REVIEW ARTICLE

Review on the Progress in Development of Finite Element Models for Functional Spinal Units: Focus on Lumbar and Lumbosacral Levels

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ABSTRACT

Functional spinal unit (FSU) has been of major interest in research related to the human spine as it is the simplest entity of spine that is believed to provide vital information useful in analyzing the biomechanics of the spine. In-vitro experiments and in-vivo tests are implemented for this purpose, but due to many restraints in using them, the use of an alternate approach such as Finite Element Analysis (FEA) seems preferential. FEA offers an edge in evaluating significant parameters that may or may not be possible through experiments. The finite element analysis of FSU's has evolved to handle complexity with the increase in computing capacity and advancement in the software packages. This paper reviews the progress in the development of finite element analysis of FSU's and also focuses on the application of FEA to analyse the lumbar (L1-L5) and lumbosacral (L5-S1) levels of the spine where spinal disorders are more prevalent.

Keywords: Functional spinal unit (FSU), Finite Element Method (FEM), Lumbar, Lumbosacral

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INTRODUCTION

FSU is the smallest functional part of the spine which comprises of two adjacent vertebrae, the interlinking Intervertebral disc (IVD) and the surrounding ligaments. It is convenient to work with an FSU due to the limited number of parts involved. The study of FSU is significant as it can enable us to extend the derived knowledge on understanding the characteristics of the entire spine (1). Enormous efforts have been laid in this direction through different methods like in-vitro experiments, in-vivo tests, and in-silico tests. Ideally, in vivo test results are a benchmark, but due to the invasive nature of performing these tests and associated risks involved, these types of studies are limited. Descent number of in vitro experiments has been carried out using cadaveric specimens, but it lacks the accuracy which is provided by in vivo tests and is very expensive (1). Most of the times it is hard to evaluate essential parameters that can improve our understanding of the functionality of FSU. With the intervention of computers, in silico tests like the finite element method are gaining popularity. The finite element method (FEM) is a mathematics-based tool to obtain a close approximation of required results and overcome the limitations of experimental studies (1). This became the main reason for its development and application in civil and aircraft industries during the 1950s. Further its usage became more widespread to different sectors of engineering including bioengineering. FEM was seen as a prospective tool that had the potential to simulate in vivo conditions efficiently. The first works of implementing FEM in biomechanics can be traced back to 1972 by Brekelmans et al. (2).

Existing finite element (FE) research on FSU spans over four decades and their objectives can be broadly classified into two categories: understanding the biomechanics of FSU and clinical research studies in FSU. Development of a validated FE model of FSU can be beneficial in assessing the biomechanics of the intact or diseased spine and it provides scope to design and evaluate spinal instrumentations. Evaluation of various parameters that govern the essential characteristic features can be performed on the developed models which may assist in improving accuracy and explore new avenues of research in spine. Due to these benefits, a lot of interest was shown to build and enhance finite element models of FSU by various research groups across the globe. It has proliferated the practice of finding more effective approaches and improving already existing finite element models. As a consequence of this trend, it is difficult to have an overview of the approaches that are widely accepted and also to keep a track of significant developments in finite element modelling of FSU. To serve this requirement is the primary aim of this review. One of the key interests of researchers is in the study of spine disorders and their restoration techniques. Spine disorders are predominant in the lower back corresponding to L1-S1 level with its major cause being defects in IVD's. For this reason, in this review, we intend to focus our primary aim on FSU in the L1-S1 zone.

METHOD

"PubMed" and "SCOPUS" databases were used to identify the literature that fulfilled the criteria of the aforementioned objective. A search was conducted during 2018-2019 using logical conditions of "AND" and "OR" with keywords "Numerical methods", "Finite element method", "Computational techniques", "Functional spinal unit", "Human", "Lumbar" and "Lumbosacral". Further, the search was expanded using the "related articles" option. This narrative review adheres to the recommended SANRA guidelines (3).

