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Research Article

Photoelastic and Finite Element Stress Analysis of the Gap between the L4 and L5 Vertebrae

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The purpose of this study was to analyze the stresses on the intervertebral disc between vertebrae L4 and L5 when a compressive load is applied on vertebra L4 using the photoelasticity transmission technique and the finite element method. Nine photoelastic models were used and were divided into three groups. Each group was formed by three models, according to the localization of the sagittal cut on vertebrae L4-L5. Simulation was carried out using a load of 23 N. The fringe orders were assessed by points close to the edge of the intervertebral disc using the Tardy compensation method. The analyses using the photoelasticity technique and the model of the finite elements showed that the stress generated by the vertebrae on the intervertebral disc was higher in the posterolateral region. Thus, this region is more susceptible to pathologies such as hernia and disc degeneration.

1. Introduction

The vertebral disc is capable of transmitting and absorbing loads, and various experimental studies have shown that mechanical stimulation is important for the performance of the intervertebral disc, and its homeostasy Compressive loads are assumed to affect the disc cell metabolism depending on the frequency and magnitude of the load (MacLean et al. [1]; Walsh and Lotz [2]). However, excessive loads on the disc may be an important factor in degeneration and the appearance of discal hernia (Adams et al. [3], Kelsey et al. [4], Lotz [5], and Wang et al. [6]).

According to Lotz [5], when the intervertebral disc is compressed, the pulpous nucleus is initially pressurized and the fibrose annulus is tensioned. If the load is continuous with a high tension of expansion/dilation, the nuclear volume diminishes. Loss of nuclear volume leads to a redistribution of the compression to the internal annulus causing a loss of collagen, and these fibers go through a selective denaturation. Stress loads may also activate proteolytic enzymes which may contribute to the disorganization of the matrix (Hsieh and Lotz [7]). With an excessive load on the spine, the increase in nuclear compaction causes degeneration and death of the cells (Hsieh et al. [8], Palmer and Lotz [9]).

Farah et al. [10] compared the photoelasticity method with the finite element method and concluded that these two techniques allow for a better understanding of the distribution of the stresses. Photoelasticity is an experimental technique that uses light to study the physical effects resulting from the action of stresses or deformations in transparent

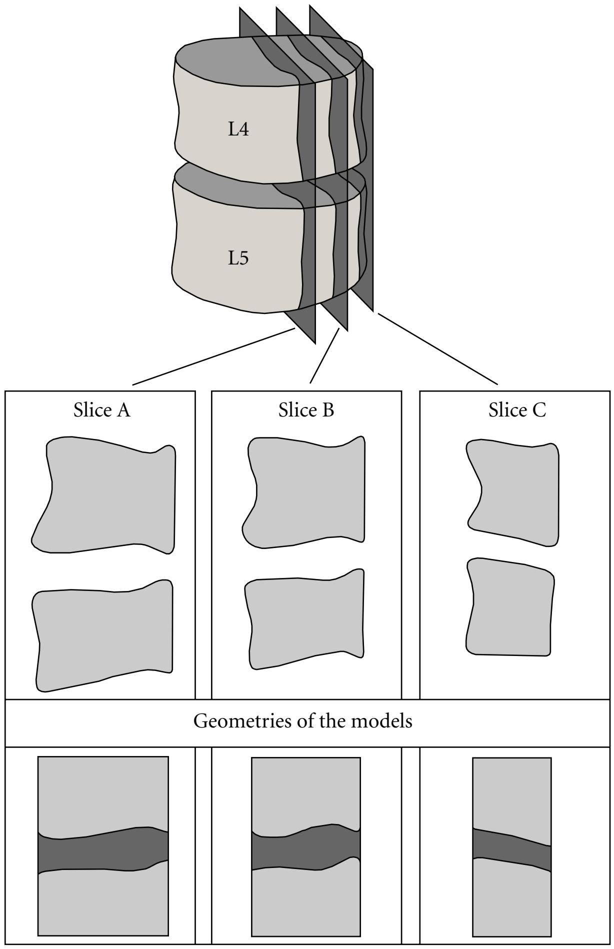

Figure 1: Schematic drawing of the three sagittal unilateral slices (A, B, and C) in the L4-L5 vertebrate bodies with the respective geometries of the models.

