A Non-linear Finite Element Model for Assessment of Lumbar Spinal Injury Due to Dynamic Loading

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Abstract: In this paper a highly detailed model of an adult lumbar spine (L1-L5) was recreated based on Computed Tomography. Next to the viscoelastic deformation of the intervertebral discs, cortical and cancellous bone anisotropy was considered, while seven types of ligaments were simulated either by solid or cable elements. The dynamic behaviour of the spine segment was assessed through stress-strain curves, provoking a non-linear response of all implicated tissues' material properties. The model was subjected to dynamic loading to determine abnormalities in the anatomy's stress equilibrium that could provoke gait disturbances. Results indicated the introduced methodology as an effective alternative to in vitro investigations, capable of providing valuable insight on critical movements and loads of potential patients, as the model can be employed to optimize therapeutic training or threshold kinematics of any given lumbar spine pathology.

1 INTRODUCTION

The lumbar spine is arguably one of the most important structural elements of our musculoskeletal system and as such, dominates complaints received by orthopaedics. Epidemiologic studies indicate that lumbar spine pathologies in industrialized environments have a life-time prevalence of about 70% (Waters et al., 1993), ranging from low back pain to disc protrusion and spinal fractures, which can occur during every day activities such as running.

Finite Element (FE) models of the lumbar spine become increasingly popular during preoperative preparation of complex surgeries, customized implant design and recently optimization of non-invasive therapeutic intervention. This can be attributed to the capacity of FE to visualize stress distributions over the entirety of the examined anatomy and indicate critical regions.

Linear elastic 3D FE models of spine parts, simulating their biomechanical response (Little et al., 2010), (Wang et al., 2006) or investigate trauma related surgical treatment (Ashish and Pramod, 2009), have been repeatedly introduced over the last years. To describe however, the biomechanics of spinal injury, non-linear properties should be considered (Xiao et al., 2011); (Schmidt et al., 2006).

Models are conventionally recovered though Computed Tomography (CT) which is considered as the golden standard in spine reconstruction (Klinder et al, 2009) while intervertebral discs were reverse engineered based on the scanned anatomical characteristics (Tsouknidas et al., 2012). The majority of available investigations consider the remaining connective tissue (ligaments) as cable elements, able of enduring only tension (Davidson-Jebaseelan et al., 2010). Even at a non-linear state, two node link elements are not capable of reflecting biomechanical alterations of the tissue i.e. degeneration or fracture. These are however highly important, as deterioration of ligamentous properties foster several spine pathogenesies due to increased range of motion within a spinal unit. El-Rich et al., (2009) introduced a two vertebral spine model with three- and four-nodal elements whereas three dimensional solid elements were also considered in studies with simplified geometrical characteristics

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and linear properties (Tsuang et al., 2008).

In this investigation, a bio-realistic model of an entire lumbar spine with regard to non-linear material properties and partially solid ligaments, is introduced, in an effort to allow the quantification of the effect of mobility and/or loading scenarios on the occurring spine biomechanics.

2 ANALYTICAL MODEL

During the reconstruction of the lumbar spine (L1-L5) high resolution CT were the imaging modality of choice due to their ability to demonstrate high inherent image contrast between bone and soft tissue. This enabled relatively unhindered segmentation of the bone from soft tissue. In order to achive the reconstruction of the desired bony tissue, consecutive CT scan slices, were overlayed (Tsouknidas et al., 2012); (Kobayashi et al., 2009). Based on this concept, a patients lumbar spine was scanned in its entirety from below the lower boundaries of L1 to the upper limit of L5 ensuring the full 3D 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 thickness of 0.5mm. The remaining volume of each vertebra was considered as cancellous bone.

Due to the severely altering density and the inhomogeneous tissue of the intervertebral discs, these were reverse engineered based on the superior and inferior surface of the connecting vertebral bodies as described by Tsouknidas et al., (2011).

During the model set up, anterior logitudial (ALL), posterior logitudial (PLL), intertransverse ligmante (ITL) and supraspinous ligament (SSL) were modelled by four uniform layers of hexahedral elements 0.3mm in thickness each, in order to encapture their viscoelastic response (Sharma et al., 1995). The remaining connective tissue, flavum (FL) and capsular (JC) were considered as two node tension elements. The simulated geometry, emphasizing on some of its critical structural elements, is demonstrated in figure 1.

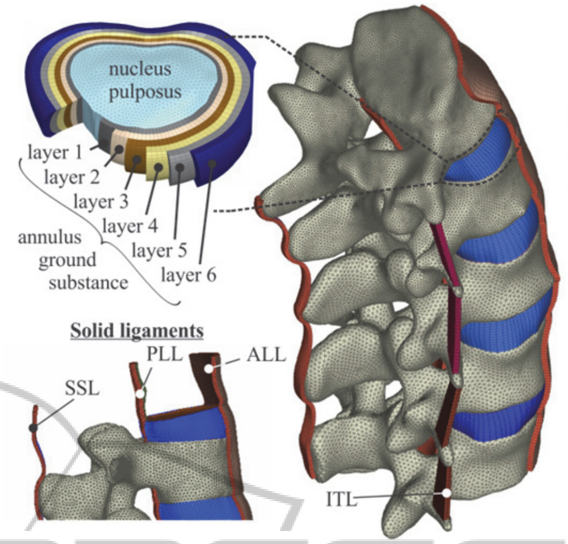

Figure 1: Meshed lumbar spine model and details of critical structural elements.

