BEHAVIOUR OF HUMAN FEMUR BONE UNDER COMPRESSIVE LOADS-AN EXPERIMENTAL STUDY

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ABSTRACT
The femur is the largest, strongest and most voluminous tubular bone in the human body. This is the principal load-bearing bone in the lower extremity. Femoral fractures are among the most common major injuries that an orthopedic surgeon will be required to treat. Evaluation of femur fractures using clinical data is confounded by multiple patient and fracture specific factors making it difficult to draw meaningful conclusions, despite the inclusion of large number of patient data. Therefore the biomechanical testing of the femur bone plays a vital role in the evaluation the femoral fractures. This experimental investigation focuses on the evaluation of hardness and compressive strength, the damage characterizing parameters in femur. The bones were tested under both the pre notched(cracked)and unnotched conditions.cIn order to evaluate the influence of the loading type, different regions of femur were loaded under hardness indentation and compressive loads. The precise load/deflection data were acquired through specially designed electronically controlled LVDT and load cells. The results have shown the femur strength is extremely variable with respect to the different regions. The compressive strength has shown maximum dependency on the matrix of the femur and its hardness. The macroscopic observations of the fractured specimens have shown that, the chipping of the bone, longitudinal cracks and the multiple cracks in femur are most dangerous.

Key Words: Femoral Head, Femoral Shaft Regions, Compressive strength, Hardness, Electronically controlled data acquisition.

1. INTRODUCTION

The human body has many interrelated systems and is made of individual or joined bones, supported and supplemented by a structure of ligaments, tendons, muscles, cartilage and other organs. The skeleton is divided into two sections, the axial skeleton refers to the bones in the middle of the body and their main functions are protection, storage and support. The appendicular skeleton consists of the limbs and the girdles to which they attach and their main functions are to provide a framework for movement, storage and manufacture of blood cells.[1-2].Bone differs from other types of connective tissue in that the organic matrix is calcified so that bone contains about 70% bone salt in the form of minute crystals of calcium hydroxyapatite. The rest is 20% organic matrix and 10% water. The organic matrix has the same composition as tendon or ligament that is 90% collagen and 10% ground substance [3-4].In humans femur is the largest most voluminous, solid inflexible and strongest bone .It can support up to 30 times the weight of an adult. Femur is responsible for bearing the largest percentage of body weight during normal bearing weight and it is solid inflexible bone. The femur is the most proximal (closest to the body) bone of the leg in vertebrates capable of walking or jumping[5-6].The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter.

The forces exerted by the soft and hard tissues of the thigh together represent a system in equilibrium.In many biomechanical analyses of the thigh, the femur is studied without considering soft tissue loading. Internal loads of the femur decreased as a result of muscle activity from proximal to distal at the hip and from distal to proximal at the knee [7]. The model of femoral loads has been introduced based on a free body analysis of the femur which includes all muscles attached to the femur as well as those crossing the femur.

Few researchers have made a review and experimentations on the mechanical behavior of human femur bone, under the action of a variety of forcesacting on it and by determining the internal stress distribution resulting from daily living activities. For attaining such a goal, knowledge of the applied forces in combinationwith the internal structureand the mechanical properties of the material of the femur are needed [8-11]. Muscularskeletal loading influences the stresses and strains within the human femur. One of the main injuries of femur is because of accidents. During many physical activity like jumping, walking and running etc, then the body weight is transferred to femur through hip joint and the femur bone is subjected to different loading conditions such as impact, bending, shear, compression and torsion loads and because of these loads lateral forces, twisting stresses, and powerful impacts may cause the bone to break or which may lead to bone desorption and thereby affect the clinical outcome [12-15].

In human femoral bone, different regions are critical for different loads. The body or shaft fracture occurs due to accidental loads. In most of the cases the femoral neck fracture is due to compressive load and shaft fracture is due to bending [16-17].When the tibiofemoral and patellofemoral compartments were compared it was found that for a given value of bone volume fraction, condylar bone is marginally harder than patellofemoral bone. In comparison with the tibia femoral bone strength showed generally higher values, and the decline of bone strength with depth plateaued at higher bone hardness values[18].

The compressive strength is different when the material is loaded in different directions and also that it is different for different samples andwas observed that the wet samples have more sharing strength than the dry ones[19].Thestate of stress of an intact femur was analyzed using a three-dimensional finite element model. One of a pair of femora was used for determination of data for the 3-D model .The other was instrumented with 34 rosette strain gauges for experimental measurements. The physiological situation is important however for the estimation of whether quality and value of the stresses after the implantation can be tolerated by the bone without desorption[20].Phosphate and fluoride ions have been demonstrated to alter mineral-organic interactions, thereby influencing the mechanical properties of bone in tension and also explores on the effects of phosphate and fluoride ions on the compressive properties of cortical bone. [21].

