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Original article

Analysis of compressive stresses on the spine with intervertebral disk injury: Numerical-experimental study on a porcine specimen

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SUMMARY. This paper describes a study aimed at determining the load distribution produced by a healthy specimen upon weight bearing and comparing it to specimens with damage of different intervertebral disk quadrants. This allows establishing the degree at which the intervertebral disk contributes to load transmission and distribution. The study was conducted on a numerical-experimental basis in order to validate the results that stem from it. The experimental portion was performed with a reflective photo elasticity technique, while the numerical portion was performed with the ANSYS finite element package, Version 7.0

Key words: spine, intervertebral disk, fractures, finite element analysis.

RESUMEN. En este artículo se presenta un estudio que consiste en determinar cuál es la distribución de esfuerzos producida en un espécimen sano cuando se le aplica carga, y compararla con especímenes que sufren daño en los diferentes cuadrantes del disco intervertebral. De esta manera, se puede establecer en qué grado contribuye el disco intervertebral a la transmisión y distribución de carga. El estudio se realizó de manera numérico-experimental con la finalidad de validar los resultados obtenidos. La parte experimental se realizó por medio de la técnica fotoelástica de reflexión, mientras que la parte numérica se realizó empleando el paquete de elementos finitos ANSYS en su versión 7.0.

Palabras clave: columna, disco intervertebral, fracturas, análisis del elemento finito.

Introduction

One of the main functions of the vertebral spine is the support, absorption and transmission of external forces it will be subjected to at all times. If the spine fails to meet any of its tasks, the impacts received from such loads may cause catastrophic distortion or damage on it as it usually happens with a vertebral or intervertebral disk fracture, for instance, caused mainly by a poor stress distribution among the elements composing it.

Several studies have been conducted to assess and quantify load distribution on the spine with experimental methods or computer models. These studies include those performed on intervertebral disks through various techniques[1-5] that help determine their mechanical function.[6-10] In some cases, load distribution and compressive stresses on the spine are determined. The study conducted by Michio Hongo[11] reports the testing during weight bearing cycles to measure the strain and compression on the thoracic and lumbar vertebrae (intact) and determine the load distribution. Different points on the verte-

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brae were highlighted and the areas with the highest stress concentration were identified to predict the onset of a possible fracture and determine that stresses increase as the force was applied. Choon-Kig[12] used an FEM modeling to determine the vertebral disk (intact) behavior by applying loads for a certain time period. Some of the results included observing the increased load transmission towards the disk. Wang Jaw-Lin[13] analyzed the physical integrity of intervertebral disks with X-rays. His results point out that although X-rays allow seeing the disk, they not always determine the presence of damage, and the stresses on the disks are greater after rupture than before the damage occurred. Hanspeter Frei[14] applied weight cycles on the spine at L3-L4 and L4-L5 (intact) and found the compressive loads on the intervertebral disk are increased upon weight lifting. When vertebral deterioration was simulated by a nucleotomy, the loads decreased.

Notice that these studies start with intact vertebrae and disks, then forces are applied and when a crack or fracture occurs, the results are analyzed. None of these studies, however, looked into what happens once the disk is injured or ruptured nor do they indicate the behavior of the loads applied to the disk and vertebrae.

The purpose of this study was to analyze the behavior of the spine with injured intervertebral disks when subjected to external forces from constant pressure. This study was conducted in a numerical-experimental format on a porcine specimen.

Material and methods

Specimens used in this analysis were segments L2-L3-L4 of the porcine spine after removal of the posterior portion of the vertebrae (facets, pedicles, process) so that only the vertebral body and intervertebral disks were used. To simulate the damage on the disk, small incisions resembling small windows were made spanning one fourth of the corresponding quadrant. Incisions were deep enough to stimulate damage to the fibrous ring and the nucleus pulposus. The damaged disk is located between L2 and L3 *(Figure 1)*. The vertebral body is varnished to indirectly establish the intervertebral disk function on load transmission when it is intact or damaged. In other words, the load distribution seen on the vertebral body is proportional to the status of the intervertebral disk. Hence, any disruption of its status modifies the strip pattern seen *(Figure 2)*.

