A Comparison of Young's Modulus values of Trabecular and Cortical bone Under Compression

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Abstract:

There are two distinct types of bone within the body: trabecular, or spongy bone, which makes up about 20% of the typical adult human skeleton, and cortical, or compact bone which makes up the other 80%. The two types of bones are very different in construction. Trabecular bone is a more porous structure while cortical bone is a dense, organized structure. The differences in structure result in different mechanical behaviors that have large impacts on bone fragility diseases such as osteoporosis. One mechanical material property that is imperative to know when analyzing bone is Young's modulus or modulus of elasticity. The purpose of this study was to determine whether the Young's modulus of trabecular bone was significantly less than that of cortical bone by testing specimens of both types in compression and analyzing the results. Using a Test Resources test frame, compression tests were performed on four chicken tibia samples of each type of bone. Linear regression and t-test statistical analysis methods were used to determine information about the Young's moduli.

Linear regression results revealed that the average Young's modulus for trabecular bone samples was 18.5 (S.D. 8.89) and the average Young's modulus for cortical bone was 0.063 (S.D. 0.039). The R^2 values of these regressions were all above 0.95, showing a high degree of goodness of fit for the regressions. The t-test comparing trabecular bone Young's modulus to cortical bone Young's modulus confirmed the hypothesis that trabecular bone values are significantly lower than that of cortical bone ($p=0.0127$). This indicates that there is a significant mechanical difference in the behavior of the two types of bone that must be accounted for in engineering applications. Future research could focus on the analysis of other materials properties of the two types of bone.

Introduction:

This study was performed to test and compare the Young's modulus of the two main types of bone found in the body: cortical and trabecular. It is important to study trabecular and cortical bone separately due to their vastly different construction. Trabecular bone is a strong yet porous structure composed of struts with marrow filling the spaces between while cortical bone is a dense, organized structure composed of microscopic cylinders aligned along the length of the bone. The wide variation in porosity among the two types of bone is a major contributor to why they must be studied separately due to the fact that porosity is a primary determinant of the mechanical properties of a tissue (Martin, 1991). In addition, the different mineral composition of the bones lead to significant mechanical differences.

Understanding the different materials properties of trabecular and cortical bone is imperative in clinical applications, such as the treatment and prevention of diagnoses such as osteoporosis. Historically, clinical research on the pathogens of bone fragility have focused on the bone remodeling of trabecular bone tissue, but more recent studies show that reasons for common fractures that occur with increase in age could be due to cortical bone remodeling (Iolascon, 2013). To fully study the impacts of trabecular and cortical bone in overall bone fragility, it is imperative to first understand the differences in their materials properties. It is essential to predict the mechanical properties of bones in order to estimate the fracture risk of certain bones under certain conditions (Sandeep and Kumar, 2016). This knowledge allows comparisons to be made between populations of different ages as well as comparing normal behavior of trabecular and cortical bone to osteoporotic behavior.

The material property of interest in the study was Young's Modulus, or Elastic Modulus. Young's modulus measures the resistance of a material to elastic, or recoverable, deformation under load. This can also be thought of as the stiffness of a material. A high value for young's modulus correlates to a high stiffness, and such a material will only deform small amounts under elastic loads. A material with a low Young's modulus is not as stiff, and will undergo more deformation under load. Broken down further, Young's modulus is a ratio of stress over strain (Eq. 1). Typically, stress and strain data are calculated from measurements of force and displacement. In this case, force is applied on the bone specimens in a normal direction, or perpendicular to the surface of the specimen, and is measured in kilograms. Stress is a measure of applied force divided by the cross-sectional area that the force is applied on (Eq. 2) and strain is the change in length divided by the original length for the specimen (Eq. 3). The equations for the values of interest can be seen below. A value for Young's modulus is also frequently found by identifying the slope of the linear region in the material's stress-strain diagram (Figure 1).

