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Yield strain behavior of trabecular bone

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Abstract

If bone adapts to maintain constant strains and if on-axis yield strains in trabecular bone are independent of apparent density, adaptive remodeling in trabecular bone should maintain a constant safety factor (yield strain/functional strain) during habitual loading. To test the hypothesis that yield strains are indeed independent of density, compressive ($n = 22$) and tensile ($n = 22$) yield strains were measured without end-artifacts for low density ($0.18 \pm 0.04\ \mathrm{g\,cm^{-3}}$) human vertebral trabecular bone specimens. Loads were applied in the superior–inferior direction along the principal trabecular orientation. These 'on-axis' yield strains were compared to those measured previously for high-density ($0.51 \pm 0.06\ \mathrm{g\,cm^{-3}}$) bovine tibial trabecular bone ($n = 44$). Mean ($\pm$ S.D.) yield strains for the human bone were $0.78 \pm 0.04\%$ in tension and $0.84 \pm 0.06\%$ in compression; corresponding values for the bovine bone were 0.78 ± 0.04 and $1.09 \pm 0.12\%$, respectively. Tensile yield strains were independent of the apparent density across the entire density range (human $p = 0.40$, bovine $p = 0.64$, pooled $p = 0.97$). By contrast, compressive yield strains were linearly correlated with apparent density for the human bone ($p < 0.001$) and the pooled data ($p < 0.001$), and a suggestive trend existed for the bovine data ($p = 0.06$). These results refute the hypothesis that on-axis yield strains for trabecular bone are independent of density for compressive loading, although values may appear constant over a narrow density range. On-axis tensile yield strains appear to be independent of both apparent density and anatomic site.

Keywords: Trabecular bone; Yield strain; Safety factor; Remodeling; Spine

1. Introduction

It has been hypothesized that bone adapts to produce uniform functional apparent strains in both cortical and trabecular bone in response to habitual loads (Turner et al., 1997). If yield strains were also uniform, this would imply that the set point for remodeling is some ratio of the yield strain to the functional strain or a 'safety factor'. Wolff's law implies that trabecular orientation aligns itself to the direction of the functional principal stresses (Cowin, 1986). As a consequence, the relevant yield strains in consideration of bone adaptation are those for 'on-axis' loading of the bone (i.e. along the principal trabecular orientation). It has also been hypothesized that aging and disease may decrease the yield strain of bone and thus its safety factor (Biewener et al., 1993). One prerequisite to establishing the above hypotheses is to determine the dependency of the on-axis yield strains of trabecular bone on apparent density and to do this for a range of anatomic sites. A more complete understanding of the yield strains in trabecular bone is also fundamental to continued progress in computer modeling of whole bones (Keyak et al., 1993; Lotz et al., 1991; Silva et al., 1996), which in turn may improve diagnosis and treatment of pathologies that weaken trabecular bone such as osteoporosis.

While there is mounting evidence that apparent failure strains in trabecular bone are independent of apparent density, the data are not conclusive. A number of studies have shown no dependence of compressive failure strains on apparent density (Ford and Keaveny, 1996; Hansson et al., 1987; Keaveny et al., 1994; Lindahl, 1976; Rohl et al., 1991), but a number of others have shown failure strains to increase (Hvid et al., 1989; Keaveny et al., 1994; Turner, 1989) or decrease (Hvid et al., 1985; Mosekilde et al., 1987) with increasing apparent density. It is not clear whether the former studies lacked statistical power to show a real dependence or if differences in anatomic

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site, trabecular orientation, definition of the failure strain, or experimental testing techniques accounted for these different findings. For example, accurate data on apparent failure strains for trabecular bone are difficult if not impossible to measure if end-artifacts are present since strain measures are highly sensitive to this artifact (Keaveny et al., 1993; 1997; Odgaard and Linde, 1991). In the context of understanding trabecular bone failure as it pertains to bone adaptation, very few data exist for on-axis apparent failure strains since specimens are usually machined along anatomic directions which rarely align with the principal trabecular orientation. Thus, there is a need for a study on trabecular failure strains that minimizes end-artifact errors, uses bone from different anatomic sites, and tests the bone in the on-axis orientation.

