Poroelastic Finite Element Modeling of a Lumbar Spine Motion Segment and Validation in Different Motions for Clinical Studies

Abstract

Introduction: About 80% of the population will experience back pain in their lifetime. Although many patients have low back pain associated with disc degeneration, the exact course of degeneration is still unclear. The disc degeneration disorder has affected one-third of the world's young population. During degeneration, the disc undergoes morphological and biochemical changes, which in turn alter the tissue hydration, permeability, and ultimately the load-bearing capacity of the disc. Therefore, the finite element model, which was designed to study the relationship between frequent loading and disc degeneration, must be able to analyze the complex loading in in-vivo conditions. The aim of this study was to construct and update models of finite element components with the poroelastic properties so that different quasi-static loads could be investigated by presenting a Patient-Specific model in different individuals. The could be applied in clinical studies to simulate the daily biomechanical behavior for accurate diagnosis and treatment.

Method: This study simulated three different modes of finite element modeling, including axisymmetric method, parametric model and exact model with poroelastic mechanical properties and its results were compared with experimental in-vivo experiments. To validate the constructed models, the results of three different quasi-static creep experiments were performed, including short-term creep, long-term creep and creep under regular daily activities.

Results: The results predicted height changes, axial displacement of the spine and the intradiscal pore pressure of the nucleus. All the proposed results indicated that the models presented in quasi-static behavior predicted acceptable results and have sufficient validity to be examined in other quasi-static experiments.

Conclusion and Discussion: Therefore, it is possible to take a step forward in examining the results of clinical activities in determining the process of intervertebral disc degeneration by proelastic finite element modeling.

Keywords: Intervertebral Discs, Finite Element Analysis, Poroelasticity, Creep, Recovery, Swelling, Patient-Specific Modeling, Spinal Biomechanics

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Introduction

About 80% percent of the population has experienced the low back pain in their lifetime. Although many patients have low back pain associated with disc degeneration, the precise course of degeneration remains unclear (¹). About one-third of the world's young population is involved with the disc degeneration disease and consequently faced with major socio-economic challenges (²). The low back pain and its resultant problems are more common among young people who need to carry heavy weights due to the nature of their job. Studies indicate that these people are prone to premature disc degeneration. Understanding relationship between disc degeneration and several consecutive years of carrying heavy weights has been difficult with in-vivo and in-vitro studies; therefore, the use of finite element analysis has been recommended (³).
Numerous in-vitro studies have addressed the mechanical properties of the spine, spinal response to the static loading, and creep response. However, these experiments do not provide a solution to distribute stress and displacement in the motion segment. The pathological experimental simulation of a segment at different stages of degeneration such as changes in water in the disc and the poroelastic properties of a disc is also difficult. Therefore, it is necessary to develop analytical disc models to complete the experimental studies. The finite element modeling of the motion segments could provide a detailed response to complex cyclic loading conditions. Moreover, with these models, it is possible to change the input parameters (for example, the poroelastic properties of the disc) and evaluate its effect on the biomechanics of the motion segment. During degeneration, the disc undergoes morphological and biochemical changes that alter the tissue hydration, permeability, and ultimately the load-bearing capacity of the disc. Therefore, the finite element model that was designed to study the relationship between repetitive lifting and disc degeneration, must first be able to explain the cause of morphological and biochemical changes that occur with damage and degeneration and then analyze the complex loadings in in-vivo correctly. This purpose was achieved by developing a three dimensional finite-element model that includes physiological parameters such as swelling pressure, strain-dependent permeability and disc tissue porosity.

The computational model play an important role in these studies, both mechanically and biologically in terms of cellular nutrition and population dynamics. Studies conducted on the activity of disc cells and disc herniation indicate that the effect of osmotic pressure is critical on the fluid flow and hydrate tissue deformation field and is directly related to the clinically relevant consequences. Complex multiphase models describe the diffusion of the interstitial fluid mobileions that interact with the fixed charges of the ground substance proteoglycans. These models are usually used for cases with relatively simple loading and geometry. Therefore, the finite element (FE) solvers are required to simulate the daily activities by developing previous models. There is a wide variation in the type of properties that could be considered for the inter vertebral discs in the finite element studies. The elastic properties and permeability of the cartilage endplate have recently been determined through experimental tissue tests. In the previous articles, there are different procedure to test the permeability of nucleus and annulus according to the different input conditions applied to different tissues and test protocols.