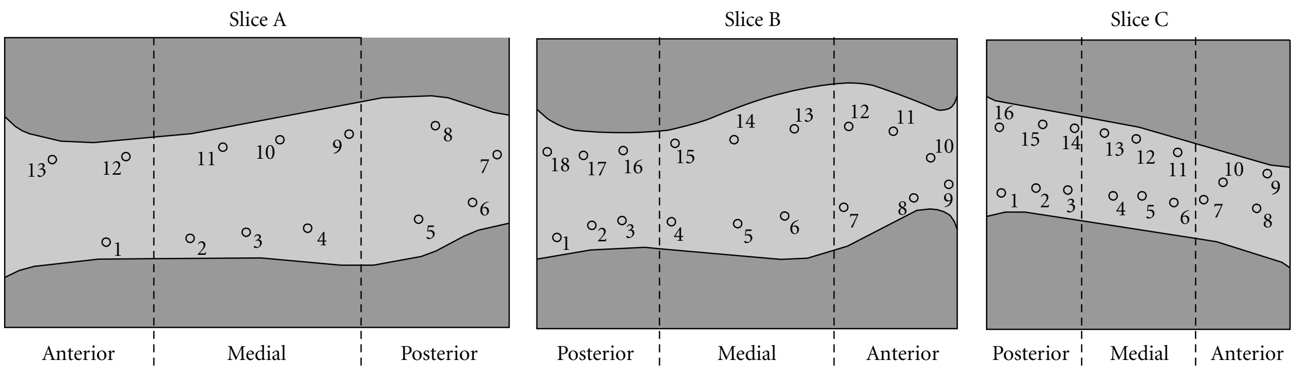

Figure 2: Diagram of the points selected following the contours of the three vertebrae slices.

elastic bodies and is used in studies of structures with complicated forms, complex load distributions, or both (Doyle and Phillips [11], Wang and Tsai [12]). This technique has been widely applied for qualitative and quantitative stress analysis in the engineering and medical field (Hirokawa et al. [13]). Thus, the purpose of this study was to analyze, by means of the transmission photoelasticity technique and the finite element method, the stresses generated by the L4 and L5 vertebrae on the intervertebral disc when subjected to a compressive load.

2. Materials and Methods

Three unilateral sagittal cuts were performed in vertebrae L4 and L5, where the distance between the slices was 16.0 mm (Figure 1). Using these slices, the geometry of vertebrae L4

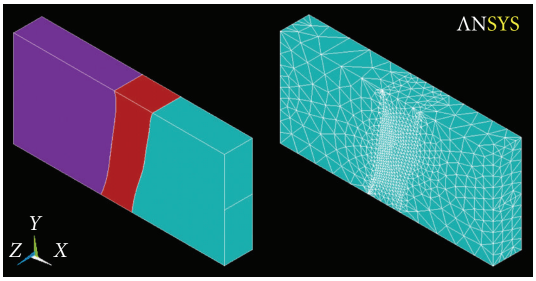

Figure 3: Numerical model developed in ANSYS showing the volume knots and elements of the whole slice C model.

and L5 was obtained. The gap between L4 and L5 was 10.0 mm in the anterior portion for slice A, while in slices B and C the gaps were of 8.5 mm and 7.0 mm, respectively.

The geometry of the vertebrae enabled the construction of photoelastic models, and a numerical model for analysis of the finite elements was developed.

2.1. Photoelastic Method. Three polytetrafluoroethylene Teflon molds were used for making the vertebral bodies (slice A, slice B, and slice C). After preparation of the vertebral bodies, the vertebral disc gap was filled with flexible photoelastic epoxy resin (Polipox). This resin has a Young's Modulus of 4.51 MPa and a Poisson's Ratio of 0.4.

For each slice, three identical models were made (total of nine models) and the width of the model was different for each slice: slice A was 40 mm, slice B was 35 mm, and slice C was 27 mm. For all the models, the height was 60 mm and the thickness was 8 mm.

These models were first assessed to determine the presence of residual stress, called the "boundary effect", before the compressive load was applied to the L4 vertebral body. The photoelastic resin used was calibrated and had an optical constant of 0.375 N/mm fringe.

The photoelastic analysis was carried out using a Transmission Polariscope with a compressive load applied to the center of the L4 vertebral body of the photoelastic model. A spring with an initial length of 12 mm and a spring constant of 0.5674 was used for the application of the load.

The inner stress produced between the L4 and L5 vertebrae in the three sagittal cuts was analyzed in a qualitative and quantitative manner. For the qualitative analysis, the initial point and the point of higher stress concentration were observed. In the quantitative analysis, the spring was compressed to a relative load of 23 N and registered in a Kratos load cell with a capacity for 100 N. The shear stress was calculated according to a standard pattern, using points following the contour of the vertebrae. For slice A, we selected 13 points, while 18 points in slice B and 16 points in slice C were used (Figure 2). For calculating the shear stress (τ), the Tardy compensation method was used (Dally and Riley [14]).

