DXA-derived section modulus and bone mineral content predict long-bone torsional strength

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Previous studies have used dual energy x-ray absorptiometry (DXA) scans to calculate the section modulus (Z) of adolescent and adult human femurs. The DXA-derived values of Z were assumed to be proportional to bone strength in bending and torsion. In this study we used dog (n 5), pig (n 4), and human (n 13) femurs covering a linear bone mineral content (BMC_L) range of 0.91–6.1 g/cm. Using DXA scans, ex vivo torsional strength tests, and torsional finite element models, we assessed the validity of using the DXA-derived Z value as an indicator of strength. The correlation between BMC_L and strength was $r^2 = 0.87$ and the correlation between Z and strength was $r^2 = 0.86$. Based on finite element results, the dog and pig section moduli were adjusted to be comparable to the human data based on cross-sectional shape and bone tissue shear strength differences. With these adjustments, the correlation between adjusted section modulus and measured strength did not improve ($r^2 = 0.87$). These data indicate that DXA-derived section modulus can be used to predict strength over a wide range of bone sizes. However, a clear advantage of using DXA-derived section modulus rather than BMC_L could not be found.

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Bone mineral content and bone mineral density, measured by dual energy x-ray absorptiometry (DXA) methods, are often used to assess fracture risk in vivo. This assessment rests on the assumption that bone mineral content is a primary determinant of whole bone strength. Several investigators have attempted to use linear bone mineral content (g/cm) as a predictor of whole bone strength in human or animal models (Borders et al. 1977, Martin et al. 1989, Nordsletten et al. 1994). To improve predictions based on bone mineral content alone, geometric parameters derived from absorptiometry methods have also been used as predictors of whole bone strength (Martin and Burr 1984, Beck et al. 1993, Myers et al. 1993). Unfortunately, there is no consensus on which predictors of whole bone strength are most accurate.

One geometric parameter that has been proposed as a predictor of whole bone strength is the section modulus (Z, cm^3) (Martin et al. 1989, Carter et al. 1996, Haapasalo et al. 1996). In bending or torsion, the section modulus relates the applied moment (or torque) to the maximum stress that arises within a cross section. In a biomechanical sense, the section modulus may be a more meaningful predictor of whole bone strength than bone mineral content alone (Martin and Burr 1984) because it is a measure of the distribution of material within a bone section.

In this study, we assessed the validity of using the section modulus, derived from DXA, as an indicator of ex vivo whole-bone torsional strength. We examined bones having section moduli (Z) and linear bone mineral contents (BMC_L, g/cm) consistent with those of human bones that had been examined in previous studies. We chose to designate bone mineral content in terms of linear bone density, BMC_L, which is directly proportional to the cross-sectional area of a bone. We accounted for differences in shape and material properties that were introduced from examining both human and animal bones in this analysis.

Material and methods

Specimen preparation

We used fresh dog (n 5), fresh pig (n 4), and embalmed human (n 13) femurs whose BMC_L values ranged from 0.91 to 6.1 g/cm and whose DXA-de-

Table 1. Nomenclature

A_c	cortical cross-sectional area (cm^2)
A_p	projected area of subregion in DXA scan (cm^2)
BMC	bone mineral content (g)
BMC_L	linear bone mineral content (g/cm)
D	effective periosteal diameter (cm)
h	height of subregion in DXA scan (cm)
K	area fraction of bone cross-section occupied by mineral
I	cross-sectional moment of inertia (cm^4)
ρ	density of bone mineral (g/cm^3)
T_{fail}	failure torque (torsional strength) (N-m)
Z	DXA-derived section modulus (cm^3)

rived Z values ranged from 0.18 to 2.5 cm^3. The pig femurs were obtained from skeletally mature animals and the dog femurs were obtained from mongrel dogs that were at least 29 weeks old at the time of sacrifice. Although the dogs may not have been skeletally mature, the material and structural properties of dog long bones do not change significantly after the age of 24 weeks (Torzilli et al. 1981, Torzilli et al. 1982). The embalmed human femurs were obtained from anatomy specimens having a mean age of 77 (63–92) years at the time of death. These human femurs had been previously studied by investigators in our laboratory and the densitometry and mechanical testing data had already been collected (Kiratli, unpublished data). The dogs weighed 24–26 kg at the time of killing; the weights of the pigs and humans were unavailable. The fresh dog and pig bones were cleaned of soft tissue and frozen at –20 °C for later testing. Since the availability of adolescent human femur specimens was limited, the dog and pig femurs were used to simulate the lower BMC_L and Z values considered in this study.

