The effect of soft tissue properties on overall biomechanical response of a human lumbar motion segment: a preliminary finite element study

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Abstract

This study investigates the relative effect of soft tissue properties on the overall response of a human spinal motion segment using an osseo-ligamentous FE model of the Visible Man L3-L4 intervertebral joint. Model geometry was obtained from the Visible Man CT dataset using custom built image processing software. Non-linear soft tissue properties were obtained from the literature. Displacement controlled simulations were performed in flexion, extension, lateral bending and axial rotation. The effect of each soft tissue structure (including the annular fibres) was assessed by removing it from the model and comparing the predicted overall stiffness to that of the intact segment. The results from this study showed that removal of the capsular ligaments and the collagen fibres in the annulus of the intervertebral disc have the largest effects on the overall stiffness of the motion segment. All other ligament structures had little impact on determining the motion response, with the exception of the anterior longitudinal ligament. Its removal caused the stiffness in extension to fall to 60 percent of the value reached for the intact model. It is concluded that correct representation of the mechanical properties of both the capsular ligament and annular fibres is most important in generating realistic FE models of the lumbar spine to predict motion segment biomechanics.
Keywords: finite element method, lumbar spine, ligaments, spine biomechanics.

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1 Introduction

The spine is a complex column comprised of an intricate grouping of various biological tissue structures. The single motion segment is the smallest repeating unit of the spine that exhibits the characteristic behaviour of the whole column. It is composed of two vertebrae connected by an intervertebral disc, facet joints and ligaments. It is the soft tissue structures of the motion segment that play a crucial role in facilitating and controlling the movement of the osseo-ligamentous spine.

Previous experimental studies have explored the biomechanical role of the soft tissues of the spine. Adams et al. [1] tested human cadaver spinal motion segments in flexion while successively dissecting key soft tissue structures. They found that during flexion, the capsular ligament and the intervertebral disc are most dominant in providing stiffness to the motion segment. Panjabi et al. [2] measured the strain induced in each spinal ligament when subjecting motion segments to various movements. However, physical experimention encounters limitations due to specimen variability and difficulty in obtaining a repeatable testing method.

Mathematical modelling of the spine, using the finite element (FE) method, has become a popular tool to analyse and predict spinal behaviour. It allows estimation of variables which can not be easily obtained in physical experiments. A wide range of geometric and material properties have been used to represent the soft tissues of the spine [3–5]. However, there is no consensus on the best approach for soft tissue modelling. Zander et al. [6] has assessed the impact of simulataneous changes in stiffnesses of all ligaments on FE model predictions of ligament force and segmental rotation. However, it would be useful to ascertain the individual contribution of each soft tissue structure in determining the biomechanical response of the spine. The aim of this study was to assess the isolated effect of each soft tissue structure of the human L3-L4 spinal motion segment using an osseo-ligamentous FE model.

2 Methods

A three-dimensional, non-linear FE-model of a human lumbar single motion segment (L3-L4) was created (Figure 1) and analysed using the ABAQUS software. The geometry for the model was obtained from the CT dataset of the Visible Man (The Visible Human Project, U.S. National Library of Medicine). Using custom image processing software, bony landmarks were manually selected and converted into three-dimensional coordinate points. The profile of each vertebral endplate was constructed using a series of elliptic and polynomial curves as described in [7]. The intervertebral disc mesh was generated between adjacent vertebral endplates. The nucleus pulposus assumed to occupy half the cross-sectional area of the disc [8]. Each facet joint was modelled by two curved surfaces with an initial offset of 0.8mm. Simplified representation of the posterior bony segments was made by defining single landmark points at the tips of the transverse and spinous processes and at the lateral borders of the lamina.

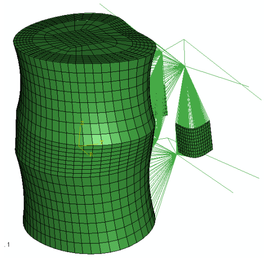

Figure 1: Finite element mesh of the visible man L3L4 lumbar motion segment.

