THE DEPENDENCE BETWEEN THE STRENGTH AND STIFFNESS OF CORTICAL BONE IS SIMILAR FOR TENSION AND COMPRESSION

Yeni, YN; Fyhrie, DP; Les, CM
Bone and Joint Center, Henry Ford Hospital, Detroit, Michigan, USA

INTRODUCTION
A strong positive correlation between the apparent ultimate strength and stiffness of bone tissue has been observed for cortical bone in tension and low-density cancellous bone in compression [1]. For practical purposes, the existence of a relationship between strength and stiffness is significant in that bone strength can be predicted using non-invasive stiffness measurements. From an evolutionary point of view, the relationship may also be important because bone stiffness is detectable by cells where strength is not. 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 [2]. This might suggest that compressive strength would relate to the stiffness, if at all, in a way that is different than tensile strength does. 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 [1]. 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 [3].

In order to examine similarities and differences in the way strength is associated with stiffness between modes of loading and tissue type, we tested cortical bone in compression. We have found for cortical bone that i) the sensitivity of strength to stiffness is the same for tension and compression, and ii) the difference between the magnitudes of compressive and tensile stiffness is the result of an additive, rather than a multiplicative factor.

METHODS
One hundred and fifty five cylindrical cortical bone specimens were milled from the third metacarpal diaphysis of ten horses. 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) were included in order to represent a variety of cortical bone types. The specimens were compressed to failure between lubricated platens using a strain rate of 0.01 s⁻¹. The apparent strength, σ, 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 [4].

Data from tensile testing of bovine cortical bone, together with literature data from tensile testing of cortical bone from multiple species, were used as was done in a previous study [1] in order to compare with our compression test results. Strength and stiffness were corrected for I ² for comparison between groups [5, 6].

The relationship between strength and stiffness was examined using linear regression for each group. Differences between regressions were examined using ANCOVA.

RESULTS
Apparent compressive strength and stiffness of equine cortical bone was significantly and positively correlated (Figure 1) with the following regression equation:

\[ \sigma_i (\text{MPa}) = 0.0063 E (\text{MPa}) + 52.1 \]  \( r^2 = 0.70, p < 0.0001 \)

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

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 than tensile strength does. The near identity in the slopes of the relationship, however, show that the difference between compressive and tensile stiffness is the result of an additive, rather than a multiplicative factor.

For high-density bovine tibial cancellous bone, it has been found that the compressive strength-stiffness relationship has a steeper slope than that for cortical bone in tension or compression [3]. The tensile strength-stiffness relationship from these bones, however, conforms with the equation for cortical bone in tension and low-density cancellous bone in compression [3]. It is, therefore, likely that the compressive strength-stiffness relationship takes a non-linear form when bones from different architectural levels are considered. 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 represents different mixtures of compressive and tensile material strengths. Therefore, the nonlinear portion of the compressive strength-stiffness relationship (Figure 2) may be attributed to a difference in this ratio between intermediate structures and those loaded predominantly with a single mode. Bone apparent stiffness and strength have been associated with the average and spread of tissue level stress distributions [7]. Together with others’ results (Figure 2), our results suggest that stress distribution statistics, hence the compressive-tensile strength mixture, is stabilized 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; Figure 2) where both compressive and tensile strength change with stiffness in the same way. Unraveling the mechanisms that build such a precise sensitivity of strength to stiffness in human bone tissue is the focus of our current efforts.

REFERENCES

Figure 1. Compressive strength of cortical bone is related to compressive stiffness through a relationship similar to that in tension. C: compression T: tension

Figure 2. 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.