet prevalence, BMDD, and/or tissue mineralization between trabecular bone from the dorsal “compression region” vs. plantar “tension region” [9]. The calcanei from ten adult animals were obtained from the sample used in our prior studies [2,9]. Transverse segments from the middle-third of each calcaneal shaft were embedded in polymethyl methacrylate. These segments were then sectioned and milled to 50 microns and mounted on slides. Confocal microscopy was used to ensure that there was no, or minimal, overlap of secondary hemiosteonal packets. Then, using the light microscope, images were obtained of the dorsal “compression region” cortical and trabecular bone, and from the plantar “tension region” cortical and trabecular bone (Fig.1). Images were obtained at 10X using circularly polarized light (CPL), and the predominant collagen fiber orientation (CFO) was quantified in terms of weighted mean gray levels (WMGL) (where brighter gray levels are expressed as higher WMGLs, and reflect “compression-adapted” CFO) [11]. The heterogeneity of CFO (CFO-het) was expressed as the full width at one-half of the maximum of the gray level profile [7,9].

Figure 1



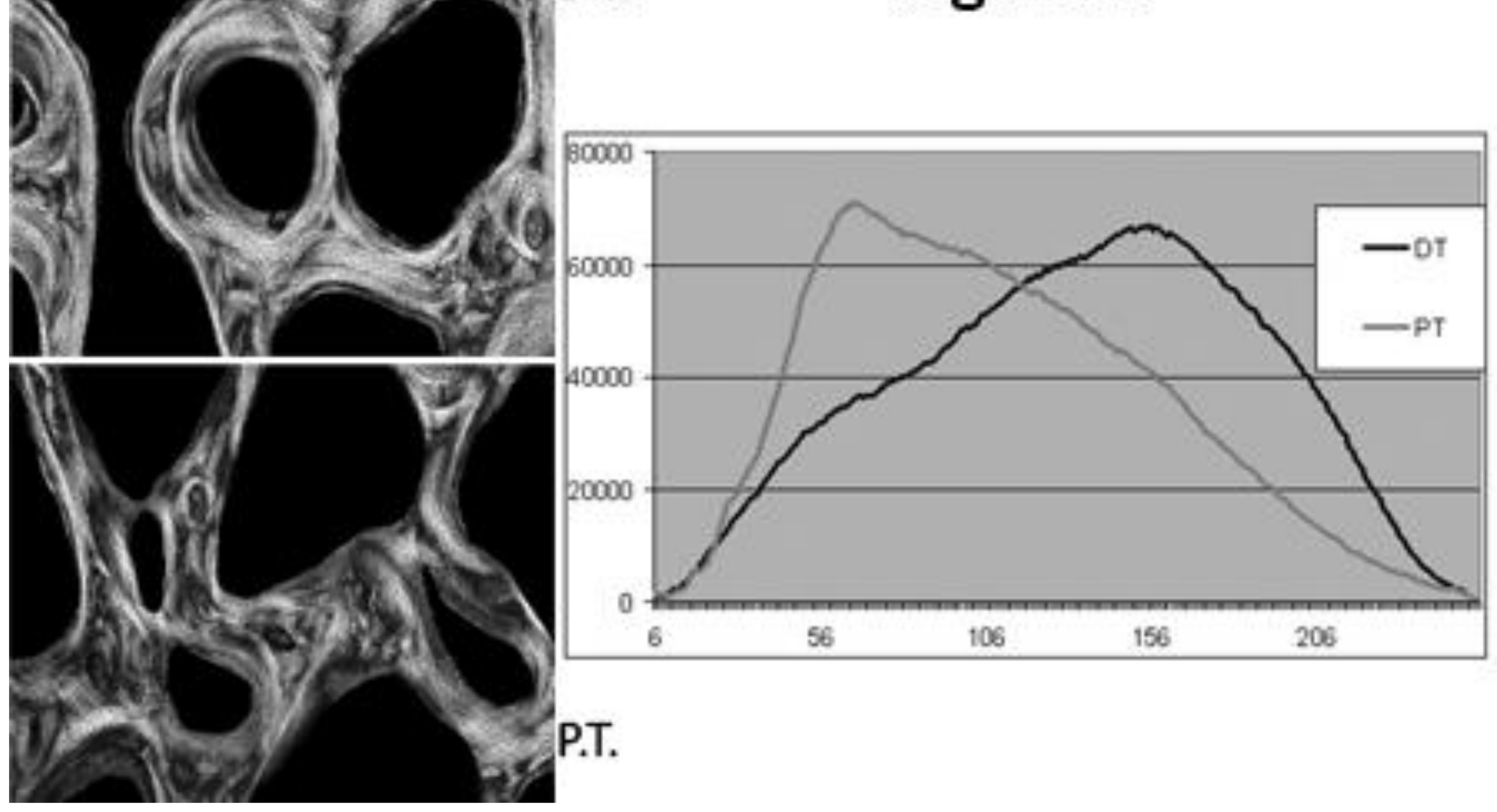
Results

Data from cortical bone showed expected CFO differences (p=0.02): more oblique-to-transverse “compression-adapted” CFO in the dorsal vs. more longitudinal “tension-adapted” CFO in the plantar cortex.

Also, supporting the hypothesis, CFO was also more oblique-to-transverse in the dorsal trabecular and more longitudinal in the plantar trabecular bone (dorsal WMGL 119.6±17.6; plantar 98.3±20.2; p<0.001) (Fig. 2).

Finally, CFO heterogeneity (CFO-het) was also significantly greater in the dorsal “compression” cortex.

Figure 2



D.T. = Dorsal Trabecular
P.T. = Plantar Trabecular

Discussion

Similar to secondary osteons in cortical bone, hemiosteons in trabecular bone can adapt in terms of their collagen/lamellar organization. These hemiosteonal “morphotypes” are therefore homologous to the secondary osteon “morphotypes” that have been described in various species, including humans and chimpanzees [9,11-13]. Similar trabecular-level adaptation might be present in bones that are habitually subject to nonuniform strain distributions, including the human femoral neck. It would be important to determine if this occurs and if these putative differences then become deficient with aging, perhaps contributing to the degradation of tissue mechanical properties (i.e., bone quality) in ways that are not detected when using measures of areal or volumetric bone mineral density (BMD; e.g., from DEXA scans).

Studies are also warranted during aging of trabecular bone in vertebral bodies and in other areas that are prone to fracture in the elderly. Resolving these issues can be clinically relevant when considering that initial failure of the proximal femur from a sideways fall is associated with failure of a tiny proportion of the bone tissue (1-6%) [3].

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