Assessing the physical condition of the intervertebral disk was primarily achieved with the experimental technique based on reflective photo elasticity. Also, a 3D mathematical model with finite elements was developed to validate or reject the results obtained. The experimental technique was reflective photo elasticity, the type of varnish used was PL1 with a PLH1 catalyst, the reflecting adhesive used was PC1 and the thickness of the varnish was 1.5 mm over a 20 x 20 cm surface.

The analytical machine used was a one-ton INSTRON. Constant 150, 200, and 250 kg loads were applied to each specimen.[8] Four specimens were analyzed representing the following cases: 1 – intact intervertebral disk; 2 – intervertebral disk with anterior damage; 3 – intervertebral disk with posterior damage; 4 – intervertebral disk with right lateral damage.

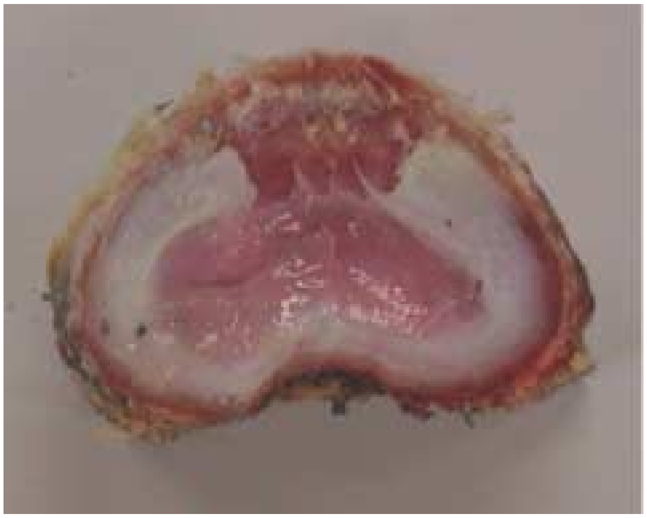

Figure 1. Intervertebral disk with anterior damage.

Figure 2. Test specimen made with photo elasticity varnish.

The isochromatic strip pattern was photographed to determine the value of the stresses generated on the vertebrae *(Figure 3)*.

Several spine models were developed using the finite element method (FEM) to determine the behavior of stresses generated applying different loads.[12,15] In this study, the geometry of porcine vertebrae and intervertebral disks used in the experimental analysis was modeled. These were sectioned and photographed. Photographs were then digitized and CAD reproduced. With the surfaces defined, the end volumetric geometry was generated in three dimensions. The resulting data were fed to the finite element program.

The elasticity module and the Poisson relationship are the mechanical properties used in the model. The values used for each kind of organic material[16,17] are shown on *Table 1* in addition to the amount of elements generated by the program *(Figure 4)*.

Six models were generated accounting for each study case (intact, anterior, posterior, right lateral, left lateral, and top). Each model developed involved 45,000 solid 92-type elements, (10 node tetrahedrons each) and was cleared by using the FEM ANSYS Research program, Version 7.0 (Ansys Inc.).

Runs are for the above study cases at the same load levels. The purpose of the numerical analysis is to provide a much broader perspective of the distribution of stresses generated in L3. The model may be rotated or moved in the desired direction, a situation seldom managed on an experimental basis *(Figure 5)*.

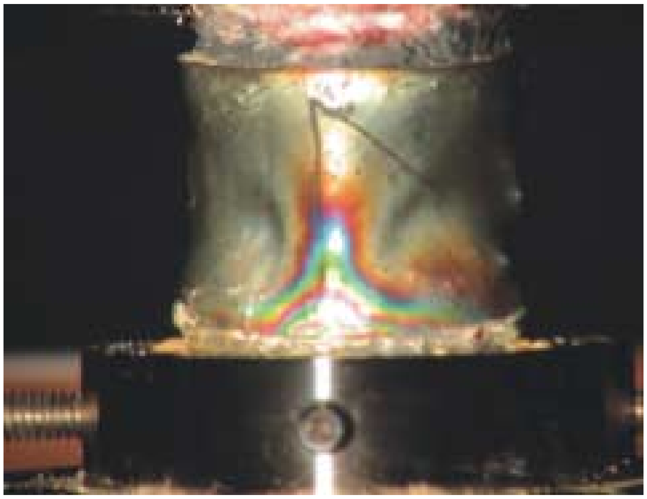

Figure 3. Test specimen with anterior damage and a 150 kg compressive load. The isochromatic strip pattern generated is clearly seen.

