FINITE ELEMENT ANALYSIS OF L3-L4 VERTEBRAE AT VARIOUS BODY POSTURES UNDER OSTEOPOROTIC CONDITION

Resmi S. L, Ananthu Mohan, Firoz N, Hashim V and Dileep P. N.
1, 3 Assistant Professor, Department of Mechanical Engineering, TKMCE, Kollam.
2 Under graduate student, Department of Mechanical Engineering, TKMCE, Kollam.
4 Associate Professor, Department of Mechanical Engineering, TKMCE, Kollam.
5 Professor, Department of Mechanical Engineering, TKMCE, Kollam.
E-mail: resmisaji@gmail.com

Abstract. The present study gives detailed quantitative information on the biomechanical behavior of osteoporotic vertebra which can be used in the evaluation of osteoporotic bone fracture. A three-dimensional finite element model has been developed and applied for the analysis of the lumbar L3-L4 disc-body unit under various body postures like normal standing, extension, weight lifting, stoop lift and squat lift. The stress and deformation of disc and vertebrae are compared with the corresponding values at 10% and 20% osteoporotic condition. It is observed that for weight lifting, stoop lifting, and squat lift under 20% osteoporotic condition the maximum value of stress obtained is close to compressive strength of the bone. Also noted that fewer than 20% osteoporotic condition the deformation of the disc is increased to 20.08% under weight lifting postures. Therefore, we come to the conclusion that people at old age should avoid risky postures which result in low back pain or lumbar fracture.

Keywords: Osteoporotic vertebra, CT based FE model

1. Introduction

Age related, osteoporotic fractures of spine are more common in women and have associated health care costs of lakhs of rupees. Probabilistic analysis can predict the variability of failure when the stress concentration exceeds the yield stress. Finite element (FE) methods have become an important tool to evaluate mechanical stresses and strains in bone and have been widely used to investigate the mechanical behavior of bone tissue. As a research tool, finite element analysis can be used to analyze the mechanisms of age-related fractures. The research potential of CT-based finite element analysis of bone structures has been recognized by many investigators [1, 2], but few have used this technique to predict the absolute failure loads of bones. Finite Element studies concluded that the highest compressive loads act on L3-L4 lumbar spine segment [3].
The present study focuses on the effect of osteoporotic behavior on the strength of human lumbar vertebra. The strength of human bone can be evaluated using FE analysis. The CT image in DICOM format is decoded to develop 3D finite element model of human bone. The material property of lumbar vertebrae and intervertebral discs is assumed to be isotropic. The various body postures considered for this study are extension, weight lifting, stoop lift and squat lift. The finite element model is developed using ABAQUS software. Initially, the finite element model of a normal human vertebra-disc assembly subjected to various body postures like weight lifting, extension, stoop lift and squat lift was analyzed and its strength is evaluated from the stress and displacement values of disc obtained using ABAQUS. The Osteoporotic behavior is simulated using a finite element model of vertebra-disc assembly with gradual reduction in bone density.

2. Geometric modeling
In computational biomechanics exclusively for orthopedic applications, CT quantitative images are more suitable for bone modeling since hard tissue (bone) has a high contrast relative to soft tissue. The DICOM image of femur bone of a healthy female patient with a body weight of 70kg is decoded to develop a computer Aided 3D model for the FE Analysis. The software simpleware (scan IP) was used to process CT image [4,5].

In the next step, finite element model is developed using ABAQUS by importing the geometric model in SAT format. Then, the geometric model is meshed into nodes and elements. The element used in the present study is the 8-noded brick element available in ABAQUS.

2.1. Loading and Boundary Conditions
For a man with 70 kg weight, the force acting on the L3-L4 vertebrae is 450N. In which 70% of the force is acting on the vertebrae column and remaining 30% on the pedicle [3]. A friction coefficient of 0.1 is provided in between all surfaces. The lower surface of the lower vertebrae is made to be fixed. The density of the bone is 1990 kg/m³ and the young’s modulus of the bone is 12000MPa and with a Poisson’s ratio of 0.3. The density of intervertebral disc is 1050 kg/m³ with a young’s modulus and Poisson’s ratio of 100MPa and 0.3 respectively. [6]The validated model has been extended for various body postures under osteoporotic condition. The table.1 shows the five body postures and the corresponding loads on L3-L4 vertebrae [7,8].

