

CT Based Finite Element Analysis Of Human Lumbar Vertebra With Accurate Geometric and Material Property Assumptions

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Abstract—Osteoporosis is considered as the one of the major diseases affecting human lumbar spine. It is the reduction in Bone Mineral Density (BMD). This disease increases the risk of fracture and ability to carry load. Computer Tomography (CT) based estimations are not adequate enough to predict the effect of BMD reduction in daily life. Finite Element Method (FEM) is an effective tool for analyzing mechanical properties of bone and characterizes some phenomenon that cannot be done by Vitro Experiments. The accuracy and reliability of the analysis depends upon the link between the Bone and its 3D Model. The Bone material properties are considered as complex, time dependant and age related. In this work a continuous relation between the bone and its 3d models were maintained. The geometries and material properties of the Lumbar Vertebrae were extracted from the CT –Scan of the same bone. Inhomogeneous material properties are used to get more realistic results.

Index Terms— Abaqus, Computer Tomography, FEA, Lumbar Vertebrae, Mechanical properties, Osteoporosis.

1 INTRODUCTION

Computer Tomography based Finite Element analysis with accurate and realistic material properties hold a great contribution to the biomechanical study of lumbar Vertebrae. This method is helpful in accurately predicting age related vertebral fracture and suggest appropriate treatment for patients having osteoporosis, bone cancer etc and model implants and their augmentation techniques .

The need of this work in Biomechanics is to study pathological conditions related to spine. Osteoporosis are characterized as the mineral density loss of bone. Bone Mineral density reduction influences the bone strength and its ability to carry load. Patients having osteoporosis come to know about their disease only after a vertebral collapse or after a severe back pain.[1]

Computer Tomography (CT) is an effective tool for identifying Bone Mass Density (BMD) reduction, but it is not good enough to predict the effect of BMD loss in daily life. Finite Element analysis (FEA) is the solution for this problem. Finite Element Analysis is a numerical analysis tool used to study the mechanical behavior of solid objects under load. This technique reduces the dependency in vitro experiments in bone analysis. FEA is helpful in finding the parameters associated with bone degradation that cannot be characterized by vitro experiments. Finite Element Method reduces cost and the time for developing treatment strategy and analyzing implants. In the early stages of FEA studies in lumbar were carried out under a generalized model and isotropic material properties. The accuracy related to such models were limited because the actual geometry of the bone and the models were not linked properly and a non realistic approach in assessing and assigning material properties.

The material property of the bone is considered as anisotropic, time dependant and it is age dependant. [2] The accuracy and reliability of FEA models mainly depend on three parameters-Approximations of the vertebral geometry, Material property and it systematic assessment. Uncertainty related to bone material property is still an unresolved problem [3]. Only a limited number of studies were conducted on the systematic CT based FEM analysis in lumbar bone.

The aim of present work is to generate a 3D CAD model of Human Lumbar Vertebral body and analyze and validate that model considering Inhomogeneous material properties. The FEM model should be directly linked with CT image for extracting geometry and material properties.

Anatomy of Lumbar spine

The lumbar spine is the section of Spinal Colum between the Thorax and Sacrum named L1 to L5 with their articular fact joints of Intervertebral Disc ligaments and surrounding muscles. Lumbar has separate regions for cortical and trabecular bones [4].

A single vertebra consists of two essential elements: Anterior and Posterior elements. The anterior element consists of the vertebral body. Vertebral body is considered as the major load carrying area in lumbar. The inside properties of vertebral body is more towards the trabecular bone and outer regions towards cortical bone. Top and bottom surfaces of the vertebral bodies have 0.5mm thick cortical end plates. The anterior elements consist of a pair of pedicles, lamina and seven processes; four articular, two transverse and one spinous process. A vertebral canal is provided for the safe passage of spinal code through it. It is positioned at the boundary of anterior and posterior elements.

2 MATERIALS AND METHOD

The CT scan of human lumbar bone (L3) was done at De-

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partment of Radiology, Bordet Institute, Belgium (ULB), with the following acquisition parameters: 120Kv, 266 mA, Pixel matrix 512, slice thickness 1.1mm and slice spacing .5mm. The scanned images are freely available on the following link isb-web.org/data/vsj/L3.

2.1 Model generation

The CT images in DICOM (Digital Imaging and Telecommunication in Medicine) were imported to Amira (Amira 5.5 Visage imaging sandiago USA). The bone and soft tissues were separated by adjusting threshold value. Those pixels without qualifying threshold values were eliminated from the window. The geometry of Human Lumbar by defying geometric boundaries with the help semi automatic segmentation tool in Amira. The vertebral body was segmented for this work.