2.2. Finite Elements Model. Three tridimension models of finite elements (slice A, slice B, and slice C) were made in a geometric configuration similar to that of the experimental model (photoelastic model). The models were developed in the Solid Edge environment (SIEMENS AG, Berlin, Germany) and later exported to the ANSYS software (ANSYS Inc., Canonsburg, Pennsylvania, USA).

The finite element mesh was obtained using a solid element of eight isoparametric knots of the ANSYS software (SOLID 185). The L4-L5 vertebrate bodies were considered glued to the interfaces of the intervertebral disc. Figure 3 shows the volume and the refined mesh in one of the slices of the finite element model and displays the conditions of the contour. The number of knots and elements used in the whole slice A model was 3,578 and 17,331, respectively. In the slice B model, there were 7,791 knots and 39,817 elements, while in the slice C model there were 4,450 knots and 21,840 elements.

The values for the Young's Modulus and the Poisson's Ratio for the photoelastic resin were 4.50 MPa and 0.34, respectively. On the other hand, for the acrylic resin T208, the Young's Modulus was 1000 MPa and the Poisson's Ratio was 0.33.

Analysis of the stress gradient in the finite element models was carried out in a similar manner to the photoelastic model, in principle using a compressive load of 23 N in the centre of the L4 vertebral body. The purpose of this analysis was to fit the finite element model to the experimental model. In this case, the fit of the numerical model was carried out by varying the size of the mesh and modifying the conditions of the contour, level, and load position. Thus, after this adjustment of the numerical model, the comparison of the stress gradient was carried out at similar points to those in the experimental model by comparing the intensity of the stresses.

3. Results

The photoelastic analysis and the finite element method were used to assess and compare the distribution of stress in the gap between L4 and L5 vertebrae. In the two analyses, the stress gradient was characterized by the intensity of the shear stress (τ). Figure 4 shows the distribution of the stresses in the three slices obtained by the two methods.

In order to demonstrate the similarity of the values obtained in the experimental and numerical techniques, a comparison of the average values of the shear stress for the slices A, B, and C was carried out, according to the points analyzed (Figure 5). The points verified in the photoelastic analysis represent the mean of the shear stress.

The mean values of the shear stress (τ) obtained from the photoelasticity and the finite element method are represented in Table 1.

4. Discussion

The intervertebral disc may suffer degeneration and cell death when subjected to excessive load (Hsieh et al. [8], Palmer and Lotz [9], Saal [15]). Under normal mechanical conditions, the pulpous nucleus can absorb compressive

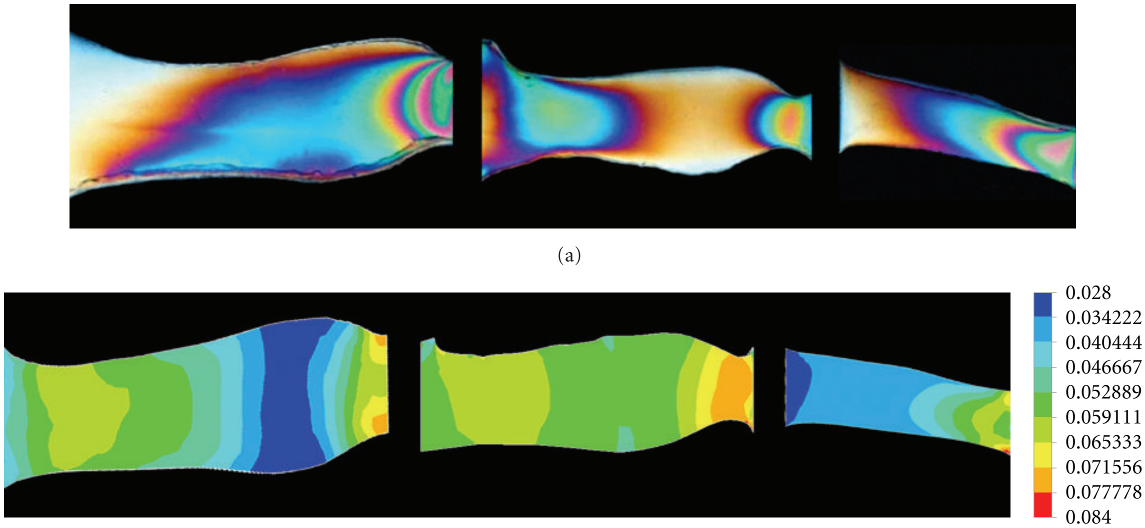

Figure 4: Distribution of the stresses in A, B, and C by means of the application of a compressive load of 23 N. (a) Photoelasticity. (b) Finite elements.