The IVD is one of the most complex parts of FSU for finite element analysis and hence the articles with noteworthy contributions related to computational studies of this area were included even if it was solely the IVD model. It is sufficient to consider single FSU models for our objective and hence except for a few works of literature on bi-segment models covering the L4-L5-S1 region, works on multiple motion segment models were excluded. Moreover, the works which are included in this review have employed validated models. Some of the exclusion criteria that were followed to filter the remaining articles are non-English articles, non-computational studies, review papers, numerical investigations on FSU other than those in the range of L1 to S1, and other biomechanical implications that are less relevant to the scope of this review. A total of 330 articles were listed by the databases used for this study, out of which about 78 articles were recognized considering the inclusion and exclusion criteria, among which 48 of them were dealing with intact IVD, 16 of them provided key contributions in the analysis of spine-related disorders that mainly affected the IVD and the rest of the 14 articles were on the analysis of the restoration techniques.

The paramount necessity of in-silico tests is to develop a finite element model of healthy or intact FSU which is validated with experimental results. On achieving this milestone, further modifications can be carried out on the validated model to simulate diseased FSU (i.e. with IVD defect) with or without surgical intervention. Although the baseline of all FSU related finite element study is a healthy FSU numerical model, based on the motive of the research, the discussions carried out in the review has been categorized into, i) In-silico studies of intact FSU, ii) In-silico studies of FSU with IVD defect, and iii) In-silico studies of FSU with IVD defect and complemented by surgical intervention.

DISCUSSION

A validated finite element model of FSU is a challenge to accomplish due to its complexity in both the geometry as well as material properties. The critical features that are necessary to be incorporated are obtained by examining and performing experimentation on cadaveric specimens of which some of the significant aspects are stated here. The vertebrae have a lot of irregularity in its geometry. They are comprised of soft porous cancellous bone which is enclosed in a hard shell of cortical bone. The vertebral body is covered on top and bottom faces by bony structures called endplates which is also most often argued to be a part of the IVD and thus it is modelled along with the IVD in only disc FEM models as well. The IVD is one of the most complex structures among the rest of the parts of FSU due to its innate structure as well as the associated material properties. It includes representation of two constituent parts, the gel-like nucleus pulposus which is surrounded by a composite-like layered structure called annulus. The annulus is again made up of fibre layers oriented at angles ±30° in alternate layers and embedded in a ground substance. The ligaments are differentiated mainly from their positioning and are found to be responsive only to tensile loads.

In-silico test of Intact FSU model

The earliest attempts towards the establishment of the finite element model of healthy FSU in the lumbar region were from Belytschko et al. (4) in the year 1974. Until the mid-90s the main source of geometry construction was either direct in-vitro measurements or published literature with the required anthropometric data. The latter method was used in (4) to create a simplistic 2D axisymmetric model of FSU corresponding to L2-L3 level. The posterior elements which are complex in geometry were excluded. The ligaments were also not considered for modelling. The vertebral body was assumed as isotropic in nature. Cortical shell and cancellous bone were modelled separately with different material properties. Nucleus was considered as incompressible fluid and this approach is still prevalent. A homogeneous orthotropic model was adopted for annulus of the disc, but the inhomogeneity in properties of the annulus was included by varying the elastic modulus along the fibre direction. Further, this model was revised by the same group of authors incorporating non-linear orthotropic properties to the annulus in (5).

Broberg et al. (6) developed a 2D model of the disc using average values of dimensions from literature. The linear orthotropic property was defined for annulus and it was built using 11 fibre layers having incompressible fluid filling the spaces between fibres. Spilker et al. (7,8) constructed a 2D model with a modulus value of annulus varied according to the loading schemes and vertebrae properties were given about annulus properties. A simple 3D linear orthotropic model excluding the posterior elements was created by Lin et al. (9) using geometrical measurements directly obtained from cadavers. Both vertebrae, as well as the annulus, were defined by orthotropic properties.

