NUMERICAL INVESTIGATION ON THE PERFORMANCE OF OSTEOPOROTIC BONE WITH AN IMPLANT- A FE APPROACH

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Abstract

A finite Element model of femur bone with implant was developed to study the effect of osteoporotic behavior of femur bone to predict the possibility of implant loosening after Total Hip Arthroplasty (THA). The current study provides detailed quantitative information on the biomechanical behavior of an osteoporotic femur which can be used in the prediction of implant loosening and premature fracture of the femur. The FE model was simulated and analysis for three distinct range of motions like, single leg stance, normal walking and stair climbing was performed using ABAQUS to derive the associated implant displacement. Gradual reduction in bone density was used to simulate osteoporotic changes within the femur. As reported, the maximum stress occurred at the prosthesis neck region for all the activities and is maximum during single leg stance. It was observed that, the rate of displacement of implant increases with decrease in bone mineral density. With a reduction of 20% of bone density in osteoporotic femur, the displacement of implant increases by 34.5% during single leg stance. The study concludes that, presence of osteoporotic condition on femur bone results in implant loosening and premature failure.

Index Terms—..

1 INTRODUCTION

Finite Element analysis of femur bone with implant is a preclinical study on total hip replacement process. That can enable us to choose patient specific implants. Maram et al., [1] pointed out many of the advantages of using compurterised tomography (CT) scans in bone modelling. CT image provide accurate information about bone geometry. The radiographic density reported in the CT images can be related to the mechanical properties of bone. Moreover, CT scanning is a mildly invasive routine diagnostic method which permits the modelling of human bones in-vivo.

Pistoia et al., [2] identified that reduction in cortical bone thickness had a major effect on predicted bone strength compared to the reduction of trabecular bone mass. Hence, cortical bone might play a larger role in load transfer. A Moulgada et al[3]Through the analysis of stress distribution in cement mantle, showed that the risk of loosening of the prosthesis is maximal at the neck region of the hip prosthesis. Arjit Kumar Saxeena, Raghvendra KumarMisra, Anurag Dixit 2015[4] studied about various bio materials and found Titanium alloy as the best suited material for making implants (low equivalent stress and low weight).

The present study focuses on the static analysis of femur bone with implant under healthy body conditions and osteoporotic condition of femur for the resultant stresses and displacement occurring on the bone as well as on the implant after Total Hip Arthoplasty (THA). The CT image in DICOM format is decoded to develop 3D finite element model of human bone. The material property of bone is assumed to be isotropic. The FE model was simulated and analysis for three distinct range of motion like, single leg stance, normal walking and stair climbing was performed using ABAQUS to derive the associated implant displacement. Gradual reduction in bone density was used to simulate osteoporotic changes within the femur.

2 GEOMETRIC MODELLING

In computational biomechanics exclusively for orthopedic applications, CT quantitative images are more suitable for bone modeling since hard tissue (bone) has a

Fig 1. 3D model of femur bone

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high contrast relative to soft tissue. The DICOM image of femur bone of a healthy female patient with a body weight of 75kg is decoded to develop a computer Aided 3D model for the FE Analysis. The software simpleware (scan IP) was used to process CT image.

In order to create an accurate three-dimensional geometric model it is essential to design region containing bone tissue. Thus image segmentation has to be done by region growing method. After completing the segmentation part smoothening of model was carried out using Recursive Gaussian Filter. It reduces image noise levels. The final 3D CAD image of femur bone with bone region and bone marrow region was saved in IGES format.

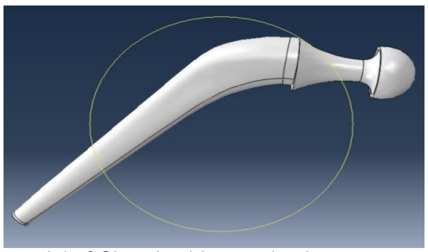

Fig 2. 3D model of Charnley hip prosthesis

Charnley implant design was selected for hip implant .The CAD model obtained was scaled to required dimensions. Assembly of implant and bone was done using Solid works software. Boolean operations was used during assembly of implant and bone.

3 ASSIGNING MATERIAL PROPERTY

Bone material was assumed to exhibit linear, homogeneous elastic behavior. The property of cortical bone is assigned which is having 15500 MPa as Young's modulus, 1990 kg\m3 as density and 0.28 as poissons ratio [5].Ti6Al4V alloy was selected as the implant material. Ti6Al4V alloy has a density of 4430kg/cm3, Young's modulus E 110000MPa and Poisson ratio 0.3 [6].