Material properties were compiled from the literature (Table 1). The vertebral bodies were modelled as a cancellous core encapsulated by a cortical shell. Both of them assumed isotropic behaviour. The posterior vertebral bone was approximated as a construct of quasi-rigid beams. A non-linear (exponential) 'softened' contact condition was defined between mating facet joint surfaces to simulate the contact of the articular cartilage lined joint. The joint was assumed frictionless. A material with hyperelastic properties was used to model the annulus ground substance [9]. Collagen fibres were assumed to be packed in concentric layers, with the fibre orientation alternating between 30 and 150 degrees to the transverse plane for each successive layer [10]. The nucleus pulposus was modelled by an incompressible fluid filled cavity [11]. Non-linear behaviour was incorporated for the spinal ligaments following the earlier proposed approach by [5].

Table 1: FE model material properties [E=elastic modulus, v=Poisson's ratio, G=Shear modulus, C10 and D1=hyperelastic material constants].

Material	Material Type	Properties	Reference
Cortical Bone	linear elastic	E = 11300 MPa, v = 0.2	[17]
Cancellous Bone	linear elastic	E = 140 MPa, v = 0.2	[17]
Posterior Bone	Quasi-rigid	Quasi-rigid	
Facet bone	linear elastic	as for Cortical bone	
Annulus ground matrix	Hyperelastic - Neo-Hookean	C10 = 0.348, D1 = 0.3 [9]	[9]
Nucleus Pulposus	Hydrostatic fluid	Incompressible	[11]
Annular collagen fibers	linear elastic	E = 500MPa, v = 0.3	[16]
ligaments	nonlinear elastic - tension only		[5]

The segment was loaded by applying rotational displacements to the superior endplate of L3, about a fixed centre of rotation. The centre of rotation was defined at the geometric center of the intervertebral disc. The inferior endplate of the L4 vertebra remained fixed throughout the test. An initial hydrostatic pressure of 70kPa was induced in the nucleus pulposus to simulate the *in vivo* condition for unloaded motion segments [12]. Rotations were applied in the major anatomical planes in accordance with the average *in vivo* ranges of motion for the L3-L4 motion segment [13], i.e., 12 degrees in flexion, 1 degree in extension, 5 degrees in left and right lateral bending and 1.5 degrees in left and right axial rotation.

To analyse the effect of individual soft tissue structures, simulations for each rotation were conducted for both the intact motion segment as well as with each of the following structures separately removed from the model: the anterior longitudinal ligament (ALL), the posterior longitudinal ligament (PLL), the supra/interspinous ligament (SISL), the intertransverse ligament (ITVL), the capsular ligament (CL), the ligamentum flavum (LF), the annulus collagen fibres (AF) and the nucleus pulposus (NP). The behaviour of the spinal segment in each simulation was compared using the following output parameters: stiffness of the spinal segment in the plane of motion, maximum force induced in each ligament, and the hydrostatic pressure in the nucleus pulposus.

In addition to the main analyses as described above, a loading study was performed. A 500N compressive load was applied to the superior surface of the L3 vertebral body to simulate a typical *in vivo* torso compression load on the L3-L4 human spinal joint [14].

3 Results

The pressure developed within the nucleus pulposus due to the torso loading was a factor of 1.6 times the calculated pressure acting on the superior disc surface. *In vivo* measurements of the nucleus pressure in human intervertebral discs have shown the ratio between nucleus pressure and applied pressure on the superior surface of the disc to be approximately 1.5 [11]. Thus the model simulation is in agreement with observed physical values.

The predicted stiffness of the intact motion segment varied in each plane of motion. The stiffest response for the intact model was seen in axial rotation at 38Nm/degree. In lateral bending the stiffness was measured as 8 Nm/degree, in flexion 18Nm/degree and in extension 4Nm/degree. The stiffness of the motion segment in each simulated case (isolated removal of various soft tissue structures) is presented in Figure 2.

Figures 3–8 show the forces in each ligament for each motion, for both the intact and the cases for which a single soft tissue structure had been removed.