Analysis approach

Dual energy x-ray absorptiometry (DXA) scans were performed on the 22 femoral diaphyses, using a Hologic QDR 1000/W X-ray bone densitometer (Hologic, Waltham, MA, USA). Each femur was placed in a plastic container filled with Dulbecco's buffered saline solution to a depth of 15 cm (the dog and pig femurs were thawed before scanning; the human femurs did not require thawing). The bones were placed in solution in order to simulate a soft tissue baseline for the DXA scans.

The DXA scans were analyzed using Hologic lumbar spine software (version 4.47.1) to determine bone mineral content (BMC, g) and bone projected area (A_p, cm^2) for each of the scan subregions (Figure 1). The DXA scan of each dog and pig femur was analyzed over 10 subregions along its diaphysis while the DXA scan of each human femur was analyzed at a single subregion located at its midshaft. An effective mid-diaphyseal periosteal diameter (D, cm) was calculated by dividing A_p by the height of the subregion (h, cm). Linear bone mineral content (BMC_L, g/cm) was calculated by dividing BMC by h. The value h was between 0.8 cm and 1.2 cm for each femur (h was calculated as one-tenth of diaphyseal length for each dog and pig femur and was set at 1 cm for each human femur). Cortical cross-sectional area (A_c, cm^2) and cross-sectional moment of inertia (I, cm^4) at each subregion were calculated using the approximate method of Martin and Burr (1984). This method uses bone mineral content and bone projected area to estimate the geometric properties of a cross section and does not make direct use of the x-ray absorption curve. This method models the mid-diaphysis as a hollow circular section and assumes that the density of the mineral fraction of bone, ρ, is 3.0 g/cm^3 (Robinson 1975). The cortical cross-sectional area (A_c) was expressed by

$$A_c = \frac{BMC_L}{K\rho} \quad (1)$$

where K is the fraction of mineral in cortical bone, a parameter which we estimated empirically. The cross-sectional moment of inertia (I, cm^4) was derived us-

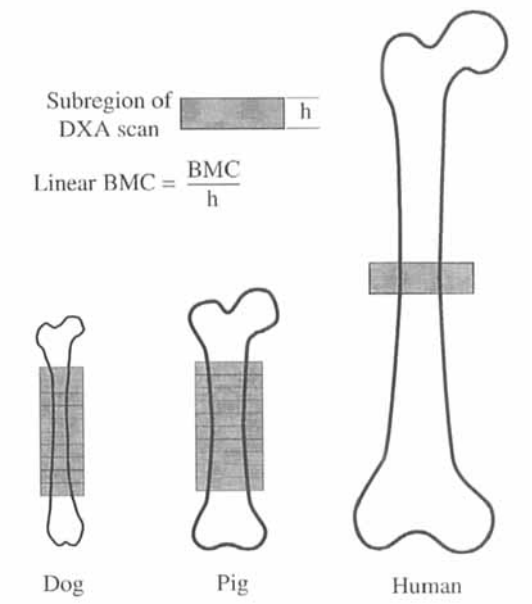

Figure 1. Subregions of each femoral diaphysis that were analyzed to determine bone mineral content (BMC, g) and bone projected area (A_p, cm^2). The entire diaphysis of each femur was scanned by DXA. Scans of dog and pig femurs were analyzed over 10 subregions, while scans of human femurs were analyzed in a single subregion located at the midshaft. Linear bone mineral content (BMC_L, g/cm) was calculated as BMC (g), divided by height (h, cm) of subregion.

ing the following relation:

$$I = \frac{A_c}{4\pi}\left(\frac{\pi}{2}D^2 - A_c\right) \quad (2)$$

Finally, the section modulus (Z, cm^3) was expressed as follows:

$$Z = \frac{2I}{D} = \frac{A_c}{2\pi D}\left(\frac{\pi}{2}D^2 - A_c\right) \quad (3)$$

For each subregion depicted in Figure 1, the section modulus was calculated by Equation (3). Each femur was then characterized by its minimum section modulus, so that a single Z value was assigned to each femur. The section modulus, a structural parameter derived using mechanical principles and incorporating bone size and geometry, is often interpreted as being approximately proportional to the mechanical load required to fracture a long bone (Alexander 1989, Selker and Carter 1989, Carter et al. 1996).