In this study, a basic model was developed with poroelastic mechanical properties to study biomechanical behaviour in a motion segment more accurately to show the biomechanical behaviour of these motion segments in various quasi-static tests and examine the effects of fluid behaviour in the poroelastic environment. Since a significant portion of spinal cord injuries are caused by repetitive loadings over time, this modeling could discuss the biomechanical behaviour, in clinical trials use by addressing the effects of fluid flow. Therefore, three different simulating modes of finite element modeling, i.e. axisymmetric, patient-specific model (parametric) and exact modeling are applied.
Method

2.1. Geometric design

The motion segment of the lumbar spine is designed by using various methods. Accordingly, three different models of axisymmetric, 3D parametric and exact modeling have been used (Figure 1) to simulate a motion segment, which is described in detail below:

2.1.1. Axisymmetric model

ABAQUS, the finite element analytical software (version 2019) has been used to design the axisymmetric model. For this FE modeling, different parts of a motion segment of lumbar spine, including L4 and L5 vertebrae and its intervertebral disc, have been modeled (Figure 1) and the mechanical properties of its various parts have been collected and selected from the previous studies (Table 1).

The dimensions used in different parts of this motion segment have been extracted from previous studies. Accordingly, the dimensions of simulated vertebrae are based on the average dimensions studied by Panjabi et al. In the simulation of intervertebral disc, the height of the disc and the diameter of the endplates are according to Nikhoo et al. The annulus to nucleus ratio percentage and the radius used in this study are based on Ferguson et al. (to simplify the model, the partial parts of the inter vertebral disc such as collagen fibres of the annulus fibrosis part and the posterior part of the vertebrae have not been modeled). All dimensions of the various segments of the axisymmetric model are presented in Table 2. According to the mesh-independence test, 7237 nodes and 2340 elements have been considered for meshing the axisymmetric model.

2.1.2. Parametric model

The parametric model used in this study was a pre-validated model in static tests by khoz et al., which underwent minor modifications to integrate with the meshing conditions due to the finite element modeling conditions with the poroelastic behavioural properties of the model. Therefore, the body of vertebrae design is separated from the posterior part and finally assembled together. The cortical and cancellous parts of the vertebral bones, as well as the different parts of the inter vertebral disc,
Poroelastic Modeling of Lumbar Motion Segment

Figure 1. A. axisymmetric poroelastic finite element model B. The updated parametric model of the motion and shear segment of the total mesh of the model and its meshed disc with different layers of collagen fiber C. The exact poroelastic finite element model

are distinguished to apply separate properties. In addition, the annulus of the proposed model is divided into inner and outer parts to apply different mechanical properties (Figure 1). To model the fiber collagen fiber of the inner and outer annulus parts, the truss elements with angles of about ±35°[12] have been used (Figure 1, Table 3).

At this stage, the average dimensions of 5 people who did not have any particular complication in their L5-L4 area were prepared to update the parametric model and its analysis (Figure 2). After completing the modeling in CATIA software [18], the model is meshed in the HyperMesh software [19] and different parts of the disc and vertebrae are inserted to the ABAQUS software to apply different mechanical properties in this software separately and determine the mechanical properties [7].
Figure 2. Lateral and anterior-posterior view of 5 samples

2.1.3. Exact model

For simulation in the exact model, like the parametric model, validated finite element model in L5-L4 level in static tests (including intervertebral rotation (IVR) in different directions and intradiscal pressure (IDP)) is applied (Figure 1). The model also includes various sections, including cortical and cancellous bones, cartilaginous endplates, annulus fibrosus, and nucleus pulposus (Table 4). Two-dimensional mesh was considered for the endplates and the cortical bone. The cancellous area elements were defined by tetrahedral mesh and the rest of the disc, including the nucleus and annulus had hexahedral elements. All these elements are first-order (linear). The elements for ligaments and collagen fibers in the annulus section are also simulated in the form of springs, which only act in tension and do not exhibit a compressive reaction in the compressive state.

2.2. Material properties

The solid phase was considered as linear elastic in all models provided for different parts of the motion segment and the poroelastic theory with respect to the permeability and the voids ratio for the desired sections is used to apply the fluid phase. According to the model conditions, the permeability \( k \) is taken to be dependent on voids ratio\(^{20}\).