$$E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon} \tag{1}$$

$$\sigma = \frac{Load}{Area\ (cross\ section)} = \frac{F}{A} \tag{2}$$

$$\varepsilon = \frac{change\ in\ length}{original\ length} = \frac{\Delta l}{l} \tag{3}$$

$$E = Young's\ Modulus \quad \sigma = stress \quad \varepsilon = strain$$

As can be seen by Equation 2, the area of the test specimen has a large impact on the stress calculation, and as can be seen by equation 3, the original length of the specimen has a large impact on the strain calculation, making the specimen dimensions very imperative in the data analysis. It is important to note that throughout this experiment, the cross-sectional area for both trabecular and cortical bone was simplified through the assumption that the bone samples roughly fit the shape of cylinders with diameter of the widest point of the top surface. Additionally, the bones were assumed to be solid rather than hollow. These two assumptions likely result in a larger value for cross-sectional area, which would lead to a smaller experimental stress and smaller Young's Modulus compared to the actual values.

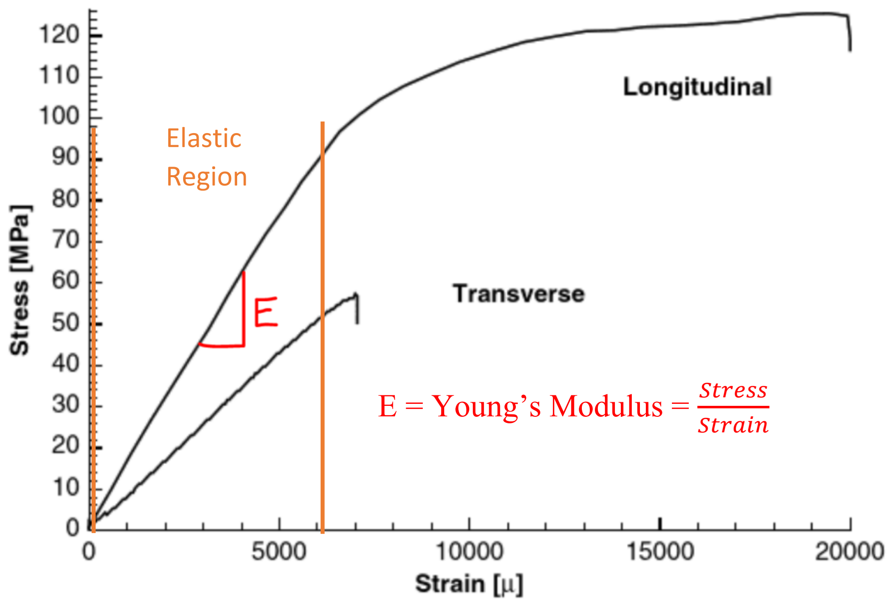

Figure 1: Typical stress-strain curve for bone in the transverse and longitudinal directions (Enderle and Bronzino, 2011) and an example of how Young's modulus can be interpreted from the curve.

Literature reveals average values for human tibia trabecular bone Young's modulus to be 10.4GPa (S.D. 3.5) and the average Young's modulus of cortical bone from the tibia to be 18.6 GPa (S.D. 3.5) (Rho *et al.*, 1993). A second study shows similar results with an average trabecular and cortical Young's modulus from a human femur to be 11.4±5.6 GPa and 19.1±5.4 GPa, respectively (Zysset, 1999). As can be seen by these studies, the mean trabecular Young's modulus was found to be significantly less than that of cortical bone. However, an important observation to make is that these values were found using human bone samples while this experiment uses chicken bone samples. Figure 2 below provides an example of the difference between cortical and trabecular stress-strain diagrams.

