Investigating mesh parameters to achieve clinically applicable finite element analysis of vertebrae

Clio G. Vossou and Christopher G. Provatidis

Abstract—**Numerical modeling of bones and especially mechanical analysis using the finite element method is a popular procedure for the investigation of the mechanical behavior of intact bones. Spine is an anatomical site, which is susceptible to degenerative pathologies and trauma. Consequently the need for mechanical analysis of its components is imperative. There are two ways to perform mechanical analysis; the first one is destructive, includes experimentation and can not be held in vivo while the second is non destructive and its main tool is the finite element method. The question of essential accuracy in order to attain reliable results arises when using the finite element method. Important parameters influencing the accuracy of finite element models are the mesh density and the element type. The objective of the present study is to review the results of the mechanical analysis of a 3D vertebra model, using different mesh densities and element types, in order to acquire a satisfactory compromise between computational time that ensures the clinical applicability of the method and accuracy. For this reason five patient specific models of the same first lumbar vertebra belonging to a young male have been created. The first one is built with voxel elements and the four others with tetrahedral or a combination of hexahedral and tetrahedral elements. Different quantities and mechanical magnitudes have been studied and compared. The finer mesh resulted in a model that was difficult to handle and did not offer essentially different results. On the other hand the coarser one needed a lot less computational time, and its results of the mechanical analysis can be considered reliable.**

I. Introduction

FINITE element (FE) modeling is a common tool used in biomechanics and is of rising use for the mechanical analysis of human spine. This computational technique makes possible the investigation of strength and stresses or strains, developed in the bones and other biological structures, in vivo. The knowledge of the values of the mechanical quantities of a vertebra, and especially of a damaged one, either by trauma or by metabolic diseases, such as osteoporosis, could provide an insight of its state giving to the doctor hints for the proper treatment.

Two different approaches are used for the creation of the geometry of such a model. The first one involves the use of generic geometry of the specific bone [1, 2]. The second one, this of patient specific bone models, is based on information retrieved from CT scans. As the CT scanners evolve the second approach becomes more and more practicable.

For the creation of a patient specific FE model of a bone two different techniques have been reported in the literature, the voxel based and the geometry based finite element modeling. The voxel based meshing implies that the element faces are oriented parallel to the three orthogonal axes defined by the coordinate system of the CT scanner, while the geometry based meshing requires the extraction of the outer contours from the CT scans of the bone [3]. Many studies, concerning vertebrae use the voxel based modeling [4-6] while others propose the use of the geometry based finite element models [7, 8].

In the present study, both techniques have been used for the creation of FE models of the same vertebra and their results have been compared. In addition to that, while using the second technique two different element types have been tested, one hexahedral and one tetrahedral. In total five different FE models have been created and analyzed in pure compression.

II. Materials & Methods

Five FE models of a healthy L1 vertebra belonging to a 34 year old volunteer man (height 180cm, weight 130kgr, DXA scan: normal T-score) were created.

A. CT Scans

The subject underwent High Resolution Computed Tomography (HRCT) scan at L1 vertebra (GE Medical systems Highspeed DX/i). A lateral scout view was used to localize the L1- L2 vertebral levels and upper and lower endplates. A volume starting 1-3 mm superior to the upper endplate of L1, and ending 1-3 mm inferior to L1 lower endplate was encompassed with: 0.8 mm thick contiguous axial slices, table speed: 2 mm/sec, reconstruction interval: 0.4 mm at settings of 120 kVp and 220 mA. Images were reconstructed using a standard abdomen reconstruction kernel with 512×512 image matrix for use in finite element mesh generation.

To relate the CT measurements to BMD, a single – slice spinal QCT scan was performed. The patient was scanned simultaneously with a bone mineral reference liquid K_2PO_4 calibration phantom. The mineral calibration phantom was compared with an ellipsoid region of interest in the center of the vertebral bodies (spongy BMD) and the cortical BMD was measured using QCT assisted by an automatic contour finding program [9].

