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Analysis of the impact responses in a degenerated spinal motion segment FE model †

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Abstract

A three-dimensional non-linear poroelastic finite element model of an L3/L4 motion segment was used to analyze the biomechanical effects of degeneration under impact loading on the spinal segment. A previously developed degeneration algorithm was applied to generate a degenerated disc model. Regional variation in intact vertebral body bone morphology was simulated by assigning different void ratios of 4.0-5.02, which were assessed for 27 regions of vertebral cancellous bone. For the osteoporotic structure of the vertebral body, the body was divided into 5 regions with 10-24 void ratios. Different material properties were assigned to the annulus fibers; hereupon our annulus model reflected variation in tensile behavior of multiple layer annulus samples. The impact load applied to the top of the L3 vertebral body was assumed to be a triangular impulsive force with a maximum compressive impact load of 3 kN and 20ms impact duration time. Calculated results indicated that the effect of the degeneration was predominant at the center of the vertebral body. The maximum von Mises stress was found at the region of near the endplate. The degeneration increased the averaged stress at the center of the vertebral body of L3 from 1.54 MPa to 1.69 MPa, the stress remaining relatively small at L4. Decreased fluid volume ratio of the degenerated nucleus tended to increase pressure slightly at the nucleus, and the averaged stress at the nucleus was almost doubled compared to the intact case. The innermost layers of the anterior annulus showed the highest stress concentration, followed by outermost anterior and posterior regions, for both the degenerated and the intact models. Despite an irregular stress distribution in the degenerated model, pore pressure showed relatively uniform distribution.

Keywords: Spine; Poroelastic model; Finite element model; Impact loading; Degeneration

1. Introduction

Being flexible, the intervertebral disc (IVD) allows the body to be able to assume a wide range of posture. While functioning as shock absorbers, its poroelastic characteristics with the fluid flow between the IVD and the cancellous core play a major role in absorbing impact energy. Its structural configuration provides that the disc is the major compression-carrying component of the spine. Degeneration of the disc will alter the mechanical function of the spine. Degeneration involves disorganization of the lamellar structure, ruptures, sometimes calcification of the disc center with or without disc height changes. The most interesting finding from the previous researches indicated that no consistent correlation was observed between disc degeneration and the mechanical behavior even though the viscoelastic behavior might turn out to be more related [1]. Degenerative changes in the spine may affect the structure property distribution in the vertebral trabeculae and its structural pattern. The earliest change seen was the loss of the horizontal trabeculae accompanied by thickening of

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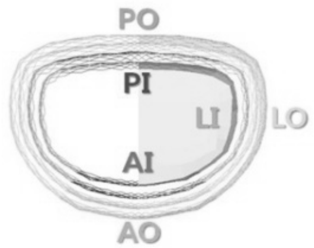
some of the vertical trabeculae.

The effect of the disc degeneration on the stiffness of the spine under impact was important to assess as this may play an important role in increasing or decreasing the risk of a vertebral fracture. Several analyses for the response to the impact loading were performed with in-vitro experiments. In the experiment, diameter change of the vertebral body [2], spinal canal encroachment [3], or neutral zone change [4] was observed for the sign of spinal injury under impact loading condition. However, experimental analysis using a human cadaver was not particularly practical to investigate the biomechanical effects due to degeneration of spinal component. A gross dissection could be made after experiment, but the assessment of disc degeneration was not quantitative. Recently, noninvasive biomechanical changes in degenerated disc in vivo were carried out with animal study [5]. They found that dorsoventral vertebral motions were dependent on mechanical excitation pulse duration. However, this experiment was conducted for only three types of pulse duration. In contrast, mathematical finite element models are well suited to overcome such limitations. Since Simon et al. [6] analyzed the response of vertebral body and disc unit under impact loading with simplified two dimensional poroelastic FE model, a rare impact analysis was carried out with an FE model [7].

