Abstract 100: Orthopaedic Research Society; Vol. 37. 2012.

Micro-Computed Tomography Characterization of the Trabecular Bone Architecture of the Deer Calcaneus: A Potential "Control Bone" for Interpreting Femoral Neck Adaptation and Loading

[1,2]Sinclair, KD; [2]Farnsworth, RW; [2]Pham, TX; [1]Knight AN, [1,2]Bloebaum, RD; +[1,2]Skedros, JG

[1]Bone and Joint Research Laboratory, Department of Veterans Affairs SLC Health Care System, [2]Univ. of Utah Dept. of Orthopaedics, Salt Lake City, UT

Corresponding Author: jskedros@utahboneandjoint.com

INTRODUCTION

Femoral neck fractures cause severe impairment of mobility, lifestyle, and even mortality. The human femoral neck has been studied extensively to understand factors that predispose individuals to fractures within this region. These characterizations have included attempts to identify the functional roles of cortical and trabecular bone. For over a century, many investigators have considered the arched trabecular patterns of the proximal human femur to represent materialized stress trajectories that convey the tension and compression stresses produced by stereotypical bending. This conception reflects the conventional modeling of the human femoral head-neck as a short cantilevered beam loaded in bending. Although this conception has formed the foundation of many biomechanical, clinical, and morphological studies of trabecular bone, there have been few attempts to contrast these data to a bone that could be considered a "control" for simple/stereotypical bending. In this study we quantified trabecular architectural characteristics in an artiodactyl (deer) calcaneus model as a first step in potentially developing this bone as a "control bone" in this context. This bone is considered a potential "control" because it has: (1) arched trabecular patterns that reflect tension/compression stress trajectories, and (2) been shown to be relatively simply loaded in bending by strain gage analyses. Using micro-computed tomography (micro-CT), calcanei from adult deer were analyzed between the dorsal "compression" and plantar "tension" tracts, where trabecular bone begins to separate and bending is relatively simple (proximal shaft). Nine trabecular architectural characteristics were evaluated; many of these have been shown to be sensitive to stress magnitude and mode. It was hypothesized that the dorsal region of the deer calcaneus would show adaptations for compressive loads, while the plantar region would show adaptations for tensile loads.

METHODS

With IACUC approval, 13 calcanei from mature, male wild Rocky Mountain mule deer were dissected free of soft tissue and measured from 0% (distal) and 100% (proximal) shaft locations [1]. The calcanei were scanned using micro-computed tomography (GE Medical Systems EVS-RS9). Regions of interest (ROI) were selected at 40 and 50% of the shaft length. The ROI were 3 mm in width along the calcaneal length. Scanning parameters included 46.4 μm resolution, 80 kVp, 450 μA, and 500 ms exposure time. Architectural characteristics examined include: degree of anisotropy (DA), bone volume fraction (BVF), bone surface density (Bs/Bv), trabecular thickness (Tb.Th), trabecular spacing (Tb.Sp), trabecular number (Tb.N), connectivity density (Conn.D), structural model index (SMI) and trabecular-cortex connections (Tb.Ct.Conn). Analysis was conducted in dorsal, middle, and plantar ROI. Statistical significance was determined using paired T tests.

RESULTS

Significant differences were found between the dorsal "compression" and plantar "tension" trabecular tracts in terms of Tb.N ($p=0.01$) and Tb.Ct.Conn ($p=0.03$) (See Table). The values for DA, BVF, Bs/Bv, Tb.Th, Tb.Sp, Conn.D, and SMI were not significantly different between dorsal-plantar regions. SMI values were suggestive of honeycomb-like trabecular architecture in the dorsal and plantar regions (Figs. 1A, 2); however, in the middle region the trabeculae are plate-like (Figs. 1B, 2).

DISCUSSION

Evaluation of the 9 trabecular architectural characteristics of the deer calcaneus revealed the possibility of specific adaptations for compression vs. tension loads, as shown by the significant differences in Tb.N and Tb.Ct.Conn. It may be that these differences enhance mechanical properties in the plantar cortex to account for the fact that trabecular bone is 30% weaker in tension vs. compression loading [2]. Support for this includes several studies that have shown that Tb.N is often one of the most important characteristics in explaining variance in trabecular stiffness and strength. However, Tb.N is usually the third or fourth most important characteristic in this context [3-6], with BVF, SMI, and Tb.Th often being more important. However, these latter characteristics did not differ between the dorsal and plantar tracts. In view of our results showing that 7 of 9 characteristics are not important, an alternative explanation is that these results reflect the fact that

