Dr. Ha Vo

BME 591/460 - Biomaterials

Comparing the Mechanical Properties of Cancellous Bone between Pig Femur Bone, Deer Femur Bone, and Human Humerus Bone

Research Paper

Gabriel Gonzalez

Jackie Harmon

Lauren Reagin

Spring 2016

Table of Contents

Abstract

Cancellous bone is a light and porous bone that often give a honeycombed or spongy appearance. The bone matrix is organized into trabeculae that are arranged along lines of stress. The spaces between often are filled with blood vessels and marrow. This bone is most commonly found in areas of bone that are not subjected to great mechanical stresses, even though the open structures of cancellous bone allows it to dampen sudden stresses (i.e., load transmission through joints).

Cancellous bone is considered nonlinearly elastic even at small strains, with it most often modeled as linearly elastic until it yields. It yields in compression at strains of exactly 1 percent, after which it can sustain large deformations of up to 50 % strain while still being able to maintain load-carrying capacity. Therefore, a cancellous bone is able to absorb a substantial amount of energy on mechanical failure. The elastic and strength properties of the cancellous bone displays heterogeneity with respect to donor age, donor health, anatomic site, loading direction based off the initial orientation of the bone, and the loading mode.

The mechanical and structural characteristic for cancellous bones also changes depending on the species the bone was gathered from. In a study completed by *Benedikt et. al*, the trabecular microstructural properties were compared and the porcine bone demonstrated the most similarities to human bone in microstructural parameters. The structural mechanical properties of the bone were also analyzed using numerical methods and it was concluded that if human bones of the proximal humerus were not available for biomechanical tests then porcine bones could possibly be the closest surrogate of the tested species (which were human, bovine, ovine, and porcine). However, in a different a study conducted by *Kieser et al.*, deer bone was compared to pig and sheep bone with morphological parameters and biomechanical tests. On average, the deer bone was found to be most similar to the human femur, but there was no single bone type that consistently resembled it.

The overall design of this experiment was to compare the mechanical characteristics while in compression for the cancellous portion of the human humerus, the pig femur, and human femur due to the proposed similarities of both animal models to the human femur. The specific characteristics that were focused on were the: axial stress, the axial strain, axial force, and Young’s modulus. These axial characteristics were obtained from testing with an MTS machine while the Young’s modulus was calculated from the axial stress over the axial strain..

From the results, there were several trends that could be observed. The first trend was that the deer bones required the highest amount of stress to deform the bones, which led to deer bones having the highest Elastic modulus. The human bone had the lowest Elastic modulus, which could possibly be linked to the fragility of the bones caused by osteoporosis. The pig bones showed the highest strain, which could possibly be linked to the dimension differences of the pig bones being 1 cm taller. Therefore, the deer bone had the highest stiffness while the human bone was the most malleable due to the differences in Elastic modulus.

Possible future studies include the use of all three bones coming from the same anatomical site instead of two femurs and a humerus or possibly different anatomical ends (i.e., upper limb bones comparison to lower limb bones). Also, since the cadaver bones were osteoporotic, an experiment could be completed to compare the differences in mechanical properties between osteoporotic cadaver bones and non-osteoporotic cadaver bones.

Introduction and Background

There are two bone types within the body: cortical bone and cancellous bone. Cortical bone makes up the shafts of the long bones and is very dense/strong which makes it harder to fracture. The cancellous bone is placed at the end of long bones where the cortical bone gives away and is much more porous and weaker than cortical bones. It can also be found in the pelvic bones, ribs, and the vertebrae [12].

Cancellous bone is a light and porous bone that often give a honeycombed or spongy appearance. The bone matrix is organized into trabeculae that are arranged along lines of stress. The spaces between often are filled with blood vessels and marrow. This bone is most commonly found in areas of bone that are not subjected to great mechanical stresses, even though the open structures of cancellous bone allows it to dampen sudden stresses (i.e., load transmission through joints) [13].

Cancellous bone is considered nonlinearly elastic even at small strains, with it most often modeled as linearly elastic until it yields. It yields in compression at strains of exactly 1 percent, after which it can sustain large deformations of up to 50 % strain while still being able to maintain load-carrying capacity. Therefore, a cancellous bone is able to absorb a substantial amount of energy on mechanical failure.

