Determination of Variation in Natural Frequencies of a Femur Bone

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Abstract — The elderly population is on the rise and this trend is expected to persist. Age-related bone loss and osteoporosis in the elderly increase the risk of fractures and morbidity in this population. It is important to identify the possible pathologic mechanisms underlying bone fragility in old age. We have selected femur bone as the bone for our study as it the longest and the heaviest bone in the human body. The bone mechanical properties such as young's modulus, Poisson's ratio, shear modulus, density and porosity vary with age. All these mechanical properties follow a decreasing trend with age. Different methods have been used to find out these variations of mechanical properties with age. The FEA model of the femur bone was imported, and static analysis was performed on that and compared with the experimental data to verify if the femur model was accurate or not. Since the femur bone is a complex structure the material properties cannot be isotropic, but they are anisotropic. Orthotropic variation of the bone mechanical properties of a human female bone were considered. Using these material properties, modal analysis was performed to determine the natural frequencies of bones for different ages. First six modes of natural frequencies for different age groups are considered. A decreasing trend has been observed in natural frequency against age. After literature survey, the variation of porosity with age has been found out. The graph between natural frequency and porosity is drawn out. Further, this graph can be used to find out the porosity in different people by finding out the intermediate parameter i.e., natural frequencies of the bone.

Keywords: Porosity, Tomography, Osteoporosis, Acoustic Impedance, Osteoblasts

I. INTRODUCTION

The proportion of elderly persons in the world population has increased substantially and will continue to do so in the coming years. Aging has multiple complex effects that result in the progressive deterioration of various organs, including the skeleton. Age-related bone loss and osteoporosis in the elderly increase the risk of fractures and morbidity in this population. Osteoporosis is a common disease of the elderly, characterized by low bone mass and microstructural deterioration of bone tissue, with an increased fracture risk. It is important to identify possible pathologic mechanisms underlying bone fragility in old age. Osteoporosis is generally asymptomatic. The main consequence of osteoporosis is the increased risk of bone fractures. The femoral neck is highly susceptible to fracture in patients with osteoporosis.

A. Human Femur Bone

Femur Bone is most important structural parts of the human body. It also improves the force by making different linkages and converting it to various types of motions.

As the femur is the only bone in the thigh, it serves as an attachment point for all the muscles that exert their force over the hip and knee joints. Some biarticular muscles – which cross two joints, like the gastrocnemius and plantaris muscles – also originate from the femur. In all, 23 individual muscles either originate from or insert onto the femur. A femoral fracture that involves the femoral head, femoral neck or the shaft of the femur immediately below the lesser trochanter may be classified as a hip fracture, especially when associated with osteoporosis. Femur fractures can be managed in a pre-hospital setting with the use of a traction splint.

Fractures of the shaft are typically a high energy injury but can occur in the elderly as a result of a low energy fall. Neck of femur fractures (NOFs) are increasingly common and tend to be sustained by the elderly population as a result of low energy falls in the presence of osteoporotic bone. They are more prevalent in women. In younger patients they tend to occur as a result of high energy accidents.

II. LITERATURE REVIEW

A. Material Properties

Proper selection of material properties for the human femur is a vital part of the design. The main factors influencing the selection of material properties are - age, gender, health, place of living and food habits. The material properties chosen should be closer to the real femur's properties. Young's modulus, Shear modulus, poisons ratio and density are required. The material of femur bone is treated to be homogenous and isotropic in nature. But the material of femur bone is anisotropic in nature. It is difficult to find out material properties in all directions. So, the material of femur is orthotropic in nature i.e., properties vary along 3 orthogonal directions. In various articles it was found that the in-homogenous models of femur predict good accuracy for the measured stress field and homogenous material femur gave less accurate results.

Variation in the bone mineral density should also be considered which can be found out from Dual energy X-ray absorptiometry (DXA). In the past decades, numerous non-invasive diagnostic techniques, such as magnetic resonance imaging, quantitative computed tomography and quantitative ultrasound attenuation techniques have been employed to assess bone porosity, none of them can directly measure the porosity of femur bone. Nuclear magnetic resonance (NMR) is used to measure the porosity and pore size distribution in human femur bone.

B. Design of Femur Bone

Center hole for bone marrow is one of the important considerations while analyzing a femur bone. since it is not constant along the length of the bone and its variation along the length is difficult to define.

Initially, a hollow shaft of uniform cross-section is considered to mimic the real femur bone. But over time, for femur bone drawing, dimensional data is taken from frozen bone, or from wet femur bone. In order to perform finite

element analysis, the 3D CAD model of femur bone is fetched that is designed in SOLIDWORKS using the geometrical data that is taken from CT (Computerized Tomography) scan of real femur bone.