The contact conditions between the implant stem surface and femoral canal surface is formulated as small sliding formulation with friction coefficient 0.4 [7].

4 LOADING AND BOUNDARY CONDITIONS

Static load represents a person of 75kg; this load analysis is based on the peak load during the normal walking activity. An abductor muscle load F (abductor muscle) is applied to the proximal area of the greater trochanter. The acting loads on the femur were evenly distributed over the femoral head and greater trochanter.

TABLE 1.
MAXIMUM LOADING CONFIGURATIONS OF THE MAJOR MUSCLES DURING SINGLE LEG STANCE [3]

Force, N	Fx	Fy	Fz
Joint contact force	177	-750	-1685.4
Abductor muscle force	-727	373	195

The boundary condition was applied by fixing the distal epiphysis, which is the distal end of the femur that is connected to the knee.The force for normal walking is calculated by Gait analysis. Gait analysis is the systematic study of animal locomotion, more specifically the study of human motion, using the eye and the brain of observers,

TABLE 2.
MAXIMUM LOADING CONFIGURATIONS OF THE MAJOR MUSCLES DURING NORMAL WALKING [3]

Force, N	Fx	Fy	Fz
Joint contact force	107	-455	-1021
Abductor muscle force	-527	280	141

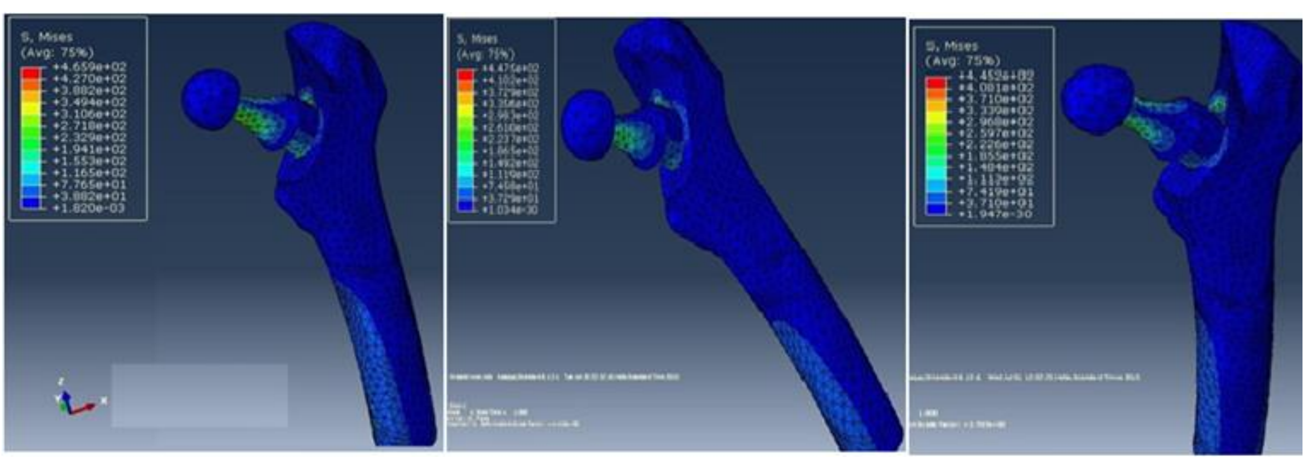

Fig.3 Stress distribution in assembly:
(a) Single leg stance (b) Normal Walking (c) Stair Climbing

TABLE 3.
MAXIMUM LOADING CONFIGURATIONS OF THE MAJOR MUSCLES DURING STAIR CLIMBING [3]

Force, N	Fx	Fy	Fz
Joint contact force	119	-505	-1135
Abductor muscle force	-660	351	177

augmented by instrumentation for measuring body movements, body mechanics, and the activity of the

TABLE 4.
VON MISES STRESS OF IMPLANT FOR HEALTHY BONE-IMPLANT ASSEMBLY

Activities	Displacement (mm)	Von Mises Stress (MPa)
Single Leg Stance	7.066	465.9
Normal walking	5.08	447.5
Stair climbing	5.989	445.2

