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RELATIVE CONTRIBUTIONS OF MATERIAL CHARACTERISTICS TO FAILURE PROPERTIES OF CORTICAL BONE IN STRAIN-MODE-SPECIFIC LOADING: IMPLICATIONS FOR FRAGILITY IN OSTEOPOROSIS & AGING

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INTRODUCTION

Recent studies of mechanical properties of cortical bone in osteoporotic and aged skeletons reveal significant reductions in toughness or energy absorption -- a hallmark of post-yield behavior (McCalden et al., 1993). Variations in mineral content (% ash), porosity, or secondary osteon population density (OPD), however, can not explain a large percentage of the variance in these mechanical test data. Additional material characteristics may also be important, including osteon crosssectional area, osteon shape, and fractional area of secondary bone (FASB) (cement line interfaces). The artiodactyl (deer) calcaneus is an ideal model for investigating the relative contributions of various material characteristics because it has remarkable regional (i.e., within the same cross-section) variability in material organization. Recent studies have shown significant regional differences in %ash, OPD, FASB, porosity, osteon crosssectional area, and osteon shape (Skedros et al., 1994a,b, 1997). These differences are greatest between cortices that experience primarily compression (cranial) or tension (caudal) loads.

In this study we examined the influence of multiple *material* characteristics on the pre- and post-yield behaviors of cortical bone of deer calcanei in the context of habitual in vivo “strain-mode-specific” loading (e.g., *compression testing* bone from a habitually *compressed* region). Evaluating mechanical influences of such histologic variables in the context of a habitual loading mode is important since: 1) in vivo studies have shown that 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.

METHODS

One calcaneus was obtained from each of 19 skeletally mature mule deer. Using a coring bit, one 3.0mm diameter, 5.0mmheight cylindrical specimen was removed from each cranial cortex of eight randomly selected bones. From the remaining calcanei, one specimen of each caudal cortex was milled into a dumbbell shape for tension testing (Riggs et al., 1993) with a gauge length of 10mm.

Compression tested cylindrical specimens were loaded to failure along the long axis of the bone (long axis of the cylinder) at a strain rate of $0.003 sec^{-1}$. (Testing machine: Model 1125, Instron Corp., Canton, MA; 5kN-load cell)

Tension tested dumbbell-shaped specimens were aligned in grips, and an extensometer (MTS 632.13F-20, MTS Corp., Minneapolis, MN) was used for measuring displacement.

Elastic (to yield), plastic, and total (elastic + plastic; to ultimate stress) energy absorption were calculated for both tension and compression loading. Fragments from near the fracture sites were examined for: **1**) %ash at 550°C, **2**) porosity, **3**) OPD, **4**) FASB, **5**) osteon cross-sectional area, and **6**) osteon cross-sectional shape.

RESULTS (Multivariate Analyses)

Elastic energy absorbed (to yield stress). Compression-specific loading showed that the greatest percentage of variance (43%; where total explained = 46%) was attributable to osteon area (r = 0.817, p=0.02) and OPD (r = -0.807, p=0.02). In tension-specific loading, all variables explained only 27% of variance.

Plastic energy absorbed (Total – Elastic). Compression-specific loading showed that the greatest percentage of variance (71%; where total explained = 72%) was attributable to OPD (r = 0.834, p=0.02), %ash (N.S. = non-significant, p > 0.1), and osteon shape (N.S.). Tension-specific loading showed that the greatest percentage of variance (72%; where total explained = 84%) was attributable to OPD (N.S.), osteon area (N.S.), and osteon shape (N.S.).

Total energy absorbed (to ultimate stress). Compression-specific loading showed that the greatest percentage of variance (40%; where total explained = 54%) was attributable to porosity (r = 0.691, p = 0.085) and %ash (N.S.). Tension-specific loading showed that the greatest percentage of variance (79%; where total explained = 81%) was attributable to OPD (N.S.), osteon area (N.S.), osteon shape (N.S.), and %ash (N.S.).

DISCUSSION

Only in compression-specific loading were significant correlations shown with the microstructural characteristics (osteon area and OPD). The conspicuous lack of statistical significance and inconsistent associations with the material characteristics and mechanical properties suggest that: 1) there is insufficient statistical power to demonstrate an effect, or 2) there are additional characteristics that more strongly, and consistently, explain the variance in these data. We favor the latter explanation. For example, predominant collagen fiber orientation has been shown to be preeminent in explaining the variance in energy absorption in strainmode-specific loading of cortical bone from horse third metacarpals (Skedros et al., 2000). Microscopic mineral heterogeneity and the percentage of intermolecular collagen cross-links should also be targeted for investigation. There are data suggesting that such differential tissue organization might be expected, and beneficial in a biomechanical context, since notable disparities in microdamage accumulation can occur in “compression” vs. “tension” cortices during physiologic loading (Reilly et al., 1997, 1999). The skeletal fragility seen in osteoporosis and aging may be strongly influenced by microdamage accumulation in poor quality bone, since impaired homeostatic remodeling processes do not maintain tissue with normal material properties.

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