A historic milestone was set by Shirazi Adl et al. (10) as they involved non-linearity of both geometries as well as material property in the 3D model developed by them for L2-L3 FSU. The posterior elements were excluded from the vertebrae and the remaining vertebral body was assumed to be isotropic with explicit representation of the cancellous and cortical region. A heterogeneous annulus was modelled where annulus fibres were explicitly modelled using a non-linear stress-strain relation and placed circumferentially in a criss-cross arrangement. This model was further enhanced by including posterior elements and ligaments in (11–13). Experimental stress-strain curves from tests on ligaments were adopted to define their material property. Shirazi Adl. (14–17) used this validated numerical model for further studying various other characteristics. Rao et al. (18) developed a model of L5-S1 unit with simple geometry, symmetric about the sagittal plane. The disc was assumed to be circular in shape and non-linear material properties from published sources were used.

In the numerical models of FSU which were discussed so far, isotropic or orthotropic elastic properties were assigned to the bones and the disc was modelled as a biphasic material having solid annulus with the inner nucleus as an incompressible fluid. These models were intended to perform static (time-independent deformation for time-independent load) or quasi-static (time-independent deformation for time-dependent load) analysis. Transient (time-dependent deformation for time-dependent load) analysis could be effectively performed by including poroelastic property which is a specific case of viscoelasticity. Poroelasticity allows for the transfer of fluid across solid phase and this phenomenon is clinically observed to be a valid in-vivo condition of FSU. The application of this concept on the human lumbar FSU of L2-L3 level was done initially by Laible et al. (19) wherein an additional feature of swelling effects in IVD was also included. A simple circular geometry symmetric about the sagittal plane was used excluding the posterior elements and ligaments. Argoubi et al. (20) used the geometry of an earlier developed model by Shirazi Adl (11-17) and properties were modified to make it a poroelastic model. An improvement in geometry creation could be achieved with the intervention of computed tomography (CT) technique. 3D poroelastic finite element models were created using data from CT in (21–23). Wu et al. (21) considers only a single L5 vertebra, facet joints and half of the IVD below for their study. Lee et al. (22) performed the impact analysis for L3-L4 FSU using its poroelastic finite element model. All the parts involved in the FSU model including the bony structures are assigned respective permeability values to incorporate poroelasticity. An inconsistency was observed in values chosen for the parameters governing the poroelastic nature by different authors (19-22). Poroelastic models have also proved their efficiency in simulating unhealthy FSU behaviour and works under this category are discussed in the next section.

A major change was observed in the source of geometry data and the consideration of the spinal level for study. Geometry extraction using CT scan data made it easier to incorporate the geometric non-linearity involved in FSU parts and thus became a preferable option for researchers. The CT/MRI source files contain a stack of 2D images in which the pixels corresponding to the region of interest are selected and labelled as shown in Fig. 1(A). This process is termed as segmentation and it can be done manually or automatically using dedicated software. A 3D surface reconstruction of the required part is developed which can be converted to a finite element model using any meshing software, as shown in Fig. 1(B) and Fig. 1(C) respectively.

Also, until the mid-1990s most of the lumbar FSU related researches were focused on the upper lumbar level of spine which eventually shifted to lower levels of lumbar realizing their predominant clinical relevance. Natarajan et al. (23) and Zander et al. (24,25) used the technique of geometry extraction from CT to model L3-L4 FSU with material assignment similar to (11). Wong et al. (26) followed a similar approach to study the L4-L5 FSU biomechanics. Henceforth, the majority of the research in lumbar FSU was inclined towards studying the L4-L5 spinal unit.

Many alternative ideas and improvements in finite element formulations gave way to different approaches in IVD finite element modelling. Mixed elements were used by Tsouknidas et al. (27) which had the combination of a primary element as quadric element and secondary element as linear cable element that could be associated with annulus ground and fibres respectively. Łodygowski et al. (28) proposed a novel approach in modelling the annulus fibres with surface rebar elements. This technique proved to be efficient and comparatively easier to model the fibres than the conventional technique of using linear tensile or spring members. Constitutive laws of continuum mechanics like Neo-Hookean, Mooney-Rivlin, Reduced polynomial, Ogden of third order and Holzapfel-Gasser-Ogden (HGO) were found to be capable of representing the non-linear hyperelastic behaviour of soft tissues with better precision and thus they have gained popularity in usage for finite element modelling of intervertebral joints and ligaments. Neo-Hookean properties were