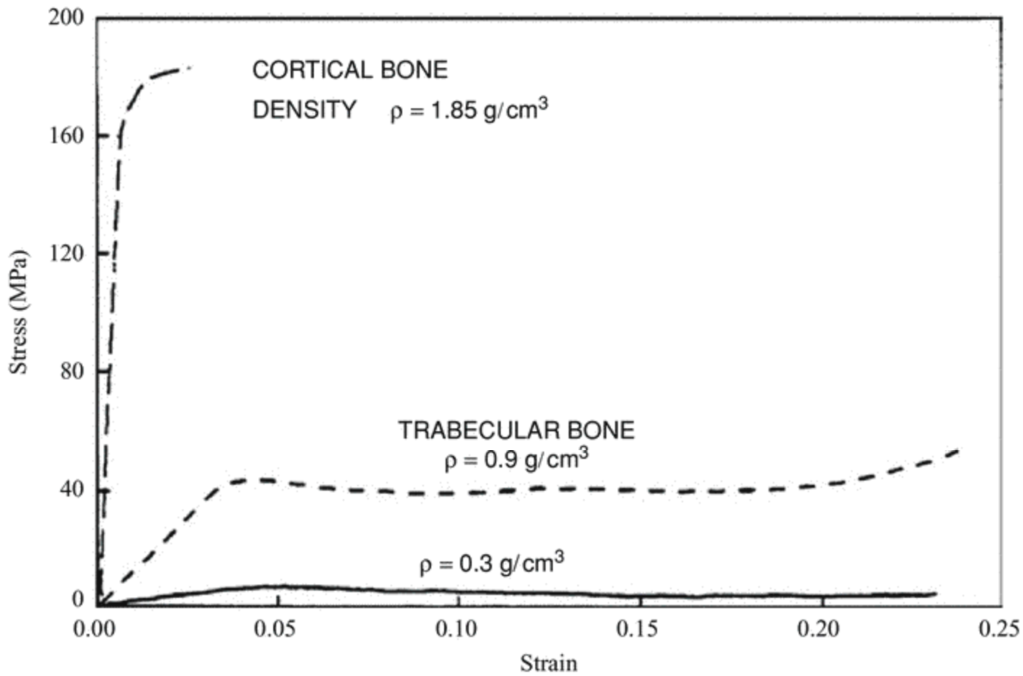

Figure 2: Typical compressive stress–strain curves for human cortical bone and two different densities of human trabecular bone (Ethier and Simmons, 2007).

In this study, a Test Resources test frame was used to test four samples of cortical chicken bone and four samples of trabecular chicken bone in compression and obtained data to calculate and compare the Young’s modulus between the two types of bone. Based on the results of previous studies, it is expected that the Young’s modulus of trabecular bone should be significantly less than that of cortical bone, therefore we hypothesize that when tested in compression, the Young’s modulus of trabecular chicken bone will be less than that of cortical chicken bone.

Materials and Methods:

To perform the experiment, four chicken tibias were dissected from the legs of a chicken and were cleaned using a scalpel. The proximal and distal epiphysis of the bones were cut and separated from the diaphysis and their respective lengths and maximum diameters were measured with a digital scalpel. The samples were assumed to be circular in cross section. The dimensions and geometry of the samples can be seen in Table A1 and Table A2 in Appendix A. Throughout the study, the diaphyses of the bones are considered to be cortical bone samples, while the epiphyses are considered to be trabecular bone samples. Figure 3 below shows trabecular and cortical bone samples and the corresponding dimensions recorded for each. For the trabecular bone sample, the height, also referred to as length, is the distance from the bottom of the bone resting on the surface to the top of the bone and would be coming out of the plane of the image. The maximum value for lengths and diameters of all samples were the values recorded for analysis.

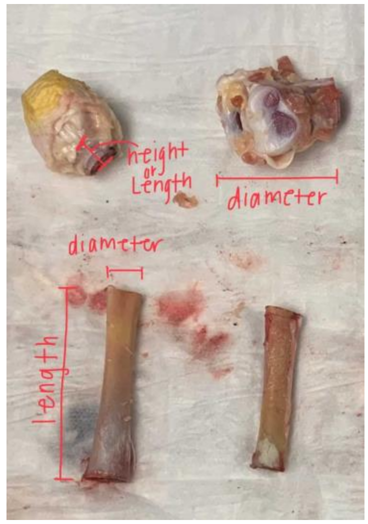

Figure 3: Two cortical (bottom) and trabecular (top) bone samples and the corresponding dimensions recorded for each.

