A HIGH ACCURACY CT BASED FEM MODEL OF THE LUMBAR SPINE TO DETERMINE ITS BIOMECHANICAL RESPONSE

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Abstract: The lumbar spine is origin of the most frequent complains among all human body parts, since almost 80% of the population will at some point in life exhibit back related pathologies which in their majority will not require invasive surgery. Regardless the cause or the development of the problem, the in-depth investigation of its cause is of the upmost importance during treatment or preoperative evaluation. In this context a model of the L1-L5 vertebra, capable of accurately assessing the biomechanical response of the lumbar spine derived from human activity as well as externally induced loads, would be an effective tool during the examination of normal or clinical conditions. This study presents a CT based FEM model of the lumbar spine taking into account all function related boundary conditions such as mechanical property anisotropy, ligaments, contact elements mesh size etc. The developed model is capable of comparing the mechanical response of a healthy lumbar spine to any given pathology, which can be easily introduced into the model, thus providing valuable insight on the stress development within the model and predict critical movements and loads of potential patients.

1 INTRODUCTION

Three dimensional finite element models representing functional parts of the spine have been repeatedly introduced over the last years in order to simulate the biomechanical response of spinal units (Little et al, 2010, Ezquerro et al, 2004, Wang et al, 2006) or investigate trauma related surgical treatment (Polikeit et al, 2003, Ashish and Pramod 2009).

Several methods used to obtain the geometrical characteristics of the investigated set of vertebra have also been introduced. Even though touch probe

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digitizers (Lee et al, 2002) and laser scanners (Heuer et al, 2007) are able to provide high accuracy measurements, thus leading to an accurate representation of the spine, non intrusive methods such as CT (Kinder et al, 2009) or nuclear magnetic resonance (NMR) (Pfirrmann, et al, 2001) ease the extraction of a patients' examined areas geometry while comparing favorably in terms of data processing and inherent defect determination.

Recent studies have used combinations of the above techniques to simulate parts of the human spine ranging from a set of vertebra (Lodygowski et al, 2005) up to several parts of the spine (Guan et al, 2006). Nevertheless, a high accuracy CT based model of the lumbar spine with regard to specific material related properties (directional anisotropy of the bone, etc.) and all relating connective tissue (unequal properties distribution among annulus fibrosus layers, ligaments, contact areas etc.) has to the best of our knowledge, yet to be introduced. This exact task is the aim of the present investigation.

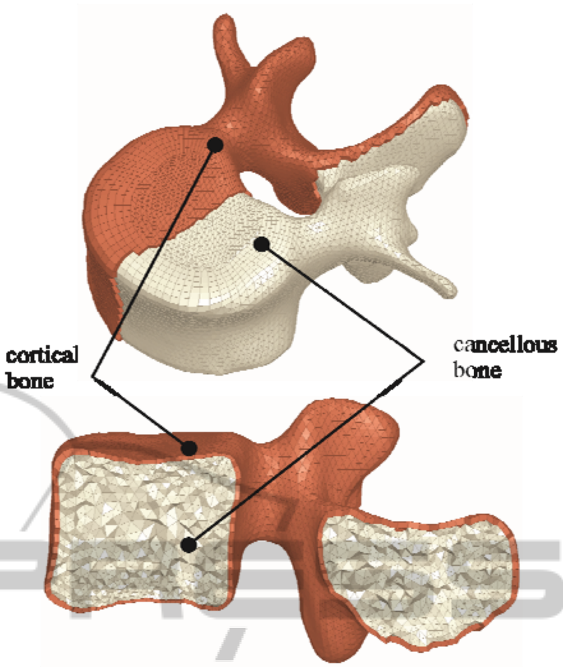

Figure 1: Resulting mesh of of the L5 vertebra.

2 ANALYTICAL MODEL

2.1 Volume Reconstruction

During the reconstruction of the lumbar spine (L1-L5) CT were the imaging modality of choice due to their ability to demonstrate high inherent image contrast between bone and soft tissue. This enables relatively unhindered segmentation of the bone from soft tissue, allowing the generation of a geometrically accurate volumetric data set of the patients lumbar spine. The basic concept is to overlay CT scan slices which represent the outline of each vertebra with respect to the angulations of the spines axis (Blankevoort et al., 2008; Beimersade et al., 2008; Kobayashi et al., 2009). During the present investigation apatients lumbar spine was scanned in its entirety from below the lower boundaries of L1 to the upper limit of L5 ensuring the full 3D visual representation of the examined area.