Based on predictions of an axial strut cellular solid model for trabecular bone (Fig. 1) (Christensen, 1986; Gent and Thomas, 1959; Gibson, 1985; Gibson and Ashby, 1988; Rajan, 1985), the hypothesis was developed in this study that, *for on-axis loading*, compressive apparent yield strains should be positively correlated with apparent density due to underlying buckling mechanisms. Since the slenderness (length/thickness) ratio of individual trabeculae decreases as apparent density increases (Snyder et al., 1993), the significance of this relationship should diminish as density increases due to a lower propensity for trabeculae to buckle. Since buckling cannot occur in tension, it was also hypothesized that the tensile apparent yield strains should remain constant regardless of anatomic site or species due to axial yielding of trabeculae. The following questions were addressed specifically: (1) What are the relationships between the compressive and tensile yield strains vs apparent density for human vertebral trabecular bone? (2) Are these yield strains and strain–density relationships different from those measured previously for bovine tibial trabecular bone (Keaveny et al., 1994)? and (3) For a single anatomic site, is the variance in yield strains small enough to reasonably assume constant yield strains in bone adaptation simulations? The results were then discussed in the context of bone adaptation, aging, and disease.

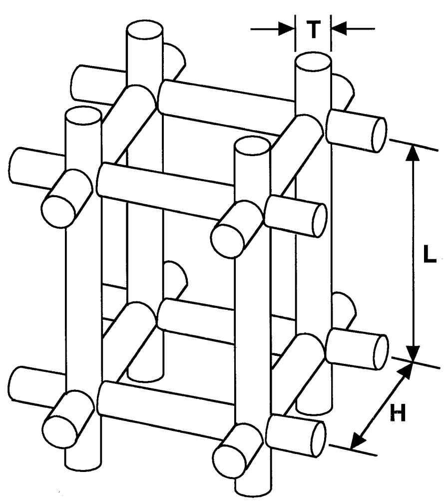

Fig. 1. Axial strut cellular solid model with strut thickness (T), vertical strut length (L) and horizontal strut length (H). This model was used to motivate the hypothesis that compressive yield strains should be positively correlated with apparent density due to buckling of trabeculae, and that tensile yield strains should be independent of density due to axial yielding of trabeculae.

2. Methods

Seventeen fresh frozen vertebrae, T10-L4, without radiographic evidence of bone pathologies, were obtained from 11 cadavers (Table 1). Forty-eight cylindrical specimens (8 mm diameter, 25 mm length nominally) were cored in water with marrow *in situ* along the superior–inferior direction. With the central portion ($\sim$ 15 mm) wrapped in damp gauze, marrow was removed from the ends ($\sim$ 5 mm), which were then glued into pre-aligned brass end-caps. The specimens were then randomly assigned to a tension or compression group. This protocol eliminates end-artifact errors during testing (Keaveny et al., 1997). The data from a previous experiment (Keaveny et al., 1994) were obtained from 44 specimens from the bovine proximal tibia. These specimens were also cored parallel to the trabecular orientation, but with a reduced cross-section.

Uniaxial compressive and tensile mechanical tests were performed on the vertebral specimens at room temperature using a servohydraulic load frame (858 mini-bionix, MTS, Eden Prairie, MN). The end-capped specimens were cycled five times nondestructively between $\pm 0.1\%$ strain (fully reversed compression-tension) at 0.5% strain per second, allowing a paired comparison between the compressive and tensile moduli.