Mechanical testing

The proximal and distal condyles of each femur specimen were embedded in a block of polyester casting resin. Once potting was complete, each femur was mounted into a servohydraulic testing machine (MTS Systems Corp., Eden Prairie, MN, USA) with axial and torsional loading capabilities. Each femur was brought to room temperature and then loaded in torsion to failure. The torsion tests were performed under angular displacement control at a displacement rate of 1 degree per second, until failure occurred. The proximal end of each specimen was kept fixed while the torque was applied to its distal end. Axial force was held at zero during the duration of the experimental period. Time, angular displacement, and torque were recorded at 10 Hz. Torque at failure (T_{fail}, N-m) was recorded for each specimen.

After failure, the specimens were removed from the testing fixtures and the site of initial fracture was recorded. A small, longitudinal crack that lay between the arms of the spiral fracture was taken as the site of fracture initiation. An initiating shear step surface that is parallel to the torsional axis (longitudinal axis for this study) is expected under pure torsional loading because the plane of maximal shear stress is oriented parallel to the axis of the bone (Reilly and Burstein 1974). If no longitudinal crack was evident, crack initiation was assumed to occur at the midpoint of the spiral crack.

A fast hardening epoxy was used to reattach the fractured ends of the femurs. The shaft of each dog and pig femur was sectioned perpendicular to the long axis of the diaphysis at the site of initial crack formation. Each human femur was sectioned at its midshaft after it was tested to failure (Kiratli, unpublished data). The cross section of each femur was digitized using Adobe Photoshop (Adobe Systems Inc., San Jose, CA, USA) computer software.

Statistics

The data were analyzed using StatView (Abacus Software, Berkeley, CA, USA) and SuperANOVA (Abacus Concepts, Berkeley, CA, USA) computer software. Linear regression analyses were performed to examine the predictive value of different model parameters on measured failure torque. The coefficients of determination (r^2) were used to characterize the predictive ability of each parameter (BMC_L, Z) on torsional strength. The correlation coefficients (r) of each model were tested for significant differences (Kleinbaum et. al. 1988) to determine whether one model parameter predicted strength better than another. Linear regressions were performed on the pooled species sample. One-factor analysis of covariance (ANCOVA) was used to test for significant differences in regression slopes among the species by examining the (species × covariate) interaction effect. The factor in these analyses was species, which acted at three levels (dog, pig, and human), and the covariate was the independent variable. Differences were considered statistically significant for $p < 0.05$.

Estimating area fraction of bone occupied by mineral (K)

The slope of a linear regression line between BMC_L and the cortical cross-sectional area (A_c) of a femur is an estimate of the product ($K\rho$) as related by Equation (1). A linear regression between our experimentally determined BMC_L and A_c data resulted in a slope of 1.27 ($r^2 = 0.93$). Assuming a mineral density, ρ, of 3.0 g/cm^3 (Robinson 1975), the fraction of bone cross-sectional area occupied by mineral (K) was estimated to be 0.42. An analysis of covariance (ANCOVA) on these data indicated that the (species × A_c) interaction effect ($p = 0.97$) was not significant at the $p = 0.05$ level. Since this interaction effect was not significant, the data were analyzed as a single regression whose slope was not dependent on species.

Results

Of the three species, the human femurs had the highest average BMC_L, T_{fail}, and Z values while the dog femurs had the lowest average BMC_L, T_{fail}, and Z values (Table 2). These differences were expected, given the size differences among the species. Experi-

Table 2. Average linear bone mineral content (BMC_L), failure torque (T_{fail}), and DXA-derived section modulus (Z) for each species. Mean *SD*, (range)