<table>
<thead>
<tr>
<th>Motion segments</th>
<th>Elastic formulation</th>
<th>Poroelastic formulation</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Elastic modulus (E)(MPa)</td>
<td>Poisson’s ratio ((\nu))</td>
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<tr>
<td>Inner Annulus</td>
<td>2.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Outer Annulus</td>
<td>2.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Nucleus pulposus</td>
<td>1.5</td>
<td>0.1</td>
</tr>
<tr>
<td>cartilaginous endplates</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>Cancellous bone of the body</td>
<td>200</td>
<td>0.25</td>
</tr>
<tr>
<td>Cortical bone of the body</td>
<td>12000</td>
<td>0.3</td>
</tr>
<tr>
<td>Bony posterior elements</td>
<td>3500</td>
<td>0.25</td>
</tr>
</tbody>
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Table 3. Mechanical properties of the parametric poroelastic finite element model
Table 4. Mechanical properties of the exact poroelastic finite element model

<table>
<thead>
<tr>
<th>Motion segments</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Elastic modulus (E)(MPa)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Kₓ</td>
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<tr>
<td>Nucleus pulposus</td>
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<td>0.1</td>
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<tr>
<td>Annulus fibrosus</td>
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<td>0.1</td>
<td>2.56×10⁻¹²</td>
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<tr>
<td>Cartilaginous endplates</td>
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<tr>
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<td>0.315</td>
<td>1×10⁻¹⁵</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>12000</td>
<td>0.3</td>
<td>1×10⁻¹⁵</td>
</tr>
</tbody>
</table>

2.3. Boundary and loading conditions

Loading is considered axially in the axisymmetric and exact model by considering the central point in the middle of the upper endplate of L4 and it is considered axially in the parametric model by the central core of the two vertebrae cancellous bone \(^{(23)}\) (figure 1). The L5 vertebra is also fixed in all models provided and the displacement in the L4 vertebra has been considered. Intervertebral rotation (IVR) to confirm static tests, the short and Tyrrell long-term creep \(^{(24)}\) and daily activity simulation over two consecutive days \(^{(25)}\) were considered in the quasi-statistical tests. To simulate the swelling phenomenon, the boundary pore pressure with the values tested and presented in previous articles \(^{(5, 10, 25)}\) are also applied to the external boundaries of the developed models \(^{(5)}\).

Results

First, 10 N moment in different directions in 3D mode (parametric and exact), which were updated with poroelastic mechanical properties, was applied to simulate various movements of the lumbar region, including flexion, extension, axial rotation and lateral bending. The results of these movements were confirmed by the experimental study of Heuer et al \(^{(26)}\). All the results of intervertebral rotations in different directions (with the applied moments) were all in the range of experimental results and models. The three-dimensional finite element models prepared under the static conditions presented acceptable results in intervertebral rotation movements.

For short-term creep test by axial loading of 800 N for 20 minutes and reduction of 400 N for 10 consecutive minutes, for simulation of long-term creep test by applying 850 N for 16 hours and reduction of 450 N for 8 consecutive hours for recovery \(^{(24)}\), the results of the axial displacement and its conversion to individual height change percentage, in axisymmetric, parametric and exact models in comparison with this experimental study for short-term and long-term creep are in the range of in-vivo results. The results of this section were validated by this method (Figure 3).
The results of axial displacement and inter vertebral disc pore pressure at the center of the nucleus in regular daily loading with a resting load of 350 N in the first 8 hours of the night followed by an average daily activity of 1000 N in 16 consecutive hours in two consecutive days were compared with experimental tests. Depending on the different variables (model geometry, voids ratio, permeability and boundary pore pressure for the constructed models and previous models), the axial displacement of the disc and the pore pressure of the nucleus center were different. Generally, these figures are reported for axial displacement in the range of 1.5 to 2 mm along the disc after two days, which has also been in the range of experimental studies (Figure 4).

The results of this study using a variety of finite element modeling and its validation in inter vertebral rotation (IVR), the percentage of individual height changes in short-term and long-term creeps, axial displacement and intradiscal pressure in two consecutive days are as follows: By adding a fluid phase to the constructed models, it is possible to predict correct numerical analysis of time-related behaviours in FE models and use it to understand the biomechanical behaviour of the inter vertebral disc to facilitate the diagnosis and treatment of injured patients in this area.