Table 1
Seventeen fresh frozen vertebrae, T10–L4, and 44 cylindrical trabecular bone specimens, none of which showed radiographic evidence of bone pathologies, were obtained from 11 human cadavers, ages 32–65 yr (mean = 54, SD = 11 yrs)

Cadaver ID	Segment level	No. of Cylindrical specimens	Age	Sex
A	L4	4	50	M
B	T11, T12	6	63	F
C	L2	3	58	F
D	T12	2	61	F
E	T12, L2	6	64	F
F	T11, T12	4	61	M
G	T12, L1	6	58	M
H	L4	2	65	F
I	L4	2	37	F
J	T10–T12	6	50	M
K	L4	3	32	M

Specimens were then loaded destructively to 3% strain in either compression or tension. Strains were measured by a 25 mm gage length extensometer (632.11F-20, MTS, Eden Prairie, MN) attached to the end-caps. (The bovine specimens had been tested previously with a miniature extensometer attached to the reduced-section, but our subsequent work on this bone has shown that this method produces strains in agreement with the current method.) The effective gage length was assumed to be the length of the bone exposed between the end-caps plus half the length of bone embedded in the end-caps. This general 'end-cap' technique has been validated for measurement of elastic properties without end-artifacts (Keaveny et al., 1997). A miniature 5 mm extensometer was attached to the central region of 29 specimens. These data verified that the end-cap technique was valid for measuring failure properties also, since specimens did not fail preferentially at their ends due to potential stress concentrations at the end-caps. Overall, 44 of the 48 specimens were successfully tested ($n = 22$, compression; $n = 22$, tension). After testing, specimens were sectioned from the end-caps and cleaned of marrow. Water was removed from the marrow space with an air jet. Hydrated apparent densities were calculated as the wet mass divided by bulk volume.

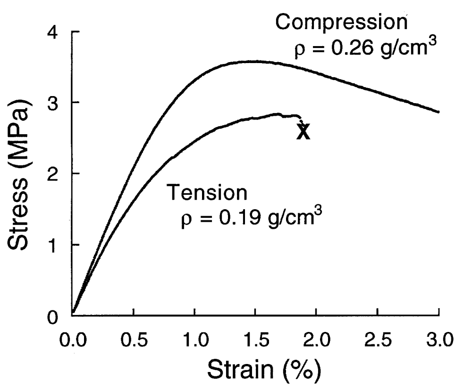

Fig. 2. Typical compression and tension stress–strain curves for the final destructive loading ramp for two human vertebral specimens of different apparent density (ρ). The lower density of the tensile specimen accounts for its lower modulus and strength. The absence of any nonlinear toe region indicates that end-artifacts were successfully eliminated. Note that the stress–strain curves for both specimens have clearly entered the nonlinear region at strains of less than 1.0%, while ultimate strains were less than 2.0%. **X** indicates fracture of the tension specimen; the compression specimen did not fracture.

Analysis of variance, *t*-tests and regression analysis were performed (Systat, Version 5.2, Systat Inc., Evanston, IL) to analyze the data. Elastic modulus was defined as the slope of the best fit straight line to the stress–strain data over a range of 0.02–0.24% strain (Fig. 2). The yield point was defined using a 0.2%-strain offset method; and the ultimate point was defined at the point of maximum stress. Similar protocols were used for the bovine tibial bone, except the modulus was defined over the range of 0.1–0.4% strain (Keaveny et al., 1994). These strain ranges were chosen in order to sample data over as much of the elastic range as possible, which was found to be larger for the bovine bone.

3. Results

Tensile yield strains for the human vertebral bone were independent of apparent density ($p = 0.31$) while compressive yield strains showed a weak but highly significant positive correlation with density ($r^2 = 0.52$, $p = 0.0002$) (Table 2). Ultimate strains were independent of apparent density in both compression ($p = 0.64$) and tension ($p = 0.19$), although these data showed considerably more scatter than the yield strains. As expected, elastic modulus (Fig. 3), yield stress (Fig. 4), and ultimate stress for the human vertebral bone demonstrated strong positive correlations with apparent density.