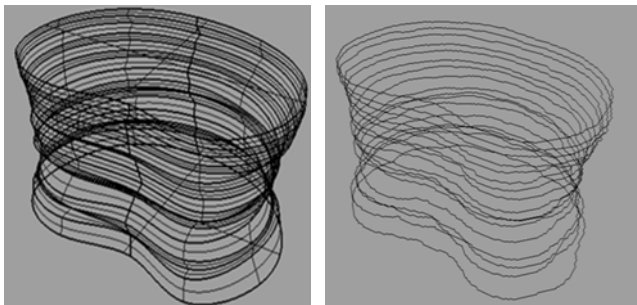


Fig. 1 Extracted contours.

Fig. 2 Edited Contours.

The segmented boundaries are stacked in z direction taking the first CT slice as the origin; each segmented line is in the form of contour (Fig. 1). The stacked contour lines were then imported to SolidWorks 2010. The contour lines were edited with B-Spline to get smooth geometry (Fig.2). The smooth stacked contours were lofted and converted to solid.

The solid geometry then exported to Abaqus (Abaqus CAE, SIMULIA, providence RI) in IGES format to create finite element model.

2.2 Isotropic Model- 1

It is the initial simple model created by lofting .It is a single part and it doesn't contain any separate regions for cortical, trabecular and end plates (Fig. 3).

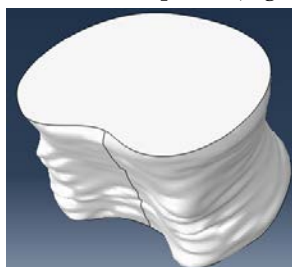


Fig. 3 L3 Isotropic Model-1

2.3 Isotropic Model- 2

This model contains four different parts of L3, two end plates, Vertebral cortical region and Vertebral trabecular regions. These four parts were modeled by taking Model -1 as the base model. The end plates having a thickness of 1mm [5]

and it is created by defining a plane 1mm from the top and bottom surfaces and removing the inside portion. The trabecular region is created by offsetting the extracted contours by 1mm inside in the same plane and then lofting. The cortical bone is created using the Boolean command between Model 1 and trabecular region (Fig. 4).

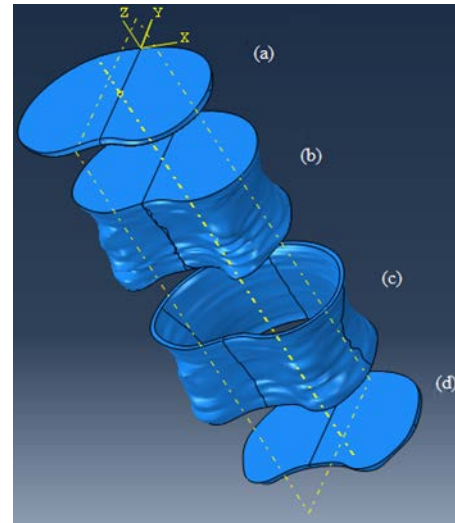


Fig. 4 isotropic Model-2

2.4 Inhomogenous Model

The inhomogenous model is created by partitioning the isotropic model- 2 with datum planes and sweep edges. The number of horizontal partitions should be in accordance with the number of CT slices. The cortical and trabecular models were created with 14 CT slices, so 14 horizontal partitons were made for both cortical and trabecular regions (Fig. 5). The number of datum planes, partitiond cells etc. are in the Table 1.

Table 1 Inhomogenous model partitions.

Parts	Datum Planes	Sweep edges	Partitions
End plate 1	4	3	32
Endplate 2	4	3	32
Cortical	17	0	112
Trabecular	17	0	112

2.5 Material Property Extraction

The material properties were extracted directly from CT scan. The House Field units (HU) at any location can be determined using imageJ (imageJ, National Institute Of Health Mary land, USA). The apparent density of the bone is linearly related to the House Field (HU) number [6].

$$\rho = 4.64 \times 10^{-4} \times \text{Hu} + 1 \text{ (g/cm}^3\text{)} \quad (1)$$

The apparent density is exponentially related to the Young's Modulus value of the bone.

$$E_c = 2065 \rho^{3.09} \text{ (MPa)} \quad (2)$$

$$E_t = 1904 \rho^{1.64} \text{ (MPa)} \quad (3)$$

Separate Young's Modulus values were found out for cortical and trabecular bones. The Poisson's ratio is considered as 0.3. [7]

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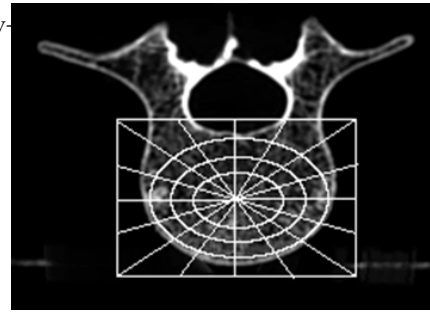


Fig. 6 CT scan partitions

The 3D -solid model segment associated with each CT segment was found out and assigned the material property manually (Fig. 7). This process was repeated according to the spacing of the horizontal datum plane. The isotropic Material Property extracted for Model1 and Model 2 is listed in Table 2.