Discussion

The overall results of the present study indicate that the models work properly under the static and quasi-static (creep) loading conditions compared to the results of previous and experimental studies. In testing the inter vertebral rotation, as mentioned in the results section, the three-dimensional models have shown acceptable results compared to the experimental study of Heuer et al. In Tyrrell short-term creep tests, the amount of creep provided after 20 minutes reports 0.63% of the decrease in height, while the axisymmetric, parametric and exact models reported the values of 0.61%, 0.60%, and 0.59% respectively. Similarly, a small difference is observed relative to the in-vivo test at the end of unloading, which means that the highest percentage of displacement in all three models is within an acceptable range compared to the Tyrell in-vivo study.
Other results presented in the experimental study of Tyrell reported a decrease in height during daily activities and the amount of recovery performed during the night. The proposed poroelastic finite element models during loading and unloading have reported acceptable results relative to the numerical range of this experimental study. The highest amount of creep applied after 16 hours of daily activity in Tyrell experimental study is 1.11%, while the results of the axisymmetric, parametric and exact model are 1.24%, 1.17% and 1.21%. According to the allowable range provided in Tyrell et al, all the analyzed models showed the best predictions. Non-reversal of the displacement, which is the result of insufficient fluid entry into the model in the recovery or unloading phase, is also observed in poroelastic models. This value can be compensated by increasing the boundary pore pressure or swelling phenomenon. This non-reversal of the model to its original state in the recovery or unloading phase is also observed in some other numerical studies (3). Therefore, the predicted values in the poroelastic models have been validated and they are acceptable. The results of daily activities over two consecutive days have also predicted appropriate values in the constructed models. This means that the results of the models presented in the consecutive daily loadings are valid and is possible to use the accuracy of the predicted information in different Patient-Specific models to advance the clinical goals. According to the results of poroelastic parametric and axisymmetric models along with the models prepared with different mechanical properties and different in-vitro studies (27-29), it can be concluded that the presented results have acceptable validity. Another chart presented in this numerical study reported the amount of pore pressure at the center of the nucleus over two consecutive days with the same previous loadings. The predicted values in the poroelastic models developed in this study are within acceptable range based on the inter vertebral disc height difference with the previous models and the
difference in the values of permeability and voids ratio and other mechanical properties such as Poisson's ratio all of which have a significant effect on the amount of this pore pressure \(^{(23)}\). The difference in Swelling pressure applied to the external boundaries of the constructed models has also been another factor in reducing the pore pressure in the center of the nucleus during loading and unloading compared to previous numerical models.

The negative pressure provided by the parametric and axisymmetric models during unloading after 24 hours is a model error in predicting the result, which is one of the limitations for these models because this negative pressure just apply in FE model and does not occur in real situation\(^{(23)}\). The amount of swelling pressure, the mechanical elastic and poroelastic properties and the amount of resting load were the factors influencing this negative pressure \(^{(23)}\). By changing these values, this negative pressure can be eliminated, but due to the effect of these cases on other creep tests, these values were considered intact and constant to provide a single value for mechanical properties in all biomechanical tests. However, the results of the pore pressure at the nucleus center of the parametric and axisymmetric models predicted results with sufficient accuracy in contrast to the previous numerical models and experimental data and the model is validated in this section.

In this process, by adding a fluid phase and validating the models in quasi-static tests, all three models have provided the possibility to simulate different grades of intervertebral disc degeneration by reducing the amount of fluid in various parts and decreasing permeability and voids ratio to clinical activities. In this way, by simulating for each patient and examining its biomechanical behaviour in similar tests, it is possible to make a reliable diagnosis and correct treatment of the patient. This tool is a great tool for surgeons to use in quasi-static tests before and after spinal operations.

Predicting biomechanical behaviour in daily long-term creep tests in different degeneration grades provide a better understanding of the motion segment’s movement at different stages of injury in this area. Given the amount of physical activity of each person, it also provides appropriate information to make a more accurate diagnosis by surgeons to study the effects of different parameters.

**Conclusion**

The quasi-static behavior of these models has been confirmed in various tests and from now on, the osteoporosis and intervertebral disc degeneration are predictable by varying the amount of mechanical properties associated with the intervertebral disc and vertebrae and use it as a clinical tool. Adding the poroelastic properties to the parametric model is a step towards completing this modeling process in Patient-Specific models.

To continue this study, it is suggested to make a complete model of the entire spine, apply the properties of the degenerated disc to the model, and simulate the fusion action to study the effect of this function on the biomechanical behavior of the spine in different static, quasi-static or dynamic states.

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The authors of this article also state that the presented article has followed the avoided publishing misconducts including plagiarism, forgery of data or double sending and publishing and there is no commercial benefit in this regard. Authors have not received any payment for their work and have delivered original content.

7. References