Thetheoretical analysis was performed to characterize potential experimental artifacts in conventionalcompression testing of trabecular bone, where strains are based on the relative displacements of the two loading platens, if friction is completely eliminated at the specimen-platen interface. Increasing the specimensize reduces the artifact only slightly. However, without friction at the interface, the platens modulus will always underestimate Young‘s modulus, thereby reducing the accuracy of this test. There was also evidence that the strength may be affected by theseartifacts [22].

The compressive properties of human cancellous bone of the distal intracondylar femurin its wet condition were determined and found that the compressive strength decreases with an increasing vertical distance from the joint. The highest compressive strength level was recorded in the posterior medial condoyle [23].Interfragmentary displacement has a main effect on callus formation in fracture healing. To test whether compressive or distractive displacements have a more pronounced effect on new bone formation, a sheep osteotomy model was created whereby the gap tissue was subjected to constant bending displacement. The cyclic compressive displacements were found to be superior over distractive displacements.[24].A biomechanical test was conducted to know the effects of positioning and notching of resurfaced femurs on femoral neck strength. Compared to the intact femurs, the loadto failure in all resurfaced femurs was significantlydecreased by 29 to 57%. Among the resurfaced femurs,valgus and anatomic femurs had the highest loadto failure, followed by valgus notched, varus, andanatomically notched femurs. Notching weakenedthe construct by a further 24 to 30%.[25].

If the femur is subjected to any type of loading like bending, impact, compressive or accidental loads, the type in which the femoral bone gets fractured is unpredictable. Also, Bone fracture, formation and adaptation are related to mechanical strains in bone. In view of the above facts an attempt has been made in this work to evaluate the compressive, load characteristics of femur bone at different regions of the male human femur of age 20-30.The experimental analysis provides a better understanding of the influence compressive loads on different regions of the human femur.

2.Material and Experimentation

This experimental study aims at determining compression behavior of human femur bone .This study attempts at providing compression properties of femur bone through compression test. The specimens were extracted from number of dead human (male) femur. Significant forces are present in the long bones, but their magnitudes have so far only been estimated from mathematical models. Knowledge of the forces acting on the human femur is of significant importance to health care professionals. The materials used and the experimental procedures are discussed in this section.

Human male femoral bones (dead) of mid age of 20 to 30 have been used.The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter are been used.The scope of this project is to measure the mechanical properties of human long (dead) bone of middle aged (20 to 30) cadaveric femur around various crack size and intensity of crack under

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compression at various loading levels. The weight bearing capability of a long bone fracture of femur can be studied. The figure.1 shows the human femur bone used in the study.

HUMAN FEMUR BONE

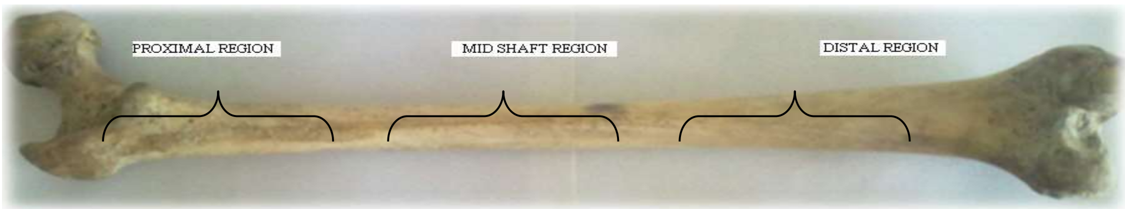

Fig. 1 Human femur

Bone differs from other types of connective tissue in that the organic matrix is calcified so that bone contains about 70% bone salt in the form of minute crystals of calcium hydroxyapatite. The rest is 20% organic matrix and 10% water. The organic matrix has the same composition as tendon or ligament that is 90% collagen and 10% ground substance. The composition of femur bone used is as given in table 1.