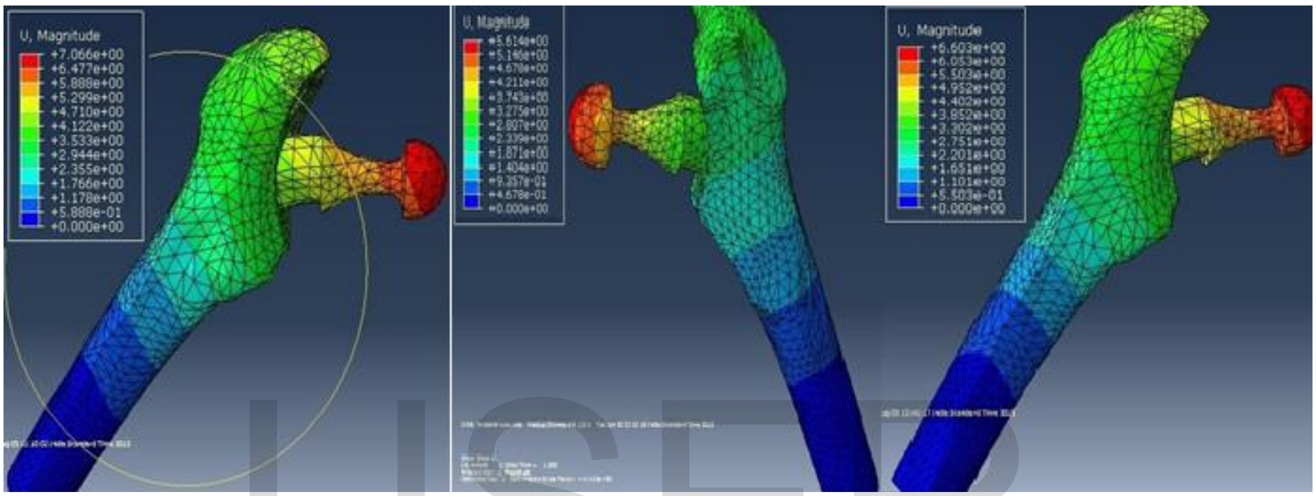

Fig 4. Displacement for bone-implant assembly for Normal walking
(a) Normal bone Density (b) Density decreased by 10% (c) Density decreased by 20%

muscles. Maximum loading configurations of the major muscles under the selected range of motions are provided in table 1, table 2, and table 3.

5 RESULT AND DISCUSSIONS

Analysis was done according to the above material properties, loading and boundary conditions for fully cortical
The von mises stress distribution of the assembly and that of individual components of the assembly is shown in fig.3. The maximum stress occurred at the prosthesis neck region for all the activities. The maximum value of stress during single leg stance was 465MPa.The minimum value of stress was found to be 445MPa during normal walking condition. .By comparing the maximum stress with the yield stress of Ti6Al4V(880MPa), there is still a safety factor superior than 2.

From the table 5 values it was found that by reducing bone mineral density from 10%to 20% of healthy bone