The elastic and strength properties of the cancellous bone displays heterogeneity with respect to donor age, donor health, anatomic site, loading direction based off the initial orientation of the bone, and the loading mode. The modulus and strength decrease at approximately 10% per decade while aging. Cancellous bone affected by osteoporosis, osteoarthritis, and bone cancer is known to affect the mechanical properties of the bone [6]. More specifically, osteoporotic bones have a lower strength and stiffness that can be related to the increased cavity area created by the disease [4].

In compression, the anisotropy of cancellous bone strength increases with a reduction in density and increasing age. The strength also depends on the loading mode, with it being highest in compression. The modulus and strength depend on apparent density, but the relationship varies for different types of cancellous bone due to age, anatomical site, and disease-related variations in bone structure. The yield failure strain and ultimate failure strain of human cancellous bone have little to no dependence on apparent density and modulus [6].

The mechanical and structural characteristic for cancellous bones also changes depending on the species the bone was gathered from. In the comparison of human and pigs, there have been similarities found in the cross-sectional diameter and area of the humerus even though pigs have a denser trabecular network [9] [11]. In a study completed by *Benedikt et. al*, the trabecular microstructural properties were compared and the porcine bone demonstrated the most similarities to human bone in microstructural parameters. The structural mechanical properties of the bone were also analyzed using numerical methods and it was concluded that if human bones of the proximal humerus were not available for biomechanical tests then porcine bones could possibly be the closest surrogate of the tested species (which were human, bovine, ovine, and porcine) [8].

In the comparison of human and deer, the deer femur has similar biomechanical properties and average length, angular, distal femoral, diaphyseal, and endosteal measurements that is closer to that of a human femur than some other animal models [5]. In a study conducted by *Kieser et al.*, deer bone was compared to pig and sheep bone with morphological parameters and biomechanical tests. On average, the deer bone was found to be most similar to the human femur, but there was no single bone type that consistently resembled it. The conclusion from the study was that “Deer femora could be considered a suitable animal model for the human femur” [7].

The Material Testing System (MTS) is an advanced technology that can be used to analyze different materials. MTS can yield results of both static and dynamic material and component testing. The MTS relies on high accuracy, flexibility, and performance. The MTS applies different forces at different rotational rates in order to create a different variety of breaks altering frequency of torque. This technology allows researchers to recreate different fractures and apply these to bones or other bone like structures. Once an experiment is conducted in the MTS, the technology transfers a complete set of data to the computer software which allows the researcher to analyze this data and draw results [10].

The overall design of this experiment was to compare the mechanical characteristics while in compression for the cancellous portion of the human humerus, the pig femur, and human femur due to the proposed similarities of both animal models to the human femur. The specific characteristics that were focused on were the: axial stress, the axial strain, axial force, and Young’s modulus. These axial characteristics were obtained from testing with an MTS machine while the Young's modulus was calculated from the axial stress over the axial strain (Figure 1). The strain was calculated by change in length divided by length, while the stress was force divided by area.

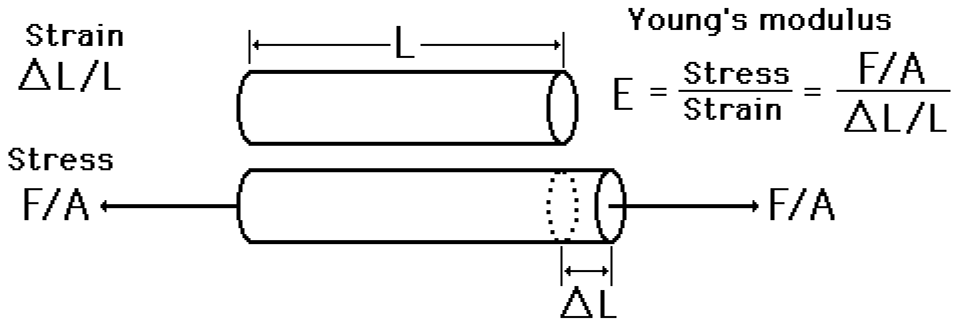


Figure 1: The visualization of stress vs. strain and equation for calculation of the Young's modulus.

The following terms are define as:

ΔL = change in length

L = length

F = Force on cross-sectional area

A = Cross-sectional area

Materials and Methods

Three types of bones were used in this research project: human bone, pig bone, and deer bone. The human bones used were cadaver humeri, while the deer and pig bones used were femurs. There were multiple bones per mammal because some bones could only produce one sample. Each bone was skinned due to the fact they were obtained with meat still attached. Samples were cut from the cancellous section of the bones, until four samples were obtained per type, making 12 samples tested all together (Figures 2-4).

