Modelling and analysis of femur bone from CT scan

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Abstract. About 200 million peoples around the world are affected by different types of bone diseases. Osteoporosis is one among them which is a low bone density disease which increases the porosity of the bone and leads to severe pain and fracture of the human bone. Women’s are most affected by this disease due to various reasons. It can be only predicted after the failure or fracture of the bone when the sudden impact of the load. The femur is the longest bone in the human body which is mainly affected by means of fracture due to osteoporosis. The strength of the bone mainly depends on its density and can be determined by the Bone Mineral Density (BMD) Test. Hence it is necessary to numerically predict the stress and deformation of bone for the osteoporosis patient in their daily activities. Nowadays many researches have been undergone in Finite Element Analysis (FEA) of human bone in order to predict the stress and deformation when subjected to various loads in daily life. In this work, Structural analysis is carried out on femur bone which is modelled from CT scan report and material properties are assigned from osteoporosis patient. The loading conditions are based on the force which exerts on the femur bone during routine activities. The analysis is carried out with two different boundary conditions and it is seen that the femur head and distal end of the femur is subjected towards maximum normal stress and deformation.

1. Introduction
Osteoporosis is a state which devastates strength of the bone which makes the bone become fragile especially for the women after the postmenopausal period where the weakness of the bone progress over a certain year and can be identified only when the unexpected impact or slight fall which causes the bone to fracture. About 200 million people around the world are affected by this disease and in India 46 million people are affected by osteoporosis. It is mainly occurred after postmenopausal due to low calcium density and vitamin D deficiency which result in extensive soreness, pain, disability, and perhaps results in the death of patients. The different aspects in osteoporosis are Nutritional factors, Nutritional status, Lifestyle, drug use and preceding history of fractures. The rich calcium and vitamin foods, exposure of sunlight in the evening which gives vitamin D, Changing lifestyle and rest are some of the treatment for the patient suffering from osteoporosis [1]. The risk of fracture is reduced by hormone replacement therapy in supplement with calcium and Vitamin D complements [2]. Now a day’s various researches have been undergoing on the FEA of the human bone in order to determine the stresses induced in the human bone on the application of practical force which people encounters in their daily life. FEA is also useful in studying the fracture mechanics of the human bone on the
external application of the force. The femur bone is the longest bone in the human body which is stressed more during walking and step climbing. These bones are subjected to maximum load during normal human activities. The patient with osteoporosis has mostly subjected towards fracture of the femur bone which is seen from the medical history. Researchers have been carried out to determine the fractural load distribution of stress and fracture morphology of the human femur bone. The fracture load and fracture morphology of the femur bone was studied practically and by means of the numerical method where both showed that good agreement with each other and also the internal bone mineral density significantly influences the fracture morphology high value of bone mineral density gives improved stiffness and strength [3]. The vibration and stress characteristics of human femur bone have been analysed and determined the deformation of the femur on the application of the load based on the human weight and the corresponding stress distribution are evaluated [4]. The human bones are imported into a solid model by the CT scan and MRI scan which is useful for FEA. The material properties and boundary condition for analysis of the femur bone are derived from the CT scan report and the linear relation between apparent bone density and Hounsfield unit (HU) can be derived from the numerical equation where the strength of the human bone depends on the density and porosity [5]. The femur is designed in CAD software and the FEA is carried out. The material properties of the human bone like given density poisons ratio and Young's modulus are imported to the designed femur model and the stress analysis were carried out with various load which acts on the femur bone during walking, standing, jumping and running [6]. The numerical analysis also carried out for finding the various stress and deformation when subjected towards various load on the healthy femur and the broken femur with the prosthesis. The analysis showed that the titanium prosthesis gives less deformation when compared with other materials [7]. The failure of the femur bone is mainly due to the sudden accident and continuous vibration which acts on the proximal area of the femur. The neck and bone shaft of the femur bone are the areas which are mainly affected by the vibration on femur which is determined from the nodal analysis with ten resonance frequency [8]. FEA is carried out for finding the stress and fracture morphology of the human femur when subjected towards the load [9]. Since osteoporosis patients are majorly affected by fracture of femur bone due to varying stress and deformations. FEA is one of the powerful models for predicting stress and deformation when subjected by the external load. In this work, a step to predict the stress and deformation of the femur bone for osteoporosis patients during their normal daily activities is taken. The material properties of the femur bone of osteoporosis patient are taken from the literatures [9], [10], [11]. The FEA are carried out in ANSYS 19 software and the results are evaluated using various boundary conditions.