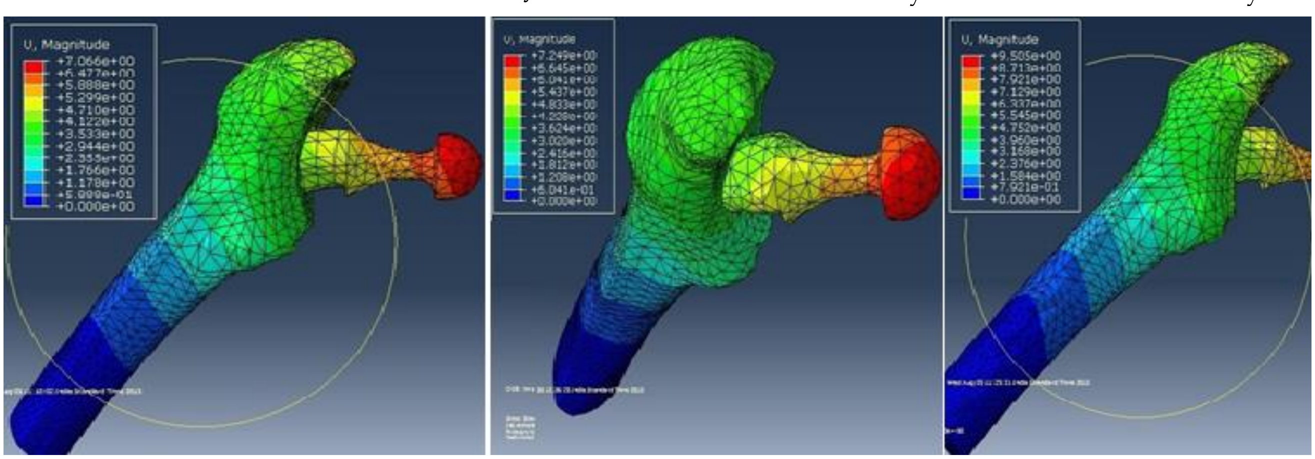

Fig 5. Displacement for bone-implant assembly for Single Leg Stance
a) Normal bone Density b) Density decreased by 10% c) Density decreased by 20%

condition on femur bone causes an increase in implant displacement by 28% to 34% respectively, leading to implant loosening with decrease in bone mineral density. Maximum displacement was detected during single leg stance loading. Where, a reduction in bone density by 10% to 20% of normal condition on femur bone causes an increase in implant displacement by 28% to 34% respectively, leading to implant loosening and premature failure of bone.

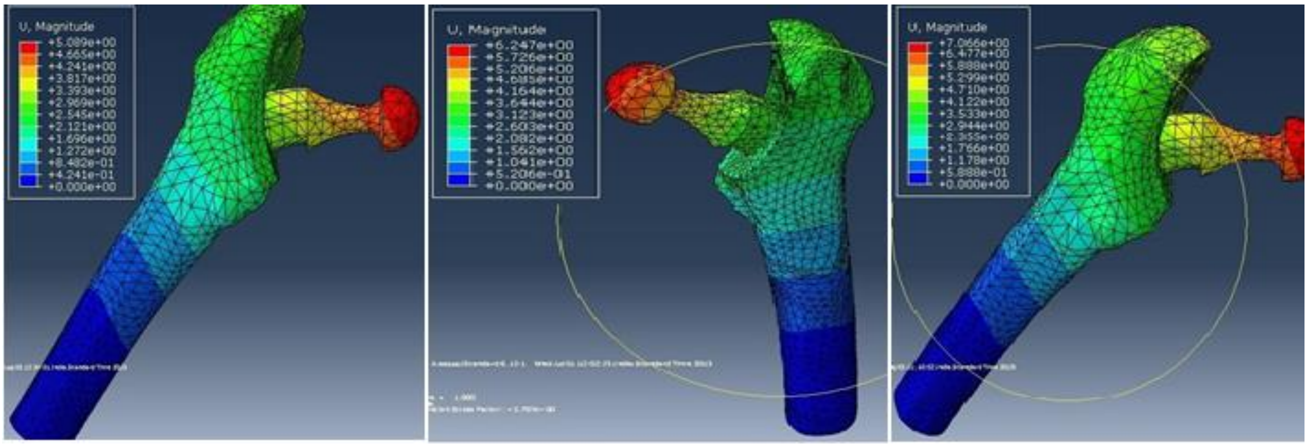

Fig 6. Displacement for bone-implant assembly for Stair Climbing:
a) Normal bone Density b) Density decreased by 10% c) Density decreased by 20%

TABLE 5.
COMPARISON OF NORMAL AND OSTEOPOROTIC FEMUR-IMPLANT DISPLACEMENT (MM)

Activities	Deformation(healthy cortical bone)	10% Decrease of BMD	20%Decrease of BMD
Single Leg Stance	7.066	7.349	9.505
Normal walking	5.08	5.61	6.603
Stair climbing	5.089	6.24	7.066

CONCLUSION

Human bone can be considered as a composite material where testing can be carried out to find out its mechanical properties. The data obtained from CT scans can be used to develop finite element models, which in turn can be used to predict structural behaviour. Finite element analysis can be used to investigate the mechanisms of failure and stress patters in human bone. Total Hip Arthroplasty (THA) is the common technique used in cases of reconstruction when the functionality of the natural hip joint and the leg is impaired. It is observed that the regenerative and remodeling processes in bone are directly triggered by loading. Due to stress shielding, bone tissue surrounding the implant will not receive enough stress or loads for further regeneration, resulting in density deterioration. This subsequently results in osteoporosis.

Present study was aimed at determining the effect of osteoporotic behaviour of femur–implant after total hip replacement. During the study on the bone implant under various range of motion namely, single leg stance, normal walking, and stair climbing for an osteoporotic bone, it was observed that the rate of displacement of implant increases

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