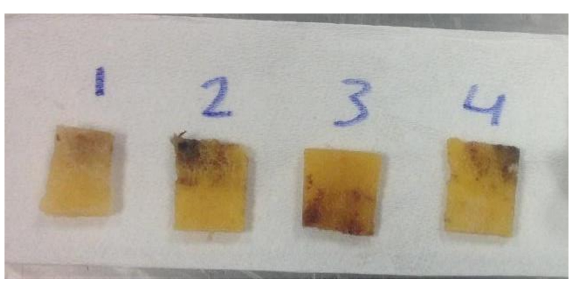


Figure 2: Samples of human bone

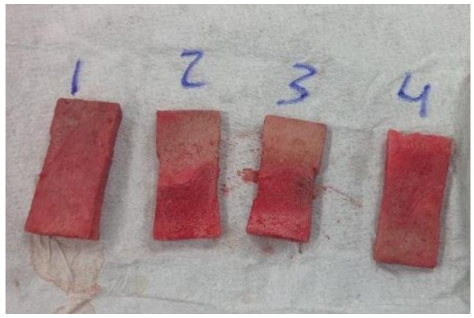


Figure 3: Samples of pig bone

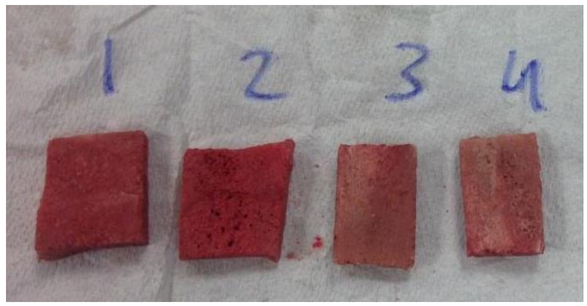


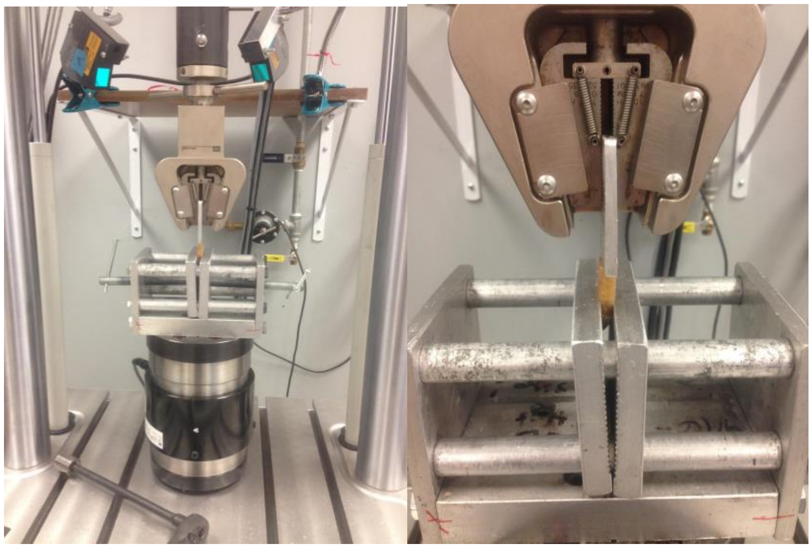
Figure 4: Samples of deer bone

Each sample was cut to be 2 cm long and 0.5 cm wide. The height of the samples were not a specific length, as long as they would fit into the MTS (around 3 cm). The weight in grams of each sample was taken using a scale, and the volume of each sample was measured in milliliters by calculating the displacement of water in a graduated cylinder after the sample was placed in the cylinder. The specific measurements can be found in Table 1.

Table 1: Bone Sample Measurements

Bone type	Sample #	Height (cm)	Length (cm)	Width (cm)	Weight (g)	Volume (ml)
Pig Femur Bone	1	4.1	1.9	0.5	5	4
	2	4	1.8	0.4	4	3
	3	3.8	1.9	0.5	3	3
	4	4.1	2	0.5	5	3
Deer Femur Bone	1	2.6	2.1	0.6	5	5
	2	2.6	2.1	0.5	5	4
	3	2.8	1.9	0.6	4	4
	4	2.8	1.8	0.5	4	3.5
Human Humerus Bone	1	2.6	1.7	0.6	3	3
	2	2.9	2	0.5	3	3
	3	2.6	2.2	0.4	3	3
	4	2.9	2.1	0.4	2	3

The MTS was not set to any special settings. The bone samples were compressed until failure at a speed of 0.01 mm/sec (Figures 5 and 6).



