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SAFETY FACTORS AS THE OBJECTIVE OF CORTICAL BONE ADAPTATION

DAYTON, M.R., NELSON, M.C., SKEDROS, J.G.†, BLOEBAUM, R.D.
Bone and Joint Research Laboratory, VA Medical Center and The Division of Orthopedic Surgery
University of Utah School of Medicine, Salt Lake City, UT 84148

Introduction Recent authors have suggested that the maintenance of uniform safety factors (ratio of bone failure stress to maximum in vivo stress) between cortical regions may represent a goal of a bone's morphologic adaptation (1). The objective of the present study is to examine this hypothesis by conducting mechanical tests on cortical specimens from a limb bone that has been subjected to rigorous characterization of its in vivo strain environment.

Methods In vivo strain gauge documentation and finite element analysis of the equine third metacarpal (MC3) reveals a neutral axis passing through the cranio-lateral cortex resulting in a narrow band of habitual tensile strains with the remainder of the cortex experiencing a wide range of compression strain magnitudes (2). Two MC3s obtained from each of ten skeletally mature animals were used for mechanical testing. Six 5x5x5 mm cubic specimens were taken from the cortex of one of each pair at 50% of length. Two cubes were machined from each of the cranio-lateral (CrL) and caudo-medial (CdM) cortices, and one each from the cranio-medial (CrM) and lateral cortices. This produced 60 specimens for compression testing. From the contralateral MC3 of each pair, four cortical tensile specimens were machined, two from each of the CrL and CdM cortices, also at the 50% level, producing an additional 40 specimens.

Compression testing was conducted using an Instron 4303 with a 25 kN load cell, and specimens were compressed to failure along the cortical longitudinal axis between parallel plates at a strain rate of 0.001 sec^{-1} (1). Strain measurements were obtained from crosshead displacements corrected for machine compliance. Tensile tests were conducted using an MTS 858 Bionix with a 2 kN load cell. Tensile specimens were aligned in grips and tested to failure at a strain rate 0.01 sec^{-1} (1). Young's modulus (E) and yield stress (YS) were calculated from force-displacement curves. A 0.2% strain offset criterion was used to determine yield point.

Normal physiologic strain values were obtained from finite element mesh data in a recent study on the in vivo mechanical milieu of the equine MC3 (2). Using E measured in the present study, strain (ε) values were converted into in vivo (physiologic) stress data ($E \times \varepsilon$). Safety factors (SFs) are expressed as the ratio of measured yield stresses to calculated in vivo stresses.

Results Mechanical YS values are roughly equivalent in all cortical regions in each mode of loading. Although E values are moderately greater in tension specimens than in compression specimens, variations in E are minor within each mode of loading. In vivo strain data demonstrates that the CdM cortex clearly experiences the highest physiological compressive stress, while the CrL is subject to tensile stresses of approximately one-tenth of the maximum physiologic compression stresses (2). This results in a wide variation in yield SFs between regions across the cortex (Table1, Fig. 1). Under compressive loads, the CrL and CrM cortices have the highest yield strength, while lateral and CdM cortical regions tolerated lower compressive YS (Table 1). No mechanically relevant differences in tension yield strength were noted between the CrL and CdM regions, even though the CrL region is habitually loaded in tension and the CdM region in compression (2).

Discussion These data show large differences in yield SFs across the cortex at the mid-shaft of the equine MC3. Comparisons of E and yield SF values of the CrL cortex in tension vs. CdM, CrM, and lateral cortices in compression are important since bone fails more easily in tension than in compression (3). Since the measured material properties are roughly equivalent between regions loaded in each strain mode, the wide variation in SFs can be attributed to the markedly heterogeneous distribution of strain magnitudes (2). Consequently, apparent regional differences in material adaptations (e.g., collagen orientation, mineral content) which have been described in the equine MC3(4) do not result in compensatory alterations in elastic and yield behaviors. Therefore, uniform SFs do not appear to be the primary objective or goal of cortical adaptation in this bone.

Recent studies by Riggs and co-workers using the equine radius (and the same methods as the present study) have suggested that uniform SFs may represent the goal of cortical bone adaptation in specific regions (1,5). In contrast, Rubin and co-workers consider a uniform SF hypothesis untenable since it would appear to require the common occurrence of relatively high stresses and strains associated with yield behavior. These investigators suggest that lower strains produced during customary physiological loading may convey some biologically beneficial information which contributes to maintaining cortical morphology with adequate, but not necessarily uniform SFs (6).

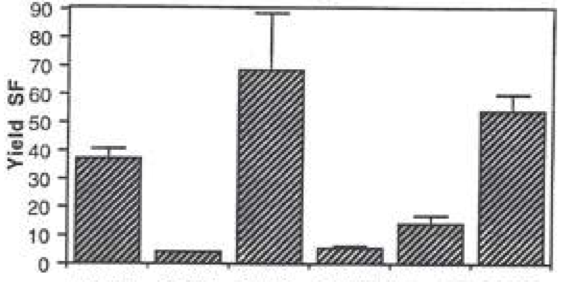
Elucidating the ultimate goals of bone adaptation poses an important challenge since this knowledge will improve our ability to apply basic biologic principles to practical therapeutic interventions in common orthopedic problems including fracture healing and osteoporosis.

Table 1*

		A	B	C	D
Test Mode	Region	Young's [GPa]	Phys Stress [MPa]	Yield Stress [MPa]	Yield SF [C/B]
Tension	CrL	17.81(1.86)	3.97(0.35)	148.59(15.45)	37.5(3.5)
	CdM	17.26(2.21)	37.20(4.83)	148.07(17.36)	4.0(0.6)
Compression	CrL	11.88(3.04)	2.65(0.67)	172.04(20.79)	68.9(20.0)
	CdM	12.97(2.56)	28.00(5.39)	157.71(23.25)	5.7(0.7)
	Lat	13.92(4.56)	11.36(3.72)	158.57(40.01)	14.4(2.6)
	CrM	14.30(2.76)	3.46(0.67)	185.68(23.85)	54.5(6.0)

* ()=1 Std. Dev., Lat=Lateral, Phys=Physiological.

Figure 1: Yield SF vs. Cortical Region**



**(T)=Tension Load, (C)=Compression Load

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†Dept. of Orthopaedic Surgery, U.S.C., Los Angeles, CA.

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FULL Name, Address, Phone, Fax, and E-Mail Numbers of Corresponding Author:

M. R. Dayton
Bone & Joint Research Lab (151F)
VA Medical Center
500 Foothill Blvd.
Salt Lake City, UT 84148
Tel: (801) 582-1565 Ext. 4607
Fax: (801) 584-2533