Table 1: Mean ± standard deviation of the shear stress (τ) determined by photoelastic analysis and by the finite elements method in three different regions of each vertebrae slice.

Region	Slice A		Slice B		Slice C	
	Ph	F.E.	Ph	F.E.	Ph	F.E.
Anterior (KPa)	26.12 ± 11.47	40.41 ± 2.31	35.78 ± 5.23	33.95 ± 4.12	25.40 ± 6.10	35.88 ± 1.10
Medial (KPa)	32.84 ± 3.72	36.12 ± 4.24	26.71 ± 6.73	31.88 ± 3.86	35.95 ± 3.96	40.61 ± 4.99
Posterior (KPa)	58.61 ± 18.75	44.82 ± 6.34	38.66 ± 15.49	41.46 ± 11.50	59.00 ± 6.14	58.51 ± 4.93

Ph = Photoelastic, F.E. = Finite elements.

loads (Li and Wang [16]). The fibrose annulus is significantly affected by the amplitude and frequency of stress when a compressive load is applied (Iatridis et al. [17], McNally, and Adams [18]).

Due to this fact, research has been focused on studying the biomechanics of the intervertebral disc, using cadavers (McNally et al. [19], Adams et al. [20], and Adams et al. [21]), animal models (Lotz et al. [22], Lotz [5], Lotz et al. [23], Larson et al. [24]), and *in vivo* (Nachemson and Morris [25], Nachemson and Elfström [26]), applying different techniques, such as the finite element method (Edwards et al. [27], Lee et al. [28], Martinez et al. [29], Schroeder et al. [30], Teo et al. [31], and Yin and Elliott [32]). Authors have shown different potentials on the overload that may cause disc protrusion (Adams and Hutton [33], McNally et al. [34], Gordon et al. [35]). However, analysis of the distribution of stress using the photoelasticity technique of plane transmission has been overlooked in studies of the intervertebral disc.

Using this technique, as well as the finite element method, it was possible to evaluate the points of higher shear stress generated by the L4 and L5 vertebrae under a compressive force. The force applied was 23 N, which did not cause a permanent deformation of the models, while the photoelastic epoxy resin had a high optic sensibility and a low Young's Modulus.

The lumbar segments evaluated were L4-L5 because they more often overloaded and have an increased incidence of hernia and disc degeneration (Holodny et al., [36] Vergauwen et al. [37]). Due to the fact that the vertebrae have symmetry, the cuts in the vertebrate bodies were done unilaterally. The analysis of the distribution of stress carried out in the three slices showed that the posterior region of the intervertebral disc, especially in slice C, was the most critical region. This suggests that this point is more susceptible to pathologies, a fact also observed by Adams, McNally, and Dolan [38]. These results are in accordance with the findings of some authors who also mentioned this region as being one of highest disc stress regions (Adams et al. [21], Adams et al. [38], Edwards et al. [27], Li and Wang [16] Schmidt et al. [39], Steffen et al. [40], and Vernon-Roberts et al. [41]). However, the scarcity of references in the field of experimental techniques makes comparison of results difficult.

It is emphasized that in this research, the analyses were carried out with a vertical load (compressive) perpendicular to the vertebral body, simulating the vertebral body in an upright posture. Authors such as Nachemson and Morris