B. 3-D model

For the creation of the external geometry of the patient specific FE models two different programs for CT processing were used. The first one is MIMICS 10.0 (Materialise BV, Belgium) and the second is ScanIP (Simpleware Ltd.). All the parameters in both programs were set in order to achieve satisfactory geometrical

C.G. Vossou is with the School of Mechanical Engineering in the National Technical University of Athens, GR-157 73 Athens, Greece (e-mail: cvossou@central.ntua.gr)

C.G. Provatidis is with the School of Mechanical Engineering in the National Technical University of Athens, GR-157 73 Athens, Greece (phone: +30-210-7721520; fax: +30-210-7722347; e-mail: cprovat@central.ntua.gr).

Manuscript received July 5, 2008. This work was supported in part by ΠΕΝΕΔ 2003

representation with fewer areas and less computational cost.

The procedure of the creation of the external geometry took the same time in both programs (approximately 15 min). In both cases, it consisted of the creation of a mask by setting two threshold numbers for higher and lower grey value. Then, the areas that belong to this interval but did not belong to the vertebra were deleted while those that belonged to the vertebra but not in the mask were included.

In the case of MIMICS the external geometry was exported in form of a stereolithography (stl) file that described the external surfaces of the vertebra. This file was transformed to an APDL file – the programming language of ANSYS – and it was imported in ANSYS in terms of external surfaces. Mesh was created using the mesh generator of ANSYS v11.0.

On the other hand, in the case of ScanIP, the external geometry was imported in ScanFE (Simpleware Ltd.) and mesh was generated. Both mesh generators, this of ANSYS and this of ScanFE, support the same kind of element types. The elements and the nodes were transformed in an APDL file and were imported in ANSYS.

C. *Material properties*

Correlation of grey values to bone density and material attribution took place in both ScanFE and MIMICS.

The Hounsfield units (HU) can be correlated to bone density values, ρ, knowing the density values of the phantoms, through a linear function [10]

$$\rho = a \cdot HU - b \quad (1)$$

The coefficients a and b in Eq.1 depend upon the CT scanner and for this particular GE CT scanner their values are 0.001 and 0.072, respectively. Bone density range was separated in nine intervals corresponding to nine materials with different elastic properties. Hereafter, the intermediate value of bone density for each material was correlated to Young's modulus through empirical relationships retrieved in the literature. The two relationships for cortical and cancellous bone were retrieved from [8, 11] respectively. In more details, for cortical bone the relationship used was:

$$E(GPa) = 4.25\rho^3 (g/cm^3) \quad (2)$$

While for cancellous bone:

$$E(GPa) = 4.73\rho^{1.56} (g/cm^3) \quad (3)$$

Where E is the elastic modulus of bone and ρ is the bone mineral density. Materials No 1-6 were considered as cancellous bone, with highest bone density this of 0.728 g/cm^3. The rest of the materials were considered as cortical bone. The value of Poisson's ratio was set to 0.3 for all materials.

D. *Loading Conditions*

All FE models were subjected to pure compression. A force of 850N, simulating 2/3 of the weight of the subject, which is the normal load of a lumbar vertebra in stance phase, was applied. The force was equally distributed on the nodes of the upper endplate. Concerning the constraints, the nodes of the lower endplate of the vertebral body were constrained in all three directions [12, 13]. The FE analysis of all five models was performed in ANSYS v11.0.

III. RESULTS

First of all, the number of elements and nodes and the mean element volume of all the abovementioned FE models are going to be investigated. From now on, the first FE model is going to be referred to "Hex45" and it is a voxel model meshed with brick Solid45 elements. Element type Solid45 is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. With the use of this model the external geometry of the vertebra is not described in an exact way and the volume of each element is 0.53mm^3. The second FE model is built with tetrahedral elements Solid95, and the representation of the external geometry of the vertebra is exact. The average volume of its elements is 0.09mm^3 and it is referred as "Tets95". The third model that from now on is mentioned as "Hex/Tets95", just like the second one, has elements of the type Solid95 that are of higher degree than Solid45 and have 20-nodes. It consists of both tetrahedral and hexahedral elements with average volume 0.21mm^3. Finally the last two models, "Tets92_Middle" and "Tets92_Low", consist merely of tetrahedral Solid92 elements. This element type is tetrahedral and it is defined by 10 nodes, with three degrees of freedom each. These models have different mesh density and their average element volume is 0.99mm^3 and 2.19mm^3, respectively.