Results

Table 2 shows he maximum and minimum derived values for the Von Mises stresses in the experimental model. This shows that damaging any of the areas under study increases stress values. When the latter were compared with the intact disk, variations were observed, ranging from a maximum 83.43% increase when the damage occurs on the anterior portion of the disk under a 150 kg load, to a minimum increase of 27.42% at a 250 kg load when the right lateral portion of the disk is injured.

The resulting values for the Von Mises compressive loads in the mathematical model are seen on *Table 3* and show that when damage to the disk occurs in any of the study areas, the values increase. The highest variation was seen when damage is located in the posterior portion of the disk (15.3 MPa) under a 250 kg load, and the lowest variation was reported when the upper disk portion was involved (1.13 MPa) at a 250 kg load.

Discussion

The trend shown by the derived results in the experimental study matches the numerical model based on finite elements as in both models the derived values increase when damage to a portion of the intervertebral disk occurs, as compared to the intact disk.

With the experimental disk, a 27.42% minimum increase occurred by applying a 250 kg load when the right lateral surface of the intervertebral disk was injured, and a maximum 83.46% increase was seen when a 150 kg load was applied to injure the anterior surface. Notice, however, that the results show a directly proportional relationship between the load applied and the resulting stress values. Therefore, when the force applied is increased, stresses increase. In other words, maximum stress values occur when a maximum 250 kg load is applied. Notice that when the minimum 150 kg load is applied, minimum values of the compressive stresses are obtained. Maximum percentage increases are also obtained and vice versa. In other words, when applying the maximum 250 kg load, maximum values for stresses and minimum percentage increases are derived. From the biomechanical point of view, this is the result of a loss or decrease in biomechanical properties. The elements that compose the spine gradually lose their

Table 1. Mechanical properties of materials used in the numerical model.

Organic material	Elasticity module (MPa)	Poisson ratio	No. of elements
Trabecular bone	0.1 (xyz)	0.3	23,371
Cortical bone	17.0e3 (z)		
	11.5e3 (xy)	0.33	4,630
Fibers	0.5 to 30°		
	150° xz plane	0.3	9,657
Nucleus pulposus	.004 (xyz)	0.499	1,265
T plates	0.5 (xyz)	0.4	7,588

capability to recover due to the physical damage and conditions to which the spine is being subjected.

In our numerical model developed with finite elements, we find similar trends. Just as in the experimental model, we saw that minimum stress values occur when the 150 kg load is applied, and maximum values are obtained when the 250 kg load is applied. When the anterior or posterior portion of the intervertebral disk is injured, the highest compressive stress values are obtained. This is, therefore, the most critical area in our analysis and the most sensitive areas to new fractures or worsening of an existing fracture due to the loads it bears.