Data acquisition was in accordance to DICOM (Digital Imaging and Communications in Medicine) and interpolation of the CT information ensured an isotropic data set. Although this process did not result in higher resolution of the reconstructed set of vertebra, it lead to smoother representation allowing the distinct removal of the remaining soft tissue in close proximity to the bone.

After the representation of the surfaces the resulting volumes were generated considering an outer cortex for each vertebra corresponding to the cortical bone with a varying thickness of 0.5-1mm depending on the longitudal slice of volume in the spines axial direction. The remaining volume of each vertebra was considered as cancellous bone and described as such in the way illustrated in Figure 1.

Unlike the aforementioned procedure, the intervertebral discs of the lumbar spine were reverse engineered based on the superior and inferior surface of the connecting vertebral bodies. This method compares favorably to the regeneration of the discs based on CT measurements due to the fact that their volume is characterized by severely altering density and the inhomogeneous tissue does not facilitate precise segmentation by imaging techniques. The geometric characteristics of the intervertebral discs were designed based on the existing spinal bone tissue while anatomic data like the inner nucleus pulposus and the surrounding outer annulus were considered. The resulting superior and inferior meshed geometry of every intervertebral disc (see Figure 2) consists of six spline based layers, proportional concentric to the outer contour of the disc, covering a total of 65% of the discs superior and inferior surface.

2.2 FEM Model

During the meshing of the intervertebral discs, quadric elements were employed for the annulus

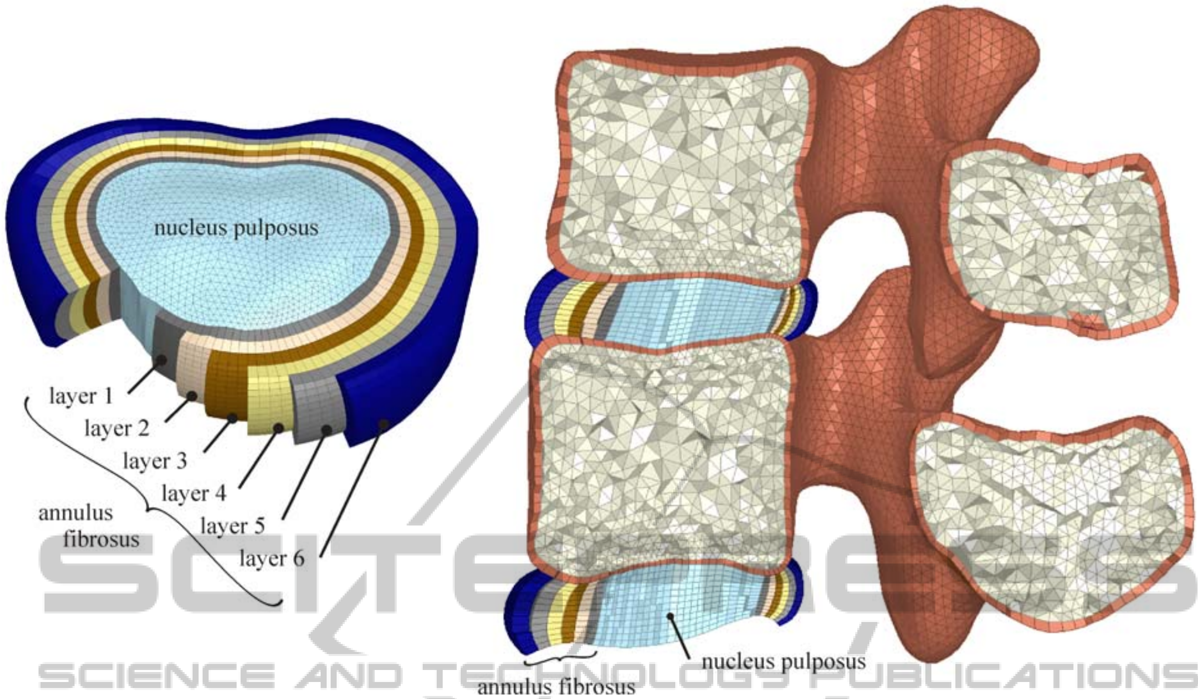

Figure 2: Intervertebral disc reconstruction with nucleus pulposus and the surrounding annulus ground substance.

ground substance in order to facilitate the implementation of the annulus fibrosus in form of cable elements positioned crosswise within the tetrahedron structure ensuring accurate simulation of their biomechanical response.