A compression test was conducted on each specimen. In each test, a sample was placed in a Test Resources test frame with a 250lb load cell between compression platens with the length of the bone perpendicular to the platen surfaces. A 100Q-controller was used to mechanically control the movements of the test frame as well as program the test done by the frame. The load and position of the frame were zeroed before each compression test. The rate of change for the position of the compression platens was set to 5mm/min and the load parameter was set to 1000N in order to ensure that the test frame applied the maximum load possible to the specimen. The sample break percent of the specimen was set to 20% so that the test would continue to run until a 20% break of the specimen was detected. The log rate was set to 32.99Hz so that at least 5 minutes of data could be collected. The test frame, 100Q-Controller, load cell, and compression platens can be seen in Figure 4 below.

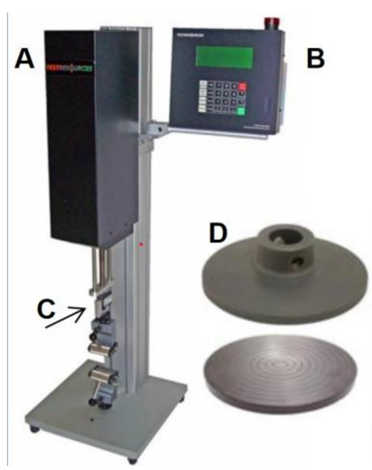

Figure 4: Test Resources test frame (A), 100Q controller (B), load cell (C), and compression platens (D) (Biomechanics, 2017).

After each compression test, the load, position, and time data values were sent from the test frame to a computer and saved as a .csv file to be analyzed in MATLAB. The load and position were used to construct stress-strain diagrams for each specimen using the equations explained in the introduction. The linear, or elastic region of each diagram was extracted and a linear regression analysis was performed in order to examine the strength of the linear relationship between stress and strain and determine the Young's modulus of the sample using the slope of the trendline. The data was fit to the model in Equation 4 below.

$$\text{stress} = 1 + \text{strain} \tag{4}$$

An unpaired, left-tailed t-test with unequal variances was employed between the trabecular bone Young's moduli and cortical bone Young's moduli to test the hypothesis that the Young's modulus of trabecular bone is less than that of cortical bone. The test was unpaired because the two populations were not related and unequal variance was assumed due to the small number of trials included in each population. The level of significance for the test was set to 5% ($\alpha = 0.05$). Example MATLAB code used to perform the linear regressions and t-test can be seen in Appendix B.

Results and Discussion

The results of the compression testing confirmed the hypothesis that the Young's modulus of trabecular bone is significantly less than that of cortical bone ($p = 0.0127$). The data obtained from each step of analysis leading up to this conclusion will be discussed. The analysis begins with calculating stress and strain values to create a stress-strain diagram. An example of both trabecular and cortical stress-strain diagrams constructed from the load and position data of the test frame can be seen in Figure 5 and Figure 6.

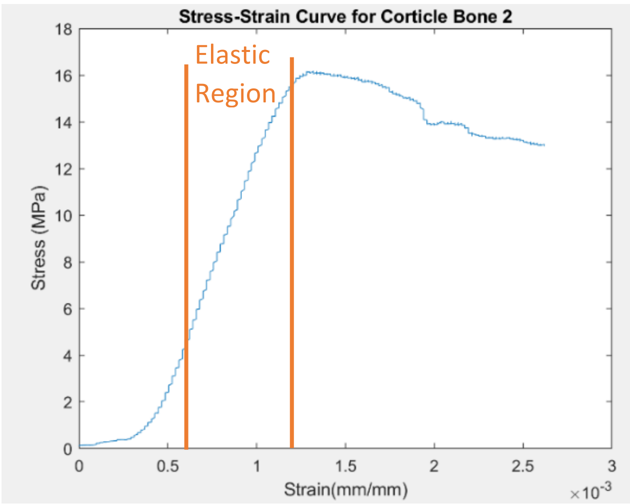

Figure 5: Example stress-strain diagram extracted from the experimental data of cortical bone test 2.

