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The dependence between the strength and stiffness of cancellous and cortical bone tissue for tension and compression: Extension of a unifying principle

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Abstract. A strong positive correlation between the apparent ultimate strength and stiffness of bone tissue that can be expressed by a unified relationship has been observed for cortical bone in tension and low-density cancellous bone in compression. For practical purposes, the existence of a relationship between strength and stiffness is significant in that bone stiffness can be measured *in vivo* using non-invasive methods.

It is generally accepted that bone strength is greater in compression than in tension whereas there is no substantial evidence that bone stiffness in compression is different from that in tension. This might suggest that compressive strength would relate to the stiffness, if at all, in a way that is different from tensile strength. In order to examine similarities and differences in the way strength is associated with stiffness between modes of loading and tissue type, we tested equine cortical bone and bovine cancellous bone in compression and examined these data together with previously reported data from compression testing of human cancellous bone as well as tensile testing of cortical bone from various sources.

We have found for cortical bone that (i) the sensitivity of strength to stiffness is the same for tension and compression ($p > 0.75$, ANCOVA), and (ii) the difference between the magnitudes of compressive and tensile strength for cortical bone is the result of an additive, rather than a multiplicative factor (52.1 MPa after adjusting to 1 microstrain/s, $p < 0.0001$, ANOVA). High-density bovine tibial cancellous bone, on the other hand, has a steeper slope for its compressive strength–stiffness relationship than that for cortical bone and human cancellous bone, resulting in a transitional relationship between compressive strength and stiffness for a range of bone types and densities.

Based on the current results and previous work, it is suggested that the offset strength in the compressive strength–stiffness relationship may be a direct manifestation of the difference between the compressive and tensile strengths of the bone material that constitutes the building blocks of the bone structure. Deviation of high-density cancellous bone compressive behavior from the other bone types and densities is attributed to stress distribution differences between the bone types.

Keywords: Bone, strength–stiffness relationship, modulus, structure–function, adaptation

1. Introduction

It has long been observed during mechanical testing of bones and bone tissue that stiff bones tend to be strong as well [1–14]. More recently, it has been demonstrated that the relationship between the

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apparent ultimate strength and stiffness of bone tissue can be unified for cortical bone in tension and low-density cancellous bone in compression [9].

Because a precise relationship between apparent stiffness and strength is maintained over a range of bone types, species and loading modes, it has been proposed that this relationship between strength and stiffness may not be coincidental but might be the result of an evolutionary process resulting in bone that is adapted to control its strength by controlling its stiffness [9]. The rationale behind this idea is that deformation (thus, bone stiffness) is detectable by cells where strength is not. Regardless of whether there is a direct control of strength through stiffness or the strength–stiffness correlation is achieved through other mechanisms such as controlling failure strains [4,15,16], the existence of a relationship between the apparent strength and stiffness of bone tissue is significant, for practical purposes, in that bone strength can be predicted using non-invasive stiffness measurements. Therefore, determining the nature of the relationship between bone strength and stiffness is desirable in order to achieve a better understanding of how bone functions and for effective use of this relationship to predict whole bone strength.

Loading patterns encountered *in vivo* are more complex than those simulated in unidirectional tests and it is not known whether bone has adapted to maintain the observed strength–stiffness relationship in other modes of loading. It is generally accepted that bone strength is greater in compression than in tension whereas there is no substantial evidence that bone stiffness in compression is different from that in tension [17,18]. This might suggest that compressive strength would relate to the stiffness, if at all, in a way that is different from tensile strength. The similarity between low-density human cancellous bone in compression and cortical bone in tension has been attributed to the presence of bending-induced tensile loads in compressed cancellous bone [9]. High density cancellous bone, on the other hand, has its compressive strength and stiffness related in a way significantly different from low-density bone in compression or cortical bone in tension [7].

In order to examine similarities and differences in the way strength is associated with stiffness between modes of loading and tissue type, we tested equine cortical bone and bovine cancellous bone in compression and examined the results together with the previously reported data from our laboratory and others.