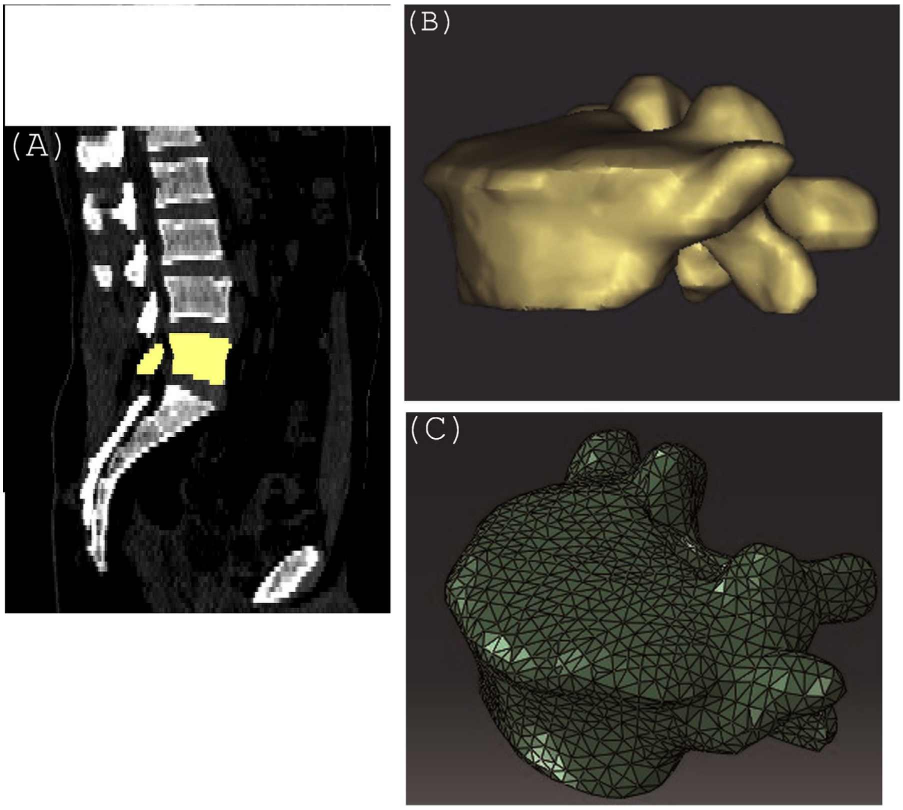

Figure 1: Workflow to obtain finite element model of L5 vertebra. (A) Segmented CT image of L5 vertebra. (B) 3D surface reconstruction of L5 vertebra. (C) Finite element model of L5 vertebra.

assigned to the facet cartilage in (31), to the nucleus in (40-41) and to the annulus ground substance in (29, 36, 39, 41, 43-44). Mooney Rivlin is an enhanced version of Neo Hookean and is preferred to model the nucleus (29, 31, 33-35, 40). Assigning the material properties of annulus ground substance using this law (29, 31, 33-34, 42) is well accepted. Hyperelastic reduced polynomial was used to model ligament in (34) and the annulus ground substance in (33, 35, 45-46). Third-order Ogden formulation was used to model ligaments in (34) and annulus ground substance in (35). The HGO model was developed to simulate the effects of arterial wall and its application has been extended to modelling the annulus of IVD. It has an additional advantage of avoiding explicit modelling of annular fibres (37, 38) as the model is capable of handling the anisotropy in material properties. Hybrid models were also developed combining properties of hyperelasticity and porosity which are referred to as porohyperelastic models (36, 47-48). Similar approaches were followed by Velísková et al. (41) and Barthelemy et al. (49) where Neo-Hookean and porous properties were attributed to the disc. Most of the in-silico FSU studies revolve around the understanding of disc mechanics. Few of them have even lead to significant explorations about growth plate (50) and vertebrae (51). Substantial changes have been observed in creation of geometry and modelling the annulus of disc leading to an improvement in the capability of performing finite element analysis. Table I presents an overview of the transformation of finite element models considering the geometry and annulus models.

