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On the load-sharing along the ligamentous lumbosacral spine in flexed and extended postures: Finite element study

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ABSTRACT

A harmonic synergy between the load-bearing and stabilizing components of the spine is necessary to maintain its normal function. This study aimed to investigate the load-sharing along the ligamentous lumbosacral spine under sagittal loading. A 3D nonlinear detailed Finite Element (FE) model of lumbosacral spine with realistic geometry was developed and validated using wide range of numerical and experimental (*in-vivo* and *in-vitro*) data. The model was subjected to 500 N compressive Follower Load (FL) combined with 7.5 Nm flexion (FLX) or extension (EXT) moments. Load-sharing was expressed as percentage of total internal force/moment developed along the spine that each spinal component carried. These internal forces and moments were determined at the discs centres and included the applied load and the resisting forces in the ligaments and facet joints.

The contribution of the facet joints and ligaments in supporting bending moments produced additional forces and moments in the discs. The intervertebral discs carried up to 81% and 68% of the total internal force in case of FL combined with FLX and EXT, respectively. The ligaments withstood up to 67% and 81% of the total internal moment in cases of FL combined with EXT and FLX, respectively. Contribution of the facet joints in resisting internal force and moment was noticeable at levels L4-S1 only particularly in case of FL combined with EXT and reached up 29% and 52% of the internal moment and force, respectively. This study demonstrated that spinal load-sharing depended on applied load and varied along the spine.

1. Introduction

A harmonic synergy between the load-bearing and stabilizing components of the spine is necessary to maintain its normal function. The ligamentous spine (devoid of muscles) which includes: vertebrae, endplates, discs, facet joints and ligaments is responsible for carrying and transferring loads to the hip and lower joints whereas the spine muscles provide both passive and active actions to maintain the spine stability. The biomechanical response of the ligamentous lumbar spine to mechanical load in terms of range of motion (ROM), intervertebral rotations (IVR), facet joints forces (FJF), intradiscal pressure (IDP) in the nucleus pulposus, and stress in the annulus fibrosus has been comprehensively studied (Park et al., 2013; Schmidt et al., 2010; Little et al., 2008; Goto et al., 2003). Forces in the spinal ligaments (Alapan et al., 2014; Wang et al., 1999) as well as forces and moments in the discs (Arjmand and Shirazi-Adl, 2006; El-Rich et al., 2004) were also predicted. Dysfunction of any spinal component results in system perturbation which may lead to immediate compensation from other components, long-term adaptation response and/or ultimately injury (Panjabi, 1992). Therefore, understanding the interaction of spinal components and their relative contribution in load-bearing (spinal load-sharing) is crucial to the spine function.

The load-sharing in cadaveric lumbar Functional Spinal Units (FSUs) subjected to extension (Adams et al., 1988) as well as flexion (Adams et al., 1980) has been investigated by removing the FSU's components one by one and then comparing the responses of the altered and intact FSUs. Similar approach was used in a numerical study conducted by Sharma et al. (1995) in which the effect of ligaments and facet joints partial/total removal on rotational instabilities of lumbar FSU was investigated. This approach provided important insights onto the role of each spinal component in the functional mechanism of an altered FSU after ligaments removal, facetectomy, or nucleotomy (Ivicsics et al., 2014; Noailly et al., 2007; Najarian et al., 2005; Sharma et al., 1995). However, using this superposition approach is not appropriate to explain the load-sharing in an intact

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FSU or a whole spine as it neglects the nonlinear interaction between spinal components while carrying load.

On the other hand, static equilibrium equations were used to estimate the forces in lumbar FSUs subjected to extension/lateral bending coupled or not with compressive preload (Goel et al., 1987). The multibody approach was also employed to study the load-sharing of the lumbar L4-5 FSU under extension/flexion moment (Abouhossein et al., 2011). The load-sharing in cervical FSUs was also studied by comparing the strain energy (Mustafy et al., 2014) and load carrying proportion (Panzer and Cronin, 2009; Goel and Clausen, 1998) among the spinal components using the Finite Element (FE) method.

The aforementioned studies have definitely provided valuable insight onto the spinal load-sharing, however, to our best knowledge there is no information on how spinal load-sharing varies with loading mode along the lumbosacral spine. This study aimed to investigate the load-sharing in the ligamentous lumbosacral spine under flexion (FLX) and extension (EXT) moment coupled with compressive follower load (FL) using nonlinear FE modelling. A 3D nonlinear detailed FE model with realistic geometry developed at tissue level was used. The responses of this model to various loading scenarios were compared to available numerical and experimental results (Dreischarf et al., 2014). The equilibrium conditions in all directions were satisfied at each spinal level to estimate the internal forces and moments in the spinal components. These internal loads were used to calculate the spinal load-sharing. In addition, the ROM, IVR, IDP, and strain in the annular fibres, were also determined.

2. Materials and methods

2.1. 3D Geometry acquisition

3D geometry of the bony structures which consist of the vertebrae L1 through L5 (L1–5) and the sacrum was reconstructed from a 20 years old male CT-Scans of 1 mm thickness taken from the University of Alberta Hospital data base. Segmentation was performed using the medical image processing software Mimics (MIMICS Research 17.0, Materialise, Belgium). Then, the geometry was cleaned from spikes and sharp edges using the software Geomagic Studio (Geomagic Studio 2014, 3D Systems, USA) (Fig. 1a).