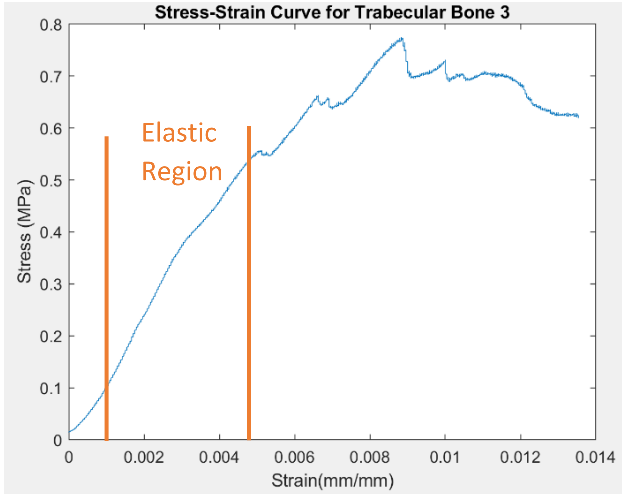

Figure 6: Example stress-strain diagram extracted from the experimental data of trabecular bone test 3.

The stress-strain data of the four cortical and four trabecular specimens largely followed the accepted shape and behavior of a normal stress-strain diagram for a sample under compression such as that seen in Figure 1. The linear regions were easily identified and extracted from the data in order to perform the linear regressions which provided the slope, or Young's modulus, as well as an R^2 value, which is measure of goodness of fit telling how linear the data truly is. Examples of the linear regression plots for cortical and trabecular bone can be seen in Figure 7 and Figure 8 respectively.

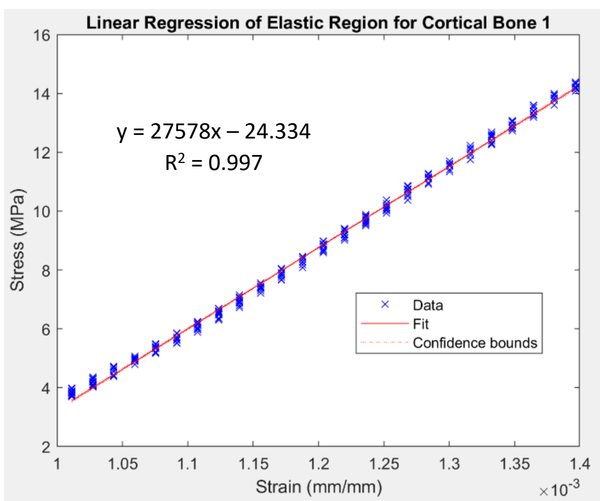

Figure 7: Linear regression plot for the elastic region of cortical bone test 1 including the line of best fit equation and R^2 value for the regression.

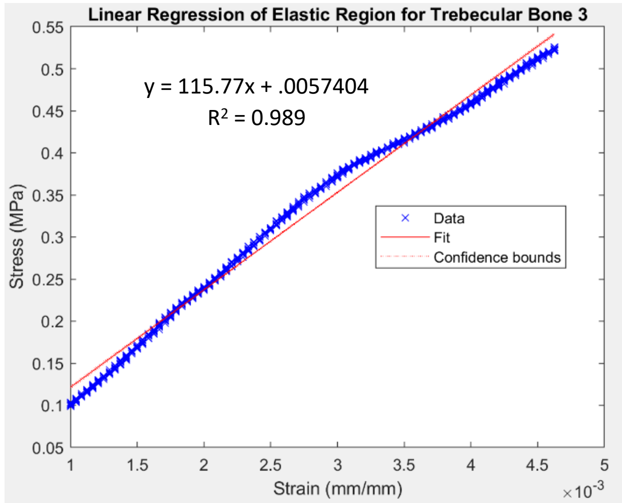

Figure 8: Linear regression plot for the elastic region of trabecular bone test 3 including the line of best fit equation and R^2 value for the regression.