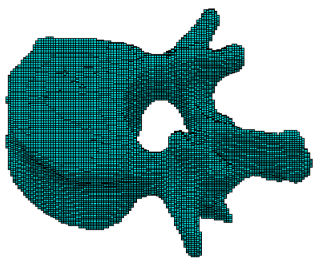
In Table I the number of the nodes and elements of the forenamed models are shown.

TABLE I
FE MODELS CREATED

	Nodes	Elements
Hex45	128320	112445
Tets95	978549	661451
Hex / Tets95	711366	285506
Tets92_Middle	89491	60401
Tets92_Low	42928	27603

The denser model is model "Tets95" while the coarser one is "Tets92_Low" This has a direct effect on the computational time needed for the performance of the finite element analysis. In a standard P IV 2.8GHz the solution of the model "Tets95" took 5 hr while the solution of the model "Tets92_Low" took less than 10 min.

A. *Geometrical Analysis*



Hex_45

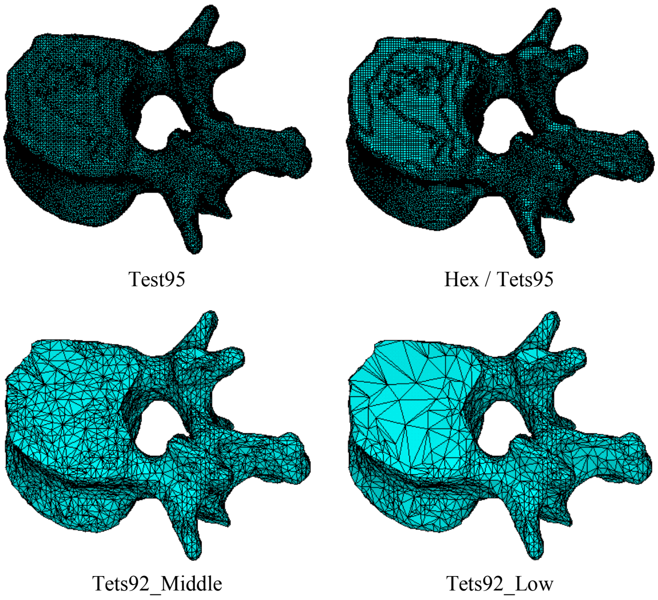


Fig. 1. FE models with different mesh densities

In Fig. 1 the five different mesh densities and three element types, the voxel based and the geometry based FE models from the finer mesh to the coarser mesh are presented.

It is obvious that the model that seems to have the exact anatomical geometry of the vertebra, without unreal angles or flat surfaces is model "Tets95". Also smooth geometry is met on the model "Tets92_Middle", while in model "Tets92_Low" the upper and lower endplate are flattened. An index of accuracy of the geometrical representation is the total volume of each FE model. The volume measured from the CT scans of the vertebra has the value of 59314.2mm^3. In Fig. 2 a histogram of the percentage of difference of the volumes calculated for each FE model from this volume is presented.

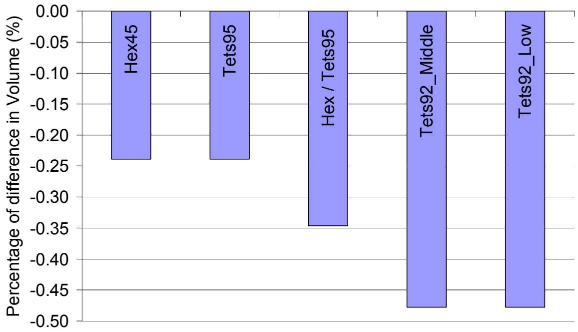


Fig. 2.The percentage of difference from the exact volume

In Fig. 3 the percentage of the total volume occupied by each material in every model is shown.