3. Results and discussions
In the present work, strength of human lumbar vertebra subjected to axial compression at various body postures is evaluated using CT based finite element method. In this study, two types of vertebrae i.e., a healthy vertebra and an osteoporotic vertebra, are modeled to study the effect of osteoporotic behavior on the strength of human lumbar vertebra. In order to predict stress and strain distributions within vertebra and disc for different phases of osteoporosis, a gradual reduction of bone density was used to model the bone.

| Body posture       | Compressive Force on L3-L4 (N) | Shear Force (N) | Moment on L3-L4 (Name) |
|--------------------|--------------------------------|-----------------|------------------------|
| Extension (20°)    | 500                           |                 | 7.5                    |
| Weight Lifting (7.4kg) | 518                        | 233             | 1                      |
| Stoop Lifting (11.5kg) | 2819                       | 436             |                        |
| Squat Lift (11.5 kg) | 2932                       | 237             |                        |
3.1 Disc deformation during extension

On conducting Static analysis on L3-L4 segment, it is found that during extension the disc deformation in the posterior direction is found to be $1.865 \times 10^{-2}$ mm and at that of 20% osteoporotic condition is found to be $1.982 \times 10^{-2}$ mm that is, deformation increased by 6.2%. But this deformation is far less to produce any pain. The maximum stress at 20% osteoporotic condition is to found to be 79.44 MPa which is below the compressive strength of the vertebrae.

**Figure 1.** Deformation on annular disc during standing at healthy condition

**Figure 2.** Deformation on annular disc during standing at 10% osteoporotic condition

**Figure 3.** Deformation on annular disc during standing at 20% osteoporotic condition

**Figure 4.** Von mises stress distribution lumbar vertebrae during standing at 20% osteoporotic condition
3.2. Disc deformation during weight lifting

During weight lifting the deformation in the anterior direction of intervertebral disc is found to be 0.1693mm and that of in 20% osteoporotic condition it found to be 0.2033mm. But for 20% osteoporotic condition deformation increased by 20.08%. The maximum stress acting on the vertebrae is found to be 96.98 N in 20% osteoporotic condition. Since the maximum stress value is very close to the allowable strength of the vertebrae. Hence chance of vertebral fracture is high.[9]
3.3. Disc deformation on stoop lift

While lifting 11.5kg load using stoop lift posture the deformation of disc obtained as $2.905 \times 10^{-4}$mm. Under same loading condition for 10% osteoporotic bone properties the percentage increase in deformation of disc is 4.8%. And for 20% osteoporotic bone property conditions percentage increase in deformation of disc is 17.2%. For 20% osteoporotic condition maximum allowable stress on the vertebrae is 100MPa, but as per the results obtained the stress value is 138MPa which is greater than 100MPa. Since there are chances of fracture in vertebrae, people of old age should avoid this posture during weight lifting. Disc deformation increases with osteoporotic conditions, hence the chance of occurrence of pain is high.
Figure 11. Deformation on annular disc during stoop lift at healthy condition

Figure 12. Deformation on annular disc during stoop lift at 10% osteoporotic condition

Figure 13. Deformation on annular disc during stoop lift at 20% osteoporotic condition

Figure 14. Von Mises stress distribution lumbar vertebrae during stoop lift at 20% osteoporotic condition.

Figure 15. Variation of compressive strength with percentage osteoporotic condition (Stoop lift)
3.4. Disc Deformation in Squat lift

![Figure 16. Deformation on annular disc during squat lift at healthy condition](image)

![Figure 17. Deformation on annular disc during squat lift at 10% osteoporotic condition](image)

![Figure 18. Deformation on annular disc during squat lift at 20% osteoporotic condition](image)

![Figure 19. Von mises stress distribution lumbar vertebrae during squat lift at 20% osteoporotic condition](image)

![Figure 20. Variation of compressive strength with percentage osteoporotic condition (Squat lift)](image)
While lifting 11.5kg load using squat lift posture the deformation of disc obtained as $1.827 \times 10^{-4}$ mm. Under same loading condition for 10% osteoporotic bone properties the percentage increase in deformation of disc is 3%. And for 20% osteoporotic bone property conditions percentage increase in deformation of disc is 11.4%. For 20% osteoporotic condition maximum allowable stress on the vertebrae is 100MPa, but as per the results obtained the stress value is 92MPa which is closer to the allowable values. Deformation of disc increases with the increase in osteoporotic conditions and thereby increases the chance of compression of nerves which results in pain.