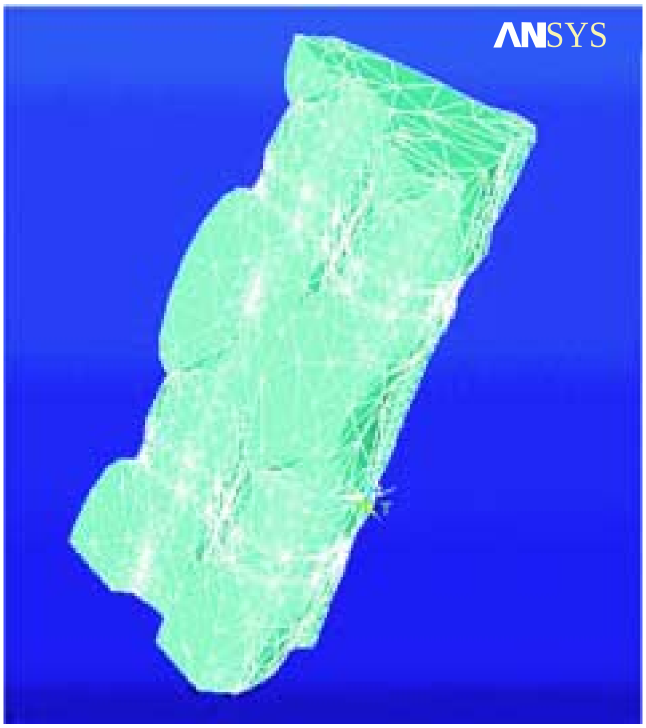

Figure 4. Method created by ANSYS.

These results derived for the compressive stresses match those obtained by Hongo,[11] Choon-Ki,[12] Wang Jam-Lin,[13] and Hansper Frei.[14] They also confirm those found by Kirkaldy-Willis,[18] who states that when an intervertebral disk undergoes degeneration or rupture, it is due to excessive stress. Our study found this same trend, i.e., the increase in stresses is variable depending on the disk area involved.

This means that, when it is damaged, the intervertebral disk stops performing its energy-buffering action. It does not, however, stop working as a load distributor, except that, with damage, the loads distributed along the vertebral body are undoubtedly increased.

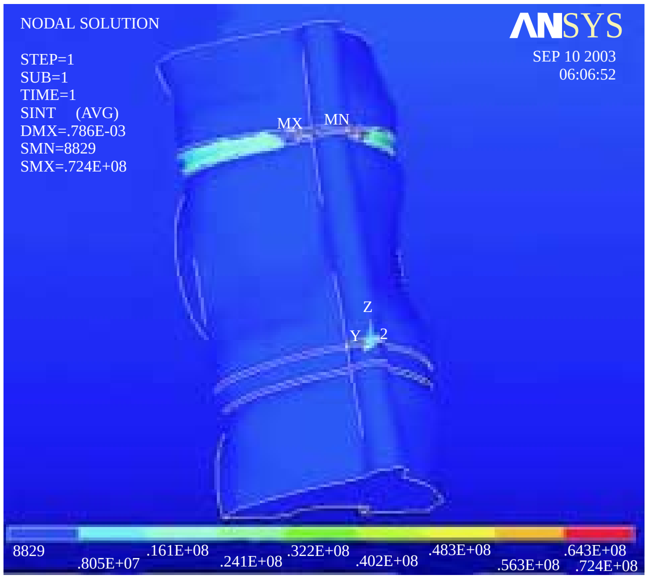

Figure 5. ANSYS run simulating the anterior damage on the intervertebral disk.

Table 2. Experimental results from photo elasticity.

	Stress derived (MPa)			
Load (kg)	Intact	Anterior	Posterior	Right
150	26.6	48.8	40.7	38.3
200	29.6	50.5	48.8	43.2
250	38.3	59.5	50.5	48.8

Table 3. Results from FEM (through the ANSYS program).

	Resulting stress (MPa)					
Load (kg)	Intact	Anterior	Posterior	Right	Left	Top
150	0.303	1.80	9.19	2.63	5.88	1.13
200	0.304	2.40	12.2	2.52	7.83	1.50
250	0.510	3.00	15.3	4.36	9.80	1.88

The increased stress on the central vertebral body is explained by the stress concept itself, from its physical conception. The stress is known to be the internal material response to external stimuli and it is measured by the force present in an element by unit of area, in the case of the intact intervertebral disk, available to support the maximum load. Hence there is a greater capacity to absorb the large amount of energy received and to distribute in a definite way the stresses to the adjacent vertebral body. When a sizeable portion is removed from this area, the stress pattern is substantially modified. The results, therefore, show that any damage to the intervertebral disk, whether to the anterior, posterior, left, right or upper portions, considerably increases the stress exerted on the central vertebral body.

Conclusions

When an intervertebral disk area is ruptured, the compressive stresses maintain an increasing trend because of the constant loads supported by that disk.

The anterior and posterior areas of the intervertebral disk bear the highest compression stresses. Therefore, they are the most likely to be injured by the forces exerted on the spine.

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