RELATIVE EFFECTS OF COLLAGEN FIBER ORIENTATION, MINERALIZATION, POROSITY, AND PERCENT AND POPULATION DENSITY OF OSTEONAL BONE ON EQUINE CORTICAL BONE MECHANICAL PROPERTIES IN MODE-SPECIFIC LOADING

J.G. Skedros¹, M.R. Dayton¹, and K.N. Bachus²
¹Bone and Joint Research Laboratories, Veterans Affairs Medical Center, Salt Lake City, Utah
²Orthopedic Bioengineering Research Laboratory, University of Utah, Salt Lake City, Utah
Email: kent.bachus@hsc.utah.edu

INTRODUCTION
Predominant collagen fiber orientation (CFO) can significantly influence the mechanical properties of cortical bone (e.g., Martin and Ishida, 1989; Martin and Broadman, 1993; Riggs et al., 1993). Previous studies have demonstrated that CFO is a strong predictor of tensile, compressive, or bending strength. Few of these studies, however, have examined the relative effects of CFO, mineralization, and other microstructural variables in the context of the in vivo habitual loading mode (“mode-specific loading” e.g., compression testing specimens from a habitually compressed cortical region, or tension testing specimens from a habitually tensed cortical region) (Riggs et al., 1993). Evaluating mechanical influences of such histologic variables in the context of a habitual loading mode is important since: 1) in vivo studies have shown long bones of all animals studied receive directionally consistent bending during typical daily gait-related activities (Biewener, 1993), and 2) cortical bone is substantially stronger and stiffer, has different fatigue behavior, and likely has greater toughness in compression than in tension. Consequently, a long limb bone must accommodate regional strain-mode-related disparities in habitual loading. Analyses of bone in specific loading modes may demonstrate a rather different role for CFO than suggested by studies that have not evaluated mechanical properties in mode-specific loading. This study tested the hypothesis that CFO will more strongly correlate with energy absorption, a measure of toughness, than with elastic modulus, yield stress, or ultimate stress in compression-tested specimens from “compression” regions.

METHODS
Cubic specimens (5x5x5mm) were cut from “compression” cortices of 10 mature standard bred horse 3rd metacarpals at mid diaphysis (n: caudal = 20, cranial-medial = 10). Specimens were tested unrestrained to ultimate failure in axial compression at 0.002/sec (Riggs et al., 1993). Specimen fragments were evaluated for percent ash content (%ash; 550°C), predominant CFO using circularly polarized light, porosity, percent of osteonal (secondary) bone, and secondary osteon population density (OPD) (Skedros et al., 1996). Data were evaluated using Pearson correlations.

RESULTS
Energy density absorbed to yield stress (0.2% offset criterion). CFO explained the greatest percentage of variance (r = 0.411, p=0.03) and was followed by percent osteonal bone (r = 0.367, p=0.05) and OPD (r = 0.346, p=0.06).
Total energy density absorbed to ultimate stress. CFO explained the greatest percentage of variance (r = 0.565, p=0.002). %Ash was the only other parameter exhibiting a significant correlation (r = 0.441, p=0.01).
**Ultimate stress.** %Ash explained the greatest percentage of variance \((r = 0.508, p=0.004)\) and was followed by OPD \((r = 0.364, p=0.05)\), percent osteonal bone \((r = 0.330, p=0.07)\), and porosity \((r = -0.312, p=0.09)\).

**Yield stress.** %Ash explained the greatest percentage of variance \((r = 0.403, p=0.03)\) and was followed by OPD \((r = 0.350, p=0.06)\).

**Elastic modulus.** %Ash explained the greatest percentage of variance \((r = 0.451, p=0.01)\). Porosity was the only other parameter approaching a significant correlation \((r = -0.310, p=0.09)\).

**Histologic correlates.** The most strongly correlated parameters were percent secondary bone and OPD \((r = 0.897, p<0.00001)\). Additional significant correlations included CFO with percent osteonal bone \((r = 0.667, p=0.0001)\) and OPD \((r = 0.614, p=0.0006)\).

**DISCUSSION**

These data demonstrate that CFO most strongly influences the elastic and total energy density absorbed. Martin and Ishida (1989) investigated the relative importance of CFO, porosity, density, and mineralization on tensile strength of bovine cortical bone. Linear regression analysis showed that CFO was consistently the single best predictor of tensile strength. Martin and Broadman (1993) demonstrated that among CFO, porosity, mineralization and histologic type (plexiform, mixed, or osteonal), CFO ranked highly as a predictor of bending properties. These data reflect conventional wisdom that the in vivo role for predominant CFO is primarily for affecting strength- or stiffness-related material properties. In contrast, the present data suggest that CFO may more strongly influence regional material “toughness” for in vivo mode-specific loading conditions. The probability that this is primarily achieved by remodeling is supported by the linked relationships of CFO with percent osteonal bone and population density of secondary osteons. It is therefore plausible that these linked relationships enable bone remodeling to affect post-yield properties (and possibly microdamage incidence) by “toughening” specific regions for locally prevalent habitual loading modes. There are data suggesting that such differential tissue organization would be beneficial since notable disparities in microdamage accumulation can occur in “compression” vs. “tension” cortical regions during physiologic loading (Reilly et al., 1997, 1999). This may be the mechanical explanation for regional ultrastructural and microstructural heterogeneities that have been reported in “tension” and “compression” cortices of various limb bones (Riggs et al., 1993; Skedros et al., 1996, 1997).

**REFERENCES**