2. Methods

Three hundred and fifty two equine bone specimens from a previous study were examined [19]. One hundred and fifty five cylindrical cortical bone specimens were milled from the third metacarpal diaphysis of ten horses. Twenty cancellous bone specimens were from the proximal and distal metaphysis of the third metacarpus. One hundred and forty three additional bone specimens classified as “dense trabecular” were from the proximal and distal metaphysis of the second, third and the fourth metacarpi. This tissue is located on the interior parts of equine long bones, adjacent to the exterior compacta, but distinctly different from equine cancellous bone and represents and intermediate bone structure between cancellous and cortical bone. The data set included different breeds (7 Thoroughbreds, 2 Arabians, 1 Quarterhorse), genders (5 intact males or geldings, 5 females), ages (5 months–20 years) and anatomical locations (3 proximo-distal levels, 6 sectors at each level) such that a variety of bone types were represented, particularly for cortical bone.

After preconditioning for 5 cycles between zero and 100 N, the specimens were compressed to failure between lubricated platens using a strain rate of 0.01 s^{-1}. Displacements were recorded using an LVDT placed near the specimen. The apparent strength, σ_u, and stiffness, E, of bone specimens were calculated as the maximum stress reached and the slope of the linear portion of the stress–strain curve, respectively [19].

Twelve additional bone cylinders were cored from bovine tibial cancellous bone as described previously [8,9]. Bovine tibial cancellous bone was utilized as "dense cancellous bone" compared to human cancellous bone. Compression testing of these specimens was performed at a strain rate of 0.001 s^{-1}. Cancellous bone specimens were glued to brass end-caps during testing to eliminate the effect of end artifacts on measured stiffness [20–22].

Data from tensile testing of bovine cortical bone, together with literature data from tensile testing of cortical bone from multiple species, and data from compression testing of human cancellous bone (low-density cancellous bone) with glued end caps were used as was done in a previous study [9] in order to compare with our compression test results. Strength and stiffness were corrected to 1 microstrain/s for comparison between groups [23,24].

The relationship between strength and stiffness was examined using linear regression for each group. Differences between regressions were examined using ANCOVA. Sigma Stat (SPSS, Inc, Chicago, IL) was used for statistical analyses. Nonlinear curve-fitting to pooled data groups was performed using Table Curve 2D (Jandel Scientific). Results with $p < 0.05$ were considered significant. For regressions, coefficient of determination, adjusted for degrees of freedom ($r^2_{\rm adj}$) was reported.

3. Results

Apparent compressive strength and stiffness of equine cortical bone were significantly and positively correlated ($r^2_{\rm adj} = 0.70$, $p < 0.0001$; Fig. 1).

The near equality between the slopes of regression equations (equal to the derivative of strength by stiffness, $d\sigma_u/dE$) from compression (0.0063) and from previously reported tension groups (0.0067 for multiple species and 0.0060 for bovine bone) was notable ($p > 0.75$; Fig. 1). Unlike cortical bone in tension [9], however, the intercept of the regression of strength against stiffness (52.1 MPa) was significant for cortical bone in compression ($p < 0.0001$).

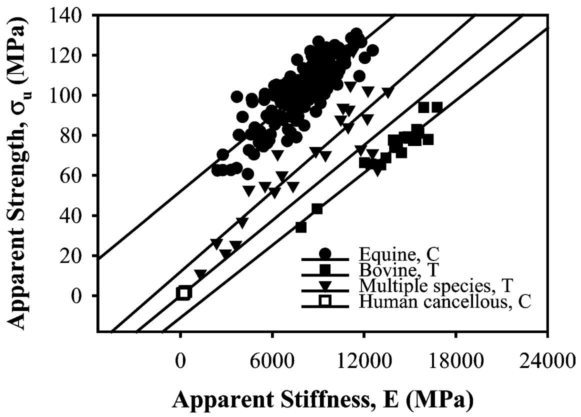


Fig. 1. Compressive strength of cortical bone is related to compressive stiffness through a relationship similar to that in tension. Note that strength and stiffness values are adjusted for 1 microstrain/sec for comparison purposes. C: compression, T: tension. σ_u (MPa) $= 0.0063E$ (MPa) $+ 52.1$ ($r^2_{\rm adj} = 0.70$, $p < 0.0001$). Equine data.