Despite the fact that a degenerated spine shows a marked trend to produce more frequent injury, none of previous studies had a precise analysis of the injury on the degenerated spinal motion segment (SMS). In this paper, we improved our previously developed poroelastic FE model to reflect the effect of degeneration on the SMS and quantified the biomechanical responses of the degenerated SMS under impact loading.

Table 1. Material properties of the fibers in annulus fibrosus.



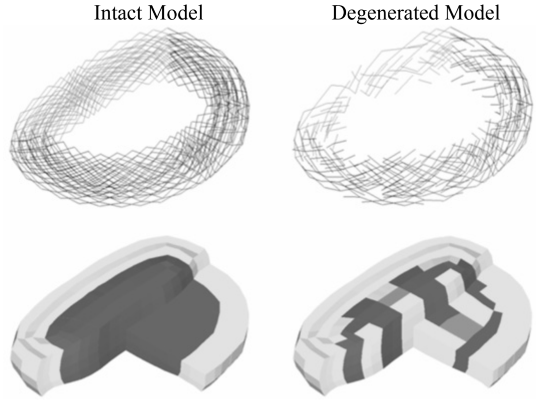
Annulus fibrosus	Young's Modulus (MPa)	Annulus fibrosus	Young's Modulus (MPa)
AI	1.4~1.7	LM2	2.45~18.73
AM1	2.13~3.77	LO	3.25 ~ 27.75
AM2	2.57~21.13	PI	0.005~0.025
AO	3.0~31.0	PM1	1.18~2.33
LI	0.7~0.86	PM2	2.34~16.34
LM1	1.66~3.05	PO	3.5 ~ 24.5

anterior (A), posterior (P), lateral (L), inner (I), outer (O), middle layer (M)

2. Methods

A three-dimensional poroelastic finite element model of L3-4 SMS that was previously developed by the authors [7, 8] was modified to incorporate more fractionized material properties within the disc and to create a degenerated SMS model. To simulate the shock-absorbing mechanism in the intervertebral joint through the fluid flow between the vertebral body and the IVD through the endplate, the cancellous core and vertebral endplate were also modeled as poroelastic materials. The model of the annulus, an amorphous ground substance with alternating ring shaped laminate structures, was composed by annulus ground matrix and reinforced collagen fibers. It was done by employing the common solid element and putting the truss elements as layer upon layer in diagonal directions. In each layer, the angle of fiber was about $\pm 34^{o}$ with horizontal axis. It was taken into account in the modeling so that the area of fiber was determined to make the total volume of collagen fibers 16% of that of annulus fibrosus. The ground substance of the annulus and nucleus was modeled as brick elements with 20 node quadratic displacement and linear pore pressure. As shown in Table 1, different material properties were assigned to the fibers; hereupon, our annulus model reflected variation in tensile behavior of multiple layer annulus samples [9].

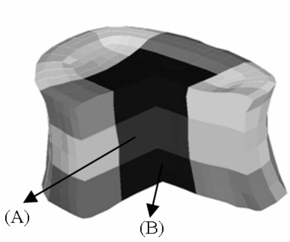
The void ratio of the annulus matrix was assumed to be 2.98 for the intact model, which corresponded to the 71% water content of the total tissue weight in the annulus. This is in agreement with Kraemer et al.'s measurement [10], in which the percentage varied between 65 – 75%. Even though the inner layers of the annulus are known to contain more water, the same void ratio was applied to every layer of the annulus model. The nucleus was



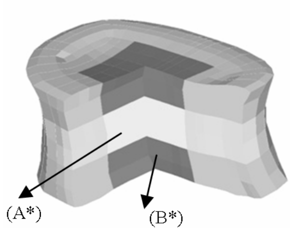
Color	Young's Modulus (MPa)	Permeability (m^4/Ns)	Void ratio	Poisson's ratio
	0.5	**3.0E-16**	**6**	**0.49**
	1.36	**1.2688E-17**	**3.79**	**0.45**
	2	**4.0096E-18**	**2.98**	**0.42**

Fig. 1. Material properties of the discs. Lines indicate the distribution of fibers in the annulus for intact and degenerated models. Parts of disc element are removed for clear view.