Figures 5 & 6: Bone sample in the MTS, and close-up

Results and Discussion

In order to analyze the raw data obtained from the MTS, all the samples for every group (cadaver, deer, and pig) were averaged into one set of data for each. Then, the average cross sectional area and the average height were calculated for each of these groups. Using all the averages, it was possible to find both the axial stress and the axial strain caused throughout the compression until failure test. The formulas used to find these sets of values are denoted in Figure 1.

Furthermore, a Stress vs. Strain graph was created for each group. These graphs, shown in Figures 7, 8, and 9 represent the Young's Modulus for each of the bones, denoting the axial strain on the Y-axis and the axial stress on the X-axis.

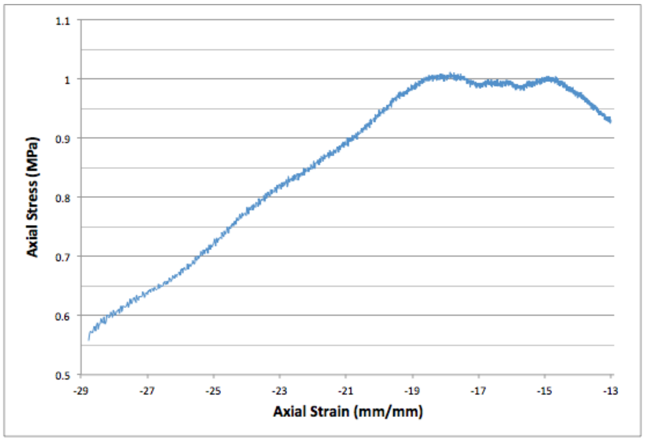


Figure 7: Cadaver Humerus Young's Modulus Graph

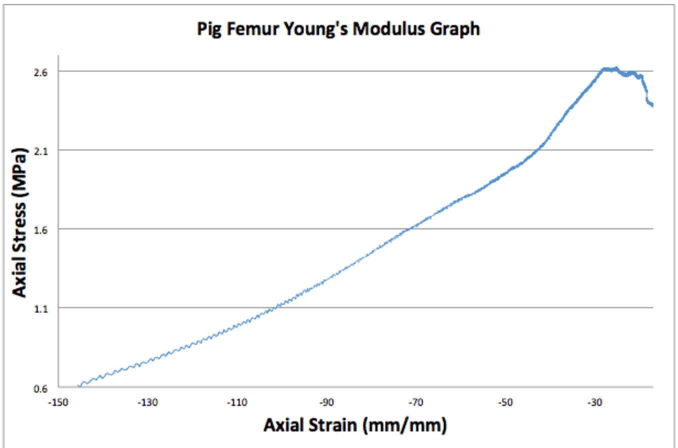


Figure 8: Pig Femur Young's Modulus Graph

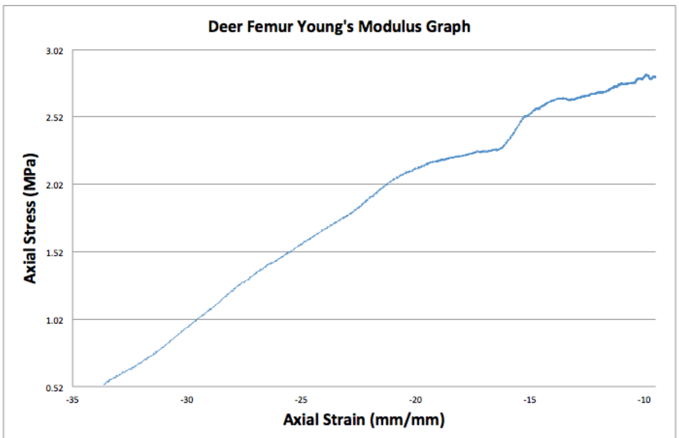


Figure 9: Deer Femur Young's Modulus Graph

When Comparing all three of the Stress vs. Strain graphs, shown in Figure 10, some observations can be made about each of these trends. The cadaver trend is oddly small in comparison to the deer and pig bone trends. This is thought to be caused by the fact that the humerus cadaver bone used for this experiment was osteoporotic. Osteoporosis definitely causes weakening of the bone through bone breakdown, resulting in smaller fracture point in terms of axial stress but still maintaining decent strain values. The pig bone trend has a significantly larger strain change in comparison to that of the deer and cadaver bone. This factor is thought to be due to the fact that the height for the pig bone pieces was averagely 1 cm greater than the height for the deer bone and the cadaver bone. This characteristic allowed the pig bone to attain a larger range of strain given its larger height size. Finally, the deer bone trend is significantly steeper in comparison to the trends of the pig and the cadaver. This is purely an indication that deer bone has an overall greater Elastic Modulus in comparison to both cadaver and pig bone.