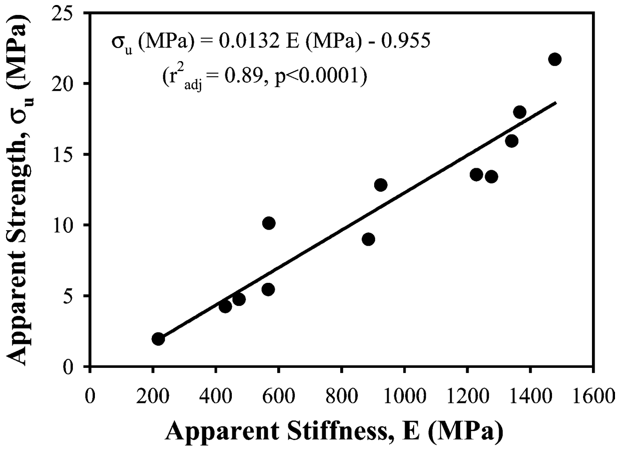


Fig. 2. The relationship between the apparent compressive strength and stiffness (corrected to 1 microstrain/sec) of bovine tibial cancellous bone. σ_u (MPa) $= 0.0132E$ (MPa) $- 0.955$ ($r^2_{\text{adj}} = 0.89$, $p < 0.0001$). Bovine data.

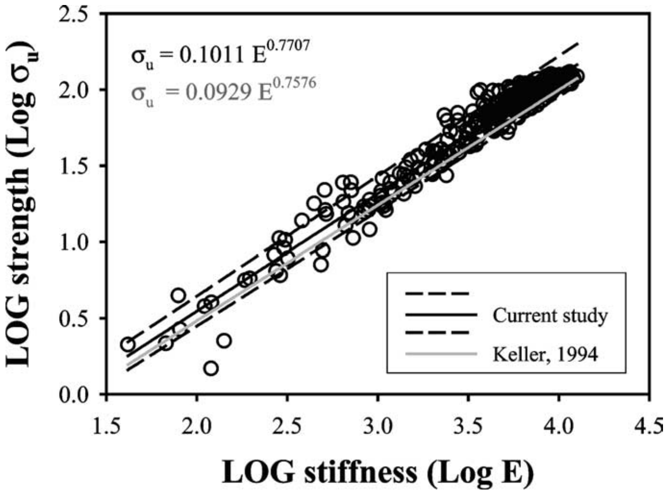
Apparent compressive strength and stiffness of bovine tibial cancellous bone were significantly and positively correlated ($r^2_{\text{adj}} = 0.89$, $p < 0.0001$; Fig. 2). The intercept of the regression line was not significant ($p > 0.5$) resulting in an equation of the form σ_u (MPa) $= 0.0124E$ (MPa) consistent with reports from other laboratories [7].

When the equine cancellous, dense trabecular and cortical bone data were examined together, the compressive strength of bone tissue was related to compressive stiffness through a power–law relationship (Fig. 3a) as was observed for human bone previously [25]. When the equine cancellous and dense trabecular bone data were replaced with human and bovine cancellous bone data from mechanical testing with glued end caps, the relationship was of a transitional form (Fig. 3b). Although both the power–law and transitional fits to the pooled data were equally explanatory (similar r^2_{adj}), strength was consistently overestimated by the power–law fit at the low-stiffness end (cancellous bone) of the data (Fig. 3c).