	Dog	Pig	Human
BMC_L (g/cm)	0.99 *0.05* (0.91–1.0)	3.7 *0.29* (3.4–4.0)	4.4 *1.2* (1.8–6.1)
T_{fail} (N-m)	31 *4.2* (26–37)	114 *8.4* (104–123)	127 *41* (56–174)
Z (cm^3)	0.22 *0.02* (0.18–0.24)	1.4 *0.16* (1.3–1.6)	1.9 *0.48* (0.84–2.5)

mentally measured torsional strength (T_{fail}) correlated strongly ($r^2 = 0.87$) with BMC_L (Figure 2). The (species × BMC_L) interaction effect ($p = 0.96$) was not significant for this regression. Hence, the regression slope between torsional strength and linear bone mineral content was not dependent on species. The correlation between T_{fail} and the DXA-derived section modulus (Z) was also strong, $r^2 = 0.86$ (Figure 3). For the T_{fail} vs. Z regression, the (species × Z) interaction effect ($p = 0.68$) was not significant. A multiple regression model, with both BMC_L and Z as regressors ($r^2 = 0.87$), was no better than BMC_L or Z alone in predicting T_{fail}. Differences between the correlation coefficients (r) were not significant ($p > 0.85$), indicating that each model predicted strength equally well.

Discussion

In this study, we assessed the validity of using the DXA-derived section modulus as a predictor of whole bone torsional strength over a wide range of bone sizes. We found that, over this range, the DXA-derived section modulus was comparable to linear bone mineral content in the ability to predict torsional fracture strength ex vivo (Figures 2 and 3). A multiple regression model accounting for both linear bone mineral content and the DXA-derived section modulus did not improve the predictive power of the simple regression models accounting for linear bone mineral content or section modulus alone.

These results are consistent with previous studies that examined both bone mineral content and geometry-based parameters as predictors of whole bone strength. Borders et al. (1977) found strong correlations between bending strength and both BMC_L and bending stiffness (flexural rigidity) in dog radii, ulnae and tibiae. Stromsoe et al. (1995) found that bone mineral content and second area moment of inertia predicted the bending strength of the distal human femur equally well. Martin et al. (1989) examined rhesus monkey femurs (n 9, approximate BMC_L range: 0.6 g/cm to 1.2 g/cm) and found that linear bone mineral content ($r^2 = 0.88$) was slightly better at predicting bending strength than was absorptiometry-derived section modulus ($r^2 = 0.85$). In the present study, we examined femurs over a wider range of BMC_L values than had been examined previously and

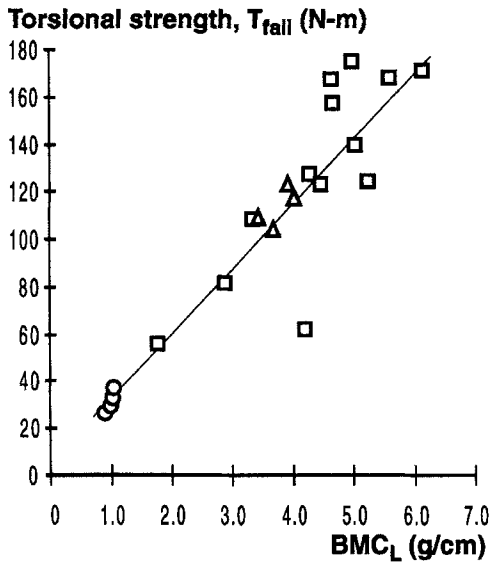

Figure 2. Torsional strength (T_{fail}) vs. linear bone mineral content (BMC_L), $r^2 = 0.87$. □ human, △ pig, ○ dog.

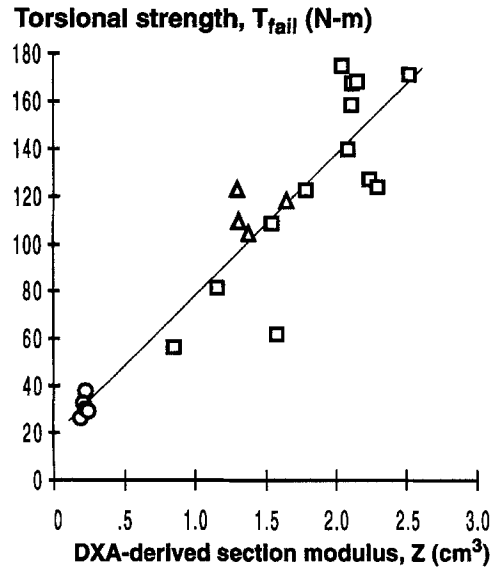

Figure 3. Torsional strength (T_{fail}) vs. DXA-derived section modulus (Z), $r^2 = 0.86$. □ human, △ pig, ○ dog.

still reached the same basic conclusion that absorptiometry-derived section modulus was not better than BMC_L at predicting whole bone strength.