Though there are a good number of works carried out on L4-L5 level intact FSU (26, 28-42), simulation studies on L5-S1 intact FSU are deficient. Charriere et al. (45) claim to be the first of works on the finite element model of L5-S1 FSU including the posterior elements developed by 3D reconstruction using CT data. Guan et al. (46) validate a bi-segment model consisting of L4-L5-S1 units considering it all together and as isolated FSU's as well. Over the years, software have been developed and improved to aid the process of FEA of biological systems. Alternative tools are available for specific tasks involved in the process of performing FEA like segmentation, mesh optimization and analysis. Segmentation can be carried out using dedicated software like Bonemat (http://www.bonemat.org/), 3D Slicer (http://www.slicer.org/), MIMICS (Materialise Inc, Belgium), etc… Software like 3-Matic (Materialise Inc, Belgium), Hypermesh (Altair Engineering Inc., USA), etc… are available for mesh optimization. The optimized mesh can be used to perform finite element analysis on commercial software like ANSYS (ANSYS Inc., USA) or ABAQUS (Simulia Inc., USA).

In-silico tests of FSU model with defected IVD

In this section, we discuss the use of the FSU finite element model in working towards the important goal of understanding its biomechanics when there are defects involved in the disc (51-67). It is observed in all of these works that a validated intact FSU finite element model serves as the base for these studies on which suitable alterations are made to simulate the required defects. Disc degeneration and its various effects on the

Table I: Overview of the transformation of FEM in FSU analysis considering Geometry and Annulus models

Geometry	Analysis capability
2D simple axisymmetric geometry without posterior elements	Only axisymmetric loads. Results exclude the effect of posterior elements. The accuracy of results is less compared to in-vitro studies.
3D symmetric geometry about sagittal plane without posterior elements (half model)	Only symmetric loads. Results exclude the effect of posterior elements. The accuracy of results is less compared to in-vitro studies.
3D symmetric geometry about sagittal plane with posterior elements (half model)	Only symmetric loads. Results include the effect of posterior elements. Accuracy of results is better than previous models excluding posterior elements.
3D symmetric geometry about sagittal plane with posterior elements (full model)	Variable loads. Results include the effect of posterior elements. The accuracy of results is better than previous models.
3D subject specific geometry	Variable loads. Results include the effect of posterior elements. The accuracy of the results is high.

Annulus models	**Analysis capability**
Homogeneous isotropic annulus ground and fibres modelled seperately with non-linear properties	Static or Quasi-static Analysis
Homogeneous orthotropic annulus ground and fibres modelled seperately with non-linear properties	
Hyperelastic (Neo-Hookean, Mooney-Rivlin, Reduced polynomial, Third-order Ogden) annulus ground and fibres modelled seperately with non-linear properties	
Hyperelastic (Holzapfel-Gasser-Ogden) annulus	
Poroelastic annulus	Quasi-static and Transient Analysis
Combination of hyperelastic (Neo-Hookean) model and properties for porosity	

biomechanics of the spine have been of prime interest to clinicians and to some extent, there has been a good contribution in this area through simulation studies.

Initially, there was curiosity in recognizing the factors that contribute to the degeneration of disc (52-54). Properties of annulus, endplate and the nucleus were changed with suitable assumptions to incorporate the degeneration process. Out of the various factors, the effect of annular lesions/tears was found to have a significant effect in accelerating the degeneration process (52). A few studies were conducted exclusively to understand the biomechanical changes that can occur due to the presence of annular tears (53-54, 57, 64). Simulating the effect of lesions was done by removing specific portions of the annulus (53). Similar approaches were followed in (57, 64). Along with these changes the properties of the nucleus were also modified to account for the decrease in its pressure during the degeneration process (54-56, 58-63, 65). Some of the models considered nucleus to be removed and its space was left as a cavity in severely degenerated cases (53, 57, 64).

The improvement in modelling goes parallel with the developments in numerical models of intact FSU's from the mid-90s. (52-55) were focused on L3-L4 FSU levels after which there was a gradual shift of focus into L4-L5 FSU (56-65). Goel et al. (53) used a compound element to represent annulus fibrosis which had cable/truss elements embedded in a quad element. The collagen fibres could be easily associated with truss elements that were inclined at ±30° and annulus ground substance was linked to the quad elements that enclosed the truss. Surface rebars were used in (54) for defining the collagen fibres. Hyperelastic constitutive laws were used in (55, 57-58, 65) to define annulus ground substance. As discussed in the earlier section, the poroelastic models (59-63) have significant contribution in understanding the various physiological changes. This is due to the fact that there is more control over the water content available in the disc in these models which governs the property changes in the disc during degeneration.