C. Structural Analysis

The femur bone modeled in SOLIDWORKS needs to be validated with the existing experimental data. These parameters insinuate how accurate the model resembles with real one. Using ANSYS, most of these analyses can be carried out. For performing FE analysis, it is important to define the force acting on the bone. The load is transmitted from hip bone to femur bone through head of femur and normal to the head of femur. Static loading involves a static study for calculating the response of bodies on which loads are applied statically or slowly.

Each structure tends to vibrate with frequencies. A natural frequency study calculates the natural frequencies, also adding the body's mode shapes. Modal analysis gives the natural frequency at which the femur bone vibrates along with different modes.

D. Research Gap

From literature survey, most studies were done either on studying the material properties of femur bone or structural analysis of the bone assuming the material is isotropic, but very few studies focus mainly on the modal analysis of femur bone considering it be orthotropic in nature. Studying the natural frequencies of the human femur and trying to analyze the natural frequencies varying with age (which in turn lead to analyzing variation of material properties of femur bone with direction, age and sex) can help in determining the femur bone's porosity of an individual. FEA on orthotropic material of femur bone has not been dived into a lot. Hence the present study was carried out to determine the natural frequencies of femur bone for different age groups considering the material of bone to be isotropic (Young's Modulus, Poisons Ratio, Shear Modulus are different along different directions). Also, there was no prior art about bringing out the relation between porosity of femur bone and its natural frequency for a range of age groups.

E. Main Objectives

The objectives of the present work are: -

- To calculate the natural frequencies of human femur and draw the mode shapes.
- To study the changing of the natural frequencies due to changing of human female femur's mechanical properties like young's modulus, Poisons ratio and density (preferably BMD) with age.

ANSYS software is used to achieve these objectives.

III. Theory for Variation of Mechanical Properties in Bones

A. Mechanical Properties of Human Bone

Bone is composed of a cellular component and an extracellular matrix. The cellular component is made of osteoblasts, bone-forming cells, bone-destroying cells, osteocytes and bone-maintaining cells which are inactive osteoblasts trapped in the extracellular matrix. The matrix, which is responsible for the mechanical strength of the bone tissue, is formed by an organic and a mineral phase. A liquid component is also present. So, we find that bone is a natural composite material. By weight, bone contains approximately 60% mineral, 10% water, and about 30% collagenous Matrix.

Most of the previous work devoted to the local mechanical quality of bone tissue quantified microhardness or acoustic impedance, which correlate to some extent, but remain physically distinct properties from elasticity constants such as Young's modulus. In addition, available experimental results on elastic properties of bone tissue differ highly according to the adopted technique because the representative volume elements and the deformation mechanisms do not coincide.

The collagen and the mineral crystals are usually oriented in the longitudinal direction of bone. Thus, the strength and stiffness of bone are always found higher in the longitudinal axis. The mineral phase most likely imparts stiffness to the bone, whereas the collagen network contributes significantly to its fracture properties. The mineral content in a bone shows little changes with increasing age, and this trend is also reflected in its stiffness. In contrast, the energy absorbed during the fracture of bone decreases significantly with increasing age. There are age related deteriorations in bone mechanical properties.

B. Different Properties in Bone

There are many methods to determine the properties of the bone. We will see each of the methods to determine the properties of the bone.

1) Young's Modulus of Bone:

This study was concerned with establishing the regional variations in the magnitude of the longitudinal Young's modulus of the cortical bone in the femoral midshaft. Several beam-shaped small specimens were methodically harvested from each pair and were used to measure the longitudinal modulus adopting the three-point bending test, which was carried out with a specially constructed and validated apparatus. CT scans of the bone were obtained, prior to harvesting the specimens, and the CT number was measured at locations corresponding with the specimen sites.

2) Materials and Methods:

The test was conducted in universal testing machine (UTM) WDW-E-100. WDW-E Series is a new kind of electronic PC control UTM. The loading capacity of this UTM is 1000 KN. We measure and plot the loading force, deformation and crosshead stroke etc. The displacement range of the machine was ± 80 mm. The specimen was bolted in the steel fixture and held in the machine grips. The test was performed at normal room temperature and pressure conditions. The load applied by machine at a crosshead speed of 1 mm/minute. During the test, the computer connected to the machine recorded the applied load and corresponding deformation. The computer records the applied load and corresponding deformation. The test was stopped as the specimen failed.