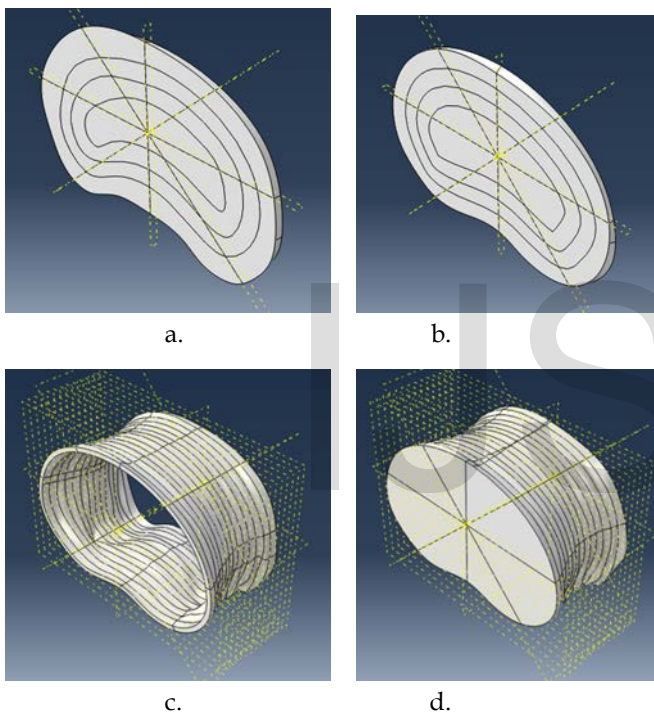


Fig. 5 Inhomogeneous Model .(a) End plate 1 (b) Endplate 2, (c) Cortical region (d) Trabecular region

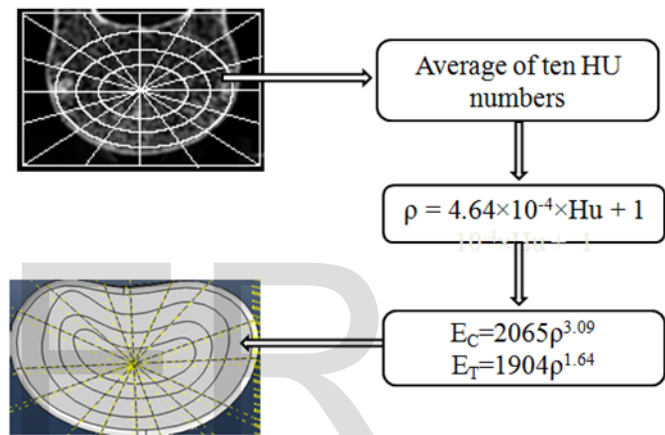


Fig. 7 Material Property Assignment.

Table 2 L3 isotropic material properties.

Model	Part	E (MPa)	Poisson's Ratio
Model -1	Vertebral Body	3603.54	0.3
	End Plate 1	3418.16	0.3
	End Plate 2	3563.48	0.3
Model -2	Cortical	5183.71	0.3
	Trabecular	2248.81	0.3

2.5 Material Property Assignment

The 3D solid model is directly linked to imageJ, for the accurate assignment of material property. Each CT slice is divided into different sections according to the partitions, which we have made in the vertebral body model (Fig. 6). The House Field Number (HU) of each segment is an average of ten different House Field numbers from different locations inside the segment. The HU value then converted to Young's Modulus using linear and exponential relations.

3 ANALYSIS

The analysis was performed in ABAQUS CAE.

3.1 MESHING

The entire model was meshed with 4 noded Tetragonal elements with size factor as 1mm.

3.2 LOADING AND BOUNDARY CONDITIONS

Janko D. Jovanovic et al [8], loaded the intervertebral disc with a forces of 450N pressure load (for a70Kg person while

standing), applied to the L3 end plate 1 in L3 models, where as its bottom was fixed in all directions. The Isotropic Model -2 and Inhomogeneous Models were defined as a contact problem, so we need to define the interactions between parts according to the load transfer. The interactions were given such a way that, if there is any movement in one part associated movements to other parts will occur. In the case of Cortical - Trabecular interaction Cortical bone is taken as Master Part, that's because the motion transfer from Cortical region to Trabecular region. In the actual case when load comes on Trabecular it compresses and not make big effect in Cortical region. The entire Cortical Body and End Plates acts as shell structure over Trabecular bone, so the interactions should be End Plated as master part and Cortical Body as slave part (Table 3).