2. Modelling of the Femur Bone

The 3-D model of the femur bone was constructed using the CT scan report which is in DICOM format from a patient of 52 years old female. This CT scan report is imported into the 3-D slicer software. The 3-D slicer is open-source and free software for visualizing the medical images and which is very much useful in analyzing the CT scan and MRI scan report of the patients. From the software 3-D model of the lower leg is extracted and the required femur bone is cropped from the whole leg segment by the region of interest option as shown in Figure 1. Then in editor option, the complete 3-D model was obtained with the threshold frequency of 756. Finally, the 3-D model meshes in editor mode and complete triangular meshed solid geometry is obtained from the software. Then this femur model is saved in .stl format and it is imported in the blender software.
Blender is open-source 3D computer graphics software. The femur model extracted from the 3D slicer has to be cleaned further for removing the unwanted objects apart from bone and the surface of the bone are made smoother as shown in Figure 2. This cleaned 3D model is stored in .stl format and this 3D model is taken for further analysis.

The Computer-Aided Design (CAD) software CATIA V5 R20 is used for converting the .stl file into a .stp format for importing the femur model in ANSYS as shown in Figure 3.
3. Assigning Material Property to the solid model

The Biomechanical capability of human bone strength can be determined based on bone strength. The essential constraint for structural analysis is assigning the material property to the solid model. The density of the bone plays an important role in determining the strength of osteoporosis patients. Bone Mineral Density (BMD) is measured from the central DXA test. The test measures the BMD and compares the score with the well-known standard and gives the T value. The T value of the normal healthy person varies from +1 to -1. If the T score value is less than -1 to -2.5 then the patients are affected with low bone density disease and are subjected to a high risk of fracture [10]. From his research, the Bone mineral density of osteoporosis patient is 0.750 g/cm3. The material property of the osteoporosis patient varies based on the porosity of the bone [11]. If the porosity increases the density and yield stress of the bone decreases linearly and ultimately decreases the strength of the bone and increases the probability of fracture. From the experimental studies, the density of the bone varies from 0.9 to 1.3 g/cm3. Hence from the literature, the material properties of the bone taken for structural analysis are shown in table 1.

| S. No | Parameter                              | Value  |
|-------|----------------------------------------|--------|
| 1     | Density (g/cm³) [10], [11]             | 0.75   |
| 2     | Young’s Modulus (MPa) [9]              | 10500  |
| 3     | Poisson’s ratio                        | 0.3    |
| 4     | Shear Modulus (Pa)                     | 4038   |

4. Loading Condition

The tetrahedral meshing is done under patch conforming algorithm for the 3 Dimensional models with the slow transition which creates 250307 nodes and 173870 elements. Normally tetrahedral meshing is used for complex geometry for good surface finish. The final geometry of the meshed femur model is shown in Figure 4.
The femur bone is subjected towards load during walking, jumping and running. During our normal daily activities, the loads exerted on the femur varies from 266N to 690N [12]. The patients with osteoporosis feel pain on their daily activities in the hip joint due to the weak bone mineral density and also even it results in failure of the femur bone when the sudden impact of forces acts on the femur. This causes the patients to the breakdown of their mobility due to severe pain. In general femur head and the distal end of the femur is liable towards more stress compared to another region because it is the place where it comes to meet the hip socket and knee joint. Hence the femur model is analysed with three different loads (270N, 400N, and 650N) under the subsequent condition.

- Case 1: Head of the femur is assumed to be fixed support and the varying loads have been applied on the distal end of the femur in order to calculate the normal stress and total deformation of femur bone at this type boundary condition.

- Case 2: Distal end of the femur is assumed to be fixed support and varying loads were applied on the head of the femur for evaluating the normal stress and total deformation of the femur bone.

5. Result and Discussion

Normal stress and Total deformation of the femur bone were calculated under two different cases and are illustrated above. First the Case 1 is discussed with the 3 different loading conditions (270N, 400N, and 650N). The normal stress induced in the femur is shown in Figure 5 (a) and (b) and Table 2 exemplifies the maximum, minimum and average normal stress induced in the femur bone under boundary condition.