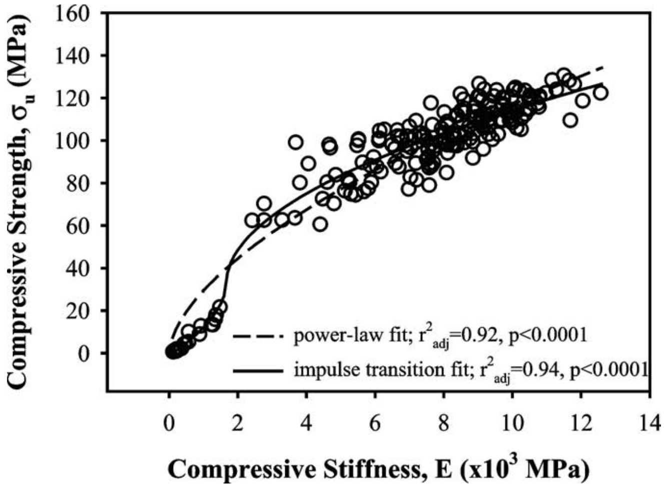
4. Discussion

A remarkable similarity between the slopes of the compressive strength–stiffness and tensile strength–stiffness regressions was found in this study indicating that the apparent strength of cortical bone tissue is sensitive to stiffness variations equally in tension and compression. Our finding that there is a significant intercept in the strength–stiffness relationship of cortical bone in compression but not in tension meets the expectation that compressive strength would relate to the stiffness in a way that is different from tensile strength. The near identity in the slopes of the relationship, however, shows that the difference between compressive and tensile strength is the result of an additive, rather than a multiplicative factor.

For high-density bovine tibial cancellous bone, the compressive strength–stiffness relationship had a steeper slope than that for cortical bone in tension or compression, consistent with previously reported results by others [7]. The tensile strength–stiffness relationship from bovine tibial cancellous bone (as determined by others), however, conforms with the equation for cortical bone in tension and low-density cancellous bone in compression [7]. It is, therefore, likely that the compressive strength–stiffness relationship takes a non-linear form when bones from different architectural levels are considered. The



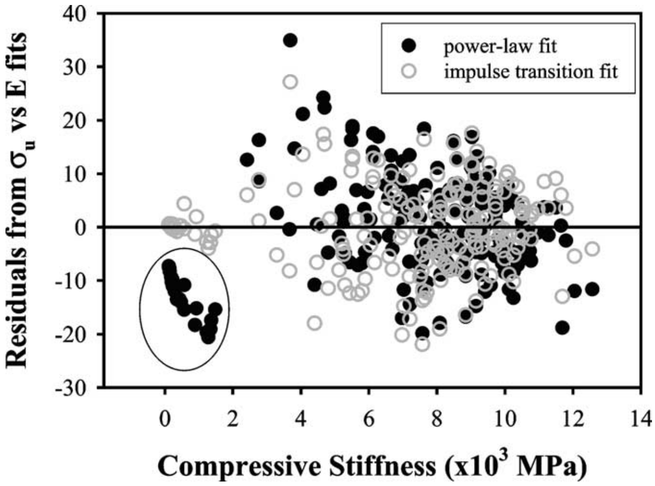
(a)



(b)

Fig. 3. Compressive strength and stiffness relationship from the mixed equine cancellous, dense trabecular and cortical bone tested between platens. Both strength and stiffness are log-transformed and corrected to 1 microstrain/sec. The average fit to the data from a similar set of mixed human cancellous and cortical bone, reported previously [25], lies within the 95% confidence interval of the fit to the equine data (dashed lines). (b) Power–law and a transitional (impulse) fit to the compressive strength–stiffness data for equine cortical bone together with bovine cancellous and human cancellous bone that were tested using a glued end-cap protocol. (c) Residuals from both fits indicate that power–law relationship consistently underestimates strength from stiffness for low-stiffness specimens (cancellous bone; encircled) although both curves are equally predictive of strength for high-stiffness specimens (cortical bone).

non-linearity of the compressive strength–stiffness relationship for bone (cancellous and cortical together) has been suggested to be in the form of a power–law relationship when the compressive testing of bone is performed between platens [25]. Our results from equine bone, tested between platens, show the same trend as in this previous suggestion (Fig. 3a). While compressive testing of cortical bone between platens is in accordance with established standards for compressive mechanical testing of other very dense, rigid materials and presumably generates accurate compressive mechanical property values [26], compressive testing of cancellous bone between platens is known to generate artifacts that result in inaccuracies in stiffness measurements [11,20,22]. Accordingly, the overall behavior of the compressive



(c)

Fig. 3. (Continued.)