The remaining model, nucleus pulposus and vertebrae, composes of tetra elements (pyramides) and the unhindered connection at the models contact areas (quadric- tetra elements interface) was ensured through the diametrical incision of two triangles in every rectangle, maintaining the same nodes throughout the intervertebral disc surface and the vicinical vertebrae. This approach obviated the usage of contact elements thus reducing the processing time of the FEM model.

The mechanical properties of cortical and cancellous bone were considered as anisotropic (Lu and Hutton, 1996, Smit et al, 1997) and are presented in Table 1 along with the strength characteristics of the nucleus pulposus and the of the annulus ground substance intervertebral discs.

Among the most important characteristics of the FEM model was the incorporation of a set of cable elements, adding valuable mechanical characteristics to the simulation. The annulus fibrosus was considered to exhibit varying young modulus for each set of layer in the radial direction of the annulus (as presented in Figure 2) in order to reflect the unequal distribution of this structures properties. Next to these several other cable elements were employed representing the remaining connective tissue between each set of vertebrae, thus ensuring the precise transition of forces among the vertebra and simulating the accurate biomechanical response of the lumbar spine.

Figure 3a demonstrates all aforementioned connections (ligaments, contact elements and annulus fibrosus) used as input to the FEM software (Ansys 12.1 Academic license) as well as a simplified model (Figure 3b) illustrating only the cable and contact elements considered during the simulation.

The mechanical properties as well as the cross sectional area of each cable element used within the model (Shirazi-ald et al, 1984, Smit et al, 1997, Lu and Hutton, 1996) are presented in Table 2. All cable elements were simulated with Ansys link 10 elements which are capable of receiving only tension loads resembling the ligaments in a rather accurate way.

The meshing of the spine segment was conducted in ANSA of BETA CAE Systems in order to ensure all above mentioned characteristics leading to a realistic and isotropic stress transition within the considered bone and intervertebral disc. The resulting max. and min. element size as well as the number of elements for each set of material considered, are demonstrated in Table 3.

Table 1: Material properties and element specifications of cortical and cancellous bone as well as nucleus pulposus and annulus ground substance.

Material type	Young modulus [Mpa]	Poisson ratio	Element type used
Cortical bone	E_{xx}= 11.300	v_{xy} = 0,484	solid 185
	E_{yy}= 11.300	v_{yz} = 0,203	
	E_{zz} 22.000	v_{xz} = 0,203	
	G_{xy}= 3.800		
	G_{yz}= 5.400		
	G_{xz} = 5.400		
Cancellous bone	E_{xx}= 140	v_{xy} = 0,45	solid 95
	E_{yy}= 140	v_{yz} = 0,315	
	E_{zz} = 200	v_{xz} = 0,315	
	G_{xy}= 48,3		
	G_{yz}= 48,3		
	G_{xz} = 48,3		
Nucleus pulposus	0,2	v = 0.4999	solid 185
Annulus ground substance	4,2	v = 0.45	solid 185

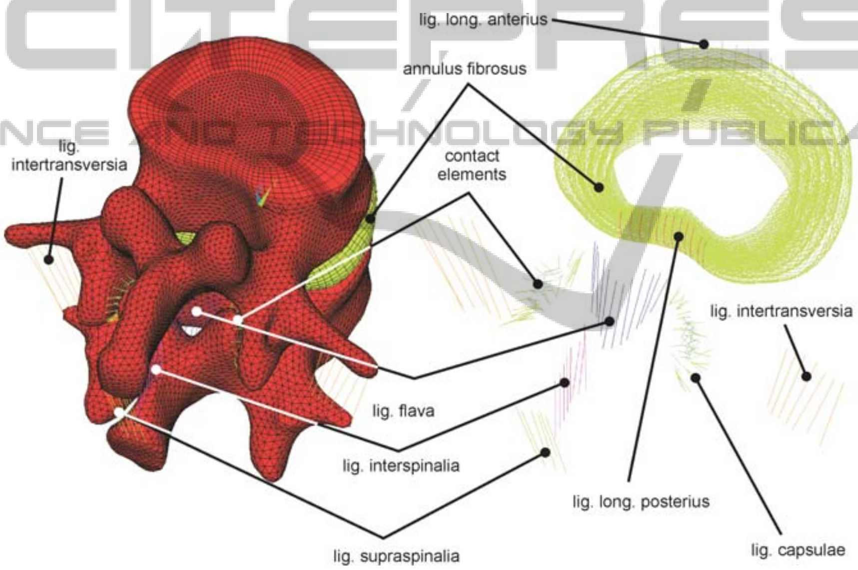

Figure 3: a) Set of two vertebrae (L4 and L5), intervertebral disc and ligaments b) simplified model without bone and tissue presenting only ligaments and contact elements.