Table 2

Linear and power law regressions relating mechanical properties (Y) to apparent density (ρ, g cm^{-3}) for the human vertebral trabecular bone. Yield strains were linearly related to apparent density in compression, but independent of apparent density in tension. Exponents for the strength vs apparent density power laws tended towards 1.6 in compression and 1.0 in tension. ($n = 22$ unless otherwise indicated)

	$Y = a + b\rho$						$Y = a\rho^b$					
	Compression			Tension			Compression			Tension		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
Yield strain (%)	0.66	1.09	0.49		NS		1.24	0.21	0.48		NS	
Ultimate strain (%)		NS			NS			NS			NS	
Yield stress (MPa)	− 1.40	19.6	0.73	—	10.1	0.51	32.6	1.60	0.70	10.0	1.04	0.51
Ultimate stress (MPa)	− 1.46	21.9	0.71	—	13.2	0.47	33.2	1.53	0.68	13.3	1.07	0.47
Modulus (MPa)[a]	—	2100	0.61				2350	1.20	0.60			

—indicates intercept in the linear regression was not significantly different from zero ($p > 0.05$); NS indicates regression was not significant ($p > 0.05$).

[a]Regressions for modulus are for pooled compression-tension data ($n = 44$).

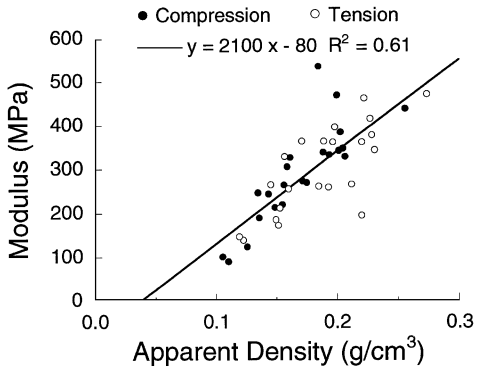

Fig. 3. Pooled compressive and tensile elastic moduli for the human vertebral specimens ($n = 44$) were linearly proportional to apparent density. The intercept was not significantly different from zero ($p = 0.10$).

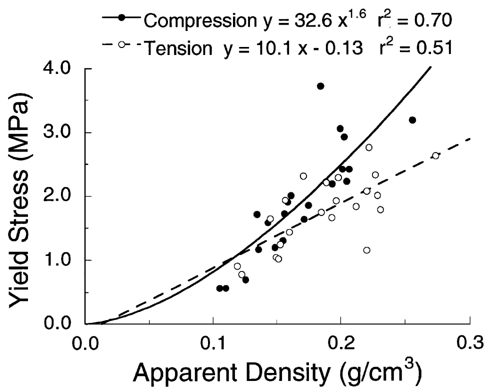

Fig. 4. Compressive and tensile yield strains were strongly correlated with apparent density. When buckling dominates compressive axial failure of trabeculae, the axial strut cellular solid model predicts a squared relationship between compressive yield strain and density. A least-squares power-law fit to this data predicts an exponent of 1.6 (Table 2). Since buckling cannot occur in tension, axial yielding dominates tensile failure and the axial strut model predicts a linear relationship.

When the low-density human vertebral and high-density[1] bovine tibial specimens were pooled, yield strain behavior remained similar across the entire range of densities for tension but differed in compression (Fig. 5). Tensile yield strains for the pooled data (mean $\pm$ S.D. $= 0.78 \pm 0.04\%$) were independent of apparent density ($p = 0.97$), and values were not different ($p = 0.99$) for the two types of bone. By contrast, the

[1]Apparent densities for the bovine trabecular bone were originally reported based on QCT mineral densities (Keaveny et al., 1994). We noticed in retrospect that values were too large with respect to similar specimens for which apparent densities were directly measured. Therefore, QCT-based apparent densities were scaled down 17% to produce a correct mean apparent density (mean $\pm$ S.D. $= 0.51 \pm 0.06\ \mathrm{g\,cm^{-3}}$, range $= 0.39$–$0.65\ \mathrm{g\,cm^{-3}}$).