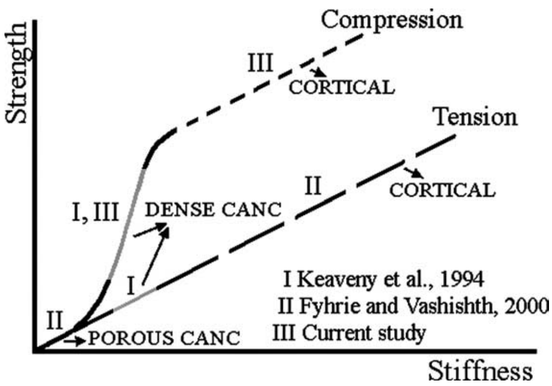


Fig. 4. Proposed strength–stiffness association: All bone tissues behave similarly under apparent tension. The behavior under compression depends on how bone structure converts apparent loads into distributions of compressive and tensile stresses.

strength–stiffness relationship was of a transitional form for the combined cortical and cancellous bone specimen group when the cancellous bone data from the equine bone data set were replaced with those from our bovine and human cancellous bone test data, collected using end boundary conditions that reduce stiffness inaccuracies.

The offset strength in the compressive strength–stiffness relationship may be a direct manifestation of the difference between the compressive and tensile strengths of the bone material that constitutes the building blocks of the bone structure, given that the compressive and tensile stiffness are equal. The ratio of the number of tension and compression "members" in a bone structure determines the numbers of elements at risk for compressive and tensile failure. Therefore, the nonlinear portion of the compressive strength–stiffness relationship (Fig. 4) may result from changes in the mix of "compressive" and "tensile" elements of the tissue. Numerical models utilizing tensile-compressive failure property asymmetry have been successful in predicting cancellous bone damage behavior and strength [27,28]. Bone apparent stiffness and strength have also been associated with the average and spread of tissue level stress distributions [29]. Together with others' results (Fig. 4), our results suggest that stress distribution statistics, hence the compressive-tensile strength mixture, is stable in bone structure under apparent tension, high-density bone under apparent compression and low-density bone under apparent compression. Human bone tends to be at either ends of the extreme (regions II and III; Fig. 4) where both compressive and tensile strength change with stiffness in the same way.

Although bone strength and stiffness seem to be different from normal in presence of bone diseases such as osteoarthritis (OA) and rheumatoid arthritis (RA) [30], it is not precisely known how bone diseases affect the relationship between bone strength and stiffness. Wixson et al. reported strength–stiffness correlations for human cancellous bone from osteoarthritis and rheumatoid arthritis cases [14], however, whether the regressions were different from each other or from normal bone was not clear. We estimated by digitizing images from Wixson et al. that the slope of the strength–stiffness regressions is 0.0303 and 0.0242 for RA and OA, respectively, for specimens tested between platens. Compared to the slopes from human vertebral cancellous bone [11] or equine cancellous bone (0.0103 and 0.0180, respectively) tested similarly, the slopes from OA and RA bones are large suggesting that bone diseases may indeed alter predictability of bone strength from stiffness measurements. Examination of bone tissue from extreme sources may provide some clues on the level of hierarchical organization and composition at which the strength–stiffness relationship may not hold. The fact that the stiffness sensitivity of strength is similar in bones from a variety of species suggests that the relationship is independent of the type of microstructural component (e.g., osteonal, plexiform). It is, however, dependent on the intermediate organization of these components as the results from the compression testing of bovine cancellous bone indicate. Bones such as red deer antler, whale rostrum and tympanic bulla that apparently do not fall on the unified strength–stiffness relationship line [9] have rather unique mineralization and ultrastructural organization levels [31]. For instance, the latter two are often characterized by their extremely high mineral content. In contrast, antler has a very low mineral content. Therefore, it could be proposed that hypo- or hypermineralization of bone tissue caused by diseases or aging [32,33] may impair the strength–stiffness relationship as in the case of these extreme bones making it difficult to predict bone strength from stiffness measurements. Mechanisms that build such a precise sensitivity of strength to stiffness in bone tissue as well as conditions that disturb this relationship are the focus of our current interest.

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