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STRAIN-MODE SPECIFIC LOADING OF CORTICAL BONE REVEALS AN IMPORTANT ROLE FOR COLLAGEN FIBER ORIENTATION IN ENERGY ABSORPTION

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INTRODUCTION: It is now well known that osteoporosis and age-related senescence significantly impair the *material* properties of *both* cancellous and cortical bone tissue. Consequently, skeletal fragility produced by these processes results from both osteopenia *and* poor-quality bone. McCalden et al. [3] studied material properties of diaphyseal cortical bone obtained from patients ranging from 20 to 102 years. They documented significant age-related reductions in ultimate stress, ultimate strain, and energy absorption. Although relative influences in calcium content, % osteon bone, and porosity were statistically examined, these variables explained only 60% of variance in the energy absorption data. They suggested that changes in other characteristics, which are not typically considered in such studies, may be relatively more influential in the degradation of this important mechanical property. Such variables include collagen cross-linking and collagen fiber orientation. However, little is known about how these variables affect bone material properties during normal physiologic loading.

Recent studies have suggested that regional variations in predominant collagen fiber orientation (CFO) may be important in affecting microdamage accumulation in cortical bone [7]. Additionally, local variations in predominant CFO explain the greatest percentage of variance in energy absorbed to failure (a measure of "toughness") in standard compression tests [9]. In addition to CFO, this recent study also examined the contributions of mineral (%ash) content, secondary osteon population density, fractional area of secondary bone, and porosity. Both of these studies utilized bone from horse third metacarpals in locations where stress fractures are prevalent. The present study further examined the role of CFO in affecting cortical bone "toughness".

MATERIALS AND METHODS: Dumb-bell-shaped specimens were machined from "tension" and "compression" cortices of 10 mature standard bred horse third metacarpals at mid diaphysis (n: cranial-lateral=12; caudal-medial=17). (Disparities and reductions in specimen numbers occurred after some were discarded because of artifactual fracture.) Strain measurements were made with an MTS extensometer and specimens were tested to ultimate failure in axial **tension** at 0.01/sec [6]. Specimen fragments were evaluated for percent ash content (550°C), predominant CFO using circularly polarized light, porosity, percent of osteonal (secondary) bone, and secondary osteon population density (OPD) [8].

RESULTS: **Only data from the habitual "tension" (cranial-lateral) cortex revealed a preeminent role for CFO:**

Total energy density absorbed to ultimate stress. CFO explained the greatest percentage of variance ($r = 0.724$, $p=0.03$). Porosity was the only other parameter exhibiting a significant correlation ($r = -0.669$, $p=0.05$).

Energy density absorbed to yield stress (0.2%-offset criterion). Porosity explained the greatest percentage of variance ($r = -0.736$, $p=0.02$). No other parameter approached a statistically significant correlation.

Ultimate stress. Porosity explained the greatest percentage of variance ($r = -0.821$, $p=0.007$) and was followed by CFO ($r = 0.505$, $p=0.17$).

Yield stress. Porosity explained the greatest percentage of variance ($r = -0.830$, $p=0.006$). No other parameter approached a statistically significant correlation.

Elastic modulus. Porosity explained the greatest percentage of variance ($r = -0.756$, $p=0.02$). No other parameter approached a statistically significant correlation.

Results from both tension and compression regions: Porosity explained the greatest percentage of variance in the total energy absorption data ($r = -0.493$, $p = 0.03$). No other parameter, including CFO, approached a statistically significant correlation. Similar to tension-region data, porosity explained the greatest percentage of variance for all other mechanical parameters.

DISCUSSION: These data demonstrate that CFO most strongly influenced the total energy density absorbed in strain-mode-specific testing (i.e., tension testing of bone habitually loaded in tension). These results seem novel in the context of past studies. For example, Martin and Ishida [1] investigated the relative importance of CFO, porosity, apparent density, and mineralization on tensile strength of bovine cortical bone. They showed that CFO was consistently the single best predictor of tensile *strength*. Martin and Broadman [2] demonstrated that among CFO, porosity, mineralization and histologic type (plexiform, mixed, or osteonal), CFO ranked highly as a predictor of *bending properties*. Although these studies did not examine physiologic "strain-mode-specific" loading, they support a conventional view that CFO primarily affects *strength- or stiffness-related* material properties. In contrast, the results of the present and a recent study [9] suggest that CFO may more strongly influence regional material "toughness" for in vivo mode-specific loading. Regional adaptation of predominant CFO may affect post-yield properties (and possibly microdamage incidence) by "toughening" local regions for the habitual loading mode. Such differential tissue adaptation would be beneficial since microdamage accumulation: 1) can occur with different frequency in "compression" vs. "tension" cortices during physiologic loading [4,5], 2) becomes more prevalent with age, and 3) has been linked to a decrease in bone strength and stiffness, which may play a role in osteoporotic fragility fractures and stress fractures.

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