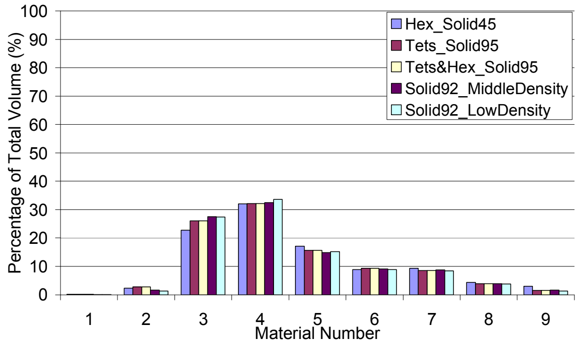


Fig. 3. Percentage of total volume occupied by each material

In all models material No 4 occupies almost 30% of the total volume, while material No 1 that has the properties of gap occupies less than 1%, with maximum percentage in the model "Hex45" and its value is 0.16%. The fact that this model has the maximum percentage of material No 1 could be attributed to the fact that in voxel representation, the material that surrounds the vertebra but does not belong to it is considered as its part. Apart from these observations, the distribution of materials is the same in all cases, and the anatomical site that each material occupies is the same.

B. Mechanical Analysis

The following paragraph concerns the results of the mechanical analysis performed on the abovementioned models. The mechanical results that are going to be reviewed for each model are the distribution of the axial displacement (Uz) and the equivalent Von Mises stress. Also, the maximum values of the equivalent Von Mises strain as well as the percentage of volume with strains more than 4500μStrains are going to be reviewed. Finally, of great importance is the value of the total strain energy of each model as well as the strain energy density of each material.

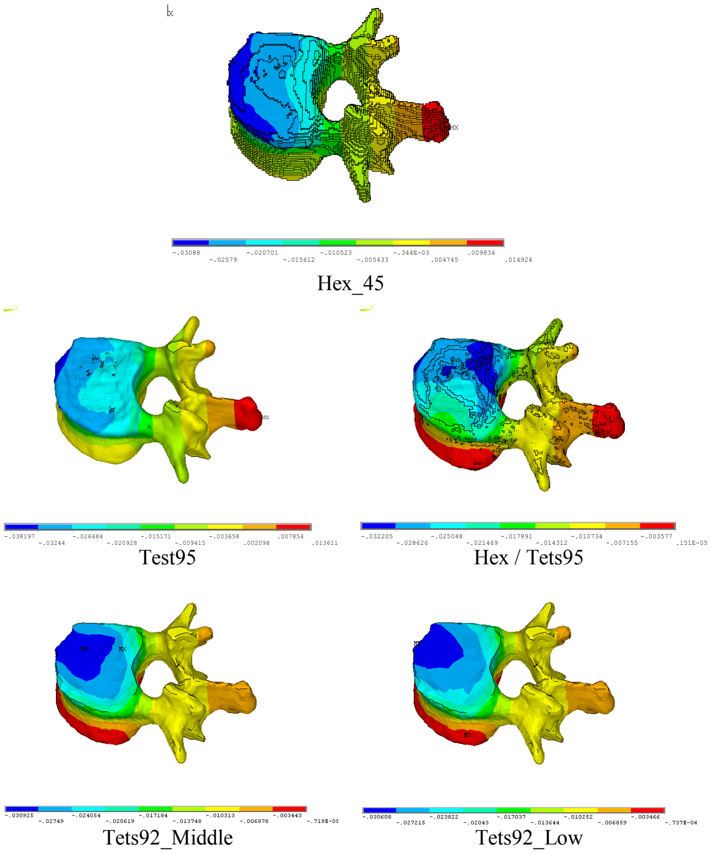


Fig. 4. Axial displacement distribution in all FE models

The distribution of the axial displacement Uz for all the models is shown in Fig. 4. Although the distribution is not the same in all cases there are some important points that remain the same regardless mesh density or element type. First of all, the minimum value of the equivalent Von Mises stress lies on the upper endplate. Likewise, in all models the maximum value lies on the lower endplate and on the back part of the spinous process.

Respectively to the distribution of the axial displacement, in Fig. 5 the distribution of the equivalent Von Mises stress is presented.