Table 2. Regional variation of material properties of the cancellous core in the vertebral bodies.



color	Void ratio	Permeability (m^4/Ns)
	5.02	4.26E-05
	4.90	4.16E-05
	4.80	4.07E-05
	4.70	3.99E-05
	4.60	3.90E-05
	4.50	3.82E-05
	4.40	3.73E-05
	4.30	3.65E-05
	4.20	3.56E-05
	4.00	3.40E-05



color	Void ratio	Permeability (m^4/Ns)
	24	20.37E-05
	19	16.13E-05
	15	12.73E-05
	10	8.49E-05

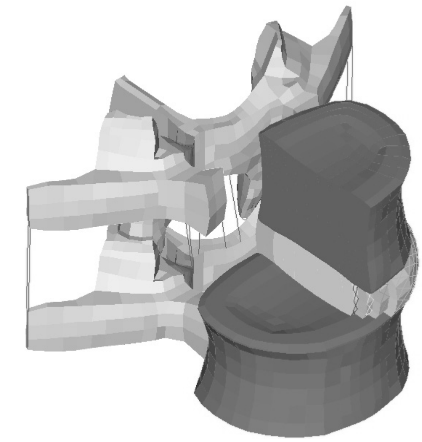


Fig. 2. L3/L4 motion segment FE model. Half of vertebral body of L3 and disc are removed for clear view.

also modeled as a poroelastic element with a void ratio of six, which implied an 86 % fluid content for an intact disc. With this modified intact model, degeneration simulation similar to Woo et al. [11] was carried out to generate a degenerated disc model. After the degeneration process, Young's modulus of the nucleus and void ratio showed regional variation of 0.5- 2.0MPa and 2.98-6.0, respectively. There are some losses in the connectivity of the annulus fibrosus due to degeneration. To mimic this phenomenon we deleted some fibers that showed excess strain during the degeneration process. Based on prior in vitro studies [9, 12], it was assumed that disc degeneration has no effect on the material properties of the annulus ground substance. Fig. 1 shows two types of disc model, intact and degenerated. The cancellous core of the vertebral body and the endplate were simulated by using homogeneous 20 node brick elements. For the cortical shell of the vertebral body, eight node shell elements were employed. Regional variation in vertebral bone morphology was simulated by assigning different void ratios of 4.0-5.02, which were assessed for 27 regions of vertebral cancellous bone**.** For the osteoporotic structure of the vertebral body, the body was divided into 5 regions with 10-24 void ratios (Table 2). A finite element model developed in this study was the motion segment of L3/4 with 7 kinds ligament as shown in Fig. 2. Neither isometric swelling pressure nor initial disc pressure was considered. A zero pressure boundary condition at the peripheral surface of the disc was applied. The impact load applied to the top of the L3 vertebral body was assumed to be a triangular impulsive force with impact duration time of 20ms. A maximum 3kN compressive force was chosen for this study to avoid divergence in calculation, even though experimental studies have indicated that initial fractures in the human spine have been found in the 9.5-13.5 kN force range. Geometrical nonlinearity was also considered for the large deformation on the disc. The general-purpose finite element program 'ABAQUS' (Hibbit, Karlsson and Soren-son, Inc., Version 6.5) was used for the execution of the models. For the time-history response the implicit method was adopted.

3. Results

A triangular compressive impulsive load with 3kN of maximum force generated the following results. The effect of the degeneration was predominant at the center of vertebral body. Averaged von Mises stress variations in the cancellous core over the entire loading period are shown in Fig. 3. The maximum stress was found at the region near the endplate (region B in Table 2).