Figure 9 shows the variation of nucleus pulposus pressure during rotation in flexion for the intact segment as well as each of the cases where a particular soft tissue had been removed from the model. For motions in lateral bending and axial rotation (not shown on the graph), the nucleus pressure increased monotonically from 70kPa to 0.2MPa and 0.13MPa, respectively, for the intact model.

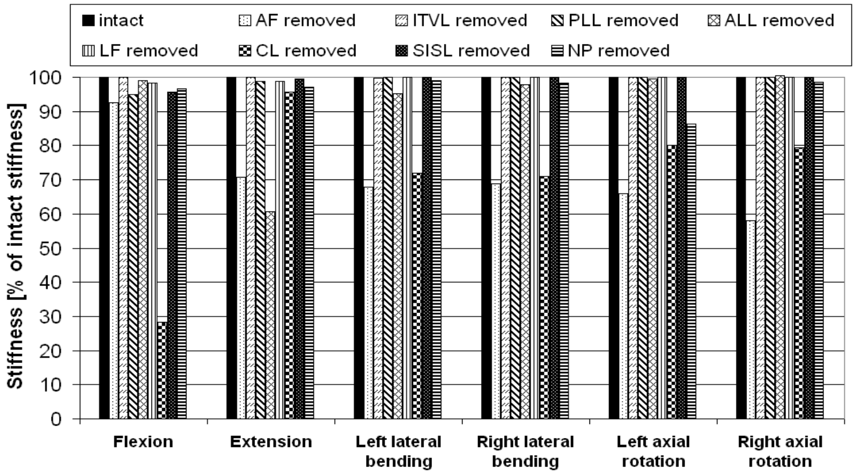

Figure 2: Stiffness of the L3L4 spinal segment model with various soft tissue structures individually removed. Stiffness is presented as a percentage of the stiffness for the corresponding intact model.

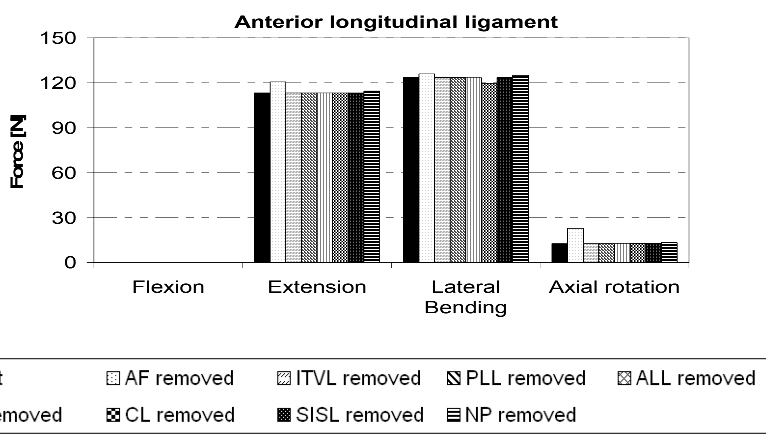

Figure 3: Force in the ALL for the intact case as well as with various soft tissue structures removed.

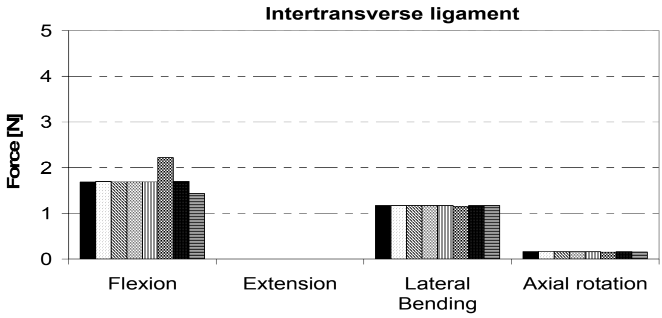

Figure 4: Force in the ITVL for the intact case as well as with various soft tissue structures removed.