From the four linear regressions performed on each type of bone, Young's modulus and R^2 values were analyzed. The average Young's modulus for cortical bone and trabecular bone were 18.5 GPa and 0.063 GPa respectively with standard deviations of 8.89 for cortical bone Young's modulus and 0.039 for trabecular bone Young's modulus. The average R^2 value for the cortical regressions was 0.9965 and the average R^2 value for the trabecular regressions was 0.9942. Table 1 below contains the exact value for Young's modulus obtained from each test and Table 2 contains the R^2 value calculated in each regression.

Table 1: Calculated Young's modulus values, measured in GPa, for each bone sample.

	Bone/Trial 1	Bone/Trial 2	Bone/Trial 3	Bone/Trial 4
Cortical YM (GPa)	27.578	20.570	6.299	19.643
Trabecular YM (GPa)	0.070843	0.031461	0.11577	0.034112

Table 2: Calculated R^2 values for the linear regression performed on the elastic region of each stress-strain diagram.

	Bone/Trial 1	Bone/Trial 2	Bone/Trial 3	Bone/Trial 4
R^2 Cortical	0.997	0.998	0.993	0.998
R^2 Trabecular	0.9997	0.990	0.989	0.998

The R^2 value being so close to 1 for each regression (Table 2) signified a very strong linear relationship between stress and strain in each test, allowing the assumption to be made that the data was an accurate representation of the elastic region for the bone samples. Knowing that the fits were reliable representations of each material allowed the Young's modulus values to be analyzed as very close to accurate for the samples. It should be noted that a limitation of the model is that the stress and strain data may not be exactly accurate due to the assumptions made in cross-sectional area calculations discussed previously in the report. Therefore, while the linear fits are good for each graph and indicate accurate values for slope, or Young's modulus, the graphs themselves may not be entirely accurate representations of each bone.

The relatively large standard deviation values occurred as a result of the limited number of trials conducted. Cortical bone sample 3 behaved significantly differently than the other samples (Table 1), having a much lower Young's modulus, bringing down the average value and impacting the standard deviation significantly. This sample could have performed differently for various reasons and further testing would be required to identify the cause for deviation from the mean. It should be noted that with more trials, this value would have increasingly less impact and overall, introducing more trials to the experiment would normalize standard deviation values.

The Young's modulus values for trabecular bone were compared to those of cortical bone in a t-test to determine whether the trabecular bone values were significantly less than that of cortical bone. The t-test resulted in a p-value of 0.0127, which was less than the chosen significance value of $\alpha=0.05$ signifying that the null hypothesis could be rejected and the hypothesis that trabecular bone Young's modulus is less than cortical bone Young's modulus should be accepted. This result makes sense in theory, aligns with previous studies, and is likely due to the differences in structure and composition between the two tissues.

Before drawing any conclusions from the data, it is important to keep in mind that the dimensions of the bones were largely simplified into solid cylindrical shapes with circular cross-sections. These assumptions likely caused an underestimation of Young's modulus due to the actual geometry of the bone being more complex and having a hollow center. The hollow center of the bone would cause the true cross-sectional area to be significantly less than that assumed by the experiment, leading to a larger stress value than calculated by the methods presented here. This introduces measurement uncertainty that may especially impact the Young's modulus of trabecular bone, which we found to be, on average, 0.063 GPa while other studies have shown it to be closer to 10.4 (Rho *et al.,* 1993) and 11.4 (Zysset, 1999). This experimental limitation would impact the trabecular values more than the cortical bone values because the trabecular bone samples had much more empty space within them due to their high degree of porosity. A second experimental limitation that contributes to the limited accuracy of the data is the small number of trials performed on each type of bone. Because of these significant sources of uncertainty in the data, it is advised to perform more trials with reduced uncertainty factors before using the results in any serious applications.