Tensile test data analysis

The stress σ was calculated using the equation.

$$\sigma = F/A$$

In the above equation, F is the load applied and A is the cross-sectional area of the specimen. The strain ε in the specimen was calculated using the equation:

$$\varepsilon = \delta/l$$

Where δ is the total deformation of the specimen until failure and l is the initial length of the specimen.

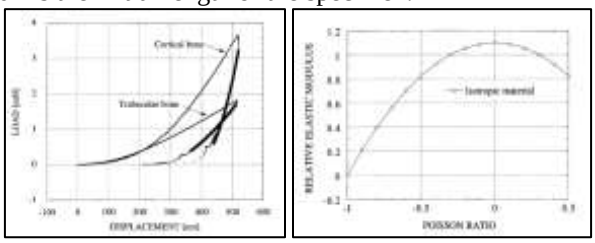

Fig. 1: Graphs relating to variation in elastic modulus.

3) Poison's Ratio:

In mechanics, Poisson's ratio is the negative of the ratio of transverse strain to lateral or axial strain. It is named after Poisson and denoted by the Greek letter 'ν'; It is the ratio of the amount of transversal expansion to the amount of axial compression for small values of these changes.

Poisson's ratio= (Transverse strain/Longitudinal strain) ⇒ν

where,

εt is the Lateral or Transverse Strain

εl is the Longitudinal or Axial Strain

ν is the Poisson's Ratio

The strain on its own is defined as the change in dimension (length, breadth, area…) divided by the original dimension.

4) Materials and Methods:

Test samples were prepared from articular cartilage on the lateral facet of non-degenerate human patella. Samples were prepared from the surface and mid-zone. Planar strips of uniform thickness and width were prepared with the length oriented parallel to the split-line direction. Samples were tested in uniaxial tension. bath using a custom-built material test system with optical image analysis. A uniform distribution of enamel markers was applied to the sample surface with an airbrush. Samples were oriented with the length aligned with the axis of loading and allowed to equilibrate under a tare load. A digital image was taken of the sample mid-substance at high resolution for calculation of the reference marker positions. Uniaxial displacements were applied to a prescribed strain of ey = 0.02, and the axial force was recorded for 1800s to equilibrium. A digital image of the sample surface was taken at the equilibrium, deformed state. The protocol was repeated in 0.02 strain increments to ey = 0.16. The coordinates of the surface markers were recorded and the planar components of Lagrangian strain (Eij) were calculated at each strain increment for triads on the sample surface using a custom-written program. The Poisson's ratio, nyx = -Exx/Eyy, was calculated for each triad and for each strain increment, where x-y is defined in the plane of the sample surface. Values for nyx were found to be relatively constant with spatial position and with strain increment, so that an average value was calculated for each sample for all triads and for all strains from ey = 0.04 - 0.10 (i.e., the linear region). The equilibrium stress-strain response was modeled by an exponential law and the tangent modulus (E) was determined in the toe (zero strain) and linear (Eyy = 0.10) regions, as described previously. A paired test was used to test for an effect of depth on the Poisson's ratio.

5) Results:

The poison's ratio for different age groups were tabulated below.

We can see almost decreasing values with respect to the age of the person, which is due to the osteoporosis of the bone with increasing age.

AGE groups	Poisson's Ratio
20-30	0.2
30-40	0.196
40-50	0.1773
50-60	0.1587
60-70	0.14
70-80	0.149
80-90	0.126

Table 1: Variation of Poisson's ratio with age

6) Bone Density:

Body mineral density is A measure of the amount of minerals (mostly calcium and phosphorous) contained in a certain volume of bone. Bone mineral density measurements are used to diagnose osteoporosis (a condition marked by decreased bone mass), to see how well osteoporosis treatments are working, and to predict how likely the bones are to break. Low bone mineral density can occur in patients treated for cancer. Also called BMD, bone density, and bone mass.

Osteoporosis of the lower extremities is a severe secondary complication in people with a spinal cord injury (SCI) causing an increased risk of (low-impact) fractures, especially in the proximal tibia and distal femur.1,2 To manage this so-called immobilization osteoporosis, bone mineral density (BMD) should therefore be measured at these specific sites.3 Dual-energy X-ray absorptiometry (DXA) is a commonly used technique to measure BMD, to diagnose and manage osteoporosis, as well as to predict fracture risk.4 There are standard clinical DXA protocols available to accurately measure whole body and regional (i.e. hip, lumbar spine and forearm) BMD5; however, the proximal tibia and distal femur are not standard measurement sites, and can therefore only be measured using a customized protocol.