4. Conclusions
Lower back pain is common clinical complaint in these present days. From the analysis it is found that, as the osteoporotic condition get worsen the maximum allowable stress acting on the vertebrae get decreased and the strain on the vertebrae get increased. From the present study it is observed that as bone mineral density decrease the deformation of the disc increases which result in compression of nerves. Hence low back pain result in old age people.

- For a 20% osteoporotic bone maximum value of compressive strength is 100MPa[9], the analysis results show that the maximum value of stress is 96MPa for weight lifting, 76MPa during extension, 138MPa for stoop lift and 92MPa for squat lift.
- Also the deformation of disc under 20% osteoporotic conditions is increased to 20.08% under weight lifting posture.

From these studies it is clear that due to osteoporosis, compressive strength of vertebrae get reduced with age. There are chances of bone failure with aging. So old age people should avoid risky postures like stoop and squat lift. The present study gives detailed quantitative information on the biomechanical behavior of the vertebra and these results are considered to be a very useful analysis tool in the risk evaluation of fracture including osteoporotic bones. The resulted information will be helpful for medical practitioners to suggest proper prevention and precaution to the patients. The integration of technologies such as computed tomography, computer aided modeling, FEA is important in medical field to reduce the cost and risk to patients and strengthening the decision making capacity of medical practitioner.

References
[1] Georg Osterhoff, Elise F. Morgan, Sandra J. Shefelbine, Lamya Karim, Laoise M. McNamara, Peter Augat (2016), “Bone mechanical properties and changes with osteoporosis”, Injury, Int. J. Care Injured 47S2, S11–S20
[2] Faulkner KG, Cann CE, Hasegawa BH, “Effect of bone distribution on vertebral strength: assessment with a patient-specific nonlinear finite element analysis”.Radiology, Vol. 179, pp. 669-674, 1991
[3] Jong Ki Shin, Tae SikGoh, Myung-Sung Kim, Keunyoung Kim, Myung Jun Shin, Seung Min Son, Hee Jin Lee, Jung Sub Lee, Chi-Seung Lee (2017), “Stress and strain analyses of single and segmental lumbar spines based on an accurate finite element model for vertebrae”, Biomedical Research 2017; Special Issue, S602-S609
[4] M.Vineeth, S.L.Resmi, M.Shannnadhand P.N.Dileep(2013),“A study on the osteoporotic behaviour of human vertebra using FEM”,In Proceeding of Second Internatinal Conference On Science and Innovative Engineering.Chennai
[5] Justin Thomas, K Pranav Krishna, Resmi S L, Dileep P N (2013), “A Study on the mechanical behaviour of lumbar vertebrae of skater using FEM”, In Proceeding of Third International Conference on Materials for the Future,GEC Thrissur.
International Conference On Aerospace & Mechanical Engineering (ICAME-2018)

[6] Sofia Pedroso de Faria (2015), “Biomechanical Analysis of the Human Lumbar Spine - An Experimental and Computational Approach”, LAETA, IDMEC, IST, Lisbon, Portugal, 1-10

[7] Shaobai Wang, Won Man Park, Yoon Hyuk Kim, Thomas Cha, Kirkham Wood, and Guoan Li (2014), “In vivo Loads in the Lumbar L3-4 Disc during a Weight Lifting Extension”, journal of clinical biomechanics, 29(2), 155-160

[8] Jaap H. van Dieen, Marco J.M. Hoozemans, Huub M. Toussaint (1999), “Stoop or squat: a review of biomechanical studies on lifting technique”, Journal of Clinical Biomechanics, 14, 685-696

[9] Dennis R Carter, Wilson C Hayes (1976), “Bone compressive strength: The influence of density and strain rate”, Journal of science, 194, 1174-1176