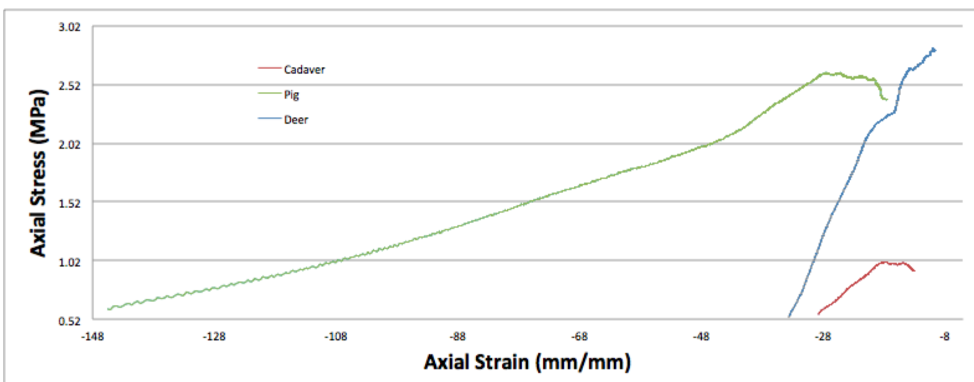


Figure 10: Comparison of all Bone’s Stress vs. Strain Diagrams

As another point of comparison, it was interesting to bring the actual Young's Modulus for all three groups together and compare them based on their change as the Axial Compression Force was applied. Such comparison, denoted on Figure 11, shows the different points at which each specific bone went from the elastic region, into plastic and then followed by fracture point. Cadaver bone was able to absorb about 91.268 N of axial force before going into the plastic region. The Elastic Modulus at this point was 0.04897 MPa. Pig bone was able to absorb about 232.88 N of axial force before going into the plastic region. The Elastic Modulus at this point was 0.0875 MPa. Deer bone was able to absorb about 246.098 N of axial force before going into the plastic region. The Elastic Modulus at this point was 0.1328 MPa.

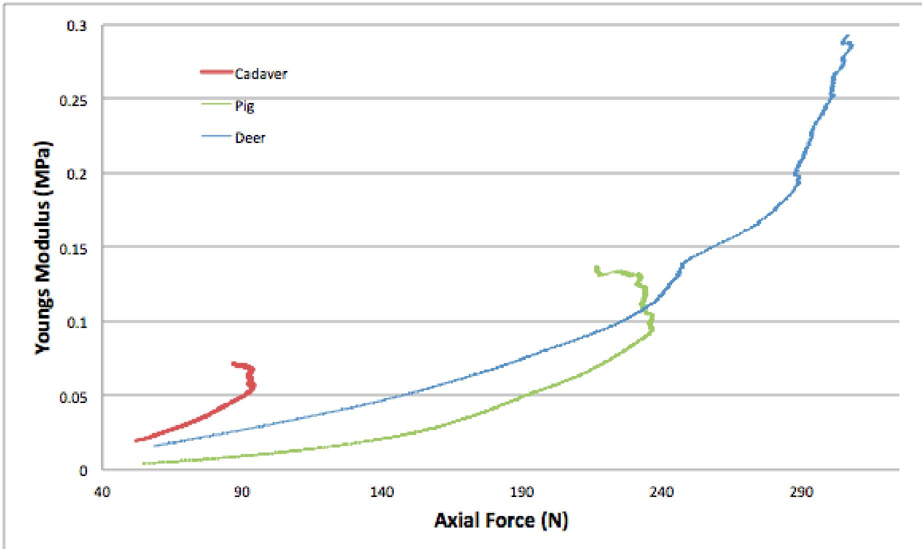


Figure 11: Comparison of Young's Modulus for all three bones

The Elastic Modulus values gathered from each of the bones, and plotted in Figure 12, offer an idea of the different elastic characteristics between these different bones. Deer having the highest elastic modulus means that deer bone has the highest stiffness and is also the hardest material to be stretch. Deer bone will usually receive the lesser deformation, or strain value, out of all three bone types. However, more stress has to be apply in order to achieve the failure point. Cadaver bone having the lowest elastic modulus, represents the most malleable material, which means it is the easiest to be deformed with lesser amount of stress applied. This factor explains why it didn't take a great axial compression force to fracture the cadaver bone.