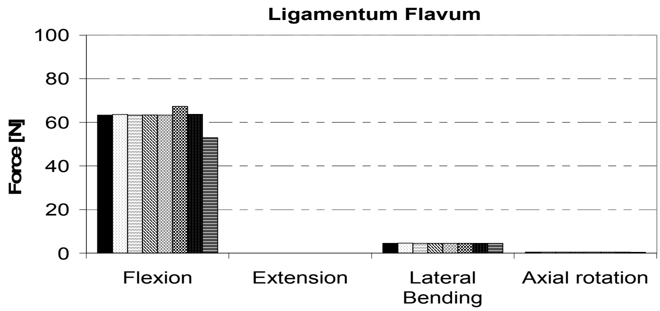

Figure 5: Force in the LF for the intact case as well as with various soft tissue structures removed.

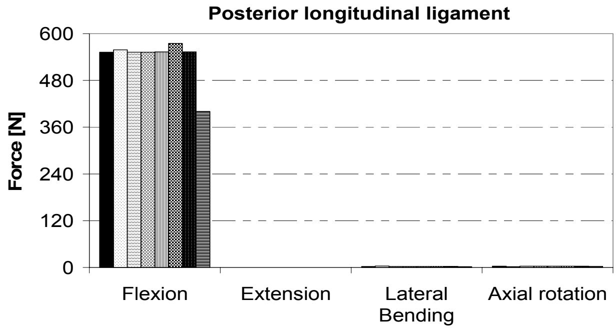

Figure 6: Force in the PLL for the intact case as well as with various soft tissue structures removed.

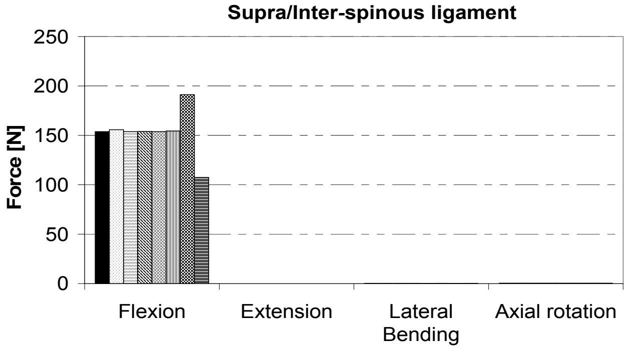

Figure 7: Force in the SISL for the intact case as well as with various soft tissue structures removed.

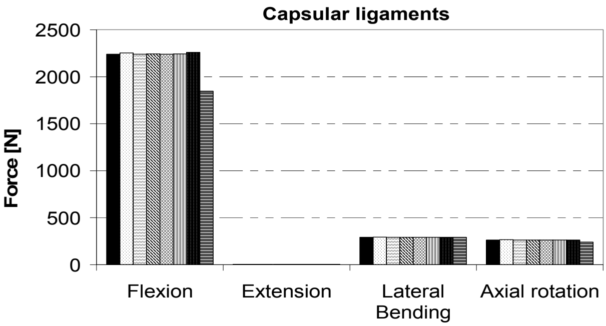

Figure 8: Force in the CL for the intact case as well as with various soft tissue structures removed.

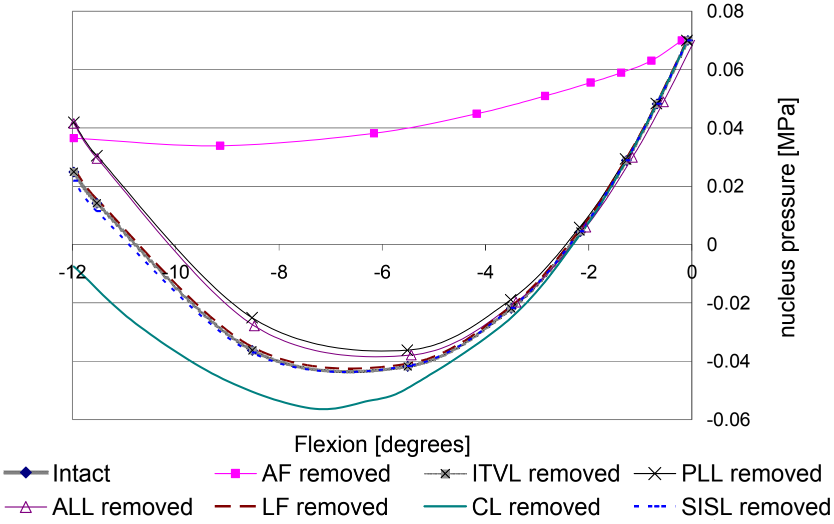

Figure 9: Predicted nucleus pulposus pressure versus flexion angle.