Table 1 Composition of the human femur

Dry matter	904
Organic matter	840
Crude protein	144
Crude fat	25
Crude fibre	150
Ash	64
Calcium	11.7
Phosphorus	5.9
Sodium	2.6
Chloride	5.8
Potassium	8.5
Magnesium	1.6
Iron	0.149
Copper	0.005
Manganese	0.044
Zinc	0.155

2.1. Specimen preparation

The femur bone is the longest bone in the human structure and carries much load. The different parts of the femur have different strength andduring functioning it undergoes a variety of loads; a drastic change in these loads may leads for the failure of these femurs. Because of this reasons the specimens from different regions have been taken to evaluate its strength under compressive, loads. Considering the above facts the specimens of the required portions for the desired test are

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prepared. For compression test six specimens with notch and six without notch are prepared and a tennon saw is used for cutting. Both the end surfaces of the each specimen are accurately flattened on surface plate using height gauge. The size of the specimen is 30mm length and average diameter is 32mm. The figure2 shows the specimens taken for compression test at different regions.

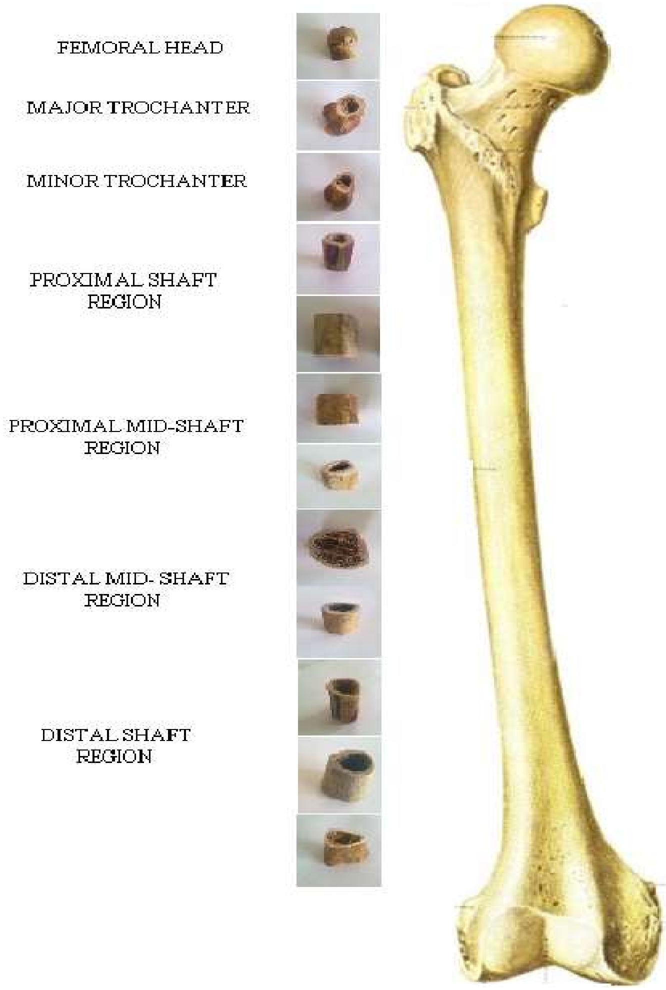

Figure2.Specimens taken for compression test at different regions.

The tests were conducted on a miniature (sub sized) testspecimens. An attempt has been made to evaluate the mechanical behavior of the femur bone with the aid of full scale specimens. To characterize the bone hardness and compressive have been carried out.

2.2. Hardness Test

The structure of the bone contains different natures in different layers starting from cortical bone to the core of the bone and the different regions of the femur like proximal, mid, distal shaft region. The major contributor for the property variation is the hardness. Because of this reason hardness tests were carried out in all these regions. The specimens of the required size t suit the Rockwell Hardness Number apparatus have been prepared and the hardness number is determined. The hardness is evaluated for the cortex, tensile fiber and compression fiber areas of the three regions.

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2.3. Compression Test

The compressive strength will vary from one region of the femur to another. Because of this reason the experimentation were carried out on six different regions of the femur bone, namely,

- Femoral head.
- Upper trochanter.
- Lower trochanter.
- Proximal.
- Mid
- Distal.

Fig 3 a) Compression test specimens

Fig 3 b) Testing on UTM

The compression testing specimen was placed in between the two jaws of UTM and the progressive compression load is applied on the specimen up to its failure. The prepared specimens, both with and without notch were tested in a universal testing machine under controlled loading condition. Compression test specimens and the experimental setup used to do compression test in a computerized UTM is as shown figure 3.

3. Results and Discussion

During the activities the femur is subjected to compressionloads.Themechanical testing of human femur is limited by the highly variable material properties of bone. In present investigation the hardness and compression strength have been evaluated experimentally. The effect of the pre

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cracks has also been determined. The mean age of the femur bone used in the analysis was 20-25 years.

