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GEOMETRIC ANALYSIS OF A TENSION/COMPRESSION SYSTEM: IMPLICATIONS FOR FEMORAL NECK MODELING

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Since the time of Meyer, Culmann, and Wolff, the distinctive arched arrangement of trabeculae seen in frontal views of the proximal human femur have been interpreted as structural features that belie the presence of principal tensile (superio-lateral) and compressive (inferio-medial) stress trajectories, which are presumably the result of bending loads [1]. Although this interpretation for the stresses in the beam-like proximal femur has largely been embodied as conventional wisdom in the orthopedic literature [2], it continues to be challenged [3]. Indeed, the roughly-elliptical to near-circular crossectional shape and the thin veneer of cortical bone in the femoral neck have been interpreted as structural evidence that bespeak the predominance of compressive, not tensile, stress across the superior aspect of this region [4,5]. The objective of this study is to document a similar crossectional geometry in a skeletal structure that actually receives principal tensile and compressive stresses and exhibits a similar distinctive arched arrangement of trabecular tracts.

MATERIALS AND METHODS: The selection of the skeletal structure derives from the landmark study by Lanyon [6] where the directions of in vivo compressive and tensile strains measured on sheep calcanei were shown to be coincident with the cranial and caudal trabecular tracts, respectively. Male Rocky Mountain mule deer (Odocoileus hemionus hemionus) calcanei were obtained from a game processing plant (Davis Co., Utah) during the 1988 Utah deer hunting season. One calcaneus from each of 28 pairs was randomly selected. These calcanei were cut transversely into seven sections from the free end (20%) to the joint end (80%). Cortical thickness was measured at the cranial (superior), caudal (inferior), medial, and lateral aspects of each section. The overall cranial-caudal height and medio-lateral width was also measured at each section. To assess the skeletal maturity of each calcaneum, the epiphyseal growth plate at the distal calcaneal tuber (shaft) was examined for the presence of cartilage. Data was analyzed in three groups: skeletally mature (n = 9), skeletally immature (n = 19), and the entire sample. Statistical significance between comparisons of cortical thickness values was assessed using an ANOVA design.

RESULTS AND DISCUSSION: Figure 1A shows the roughly-elliptical shapes of the sections taken from the free end of the tuber. This shape, along with the thin veneer of cortical bone and predominance of cancellous bone, resembles that exhibited by the human femoral neck (fig. 1B). Linear regression analysis showed that in both skeletally mature and immature calcanei, the cortical thickness progressively increased along cranial ($r = 0.98$, $p < 0.001$) and caudal ($r = 0.93$, $p < 0.005$) cortices from the free end to the joint. Medial and lateral cortical thicknesses were not significantly different in all medial to lateral comparisons at any given section in both groups ($p > 0.05$).

The calcanei of sheep and deer are cantilevered, beam-like skeletal structures that receive bending loads imparted at the free end from the extensor musculature which primarily confines actions and their resulting bending deformations to the sagittal plane. These loads place the cranial cortex, and presumably cranial trabecular tract, in net compression and the caudal cortex, and presumably the caudal trabecular tract, in net tension [6] (fig. 2). In lateral view, this skeletal structure resembles a plane straight cantilever with parabolic stress trajectories. In designing his now-famous crane, Culmann first drew a similar-appearing plane cantilever, then bent it into a curved crane-like bar [1]. Wolff, convinced that the stress trajectories in Culmann's crane corresponded exactly to the distinctive trabecular architecture in the proximal human femur, predicated his doctrine on these trajectories [1] (fig. 2). The mule deer calcaneus not only exhibits distinctive arched trabecular patterns and fluted cortices similar to those in Culmann's crane, but also displays a roughly-circular crossectional geometry with a thin veneer of cortical bone in the region that coincides with intersections of the trabecular tracts in both Culmann's crane and the human femoral neck. It is suggested that the presence of distinctive arched trabecular patterns, fluted cortical architecture, and similar crossectional geometries in the deer calcaneus, Culmann's crane, and the proximal human femur bespeaks somewhat similar stress distributions. In light of these observations, there is no clear structural evidence that the human femoral neck is a compression/compression (superior/inferior) or tension/compression (superior/inferior) system. Further study is warranted to clarify the magnitudes and distributions principal of tensile stresses across the human femoral neck during normal activity.

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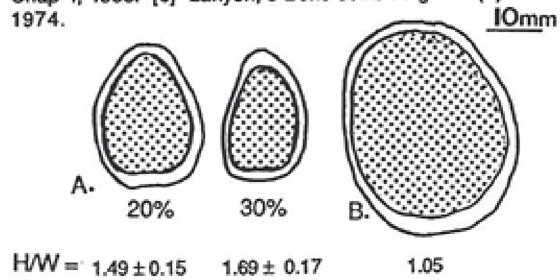

Fig. 1A: 20 & 30% sections from the free end of the deer calcaneus. **B:** Human femoral neck. H/W = height/width ratio.

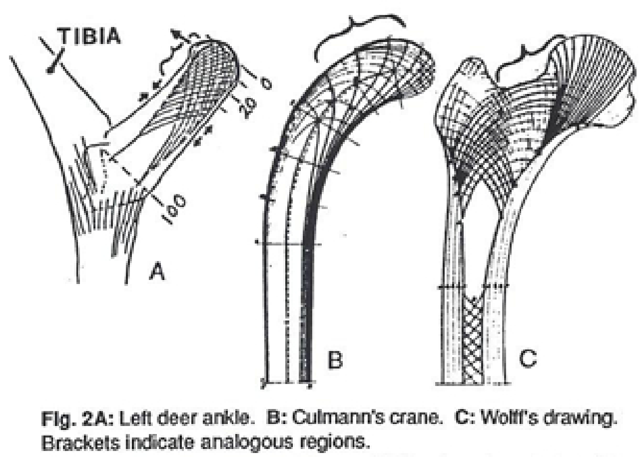

Fig. 2A: Left deer ankle. **B:** Culmann's crane. **C:** Wolff's drawing. Brackets indicate analogous regions.

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