4 Discussion

Finite element studies are a useful analytical tool to investigate the mechanics of geometrically complex structures such as the human spine. In this study, a FE model of a human L3-L4 motion segment was used to explore the effect of isolated removal of soft tissues structures on overall motion segment response. This allowed the relative biomechanical importance of each soft tissue structure to be determined for the motions investigated. It also allowed attention to be focussed on determining geometric and material properties for the most critical soft tissues.

The form of loading that was applied to the model was designed to simulate the loading delivered by a displacement-controlled robotic testing facility currently being used for spine biomechanics research in our laboratory. It is understood that this loading does not exactly represent the *in vivo* condition, where the center of rotation for a spinal joint is known to change during motion. However, the fixed center of rotation, while it may induce higher resistive forces, greatly simplifies the kinematics of the motion segment and therefore allows direct comparison between models where the effect of changes in material or geometric properties are the main focus.

Spinal FE models require validation against known biomechanical behaviour. In addition to the correct prediction of nucleus pressure under compressive loading, an earlier form of the FE model presented in this paper was used to investigate spinal kinematics by Little et al. [15]. The model's predicted primary motions in all three anatomical planes were found to be in agreement with average in-vivo rotations reported by Pearcy [13].

Removal of the capsular ligaments and the collagen fibres in the annulus of the intervertebral disc were seen to have the largest effects on the overall stiffness of the motion segment. All ligament structures, except for with the ALL, had little impact on the motion response. Removal of the ALL caused the stiffness in extension to fall to 60 percent of the value reached for the intact model. These results suggest that the action of the capsular ligaments and the collagen fibres in the intervertebral disc dominate the action of the surrounding soft tissue structures. This finding correlates well with conclusions drawn from experimental data in flexion [1].

With reference to Figures 3–8 the results of this modelling study found that all ligaments are active in flexion except for the anterior longitudinal ligament, which conversely was the only ligament to bear load during extension. The posterior longitudinal ligament, ligamentum flavum, spinous ligaments and capsular ligament are most active during flexion.

The isolated removal of the ligamentum flavum, anterior longitudinal ligament, posterior longitudinal ligament, intertransverse ligament and supra/interspinous ligament caused no change in the stresses borne by the spinous and capsular ligaments. Removal of the capsular ligament however, may increase the force that the ligamentum flavum and posterior longitudinal ligament must bear during flexion. Likewise, removal of the annular fibres may transfer load to the anterior longitudinal ligament, especially during axial

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rotation. Following a similar argument, it is hypothesised that the removal of the nucleus pulposus may reduce the forces carried by the ligaments that are active during flexion.

With regard to Figure 9, the nucleus pulposus pressures are seen to become negative in the middle of the applied flexion motion. Negative nucleus pressures imply that the intervertebral disc is being subjected to hydrostatic tension. This result is due to the application of a flexion motion without the gravitational compressive load, which usually accompanies spinal motions. As mentioned earlier, the fixed-axis loading applied in this study was intended to simplify the kinematics to assess the relative importance of isolated soft tissue structures. The presence of a superimposed torso-weight compressive load during flexion would be expected to shift the nucleus pressure graph in the positive direction, and these more complex combined loading cases will be investigated in future studies.

The results of this study demonstrate that some soft tissue structures are more critical than others in determining the biomechanical behaviour of the spine. For rotation movements correct representation of the constitutive properties of both the capsular ligament and annular fibres is important in generating FE models of the spine to deliver realistic predictions of the biomechanics of the spine.

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