7) Porosity:

Porosity is customarily used as an explanatory variable for bone strength. Porosity of the proximal femur was determined by first creating a fiducial mask over the entire femoral head and neck. A morphological closing operation was performed on the solid bone phase with a sphere kernel of radius 200 voxels (11.5mm). The effect of this is to fill in the internal porosity of the bone. The bone volume fraction is then defined as the ratio of number of bone pore voxels to the total number of voxels in the fiducial volume.

$$\phi_{\text{bone}} = \frac{N_{\text{bone}}}{N_{\text{fiducial}}}.$$

The porosity is one minus the bone volume fraction

$$\phi_{\text{pore}} = 1 - \phi_{\text{bone}}.$$

We observe a porosity range of between 0.596 to 0.821 for a femur bone.

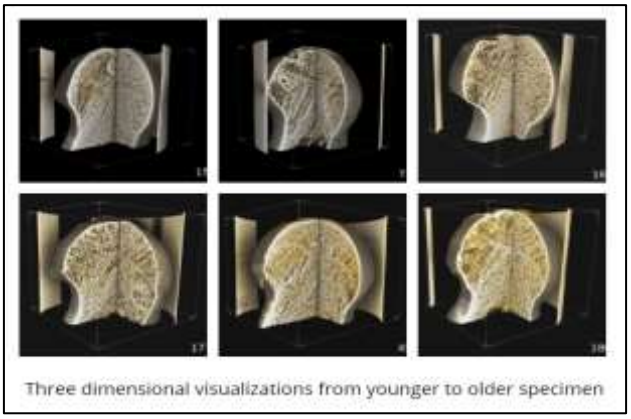

Fig. 2: Three-dimensional Visualization of porosity

We investigated the relationship between porosity within the FN/FH region with age and tabulated results. We observe a trend of increasing porosity of the femoral neck and head region with age. A linear regression was fitted to the data: $\varphi = 0.54693 + 0.0028282x$, where x is age in years. This linear regression has a coefficient of determination, $r\,2 = 0.59$. This corresponds to an increase in porosity of approximately 0.028 per decade ($p < 0.01$). This data is consistent with results for femoral neck bone volume fraction.

C. Properties Variation with Age

1) Density:

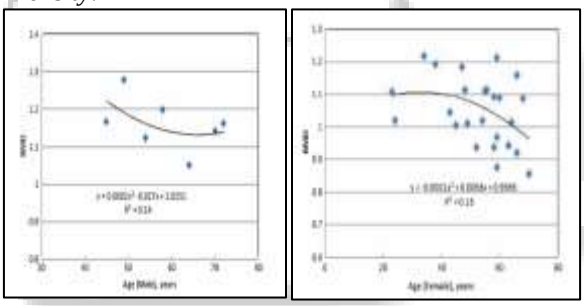

Fig. 3: Graphs for BMD versus different ages of males and females is as shown above.

2) Young's Modulus:

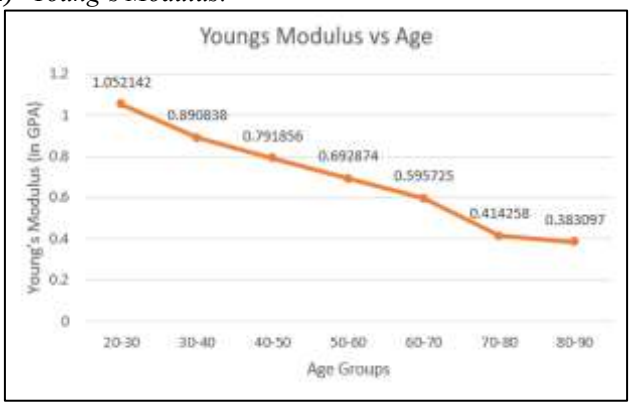

Fig. 4: Plot between young's modulus and age

3) Porosity:

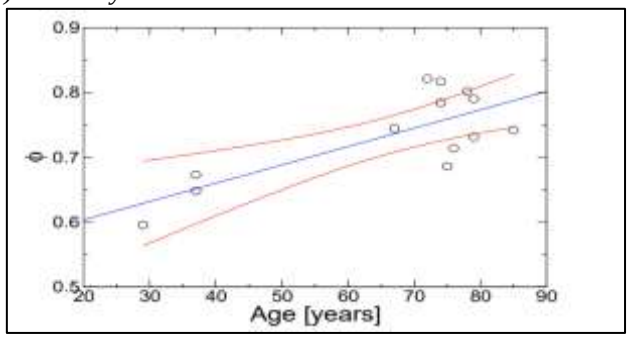

Fig. 5: Relationship between porosity and age

4) Poisson's Ratio:

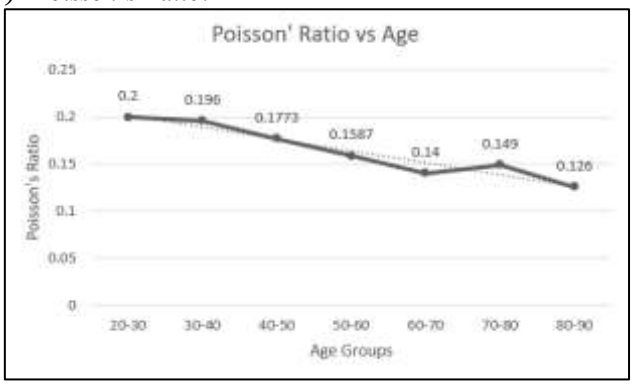

Fig. 6: Relationship between Poisson's Ratio and age

IV. PRODUCT METHODOLOGY

As Bone strength is a very important parameter. Our aim is to study various properties of femur bone such as Youngs Modulus, Poisson's Ratio, Shear Modulus, Density, Porosity, the methods used to experimentally determine those properties for a given model of femur bone. And, to study the variation of these properties of femur bone with age. Performing modal analysis of femur bone and determining the variation of natural frequencies with age becomes as key factor in measuring the quality of a given femur bone.

Initially various properties of femur bone were studied. Experimental methods to measure those properties were researched. Variation of the mechanical properties with age was determined. The properties are Youngs Modulus, Poisson's Ratio, Shear Modulus, Density, Porosity etc. Table was made which contains different ages in rows and corresponding properties on the column. The properties obtained was for Caucasian female for different age groups from a reference paper where was experimentally determined by scanning the bones. Static stress analysis was done for weakest age group, by giving fixed support at one end and force acting at 60-degree angle to femur shaft at femoral head, from which maximum stresses and deformations were obtained. And Modal analysis was done by giving fixed support at one end as constraint. This was done for different age groups by applying corresponding properties. Trend of change of properties with age was observed and inference was taken.

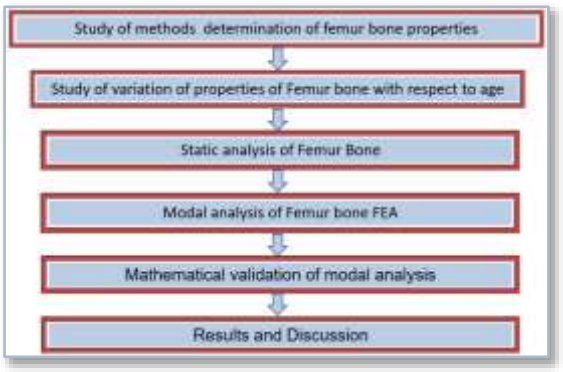

Fig. 7: Methodology

V. FINITE ELEMENT ANALYSIS OF FEMUR BONE

A. Parts of Femur Bone

The femur is the only bone in the thigh and the longest bone in the body. It acts as the site of origin and attachment of many muscles and ligaments, and can be divided into three parts: proximal, shaft and distal.

1) Proximal: The proximal aspect of the femur articulates with the acetabulum of the pelvis to form the hip joint. It consists of a head and neck, and two bony processes – the greater and lesser trochanters. There are also two bony ridges connecting the two trochanters: the intertrochanteric line anteriorly and the trochanteric crest posteriorly.
   - Head: Articulates with the acetabulum of the pelvis to form the hip joint. It has a smooth surface, covered with articular cartilage.
   - Neck: Connects the head of the femur with the shaft. It is cylindrical, projecting in a superior and medial direction. It is set at an angle of approximately 135 degrees to the shaft. This angle of projection allows for an increased range of movement at the hip joint.
2) The Shaft: The shaft of the femur descends in a slight medial direction. This brings the knees closer to the body's Centre of gravity, increasing stability. A cross section of the shaft in the middle is circular but flattened posteriorly at the proximal and distal aspects.
3) Distal: The distal end of the femur is characterized by the presence of the medial and lateral condyles, which articulate with the tibia and patella to form the knee joint.