2.2. Mesh generation

The obtained geometry was meshed using the software Hypermesh (Hyperworks 12.0, Altair, USA) (Fig. 1b). The cortical bone and endplates were meshed using 3-node shell elements with a uniform thickness of 1 mm. The cortical bone was then filled with 4-node (tetrahedral) solid elements to represent the cancellous core. The mesh of two intervening endplates was used to create the disc by extruding 7 circumferential layers of solid elements for the annulus fibrosus ground enclosing the nucleus mesh (Fig. 1b). These layers were reinforced by unidirectional springs distributed in concentric lamellae with crosswise pattern close to $\pm 35°$ (El-Rich et al., 2009; Schmidt et al., 2007) to represent the annular fibres (Fig. 1b). The disc volume was divided with a proportion according to the histological findings (44%_nucleus and 56%_annulus) (El-Rich et al., 2009; Schmidt et al., 2006). The ligaments included the Anterior Longitudinal Ligament (ALL), Posterior Longitudinal Ligament (PLL), Capsular Ligament (CL), Intertransverse Ligament (ITL), Ligamentum Flavium (LF), Supraspinous Ligament (SSL), and Interspinous Ligament (ISL) and were modelled by unidirectional springs (Breau et al., 1991). A frictionless surface to surface contact with minimum gap distance equal to 2 mm was used to simulate the facet joint articulation. A fine mesh particularly in the facet joints areas was used to ensure the accuracy of the predicted response (Ayturk and Puttlitz, 2011).

2.3. Material properties

The behavior of the bony structures and cartilaginous endplates was assumed linear elastic while the annulus and nucleus were governed by hyper-elastic material law using the first-order of Mooney–Rivlin formulation. The properties are summarized in Table 1. Nonlinear force displacement curves adopted from Rohlmann et al. (2006) (Table 1) were assigned to the ligament springs to resist tension only. The annular fibres had nonlinear force displacement relationship with stiffness increasing from inner to outer lamella (Schmidt et al., 2006; Shirazi-Adl et al., 1986).

2.4. Loading and boundary conditions

The FE analyses were conducted using the implicit solver of Abaqus (Abaqus 6.13-4, Dassault Systems Simulia Corp., USA). To minimize the intervertebral rotations and improve the spine stability under compression while it lacks muscles, the model was subjected to compressive FL whose line of action followed the spine curvature and passed through the vertebral bodies centroids (Fry et al., 2014; Kim et al., 2011, Renner et al., 2007; Shirazi-Adl, 2006). This FL was applied using pre-compressed unidirectional springs inserted between the centroids of two adjacent vertebral bodies (Fig. 1c) (Naserkhaki et al., 2014).

2.4.1. Validation tests

As the available numerical and experimental data used for validation correspond to the lumbar spine, only the segment L1–5 of the current model was used in

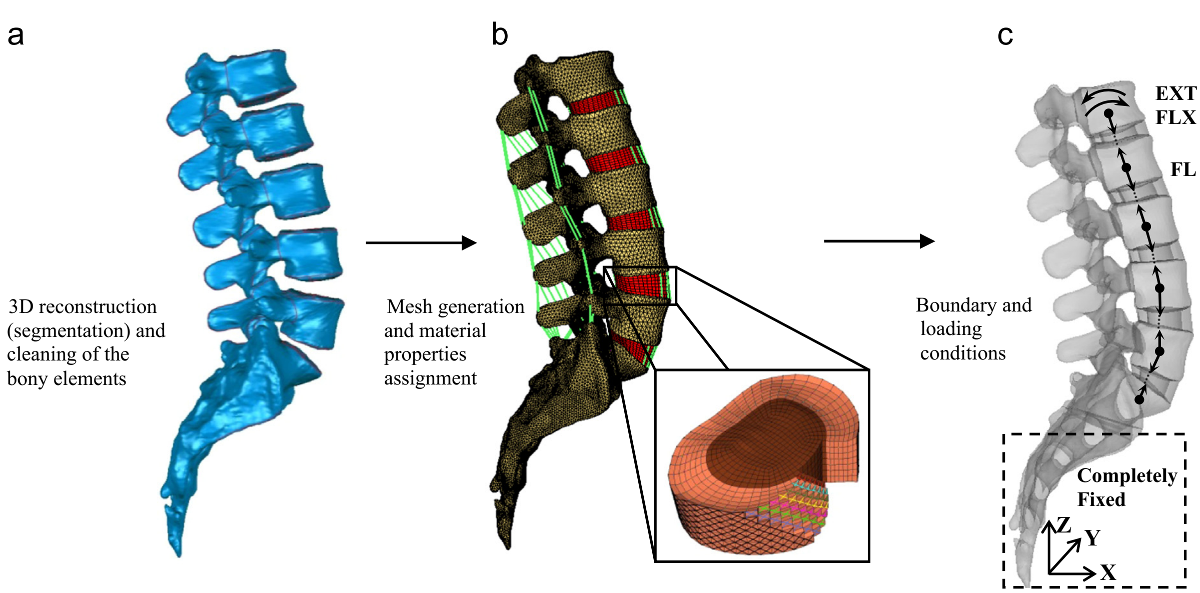

Fig. 1. Step-by-step FE model creation.