Maximum Stress	1.042 MPa	0.421 MPa	0.694 MPa
Maximum displacement	0.56 mm	0.49 mm	0.43mm

Table 3 Isotropic Model 1& 2 and inhomogeneous model interaction properties.

Master Part	Slave Part	Interactions
End Plate 1	Cortical	Tie
Cortical	Trabecular	Tie
Trabecular	End Plate 2	Tie
End Plate 2	Ground	Encastre
Top of L3 Trabecular		Coupling

4 RESULTS

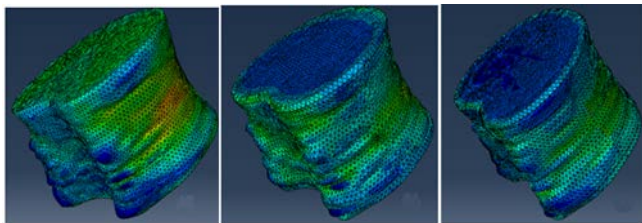


Fig. 8 (a) Maximum Stress in Isotropic model -1,(b) Maximum Stress in isotropic model- 2 ,(c) Maximum Stress in Inhomogeneous model.

The stress concentration in all three models was at the cortical region. Isotropic Model 1&2 and inhomogeneous models shows same region as stress concentration (Fig. 8). In inhomogeneous model we can accurately find out, in which section stress concentration occur and what are the properties of that region.

Table 4 L4 vertebra results.

Results	Isotropic Model 1	Isotropic Model 2	Inhomogeneous Model
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Bouzakis, et al [9] conducted a compression test in lumbar vertebra. The experiment results shows a linear behaviour below 1500 N. The experiment gives a result of 0.3125 mm displacement at 450N load. Fig. 9 shows the experimental settings and resulting graph of lumbar.

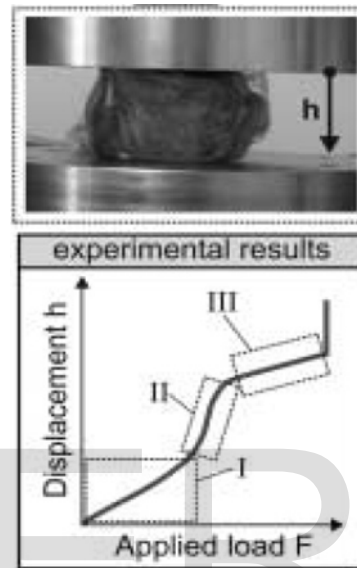


Fig. 9 Experiment settings and results from Bouzakis, et al.[9]

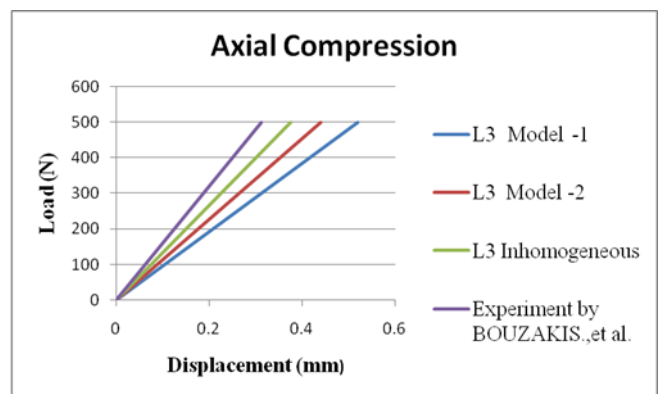


Fig. 10 Load Vs Displacement curve.

Fig. 10 is a comparison between the experimental results and FE results. The graph shows that inhomogeneous model is closely related to the experimental results. The inhomogeneous model properties are closely related to the actual bone. Hans-Jocabian et al, [10] found the stress range in L4 and L5 as 0.1Mpa-1.7Mpa. Only some slight changes are reported in the shape of vertebrae, so we can generalize this result to other vertebrae also. The stress generated in all the three models were within this stress limit.

5 CONCLUSION

The goal of this study was to determine the behavior on the strength of human L3 lumbar vertebra with inhomogeneous material properties retrieved from CT scan. Initially, the strength of a human vertebra subjected to axial compression is analytically evaluated using finite element analysis. The maximum value of stress developed in a healthy vertebra under normal load is evaluated and is found to be well within the strength limits. The accuracy of the present model can be increased by extracting pixel based material property data and assigning in the model with the help of programs.

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 the medical practitioner 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. The data obtained in this way can be used for accurate implant design for those who are suffering from osteoporosis, bone cancer etc.

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