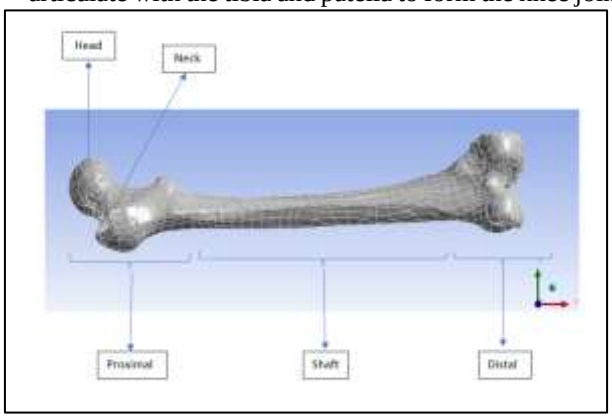

Fig. 8: Bone FEM Model

The structure of the femur has two types: one is cortical or compact bone. This bone is a dense outer layer which prevents bending. Another one is cancellous or spongy which is an inner portion of the mature bones, and it has resistance to compression and dislodge themselves along the direction of functional pressure. Femur bone was selected for modeling and analysis because it is the longest, strongest, and heaviest in the whole human body.

B. Complexity involved in FE analysis of bone

Finite element models have been widely employed to quantify the stress and strain distribution around implanted prostheses and to explore the influence of these distributions on their long-term stability. In order to provide meaningful predictions, such models must contain an appropriate reflection of mechanical properties.

Determination of the geometry and distribution of elastic constants incorporated into such FE models therefore needs to be performed before the models can be used with any confidence. This validation is commonly achieved by comparing some aspect of experimental model behavior with corresponding FE predictions.

The complex micro architecture of the trabecular bone within the proximal femur exhibits anisotropic mechanical behavior, and it is highly difficult to resolve by clinical resolution and therefore it is unavailable. The Femur Bone, being considered in the present study, has a complex and dense finite element model. Since the procedure required to model the femur bone is not feasible with the available tools with us, we downloaded the CAD model of the femur bone with a central hole and imported the same into ANSYS. All the parts of the bone such as head, neck, shaft and distal have been according to the default settings in the ANSYS software for the simplification of analysis.

C. Static Analysis

Three-dimensional finite element (FE) modeling is widely used to generate reliable subject-specific FE model using computed tomography data that accurately predict information about bone morphology and tissue density. The mechanical behavior of the long bones has been explained by the FE modeling.

Being an important structure femur serves two distinct functions: it acts as a supporting structure allowing the weight of the upper body to be transferred from the hip joint to the knee joint, and it also acts as a stiff structure about which muscles act to facilitate movement at both the hip and knee joints.

Static structural analysis was performed on the downloaded CAD model of the human femur bone, to check whether the model we downloaded is accurate or not. To verify the bone model, static analysis was done, and the results obtained from the analysis were compared to the results from a research paper, in which the same static structural analysis was performed. The material, loading and the boundary conditions used in the analysis were taken from the same research paper [9].

The static analysis that was done to validate the bone model is shown in the Fig -9. A pressure was applied at the head part of the femur bone and the total deformation, equivalent stress, equivalent elastic strain was calculated and compared to those values in the research paper.

Some works proved that the FEA technique is much suited to find out stress and strain value in real femur bone rather than any experimental work. It is very useful for the orthopedic surgeons and medical engineers.

Fig. 9: Static Analysis on FE model of a femur bone

D. Modal Analysis

Modal analysis was then performed on the FE model using the Ansys Workbench FE software in order to predict the natural frequencies of the bone for this initial set of material properties. Free–free boundary conditions were assumed in the model and the lower or the distal end of the femur bone was given the fixed support boundary condition.

After performing the analysis, we obtained the first six natural frequencies of the femur bone FE model considered. This process involved variation of six orthotropic elastic properties of the bone along with the variation of Poisson's ration and density with age.

Here are the images of the first six modes of natural frequencies obtained from the modal analysis performed using the properties of a certain age group (30-40 years). In the same way the modal analysis was performed for the remaining age groups as well and the natural frequencies and mode shapes for those models of different age groups were also obtained and tabulated.

Some of the properties and data of the FE model on which the modal analysis was performed are as follows.

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Volume	4.9143e-004 m³
Mass	0.59954 kg
Nodes	21260
Elements	12070
Max Modes to Find	6
Age group	30-40 years

Table 2: Properties and data of performed modal Analysis.