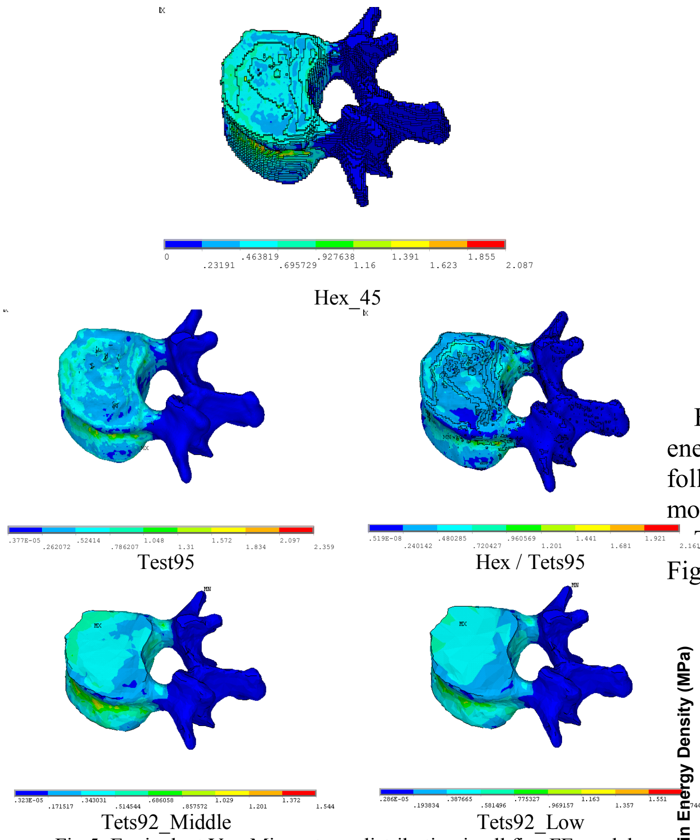


Fig 5. Equivalent Von Mises stress distribution in all five FE models

Also the distribution of the stresses has resemblances for all the FE models. In all cases the processes are not stressed and a site of stress concentration lies on the middle left part of the vertebral body.

Other important information retrieved from the mechanical analysis with the FE method of bone structures in general, is the strain magnitude. The maximum value of equivalent strains in all models is shown in Fig. 6.

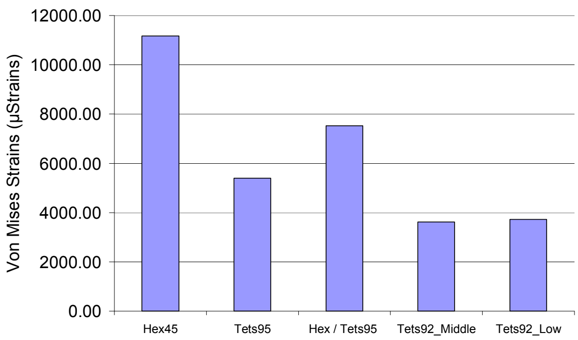


Fig. 6. Maximum equivalent Von Mises strain per model

The value presented here is the maximum value averaged from the nodes to each element and averaged again with the neighboring elements. In all models the maximum value is located in the posterior area of the vertebral body, on the area of entrance of the basivertebral vein in the vertebral body. This value in all cases is localized in just a few elements with the lowest Young's Modulus, for this reason can not be considered alone. Model "Hex45" has the highest value of maximum Von Mises strain among the five models.

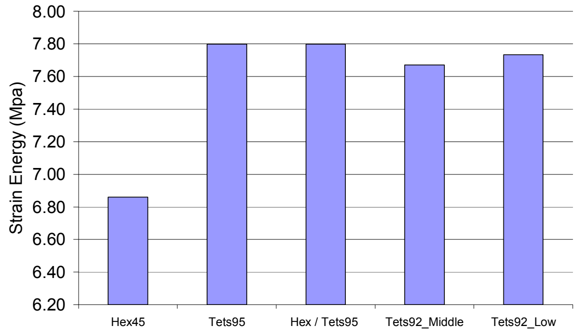


Fig. 8. Total strain energy per model

Finally, the values of strain energy as well as the strain energy density per material are going to be reviewed in the following figures. In Fig. 8 the total strain energy of each model is presented.