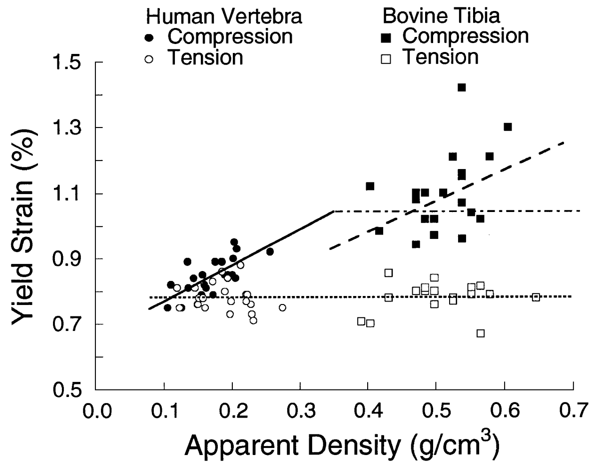

Fig. 5. Compressive and tensile yield strains vs wet apparent density for both human vertebral (current study) and bovine proximal tibial (Keaveny et al., 1994) trabecular bone specimens tested on-axis without end-artifacts. Tensile yield strains were constant at approximately 0.78% strain across the entire range of densities (dotted line). At low densities, compressive yield strains were linearly related to density ($p = 0.0003$, solid line), but approximately constant at 1.09% strain at high densities (horizontal dash–dot line) although a positive trend did exist ($p = 0.06$, dashed line).

Table 3
Mean values ($\pm$ S.D.) and ranges of compressive and tensile mechanical properties for the human vertebral specimens. Yield strains were significantly higher in compression. All other measures were statistically similar in compression and tension. Corresponding data for the bovine tibial specimens are reported elsewhere (Keaveny et al., 1994)

	Compression ($n = 22$)	Tension ($n = 22$)	p[a]
Wet apparent density ($\mathrm{g\,cm^{-3}}$)	0.17 ± 0.04 $0.11 - 0.26$	0.19 ± 0.04 $0.12 - 0.27$	0.12
Modulus (MPa)	291 ± 113 $90 - 536$	301 ± 100 $139 - 472$	0.76[b]
Yield strain (%)	0.84 ± 0.06 $0.75 - 0.95$	0.78 ± 0.04 $0.71 - 0.88$	0.0003
Ultimate strain (%)	1.45 ± 0.33 $0.96 - 2.30$	1.59 ± 0.33 $1.09 - 2.51$	0.18
Yield stress (MPa)	1.92 ± 0.84 $0.56 - 3.71$	1.75 ± 0.65 $0.77 - 2.75$	0.46
Ultimate stress (MPa)	2.23 ± 0.95 $0.70 - 4.33$	2.23 ± 0.76 $1.33 - 3.53$	0.99

[a]p-values for comparison of compressive vs tensile group means, using unpaired Student's t-test.
[b]A paired Student's t-test ($n = 44$) for compressive vs tensile moduli for each specimen indicated that tensile modulus was significantly higher than compressive modulus ($p < 0.001$), but the difference was negligible ($<1\%$). Thus, the compressive and tensile moduli of each specimen were considered as equal. The mean ($\pm$ S.D.) modulus for the pooled data was 309 ± 109 MPa.

mean ($\pm$ S.D.) compressive yield strains for the bovine tibial bone ($1.09 \pm 0.12\%$) were larger than values for the human vertebral bone ($0.84 \pm 0.06\%$) by 30% ($p < 0.0001$). The pooled compressive yield strain data had a strong positive linear correlation ($p = 0.0003$) with apparent density, although the high density bovine bone, when considered alone, had only a marginal correlation ($p = 0.06$).

The variation in tensile yield strains was small for the entire density range considered, while the variation in compressive yield strain was small only for a single anatomic site (Table 3). For the entire density range, the percentage coefficient of variation for tensile yield strains was only 5.5%. Despite the dependence of compressive yield strains on apparent density for the low density human vertebral bone, the coefficient of variation for compressive yield strains was only 6.8% (Table 3). This was lower than the coefficient of variation for the higher density bovine bone (11.3%), and for the pooled data (16.1%). Thus, the error induced by assuming constant compressive yield strains increased as both the density and the density range increased.