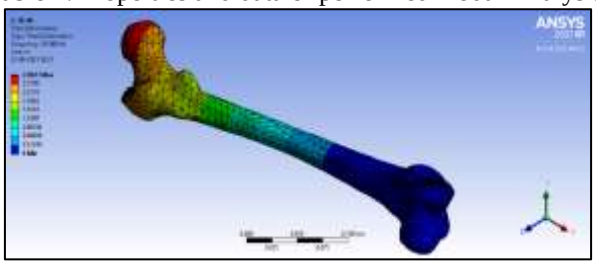

Fig. 10: Mode 1

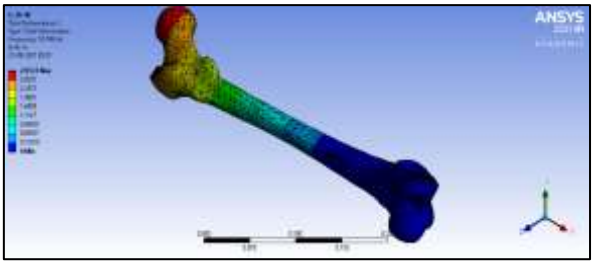

Fig. 11: Mode 2

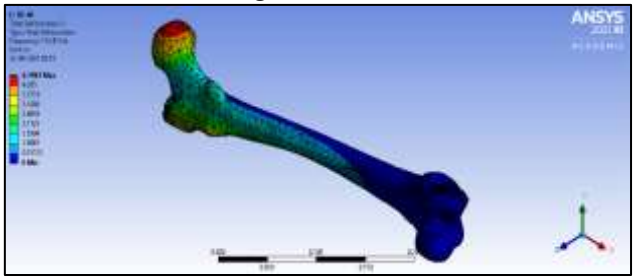

Fig. 12: Mode 3

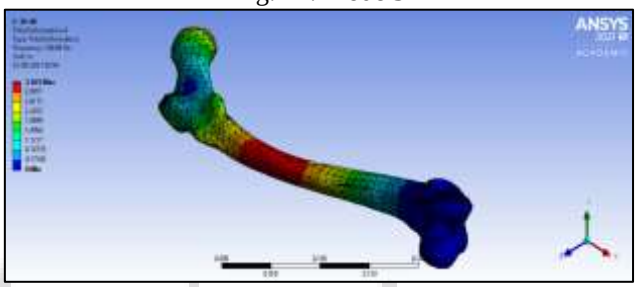

Fig. 13: Mode 4

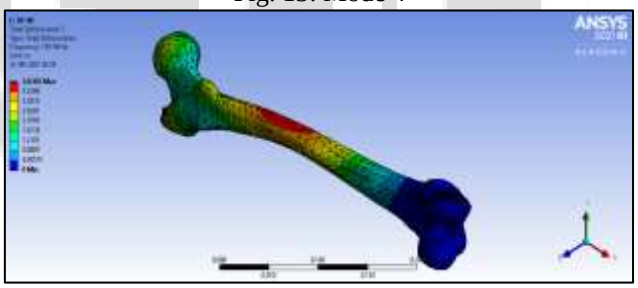

Fig. 14: Mode 5

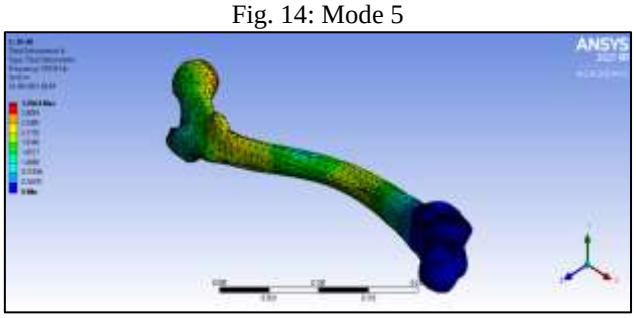

Fig. 15: Mode 6

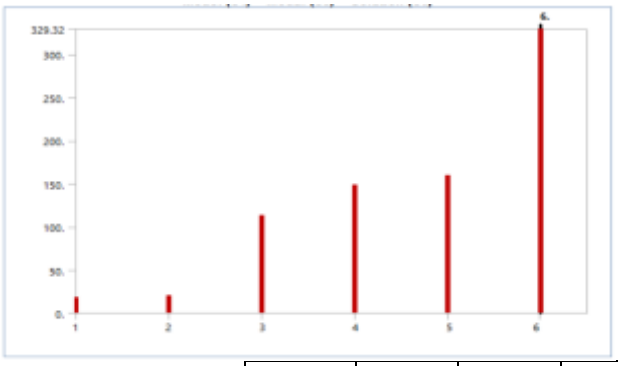

Fig. 16: Bar Chart of first six modes of frequencies

The above images and bar chart were from the modal analysis of a femur bone of 30-40 years age group. The modal analysis for the remaining age groups and their first six modes of natural frequencies are shown in Table 4.3. The unit of the frequencies shown in the table is Hertz (Hz).