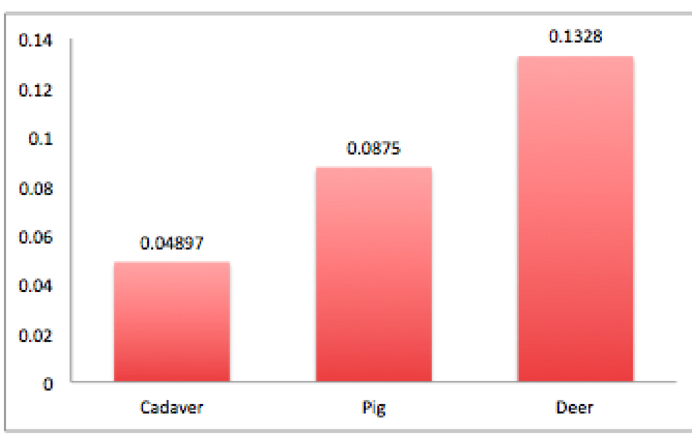


Figure 12: Young's Modulus of each group at elastic-plastic region interphase.

After analyzing the previous graphs, there were two different averages generated to further compare these three materials. At first, shown in Figure 13, the entire range of the stress and strain data of generated by the MTS was averaged into one valued as the elastic modulus. In other words, this average includes the data from the very beginning of the test until full full failure is completed. It is remarkable that the values are relatively equal to the previous elastic moduli with the deer bone having the greatest elastic modulus and cadaver bone having the smallest.

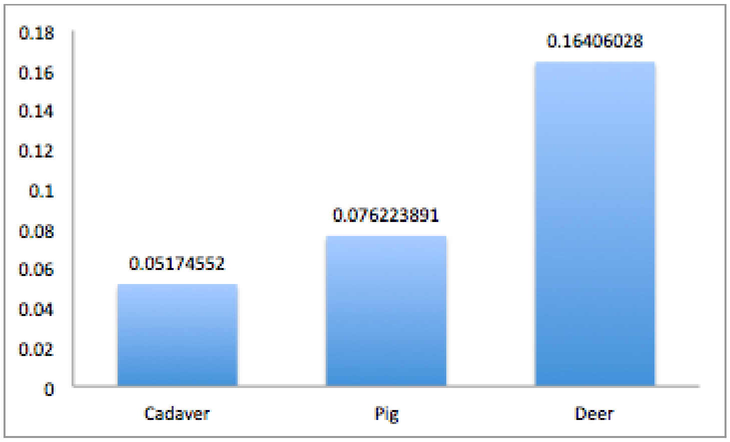


Figure 13: Average Young's Modulus of each group (Includes full data range).

In order to obtain a better idea for the slope, or elastic modulus, of each of the groups the data shown in figure 14 was generated by only averaging the values of the strictly linear section for each graph. As observed on the values, deer bone still predominates with an even higher elastic modulus, in comparison to pig and cadaver bone. In this case, the cadaver bone came out to have a higher elastic modulus than that of pig bone. This change may be due to the fact that, as only the linear section of the graph is being considered, due to its greater length, in comparison to the other groups, the pig bone results on a lower Young's Modulus.

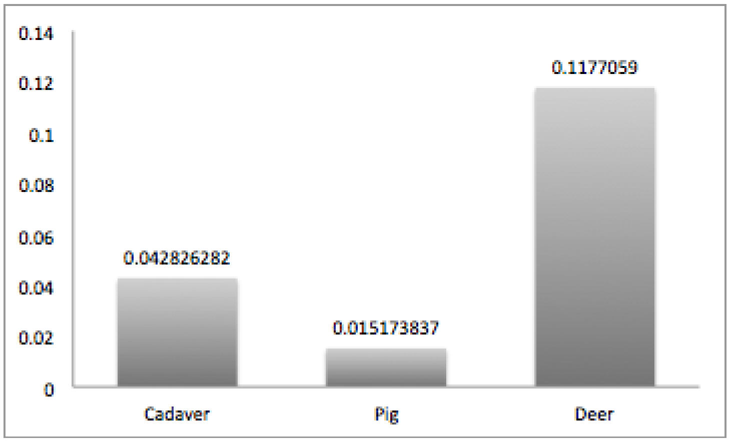


Figure 14: Average Young's Modulus of each group (Includes only a selected data range).