4. Discussion

The goal of this work was to provide comprehensive data on the failure strains of trabecular bone, with specific reference to their role in bone adaptation, disease, and aging. Our results provide strong evidence that (1) the on-axis compressive apparent yield strains correlate positively but weakly with apparent density, the correlation being stronger in less dense bone; and (2) the on-axis tensile apparent yield strains represent a uniform failure property independent of anatomic site and apparent density. With respect to analysis of bone adaptation and failure, these results demonstrate that over a narrow density range, and particularly at high densities, trabecular yield strains can reasonably be assumed to be constant. If the range of densities in a region of interest is not known a priori, tensile yield strains may still be considered constant, but compressive yield strains should be assigned as a function of density as reported here.

Biewener (1993) has suggested that safety factors are lower in osteoporotic bone due to a decrease in the yield strain with decreased density. Results of this study suggest otherwise, namely that an increase in functional strains – and not a decrease in failure strains — is mostly responsible for age related decreases in the safety factor of whole bones. Changes in yield strain due to changes in density (and presumably age) at a specific anatomic site are minor, and therefore may have only a minor effect on reductions in safety factors for trabecular bone. Instead, the strong correlation between modulus and density indicates that the decrease in density that accompanies aging (Mosekilde et al., 1987) results in bone that is more compliant, i.e. that strains more for a given load. Thus, functional strains will tend to approach the yield strain as density decreases with aging.

The validity of these conclusions is largely supported by the accuracy of the mechanical test data and the wide range of bone analyzed. The data sets for each anatomic site were generated using similar techniques that ensured elimination of end-artifacts and on-axis loading. For the human vertebral trabecular bone, the mean modulus (309 ± 109 MPa), while 4.5–13.5 times higher than previous studies that mechanically tested human vertebral bone between platens (Hansson et al., 1987; Lindahl 1976; Mosekilde et al., 1987), is similar to values reported where end-artifacts errors were eliminated (Ashman et al., 1987; Neil et al., 1983). The mean compressive ultimate strain (1.45%) is five times lower than those from studies using a platens test configuration (Hansson et al., 1987; Mosekilde et al., 1987). Although no previous studies have reported ultimate strains free of end-artifact errors for human vertebral bone, mean values of 1.11–1.86% strain have been reported for other anatomic sites (Keaveny et al., 1994; Rohl et al., 1991) and thus are consistent with these new data. The use of bone from two anatomic sites that exhibited large differences in apparent density and architecture (rod for human vertebral bone vs plate for bovine tibial bone) also provides substantial generality to the results.

Despite these advantages, some caveats exist. In formulating our hypothesis, an assumption was made that the failure properties of the tissue comprising individual trabeculae were uniform. The small coefficient of variation in tensile apparent yield strains (5.5%) and their similarity between human vertebral vs bovine tibial specimens indicates that age- or site-related differences in trabecular tissue morphology must have only a minor effect on tissue yield strains. Another caveat is that these results only apply to on-axis loads. Thus, there is direct application to biomechanical analysis of habitual activities in which loads presumably act along the principal trabecular orientation by implication of Wolff's law (Cowin, 1986). Traumatic fractures resulting from off-axis loads, such as a fall to the side of the hip, result in multiaxial stresses with respect to the on-axis coordinate system, and the trends reported here may not apply to that situation.

With the hindsight provided by this study, the data from the literature are consistent with the principle that yield strains in trabecular bone demonstrate a weak dependence on apparent density in compression, but not in tension (Table 4). Our data indicate that the small slope of the density-failure strain regression may go undetected statistically if considerable scatter exists in the failure strain data, particularly if ultimate strains are used instead of yield strains. This would explain why studies with relatively small sample sizes found no significant relationship between ultimate strains and density (Keaveny et al., 1994; Rohl et al., 1991), while others did find a significant relationship by using a large sample size (Hvid et al., 1989) or by defining failure at the yield point

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