3.1. Hardness of the different femoral regions.

Bones as a complex highly organized and specialized connective tissue. Bones are made up of a mixture of hard materials that gives them the strength. Bone contains lot of calcium. Bone differs from other type connective tissues in matrix, which is highly calcified. Due to this bone contains about 70% bone salt in the form of minute crystals of calcium hydroxypatite. The rest is 20% organic matrix and 10% water. The dispersion of these minute crystals is not uniform throughout the femur. In a femur the three major regions of highly load bearing capacities are cortex, tensile fiber and compression fiber is shown in figure 4. The Rockwell 'C' test has been conducted on three major regions (like proximal, mid shaft and distal regions), of the femur. The results of which have been tabulated in the table 5.1.

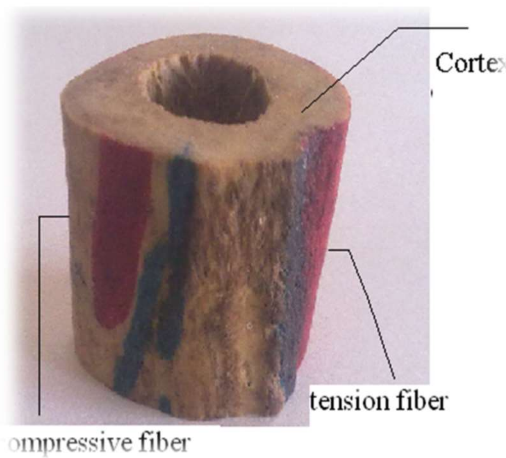

Figure 4. Different regions of hardness test specimens.

The maximum Hardness is obtained in the distal end at the tension fiber in femur shaft (that is 45.30 RHN No.) and at compressive fiber (that is 32.5 RHN). The minimum Hardness obtained in proximal end at cortex region (that is 21.56 RHN).From table 2,It can be observed that hardness of the femoral shaft is more at distal region in tension fiber that is, 45.30 RHN and minimum at cortex that is. 21.56 RHN and the hardness of the femoral shaft increases from proximal to distal region.

Table 2. Hardness of femur in different reagions

Femoral Regions	RHN		
	Cortex	Tension Fiber	Compressive Fiber
Proximal	21.56	24.5	22.16
Mid Shaft	23.00	32.25	27.66
Distal	24.91	45.30	32.50

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The maximum hardness is obtained at the distal region of the femur and minimum hardness is obtained at the proximal region of the femur. In the longitudinal direction of the femur the hardness seems to be increasing from proximal, this is because of the maximum dispersion of the calcium and the hard growth of the bone in these regions. The hueso compact region has lees hardness compared to the other two regions because of the layered composition and nature of the femur. By the macroscopic observations it is also found that, the indentation of the indentor is surrounded by the radial cracks. It can be inferred that, maximum attention has to be given to the fractures in cortex region.

3.2 Compressive load carrying capacity and nature of fracture on femur bone.

As discussed in the previous sections the hardness has shown the deepest dependency on the regional composition of the femur bone. Test coupons have been prepared from the six different regions of the femur.Femur bone is voluminous bone in the human anatomy which will come across a composite; due to this it will exhibits a crushing phenomenon associated with progressive pore collapse and stabilization. During the testing ample care has been taken to maintain the flatness of the specimen. In this experiment failure is attributed as the point at which pore collapse is first observed (typically the point at which initial drop in load is observed).

From the experimental data, the strength of the different femoral regions under compressive loads has been evaluated. The tests have been conducted on the both notched and unnotched specimens. The results of which have been tabulated in the table 3

Table 3. Compression test resuts

Femoral Shaft Regions	**Max Compressive Load in N**		**Compressive strength in N/mm^2**	
	Without Notch	**With Notch**	**Without Notch**	**With Notch**
Proximal	56898.00	45714.60	143.73	138.58
	48910.80	43126.00	141.53	127.99
Proximal mid-shaft	42379.20	39824.60	117.30	105.42
	39183.00	35394.48	112.72	98.828
Distal mid-shaft	36493.20	32144.00	109.84	85.26
	28487.00	25898.00	116.25	89.36
Distal	27113.60	23917.40	117.55	92.56
	24544.00	22563.00	119.89	97.44

Different regions of femoral shaft have undergone compression loading and regional compressive strength of the femur bone without notch of proximal region anddistal regionareσ_{comp}=131.29 N/mm^2 and σ_{comp}=89.18 N/mm^{2}repectively.Similarly the compressive strength with notch are, σ_{comp}=125.9 N/mm^2 and 82.744 N/mm^2 respectively. Based on these experimental data, thegraphs of load and compressive strength against femoral regions have been plotted as shown in figure 5 and figure 6 respectively.