The annulus ground substance of the intervertebral discs, was meshed by hexahedral elements to facilitate the implementation of collagen fibers positioned crosswise within the tetrahedron structure. The remaining model, nucleus pulposus and vertebrae, composes of tetrahedral elements and the unhindered connection at the models contact areas (hexa - tetrahedral 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. The same approach was employed for the solid ligaments (ALL, PLL, ITL and SSL). These ligaments were modelled through the stress strain curves illustrated in figure 2 accurate way.

Intrinsic properties were considered for the remaining ligamentus tissue. Their Young's module and poisson ratio as well as the cross sectional area of each cable element used within the model originated from literature data (Shirazi-ald et al., 1984); (Smit et al., 1997).

The annulus fibrosus was considered to exhibit a incompressible fluid like behaviour in order to enrapture its hyperelastic response. In order to do so, the Mooney-Rivlin strain energy density function was employed as describer by Xiao et al., (2011).

The mechanical properties of bony tissue were described by the Johnson-Cook elasto-plastic material law considering strain rate dependent stress-strain curves.

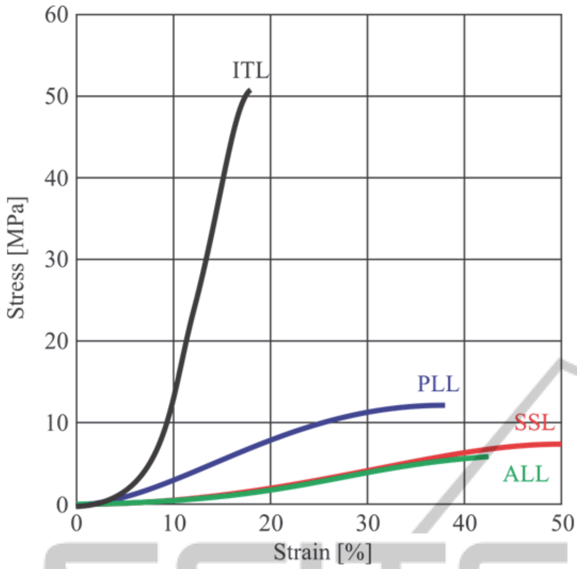

Figure 2: Non-linear properties of solid ligamentus tissue.

To avoid element shear locking and hourglassing phenomena during the numerical analysis of the model, second order elements with reduced integration were employed for all model entities. Solid ligaments were modelled to comprise of four layer each, to further supress the appearance of artificial energy within the model.

Table 1: Mesh related data.

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
ALL	4260	1,92 mm	1,54 mm
PLL	2100	1,78 mm	1,52 mm
SSL	1420	1,83 mm	1,54 mm
ITL	1380	1,74 mm	1,53 mm

The mesh grid of the spine segment was generated in ANSA by BETA CAE Systems in order to ensure anatomic based meshing, leading to a realistic and isotropic stress transition within the entire model. Convergence studies were conducted for every model entity individually, indicating the optimum mesh density in terms of processing time, with regard to the results accuracy, related information are demonstrated in Table 1.

3 RESULTS

Employing the introduced model in for two mobility scenarios, walking and running, facilitated the determination of FSU's biomechanical response to external stimuli. Corresponding results are presented in figure 3.

When interpreting these results, it is highly important to consider that the same scale is used to indicate stress development of both soft and bony tissue.

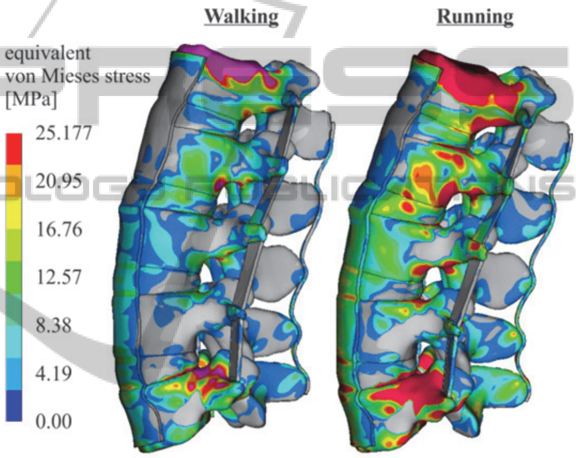

Figure 3: Stress development in the FSU during walking and running.

Even though stress concentrations are apparent in the vertebral bodies of both models, these are not considered as critical as even the highest values (25.14 and 42.36 respectively) lie below their strength characteristics. In the running scenario however, some critical regions can be observed within intervertebral discs, both qualitative and quantitative, indicating that health condition of patients with spinal injuries could be affected drastically based on everyday activities.

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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