Biomechanical changes due to defects like spondylolisthesis (66), spondylolysis (67) and herniation (68) were also studied using in-silico tests. A bi-segment L4-S1 model was used by Natarajan et al. (66) to understand the effects of slip due to spondylolisthesis. El Rich et al. (67) studied the effect spondylolysis in the L5-S1 level which is the most susceptible level for this type of defect to occur.

In silico studies of diseased FSU with clinical treatment/surgical interventions

Studies on various treatment options available for rectification of defected IVDs can be useful in improving its efficiency and aid clinicians to gain better insight on the treatment processes. In-silico tests can be considered to be a good solution for this purpose (68-81). One of the initial attempts in this direction was made by Dietrich et al. (68) where the effects of herniation and its conservative treatment (i.e. traction method) were simulated for the L2-L3 spinal level. A truncated FSU model was developed where IVD (i.e. annulus fibrosis and nucleus), endplates and only a portion of vertebrae were considered. Orthotropic properties were assigned to vertebrae and annulus fibrosis which varied in cartesian and cylindrical form respectively. The herniated disc was simulated by decreasing the Young's modulus by 5 or 2 times in the affected zone. The effect of traction is tested by subjecting the model to tension. It was observed that the herniated portion is sucked inwards hence reducing its intensity. Holekamp et al. (69), studied ideal properties for annulus sealants in restoring the discs in a finite element model of L3-L4 FSU after the surgical treatment of discectomy for herniation.

Different types of fusion techniques like facet fusion (70-71), posterolateral fusion (70-71), posterior fusion (71), and anterior lumbar interbody fusion (72-74, 76) which are used to stabilize the spine with degenerative conditions were also analysed by numerical studies. Totoribe et al. (70-71) had a major contribution in studying the effects of various fusion techniques in the biomechanics of FSU's. The finite element models of facet fusion, posterolateral fusion, and posterior fusion mainly involved the use of bone grafts to fuse facets, transverse processes and spinous processes of consecutive vertebrae respectively. Usually, the anterior interbody fusion process involves the replacement of a degenerated disc portion with cage implants that encloses bone morsels (73). Evaluation of cage material and various other parameters of its design was possible using these finite element models. The possibility of stand-alone cage implants without the need for stabilization in the posterior was probed by Calvo Echenique et al. (78). Recently, Coogan et al. (77) conducted investigations on nucleus replacement implant on a numerical model of L3-L4 FSU. The performance test of different designs of implants for total disc replacement was done by Schmidt et al. (75). Numerical studies on pedicle screw implants (79-81) for FSU stabilization have been performed with different materials (79, 80) and designs (80). These comparative studies can lead to enhancement of the durability and also preserve the original biomechanics of the spine to the possible extent. Most of the works discussed in this section were interested in analysing various treatment strategies on L4-L5 FSU (70-72, 75, 76, 78, 79). Chen et al. (81) was found to be a rare work on L5-S1 FSU where the pedicle screw stabilization effects were studied on a case of spondylolisthesis.

CONCLUSION

A remarkable transformation has been observed in finite element modelling of FSU over the period of time from 2D simplistic linear models to 3D subject-specific complex non-linear models. The development of new tools and ideas have immensely contributed to the phenomenal improvement in our capability to perform finite element modelling and analysis. Apart from advancement in establishing finite element models of intact FSU which can approximate the biomechanics in-vivo conditions, a reasonably good amount of work has been carried out to evaluate FSU with IVD defects. Attempts have also been made to understand the influence of conservative as well as surgical treatments on FSU with IVD defects. The review of literature has revealed that not many attempts have been made to undertake finite element modelling and analysis of L5-S1 FSU. There is an even greater necessity for the numerical investigation of defects and their respective treatment modalities of this unit, which could be scope for future work.

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