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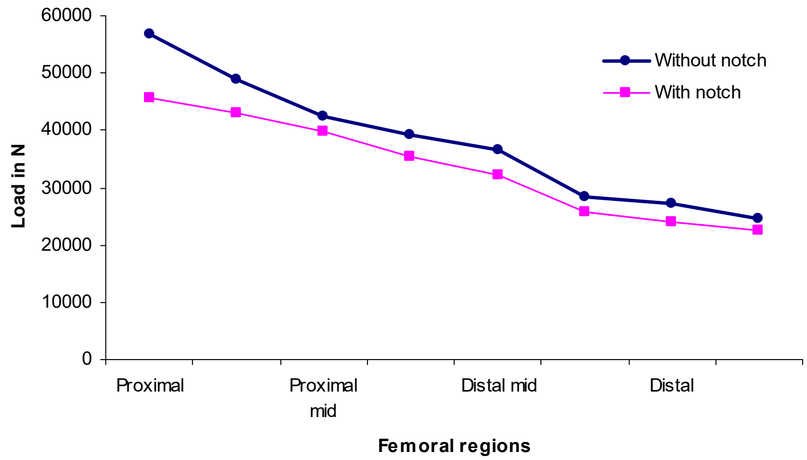

Figure 5.Regional compressive load carrying capacity of femur.

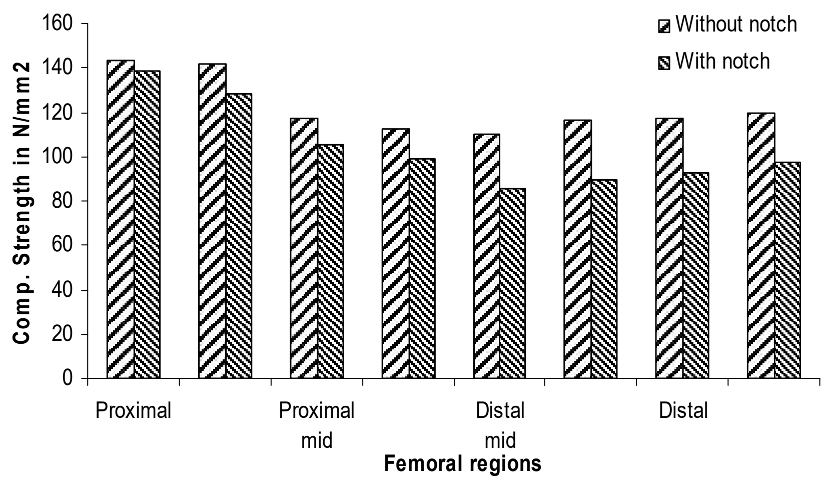

Figure 6.Compressive strength of femur at different Regions.

The proximal region has found to have maximum compressive strength. It is mainly because of the maximized pores present in this region. In support of this as discussed in the early sections the hardness in this region is found to be less. The compressive loaded specimens after testing have been shown in figure 7. It can be clearly observed from the figure that, the crushing load has caused only a damage of the superficial layer of the bone. A minimum chipping is observed as shown in figure 7a and b. The same proximal specimens with notch have shown less compression load carrying capacity; this is mainly because of the longitudinal cracks originated from the route of the circumferential notch. This behavior can be seen in figure 7 c and d.