Conclusions and Future Studies

There were several trends in the results of this research experiment. First, when comparing the stress it took to deform the bones, the deer bones required the most, meaning it had the highest Elastic Modulus. The cadaver bone had a very small one, but this was most likely due to the fragility of bones with osteoporosis. The pig bones had the highest strain, most likely due to the pig bones being about 1 cm taller than the other two bone types. In conclusion, the deer bone having the highest Elastic Modulus means that it has the highest stiffness and is the hardest material to be stretched. Cadaver bone, having the lowest Elastic Modulus, represents the most malleable material, which means it is the easiest to be deformed with lesser amount of stress applied.

In the future, this experiment could use different bones to see how the results differ; for example, the cadaver bones were from the humerus, while the deer and pig bones were femurs. This experiment could be all three types of bones being femurs or all three types of bones being humeri. Another way to do this experiment would be to compare cadaver bones without osteoporosis to cadaver bones with osteoporosis. Lastly, this experiment could be done again by comparing bones from one anatomical origin to another; for example, bones from the upper limbs in comparison to bones from the lower limbs.

References

[1] BME 591: Biomaterials by *Dr. Ha Vo*

[2] BME 636: Advanced Biomedical in Orthopedics Surgery *by Dr. Ha Vo*

[3] Aerssens J, Boonen S, Lowet G, Dequeker J (1997) Interspecies Differences in Bone Composition, Density, and Quality: Potential Implications for in Vivo Research. Retrieved from http://press.endocrine.org/doi/full/10.1210/endo.139.2.5751

[4] Dickenson R, Hutton W, Stott J (1981) The Mechanical Properties of Bone in Osteoporosis. Retrieved from http://www.boneandjoint.org.uk/content/jbjsbr/63-B/2/233.full.pdf

[5] Hedgeland M, Libruk M, Corbiere N, Ciani M, Kuxhaus L (2016) The *Odocoileus virginianus* Femur: Mechanical Behavior and Morphology. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4710509/

[6] Keaveny T, Morgan E, Yeh O (2004) Chapter 8: Bone Mechanics. Retrieved from http://www.unhas.ac.id/tahir/BAHAN-KULIAH/BIO-MEDICAL/NEW/HANBOOK/Bone_Mechanics.pdf

[7] Kieser DX, Kanade S, Waddell NK, Kieser JA, Theis JC, Swain MV (2014) The deer femur--a morphological and biomechanical animal model for the human femur. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24948453

[8] Kropp B, Chevalier Y, Muller P, Pietschmann M (2015) Porcine bone is a better surrogate than bovine and ovine for microstructural and apparent properties of human trabecular bone at the greater trochanter. Retrieved from http://www.egms.de/static/de/meetings/dkou2015/15dkou749.shtml#References

[9] Mosekilde L, Weisbrode SE, Safron JA, Stills HF, Jankowsky ML, Ebert DC, Danielsen CC, Sogaard CH, Franks AF, Stevens ML, Paddock CL, Boyce RW (1993) Calcium-restricted ovariectomized Sinclair S-1 minipigs: an animal model of osteopenia and trabecular plate perforation. Bone 14: 379-382.

[10] MTS Systems Corporation (2006) MTS 810 & 858 Material Testing Systems. Retrieved from http://www.upc.edu/sct/documents_equipament/d_77_id-412.pdf

[11] Raab DM, Crenshaw TD, Kimmel DB, Smith EL (1991) A histomorphometric study of cortical bone activity during increased weight-bearing exercise. J Bone Miner Res 6: 741-749.

[12] Study.com (2016) Cancellous Bone: Definition, Structure & Function. Retrieved from http://study.com/academy/lesson/cancellous-bone-definition-structure-function.html

[13] The Editors of Encyclopedia Britannica (2016) Cancellous Bone. Retrieved from http://www.britannica.com/science/cancellous-bone