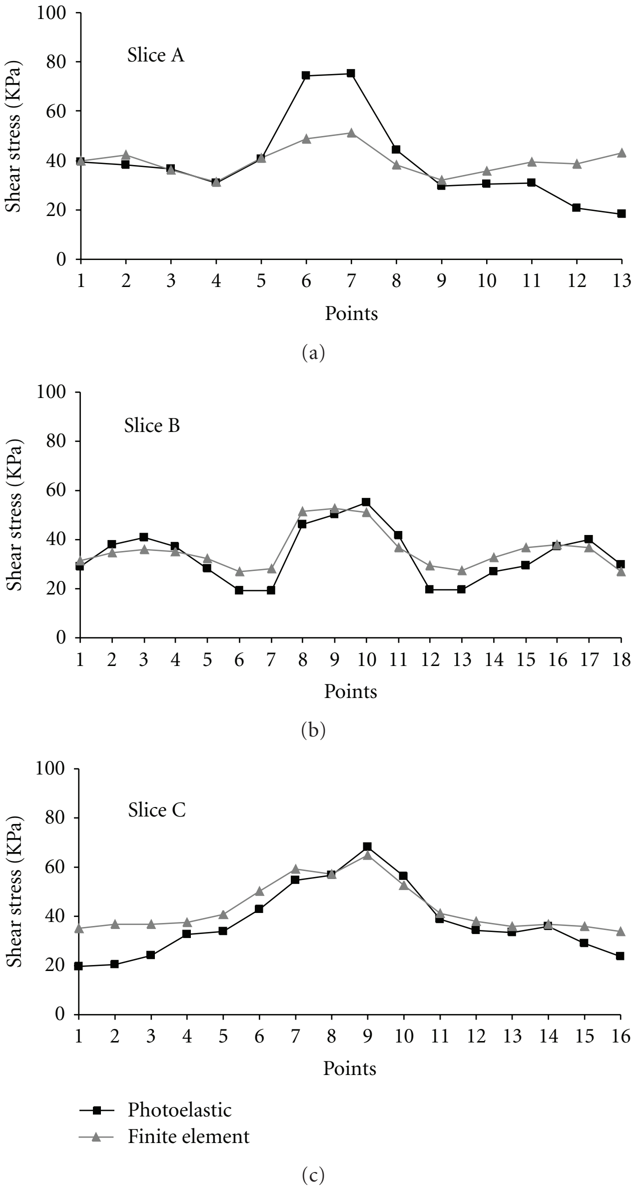

Figure 5: Shear stress mean obtained from the photoelasticity and finite element method in the slices A, B and C.

(Nachemson and Morris [25], Nachemson and Elfström [26]) have noted that the intradiscal pressure as well as the compressive load can increase when there is a change in the position of the vertebral body, as occurs in inclinations of the spine.

5. Conclusion

Using the photoelastic transmission technique and the finite element method, this study shows that the posterolateral region of the intervertebral disc experiences higher levels of shear stress; therefore, it is the most critical, according to the dimensions and geometry used in the study. Thus, these results confirm that the high predisposition of this region to pathologies, such as hernia and disc degeneration, may be due to the higher concentration of stress.

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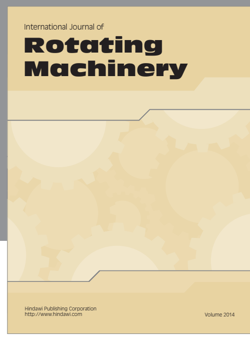
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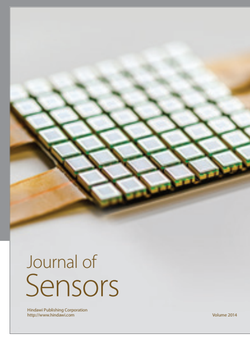
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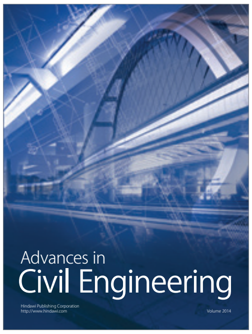
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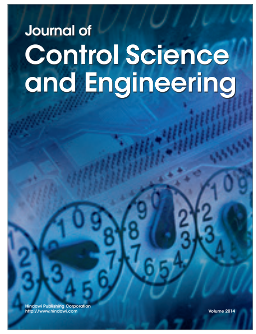
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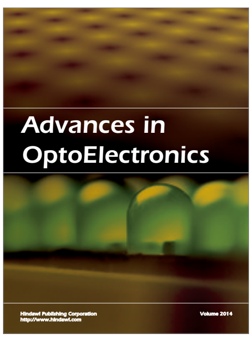
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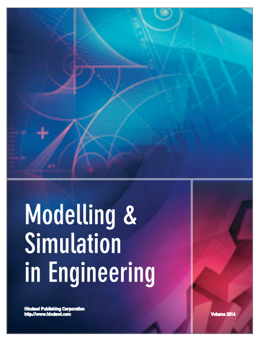
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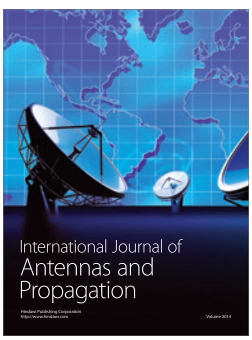
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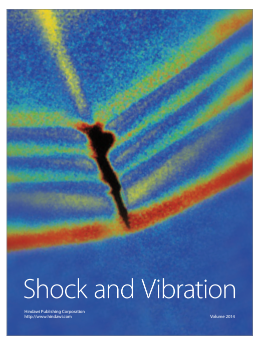
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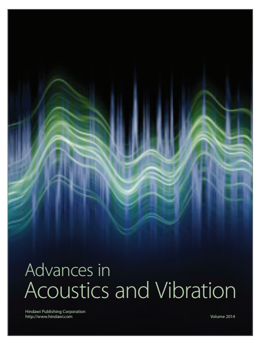
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