The strain energy density per material in presented in Fig. 9 that follows.

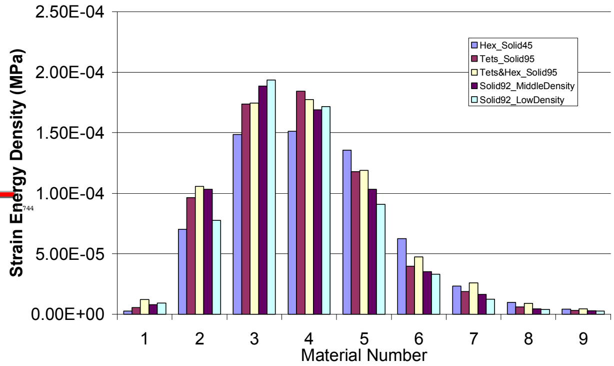


Fig. 9. Strain energy density per material for the FE models under investigation.

IV. Discussion

Regarding the accuracy of the geometrical representation, all the available models overestimate the volume but none of them more than 0.5%. Actually, the models built with hexahedral Solid45 and tetrahedral Solid95 differ less than 0.25% while the greater difference belongs to the two models built with tetrahedral Solid92 elements and it is 0.48%. This difference could be attributed to the use of different programs of CT image processing, but in both cases is a very low percentage to be taken under consideration.

To evaluate the material distribution in the proposed FE models an extra, dense voxel model with voxel size equal to 0.2x0.2x0.4mm (pixel x pixel x CT spacing) was built and material attribution has been performed in the same way with the ScanFE software. The difference in the distribution of materials from this base model is presented in the following figure (Fig. 10).

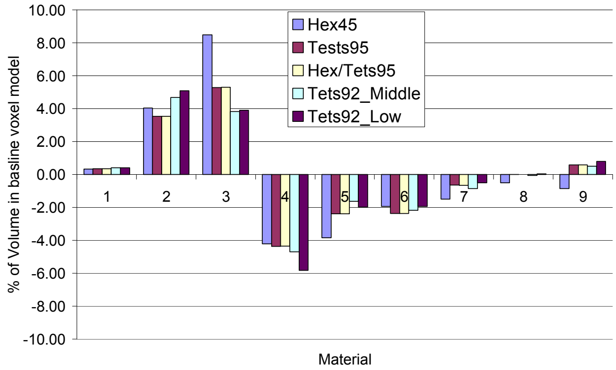


Fig. 10 Difference in % of the distribution of materials.

Comparing the material distribution of the five models to this of the detailed one, seems that in all cases the volume of the first three materials is overestimated while the volume of the materials 4-8 is underestimated. The volume of the ninth material is underestimated in model "Hex45" and overestimated in the rest of the models. Although this could cause changes in the total stiffness of the vertebra, it seems like it does not affect it. Comparing the models to each other seems that the over- or under-estimation of the volume of each material is the same, so in the proposed comparison, the distribution of the materials in the volume of the vertebra is the same.

As far as the distributions of the axial displacements and the equivalent stresses are concerned whereas they seem to change, the anatomical sites with increased values remain the same. For example in all the distributions of the axial displacement the site with the maximum absolute value lies on the anterior part of the upper endplate. However the site with the minimum value lies on the lower endplate and the posterior part of the spinous process. The only exception to that is the model "Tets95" where there are two sites with increased values of axial displacement, one on the anterior part of the upper endplate, just like all the models, and another one on the posterior part of the upper endplate.

The stress distributions also look alike. In all models the anatomical site with stress concentration is the left part of the vertebral body and the site of the processes has the lowest values.

The fraction of volume with strains more than 4500 μstrains (Fig. 11) is important because it could be an indicator of bone volume that could possibly fracture [14, 15]. The model with highest percentage of volume with strains more than 4500 μStrains is the model that combines tetrahedral and hexahedral elements and this value is 0.055%. For the rest of the models this value is less than 0.02%.