The femurs of each species (dog, pig, human) considered in this study possessed inherently different cortical thicknesses, circularity, and tissue material strength. To account for these differences, we used torsional finite element analysis (Levenston et al. 1994) to estimate the material strength of each type of bone tissue and to characterize the noncircularity and nonuniformity of the femur cross sections based on the digitized cross-sections of each femur. We adjusted the section moduli of the dog and pig femurs relative to the human femurs based on their cross-sectional shape and material strength differences. However, the correlation between adjusted section modulus and measured strength did not improve ($r^2 = 0.87$). Furthermore, if the nonhuman data were omitted from this study, the basic conclusion would be the same. In this case, BMC_L ($r^2 = 0.65$), Z ($r^2 = 0.69$) and the multiple regression model ($r^2 = 0.70$) each predicted strength of the human femurs equally well (differences between the correlation coefficients were not significant, $p > 0.73$).

Several assumptions were made in this study. Our model assumed that fracture would start at the diaphyseal subregion (Figure 1) having the lowest section modulus; this subregion corresponded to the midshaft in 7 of the 9 animal (dog and pig) femurs. For the majority of the specimens examined in this study, however, the site of fracture initiation did not correspond to the site having the lowest section modulus. This discrepancy is most likely due to our modeling approach, which did not take stress concentrations or microstructural variations into account (Martin 1991). Our approach addressed regional variations of bone mineral content along the length of the diaphysis, not within each cross section perpendicular to the long axis. It is possible that a local area of decreased density or a local site of remodeling within a cross section could have led to an increased risk of fracture at that specific location (Hsu et al. 1993). In addition, we considered both fresh and embalmed femurs in this study. Unfortunately, there does not appear to be any well-established and reproducible data in the literature regarding the effects of embalming on the properties of bone because the effects of embalming can be highly variable. With this in mind, we examined data from a 1951 study by Calabrisi and Smith, as referenced by Evans (1973), which indicates that embalming reduces the compressive strength of human femoral cortical bone by 4.8% to 17%. If embalming has a similar effect on the shear strength, the basic results of our study would not change.

In general, BMC_L is proportional to cortical cross-sectional area, A_c. A regression between BMC_L and A_c obtained from digitizing the cross-sections corroborated this relationship. For bones whose dimensions scale proportionally (i.e., are geometrically similar), the section modulus is expected to be proportional to A_c (and thus BMC_L) raised to the 1.5 power. Our data did not reflect this relationship. Based on our findings, the exponent, x, in the relation $Z \propto (BMC_L)^x$ was between 1.26 and 1.49 (95% confidence interval). This relation indicated that the larger femurs were thicker, relative to their diameter, than the smaller femurs (Selker and Carter 1989). The femurs considered in this study do not scale geometrically. Analysis of the human data supports the finding that human femurs, in general, do not scale geometrically (the exponent in this case was between 0.72 and 1.08). Human femur data reported by Martin and Atkinson (1977) are consistent with this result. In addition, based on our analysis of the data reported by Martin and Atkinson, scaling in human femurs is gender-specific. This result implies that there is no overall consistency in scaling for human femurs. Moreover, we suspect the scaling laws that apply to adolescent human femurs would be different as well. Without data on the scaling laws of dog or adolescent human femurs, we chose to substitute dog femurs whose BMC_L and Z ranges were consistent with the in vivo measurements of adolescent human femurs reported by Moro et al. (1996) and van der Meulen et al. (1996).

On the assumptions of previous investigations and on beam theory, section modulus was expected to be a better predictor of strength than linear bone mineral content (or cross-sectional area). The scatter in the data and the relatively small sample size considered may contribute to the discrepancy between theory and experiment. In a larger sample size, incorporating femurs that encompass a large BMC_L and Z range, one would expect, following engineering principles, the section modulus to outperform BMC_L. To our knowledge, this study is the first to use human bones in comparing linear bone mineral content and DXA-derived section modulus as predictors of whole bone torsional strength. Our results indicate that both linear bone mineral content and DXA-derived section modulus predict torsional strength equally well across the range of bone sizes used in this study. While the section modulus may have more biomechanical significance than bone mineral content alone, as proposed by Martin and Burr (1984), a clear advantage of using DXA-derived section modulus, rather than linear bone mineral content, to predict whole bone strength could not be shown in this study. However, we sug-

gest using the DXA-derived section modulus prospectively to predict the strength of a human patient's femur, because it relies on mechanical principles.

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