Conclusions

This study was conducted to determine whether the Young's modulus of trabecular bone is significantly lower than the Young's modulus of cortical bone. The Young's modulus of trabecular and cortical bone are important quantities to understand because of their implications in studying bone fragility diseases such as osteoporosis as well as engineering prevention and treatment methods. The experiment resulted in a Young's modulus value of $0.063\pm.03948$ for trabecular bone and 18.5 ± 8.89 for cortical bone. The value for cortical bone is largely supported by previous studies, in which the modulus values were found to be 18.6 GPa (Rho *et al.,* 1993) and 19.1 ± 5.4 GPa (Zysset, 1999). The experimental values for trabecular bone were farther from previous studies which found the Young's modulus to be 10.4 (Rho *et al.,* 1993) and 11.4 (Zysset, 1999). This difference is likely due to limitations in the experimental methods for calculating the sample cross sectional area in data analysis.

A linear regression analysis revealed that the elastic regions of the stress-strain diagrams for the bone samples had appropriate linear fits and a t-test performed on the two populations of Young's modulus values showed that the Young's modulus of trabecular bone was significantly lower than that of cortical bone ($p = 0.0127$). Both Rho *et al.* and Zysset found the Young's modulus of trabecular bone to be significantly less than that of cortical, supporting the results obtained in this experiment. These results aid in the understanding of bone biomechanics, because they quantitatively show why the two regions of bone have different functions in the body. With a lower Young's modulus, trabecular bone is able to undergo larger amounts of strain than cortical bone without fracturing, thus it can act as a shock absorber and transfer mechanical loads from the joint surfaces to the cortical bone. The higher Young's modulus of cortical bone means that it can withstand greater stresses before fracturing, explaining why cortical bone functions in supporting and protecting the body. With this information in mind, a weakening of bone and lowering of Young's modulus in diagnoses such as osteoporosis would have many negative implications, and methods of prevention and treatment would be largely dependent on which type of bone the majority of osteoporotic effects are resulting from.

The conclusions found in this study would be strengthened by increasing the number of trials performed and by using a more accurate calculation for the cross-sectional area of the bone samples. Future experiments that could be done to compliment and reinforce the findings that trabecular bone Young's modulus is less than that of cortical bone would be obtaining the same sets of data from bones of other species and performing a similar comparison. Additional studies to deepen knowledge of impacts of cortical and trabecular bone on bone fragility diseases could involve comparison of other mechanical properties of the two types of bone.

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APPENDIX A

Measurements

Table A1: Trabecular dimensions

	Bone 1	Bone 2	Bone 3	Bone 4
Height (mm)	19.24	21.12	24.00	18.00
Diameter (mm)	27.39	33.53	35.48	32.59
Cross-sectional Area (mm^2)	589.22	882.99	988.68	834.18

Table A2: Cortical dimensions

	Bone 1	Bone 2	Bone 3	Bone 4
Height (mm)	62.30	51.55	56.27	57.51
Diameter (mm)	8.19	8.55	11.38	8.10
Cross-sectional Area (mm^2)	52.68	57.41	101.71	51.53

APPENDIX B

Matlab Code

Code B1: Performing a linear regression on the stress-strain data in elastic region of the curves.

```
%% Linear regression for elastic region
% variables strain and stress imported from the .csv files

tbl = table(strain,stress)

mdl = fitlm(tbl)

plot(mdl)
xlabel('Strain (mm/mm)')
ylabel('Stress (MPa)')
title('Linear Regression of Elastic Region for Cortical Bone 1')
```

Code B2: Performing a t-test on the values for trabecular Young's modulus and cortical Young's modulus to determine if trabecular values are significantly smaller than cortical values.

```
%% t-test on Young's modulus calculations
%
% make arrays for young's modulus data of corticle and
trabecular bone

cort = [27578, 20570, 6299, 19643];
treb = [70.843, 31.461, 115.77, 34.112];

% Test the alternative hypothesis that the population mean of x
(trabecular)is less than the population mean of y (cortical).
% Conduct test using the assumption that x and y are from normal
% distributions with unknown and unequal variances. This is
called the Behrens-Fisher problem.
% ttest2 uses Satterthwaite's approximation for the effective
degrees of freedom.

[h,p] = ttest2(treb,cort,'Vartype','unequal','Tail','left')

% h = 1 rejects the null hypothesis at the 5% significance level
% (alpha = .05)
```