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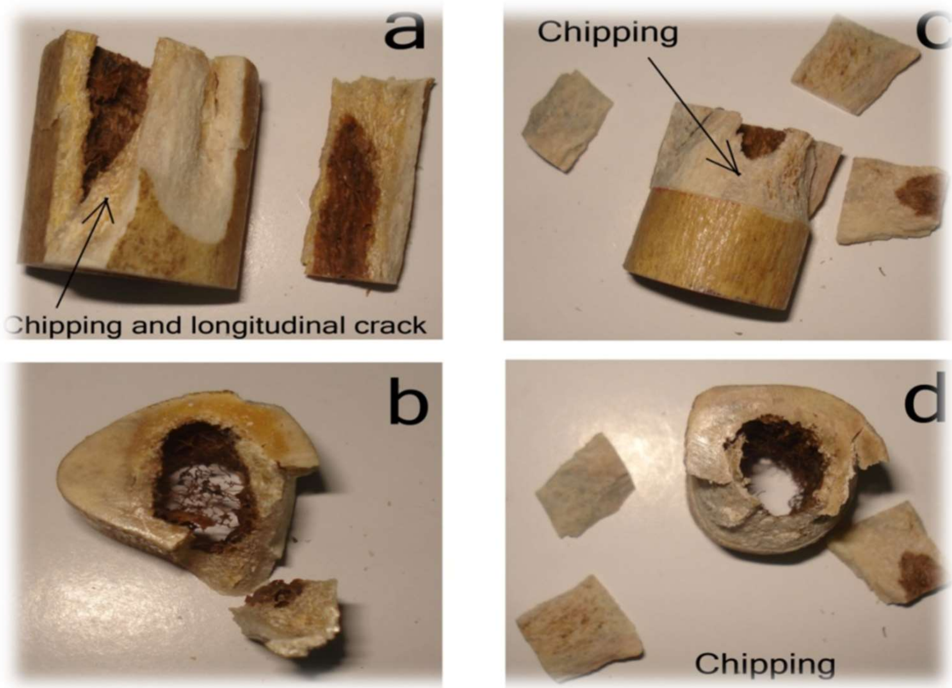

Figure 7.Proximal regional compression test specimens after test.

A reduced amount of compressive strength has been observedin the mid shaft region in case of the both notched and unnotched specimens. This mainly because of the drastic increase in the cracks developed and the clipping of the bone. This behavior can be clearly seen in figure 8a and b. the mid shaft fracture is a complete displaced fracture, which breaks into two or more pieces and is no longer correctly aligned. The effect of notch has also reduced the load carrying capacity. For a notched sample deep root cracks will be induced by the compressive loads and leads to the complete failure of this region. Since femur has an anterior bow, the applied compressive load acts as bending load and fracture occurs. Care should be taken to avoid multiple fractures of the mid shaft region.

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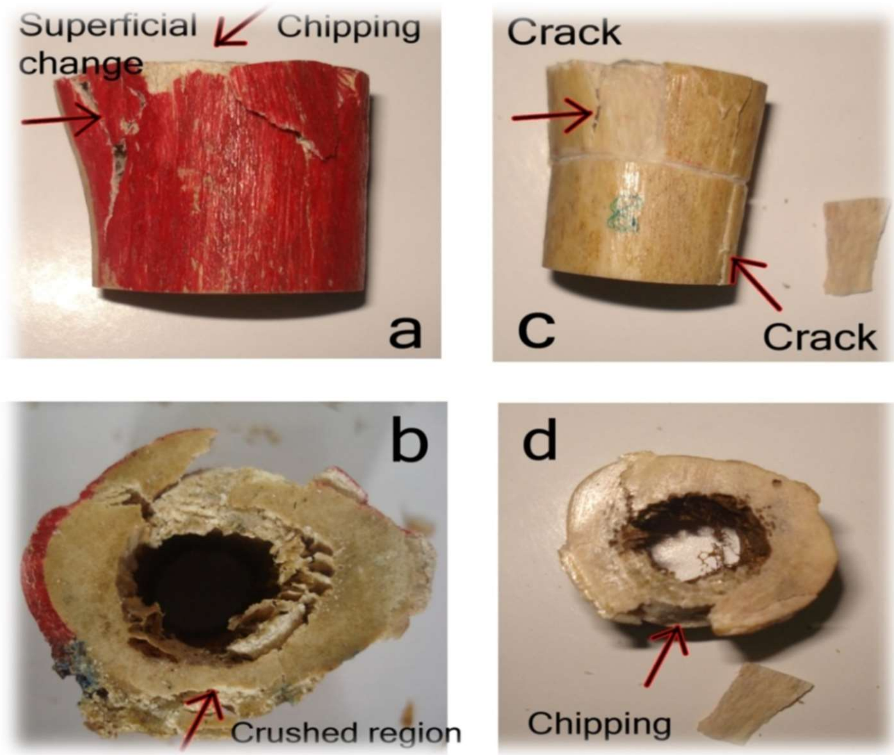

Figure 8. Mid shaft regional compression test specimens after test.