![Figure 5. Normal stress (case 1) at (a) 270N and (b) 400N.](image)

From Table 2, it is seen that Normal stress value increases gradually with the increase of the load. The femur neck exhibits maximum stress with the given two loads. When the load of 650N applied the Normal stress increases abruptly and the structural analysis for the 650N load cannot predict by the software as the loading condition exceeds the maximum value.
Table 2. Normal stress at different loads (case 1).

| Load (N) | Minimum (Mpa) | Maximum (Mpa) | Average (Mpa) |
|----------|---------------|---------------|---------------|
| 270      | -5.2637       | 13.523        | -0.12819      |
| 400      | -7.7981       | 20.035        | -0.18991      |
| 650      | -             | -             | -             |

Hence for the patients with these material properties, if the sudden impact of 650N acts on the femur head leads to fracture of the neck and leads to unpredictable pain for the patients. With the load of 270N and 400N, the stress-induced the femur neck is found to be maximum and leads to the stepping stone of fracture. Similarly, the deformation of femur bone under the same boundary condition is carried out are shown in Figure 6 (a) and(b) and the average of deformation are shown in Table 3.

Table 3. Deformation (case 1) at different loads.

| Load (N) | Minimum (mm) | Maximum (mm) | Average (mm) |
|----------|--------------|--------------|--------------|
| 270      | 0            | 27.601       | 9.2896       |
| 400      | 0            | 40.89        | 13.762       |
| 650      | -            | -            | -            |

It is also seen that the deformation for the minimum load of 270N is found to be higher and increases rapidly for the higher loads. Hence from the analysis under bounder condition case 1, the patients of low bone density when they experience a load of 270N it leads to failure of the femur bone, especially at the neck. Hence intense care and treatment must be an encounter for enhancing the bone density.

Figure 6. Normal stress (case 2) at (a) 270N and (b) 400N.

Now in Case 2, the distal end of the femur is assumed to be force acting area and the head of the femur is considered as fixed support. For the same boundary condition the structural analysis in the distal end of the femur was carried out and the result of normal stress is shown in Figure 7 (a), (b) and (c) and total deformation are shown in Figure 8 (a), (b) and (c). Table 4 and 5 denotes the normal stress and the deformation values of minimum, maximum and average.
Figure 7. Normal stress (case 2) at (a) 270N, (b) 400N and (c) 650N.

Table 4. Normal stress at different loads (case 2).

| Load (N) | Minimum (Mpa) | Maximum (Mpa) | Average (Mpa) |
|----------|---------------|---------------|---------------|
| 270      | -4.6451       | 10.442        | 1.3011e-003   |
| 400      | -6.8816       | 15.469        | 1.9275e-003   |
| 650      | -11.527       | 25.911        | 3.2285e-003   |
From the Case 2 analysis, it is seen that Normal stress increases by 5% of the incremental load values taken for the study. The distal end of the femur is affected extremely at the incremental of loads. At maximum load of 650N the entire femur bone is stressed at maximum level hence there exists a higher risk of failure especially at the distal end of the femur. When the distal end is loaded by fixing femur head as fixed support it is seen that maximum deformation occurs at the distal end than the surface of the femur. Even in the minimum load of 270N, it is clearly seen that the distal end of the femur has a high risk of failure.

| Load (N) | Minimum (mm) | Maximum (mm) | Average (mm) |
|---------|--------------|--------------|--------------|
| 270     | 0            | 4.5362       | 1.6479       |
| 400     | 0.           | 6.7203       | 2.4414       |
| 650     | 0.           | 11.257       | 4.0893       |

6. Conclusion

The 3-D model of the femur bone obtained from the CT scan data of 52 years old female is taken for the study. From the static structural analysis, the following conclusions are made.

- Structural analysis of the femur bone model is carried out with two different boundary conditions and the normal stress and deformation studies are undergone to find the probability of risk of failure of a femur bone for the patient affected by osteoporosis.
- In case 1 boundary condition the maximum deformation is seen in the area of the head of the femur and the Maximum normal stress also acts at the femur head.
- In case 2 boundary conditions under the same loading condition the maximum deformation and normal stress are observed at the distal end of the femur.
- By comparing the above two cases the femur head is the area where it is exposed to a high risk of fracture and even unpredictable pain may induce for the patient with osteoporosis.
- Hence Finite Element Analysis is helpful to visualize the stress and deformation of the femur bone under various boundary conditions. The people having low bone density have to take proper treatment and exercise in order to keep away from the risk of fracture.

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