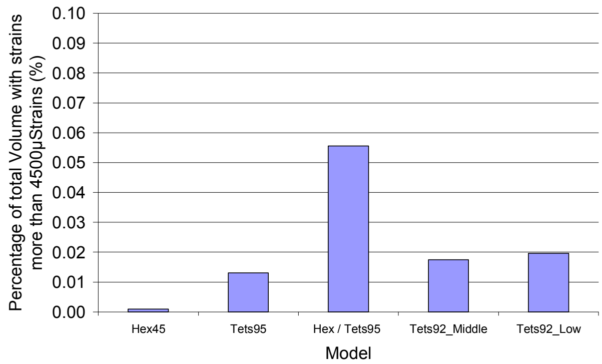


Figure 11. Percentage of volume with strains more than 4500μStrains

Strain energy is a measure of the energy that the vertebra has consumed for its elastic deformation. Apart from model "Hex45" that presents low value of strain energy (6.9 kJ) the rest of the models have total strain energy in the interval of 7.6-7.8 kJ.

The way that this energy is allocated in every material is shown in Fig. 8 where the strain energy density per material is presented. There it is shown that in all FE models the distribution of strain energy density is almost the same, with material No 3 having the maximum value and material No 9 having the minimum one. In all cases the distribution is close to normal.

V. Conclusions

As it is mentioned before the spinal column is a biological structure susceptible to metabolic diseases and trauma. FE analysis can be a useful tool of clinical evaluation, either of trauma or of osteoporosis. In order, though, to develop FE models of a damaged vertebra or spinal segment it is important to have settled down in the way of FE modeling (voxel, hexahedral or tetrahedral elements) and in the accuracy of the FE model needed in terms of the number of FE used. For this reason in the present study different ways of modeling a healthy lumbar vertebra and the obtained results have been reviewed.

As far as the geometrical representation accuracy is concerned it is shown that voxel modeling or very fine mesh does not provide higher accuracy in terms of total volume or material distribution.

In Fig. 4 and 5 the distributions of axial displacement and Von Mises stress are different in each model but they all have common topology of areas of increased values leading to the conclusion that if one is interested in the gross topology is preferred to use the model with tetrahedral elements since less time for the analysis if needed. Although the maximum values differ and as the mesh gets coarser the value of the maximum stress lowers, it is worth mentioning that the maximum calculated stress within all the proposed models (2.39 MPa) is significantly smaller than its strength, which is about 100 MPa for cortical bone [16]. Therefore, the failure of the vertebra commonly can be attributed to high strains so the absolute value of stress or displacement is not of great concern.

As far as the Von Mises strains are concerned it is shown that the maximum value changes but the same does not happen to the area where this value appears. Also the volume with strains more than 4500 μStrains is almost the same for three out of five models, so these can be considered as accurate. It is important to stress out that the common feature of these models is the fact that only tetrahedral elements are used and in these three models the denser and the coarse mesh are included.

In the same three models strain energy density remains the same and in all the models the strain energy density distribution is the same.

Concluding it is important to mention that in the literature many material models for bone appear and they are used for the attribution of the elastic modulus. Therefore the absolute values of displacement, stress and strain can not be considered as an absolute index of the pathology of a vertebra but as a comparative measure. In bottom line to evaluate the situation of a vertebra, the high mesh density is not useful since it does not affect the topology.

On the other hand the computational cost is of vital importance for the final choice of the model, especially in terms of clinical applicability. The analysis of the coarser model in a standard P IV 2.8GHz personal computer needed less than 10 min, while the analysis of the model “Tet95” needed more than 2 hr. Without experimenting on the scanned vertebra, one can tell that models “Tet95”, “Tet92_Middle” and “Tet92_Low” produce similar results, so one of these should be preferred; this leads to the model “Tet92_Middle” since it is of middle density and does not have grave differences in the results or in computational time from the densest one.

References

[1] F. Lavaste, W. Skalli, S. Robin, R. Roycamille, and C. Mazel, “3-Dimensional Geometrical and Mechanical Modeling of the Lumbar Spine,” *Journal of Biomechanics*, vol. 25, (no. 10), pp. 1153-1164, Oct 1992.