Table 2: Mechanical properties of ligaments, contact elements and annulus fibrosus layers.

Cable element type	Young modulus [Mpa]	Poisson ratio	Cross-sectional area [mm^2]
Lig. long. anterius	20	0,3	38
Lig. long. Posterius	70	0,3	20
Lig. flava	50	0,3	60
Lig. intertransversia	50	0,3	10
Lig. interspinalia	28	0,3	35,5
Lig. supraspinalia	28	0,3	35,5
Lig. capsulae	20	0,3	40
Annulus fibrosus layer 1	550	0,45	0,7
Annulus fibrosus layer 2	495	0,45	0,63
Annulus fibrosus layer 3	440	0,45	0,55
Annulus fibrosus layer 4	420	0,45	0,49
Annulus fibrosus layer 5	385	0,45	0,41
Annulus fibrosus layer 6	360	0,45	0,3

Table 3: Mesh related figures of the lumbar spine model.

Material type	no. of Elements	max size Element	min size Element
Cortical bone	87.521	1,78 mm	0,08 mm
Cancellous bone	712.361	3,04 mm	0,97 mm
Nucleus pulposus	317.251	2,27 mm	0,72 mm
Annulus	298.657	3,71 mm	1,87 mm

3 RESULTS

The validation of the model was based on torsion, extension, flextion, left and right bending simulations to determine the resulting inclination of spine segments under specific loads and compare those to experimental values found in literature (Panjabi et al, 1994). Figure 4 demonstrates the developing stress distribution of the examined set and intervertebral disc for a 10Nm flexion moment.

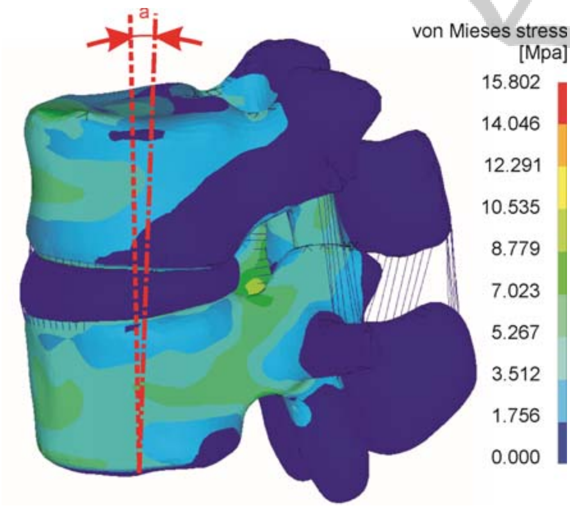

Figure 4: Calculated stress distribution on a set of L2-L3 vertebrae subjected to extension.

Figure 5 exhibits that the load induced response of the vertebra is almost identical to its experimentally determined one.

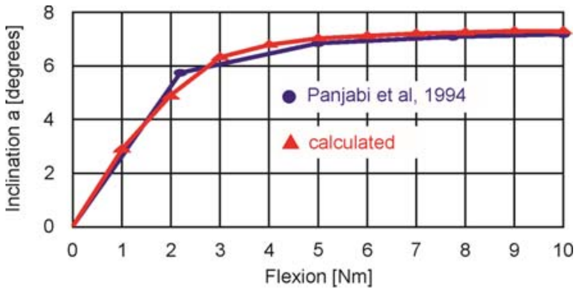

Figure 5: Calculated and experimental load-inclination diagram.

4 CONCLUSIONS

The introduced model facilitates the evaluation of induced loads on the lumbar spine. Pathological defects, trauma as well as therapy oriented intervention can be assessed prior to the actual practice on the patient. This model may also be a valuable tool in preoperative evaluation of the biomechanical response of the system to a function specific implant.

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