Age	20-30	30-40	40-50	50-60	60-70	70-80	80-90
Mode 1	20.911	18.368	18.695	17.802	16.974	14.488	14.272
Mode 2	22.485	19.748	20.115	19.174	18.303	15.612	15.374
Mode 3	126.23	112.91	117.02	114.41	112.43	95.044	92.41
Mode 4	169.69	148.94	152.06	145.46	139.4	118.7	116.57
Mode 5	181.64	159.76	163.52	157.2	151.77	128.77	126.04
Mode 6	375.38	329.32	335.96	321.04	307.33	261.81	257.14

Table 3: Natural frequencies obtained after analysis.

E. Validation of Results from Analysis

By performing the modal analysis of the femur bone FE model in the ANSYS workbench software the first six modes of natural frequencies for different age groups were obtained. Here, we analytically calculate the first mode of natural frequency to validate it with numerical solution.

The formula used to calculate the natural frequency is given by,

$$f_n = \frac{K_n}{2\pi}\sqrt{\frac{EIg}{wl^4}}$$

f_n = first natural frequency
K_n = constant where n refers to the mode of vibration
ω = load per unit length
E = modulus of elasticity
I = moment of inertia
g = acceleration due to gravity
l = length

$$f_n = \frac{3.25}{2\pi}\left(\frac{0.963x\ 10^{9}\ x\ 44924\ x\ 10^{-12} x\ 9.81}{12.4\ x(0.414)^4}\right)^{0.5} = 19.122 \text{ Hz}$$

From the FEA analysis, the first mode natural frequency for the femur bone of age group 30-40 is 18.368 Hz and the analytically calculated value is 19.122 Hz, the percentage of error is less. Therefore, the FEA analysis is mathematically validated.

VI. RESULTS AND DISCUSSION

A. Relation between Natural Frequency and Age

The mechanical properties and corresponding natural frequencies are shown in the below table:

	Youngs Modulus			Poisson's Ratio			Shear Modulus			Density	Frequency
AGE groups	E1	E2	E3	V21	V31	V32	G23	G31	G12	ρ	f
20-30	1.052142	1.004484	1.407744	0.2	0.291	0.21	0.296946	0.322608	0.254787	1.109	20.911
30-40	0.890838	0.852345	1.158456	0.196	0.279	0.209	0.291447	0.313443	0.205296	1.22	18.368
40-50	0.791856	0.779025	1.105299	0.1773	0.332	0.204	0.273117	0.29328	0.190632	1.05	18.695
50-60	0.692874	0.708088	1.053975	0.1587	0.385	0.199	0.25662	0.273117	0.179634	1.018	17.802
60-70	0.595725	0.636051	1.002651	0.14	0.438	0.194	0.240123	0.254787	0.168636	0.968	16.974
70-80	0.414258	0.436254	0.716703	0.149	0.426	0.179	0.16497	0.174135	0.111813	0.922	14.488
80-90	0.383097	0.405093	0.625053	0.126	0.393	0.208	0.155805	0.157638	0.095316	0.876	14.272

Table 4: Different parameters change with Age.

It can be concluded that natural frequency of femur bone decreases with respect to age. Thus, relation between natural frequency and age of a femur bone is established.

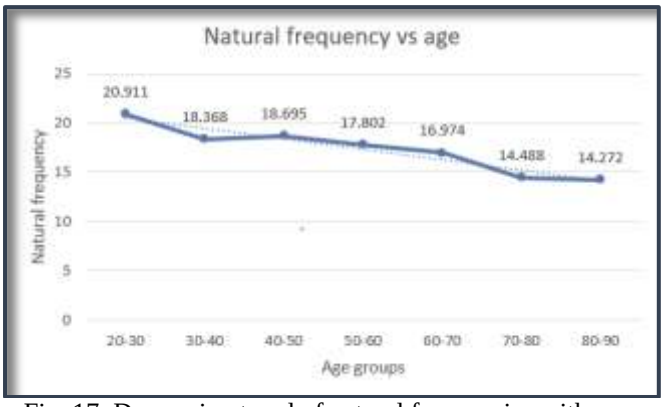

Fig. 17: Decreasing trend of natural frequencies with age

VII. CONCLUSIONS

- Research has been done on various properties of femur bone and their significance and found out that orthotropic properties can provide accurate results for FEA analysis.
- Various methods have been found to accurately determine the properties of femur bone.
- The CAED model taken from online source was verified by performing static analysis and replicating the results from research paper and thus was also able to determine that given bone is safe under applied loads.
- Modal analysis performed for various age groups has provided the variation of natural frequencies with respect to age.
- And the relation between porosity and natural frequencies has also been found out through tables and graphs plotted from data.

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