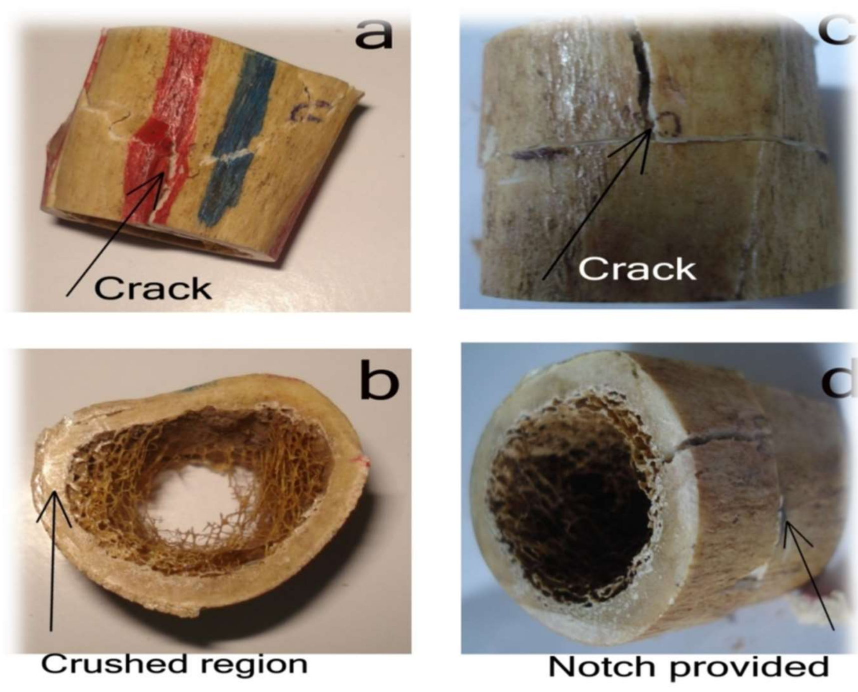

Figure 9.Distal regional compression test specimens after test.

The distal region of the femur has shown a dramatic change in the compressive strength. The strength of this region is higher than the mid shaft region. Even though the thickness is very less

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as compared to the other regions the strength is higher, this is mainly because of the reduced chipping and absence of through length cracks development. This behavior can be seen in figure 9a and b.The specimens after testing have shown in figure 10 a, b and c.