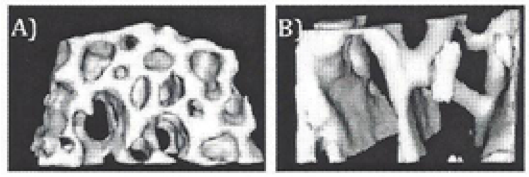
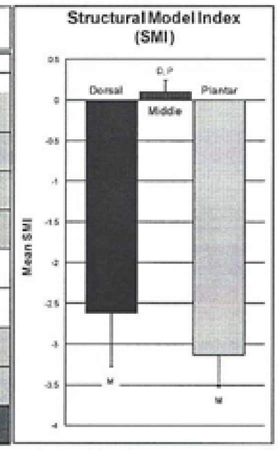


Figure 1: Micro-CT images of deer calcaneus trabecular bone.

Architectural Characteristics [Means (Standard Errors)]

	Proximal (40%-50% locations)		
	Dorsal	Middle	Plantar
DA	4.99 [M] (0.31)	6.09 [D, P] (0.88)	4.25 [M] (0.33)
BVF	0.54 [M] (0.03)	0.34 [D, P] (0.01)	0.56 [M] (0.02)
Bs/Bv	5.59 [M] (0.37)	9.33 [D, P] (0.30)	5.95 [M] (0.38)
Tb.Th	0.44 [M] (0.04)	0.25 [D, P] (0.01)	0.41 [M] (0.05)
Tb.Sp	0.58 (0.06)	0.71 [P] (0.11)	0.47 [M] (0.03)
Tb.N	**1.46 [M, P]** (0.06)	1.59 [D] (0.09)	**1.64 [D]** (0.06)
Conn.D	2.18 [M] (0.21)	4.42 [D, P] (0.45)	2.79 [M] (0.26)
SMI	-2.62 [M] (0.65)	0.10 [D, P] (0.15)	-3.13 [M] (0.38)
Tb.Ct.Conn	13.58 [M, P] (0.78)	8.14 [D, P] (0.44)	18.41 [M, P] (1.32)



[dark shading] = Each location is statistically different ($p \leq 0.05$) from the other locations.
[light shading] = Middle is statistically different ($p \leq 0.05$) from dorsal and plantar.
Bolded Text = Dorsal and plantar locations are statistically different ($p \leq 0.05$).
Superscript letters represent significant differences ($p \leq 0.05$) between trabecular locations (D = Dorsal; M = Middle; P = Plantar).

Table 1: Results of structural variables analysis.

Figure 2: SMI data for the deer calcaneus indicated negative values (honeycomb-like trabeculae) in the dorsal and plantar regions, with values approaching 0 (plate-like trabeculae) in the middle region.

adaptation for tension or compression is not strongly revealed by isolated trabecular characteristics. Important synergisms likely occur between trabecular and nearby cortical bone, in addition to the load-sharing functions of nearby musculo-tendinous structures. For example, it is likely that the asymmetric cortical thickness (thicker dorsal cortex) coupled with the dorsally-plantarly elongated (elliptical) cross section are important in modifying the strains seen in the trabecular tracts [7]. Significant differences in dorsal vs. plantar Tb.Ct.Conn might reflect this synergism. The plantar ligament and superficial digital flexor tendon also have been shown to be important load-sharing members [8]. Studies of these synergisms are needed to establish the deer calcaneus as a "control bone" for trabecular architectural adaptation. Multiple regression analyses in the context of tension and compression loading of both tracts, and in terms of many trabecular architectural characteristics, are also an obvious next step in further developing this model.

SIGNIFICANCE

The femoral neck has been studied extensively in an attempt to understand the factors that predispose individuals to fractures in this region. Due to the inability to directly measure strains on the femoral neck, the experimentally accessible artiodactyl calcaneus model has been used to determine the effects of simple, uniaxial loading on the physical properties of bone [9]. Our results are a further step toward establishing the strengths and limitations of the deer calcaneus as a "control bone" for habitual bending, as is thought to often occur in the human femoral neck.

REFERENCES

[1] Skedros et al. 2004 J Morphol 259:281-; [2] Keaveny et al. 1994 J Biomech 27:1137-; [3] Mittra et al. 2005 J Biomech 38:1229-; [4] Diederichs et al. 2009 Bone 44:976-; [5] Liu et al. 2010 J Bone Miner Res 25:746-; [6] Ulrich et al. 1999 Bone 25:55; [7] Fox and Keaveny, 2001 J Theor Biol 212:211-; [8] Su et al. 1999 J Exp Biol 202:3239-; [9] Skedros and Baucom 2007 J Theor Biol 244:15-.