[2] B. Couteau, Y. Payan, and S. Lavallee, “The mesh-matching algorithm: an automatic 3D mesh generator for finite element structures,” *Journal of Biomechanics*, vol. 33, (no. 8), pp. 1005-1009, Aug 2000.

[3] M. Lengsfeld, J. Schmitt, P. Alter, J. Kaminsky, and R. Leppek, “Comparison of geometry-based and CT voxel-based finite element modelling and experimental validation,” *Medical Engineering & Physics*, vol. 20, (no. 7), pp. 515-522, Oct 1998.

[4] J.M. Buckley, D.C. Leang, and T.M. Keaveny, “Sensitivity of vertebral compressive strength to endplate loading distribution,” *Journal of Biomechanical Engineering-Transactions of the Asme*, vol. 128, (no. 5), pp. 641-646, Oct 2006.

[5] R.P. Crawford, W.S. Rosenberg, and T.M. Keaveny, “Quantitative computed tomography-based finite element models of the human lumbar vertebral body: Effect of element size on stiffness, damage, and fracture strength predictions,” *Journal of Biomechanical Engineering-Transactions of the Asme*, vol. 125, (no. 4), pp. 434-438, Aug 2003.

[6] J. Homminga, H. Weinans, W. Gowin, D. Felsenberg, and R. Huiskes, “Osteoporosis changes the amount of vertebral trabecular bone at risk of fracture but not the vertebral load distribution,” *Spine*, vol. 26, (no. 14), pp. 1555-1560, Jul 15 2001.

[7] D.S. Shin, K. Lee, and D. Kim, “Biomechanical study of lumbar spine with dynamic stabilization device using finite element method,” *Computer-Aided Design*, vol. 39, (no. 7), pp. 559-567, Jul 2007.

[8] A. Polikeit, L.P. Nolte, and S.J. Ferguson, “Simulated influence of osteoporosis and disc degeneration on the load transfer in a lumbar functional spinal unit,” *Journal of Biomechanics*, vol. 37, (no. 7), pp. 1061-1069, Jul 2004.

[9] W.A. Kalender, D. Felsenberg, O. Louis, P. Lopez, E. Klotz, M. Osteaux, and J. Fraga, “Reference Values for Trabecular and Cortical Vertebral Bone-Density in Single and Dual-Energy Quantitative Computed-Tomography,” *European Journal of Radiology*, vol. 9, (no. 2), pp. 75-80, May 1989.

[10] J.Y. Rho, M.C. Hobatho and R.B. Ashman, "Relations of mechanical properties to density and CT numbers in human bone", Med. Eng. & Phys, vol.17(5), pp.347-55, 1995.

[11] E.F. Morgan, H.H. Bayraktar, and T.M. Keaveny, “Trabecular bone modulus-density relationships depend on anatomic site,” *Journal of Biomechanics*, vol. 36, (no. 7), pp. 897-904, Jul 2003.

[12] F. Nabhani and M. Wake, “Computer modelling and stress analysis of the lumbar spine,” *Journal of Materials Processing Technology*, vol. 127, (no. 1), pp. 40-47, Sep 20 2002.

[13] J. Mizrahi, M.J. Silva, T.M. Keaveny, W.T. Edwards, and W.C. Hayes, “Finite-Element Stress-Analysis of the Normal and Osteoporotic Lumbar Vertebral Body,” *Spine*, vol. 18, (no. 14), pp. 2088-2096, Oct 15 1993.

[14] J. Homminga, B. Van-Rietbergen, E.M. Lochmuller, H. Weinans, F. Eckstein, and R. Huiskes, “The osteoporotic vertebral structure is well adapted to the loads of daily life, but not to infrequent "error" loads,” *Bone*, vol. 34, (no. 3), pp. 510-516, Mar 2004.

[15] H.M. Frost, “A Determinant of Bone Architecture - the Minimum Effective Strain,” *Clinical Orthopaedics and Related Research*, (no. 175), pp. 286-292, 1983.

[16] C.L. Liu, H.H. Chen, C.K. Cheng, H.C. Kao, and W.H. Lo, “Biomechanical evaluation of a new anterior spinal implant,” *Clinical Biomechanics*, vol. 13, pp. S40-S45, 1998.