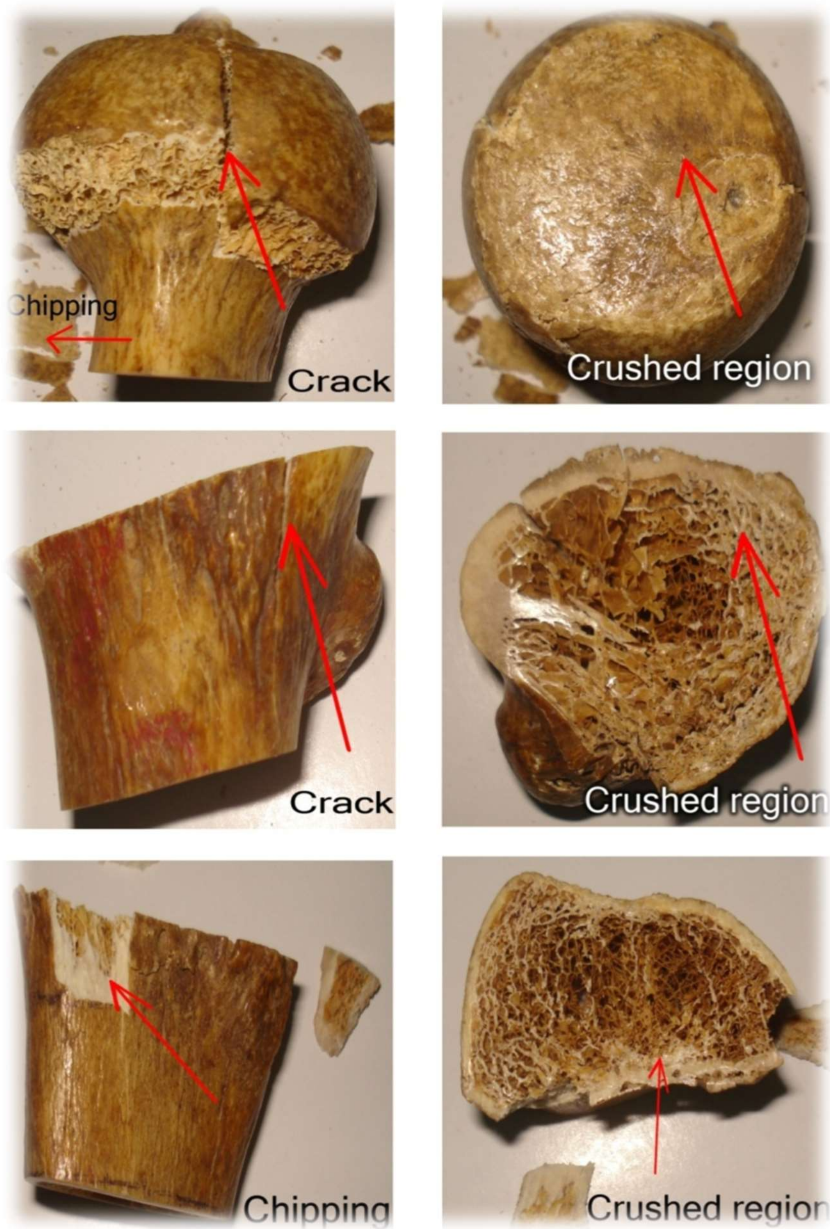

Figure 10 a). Femoral headb) Trochanter and c) distal regional compression test specimens after test.

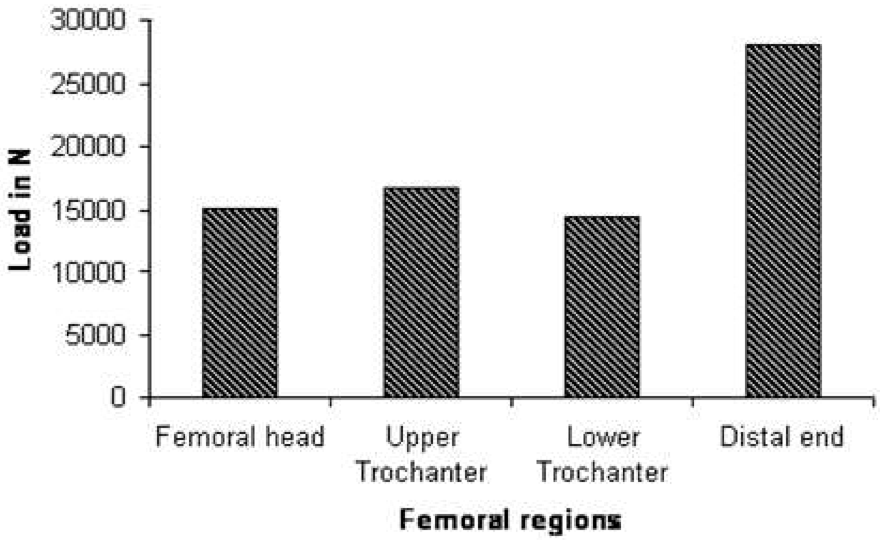

Figure 11.Regional compressive strength of femur

Fractures of the femoral head are rare injuries, which typically occur after posterior hip dislocation. The injury is mostly caused by high-energy trauma, such as motor vehicle accidents or falls from a significant height. There is an ongoing controversy about the suitable surgical approach (anterior vs. posterior) for addressing fractures of the femoral head. Fracture location, degree of displacement, joint congruity and the presence of loose fragments, as well as concomitant injuries are crucial factors in choosing the adequate surgical approach. Majority of the head failures are due to impact and compressive loads. Since the femoral head has got a spherical shape and highly porous media an attempt has been made to identify the compression load carrying capacity of this region. As can be seen in figure 10, the head has sustained much load before failure, but the simulated extreme condition has induced a crack in the direction of loading itself. Also the most sensitive region like trochanter and distal end of the shaft has been separately tested under compressive loads. The results of which have been shown in figure 11. From the figure 11, it can be seen that high range of compressive loads are sustained by the distal end of the shaft. The head has also shown a moderate strength in bearing compressive loads.

CONCLUSIONS

From the experimental analysis carried out on human male femoral bone of age 20-30. The following conclusions were desired.

- During normal activities, the femur is sensitive to different types of loads and different regions of femur process different mechanical properties. These mechanical properties like hardness and compression vary from region to region because of its composition.
- The hardness of the femur shaft increases from proximal to distal region. Hardness is maximum at distal region and is found to be minimum at proximal region.

- The proximal region has found to have maximum compressive strength because of maximized porous reduced chipping and less hardness. This reduce amount of compressive strength. The midshaft region because of drastic increase in cracks and chipping of the bone. Distal region has higher compressive strength than midshaft. This is because of reduced chipping and absence of through length cracks.
- The head and trochanter has a moderate compressive strength and this is found to be more in distal and as compared to head and trochanter region.

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