The degeneration increased average stress at the center of the vertebral body of L3 from 1.54MPa to 1.693MPa. Similar change was noted at the L4 vertebral body even though it showed relatively small stress values. Fig. 4 shows the averaged stress and pore pressure histories at the annulus matrix and the nucleus. Due to the intact nucleus, relatively large stress and pressure was found in the annulus of the intact disc model. Decreased fluid volume ratio of the degenerated nucleus tended to increase pressure slightly at the nucleus as shown in the Fig. 4. Averaged stress at the nucleus was almost doubled compared to the intact case.

The stress and pore pressure distribution at the center plane of the disc are shown in Fig. 5 and Fig. 6.

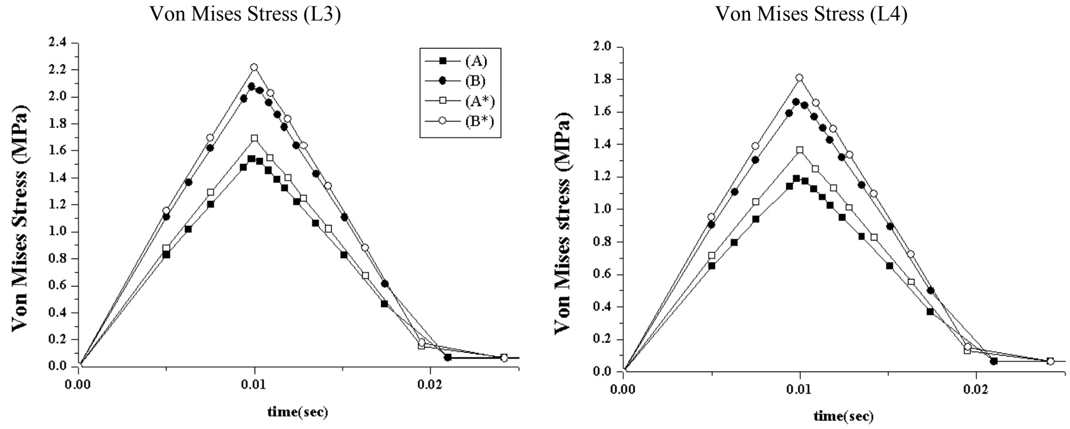
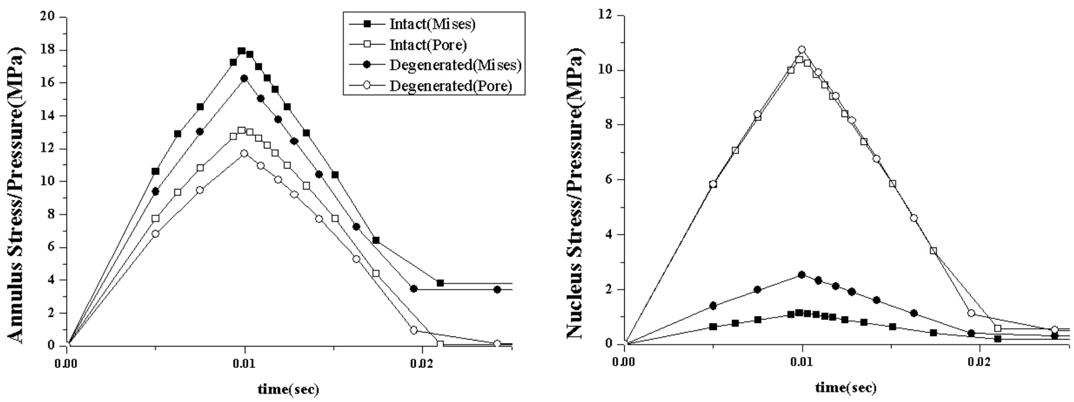


Fig. 3. Averaged stress history in the vertebral bodies. (A), (B) and (A*), (B*) indicate different regions in the intact and degenerated motion segment respectively. These regions are indicated in Table 2.



(a) (b)

Fig. 4. Von Mises stress and pore pressure history in the annulus (A) and nucleus (B) of the disc.

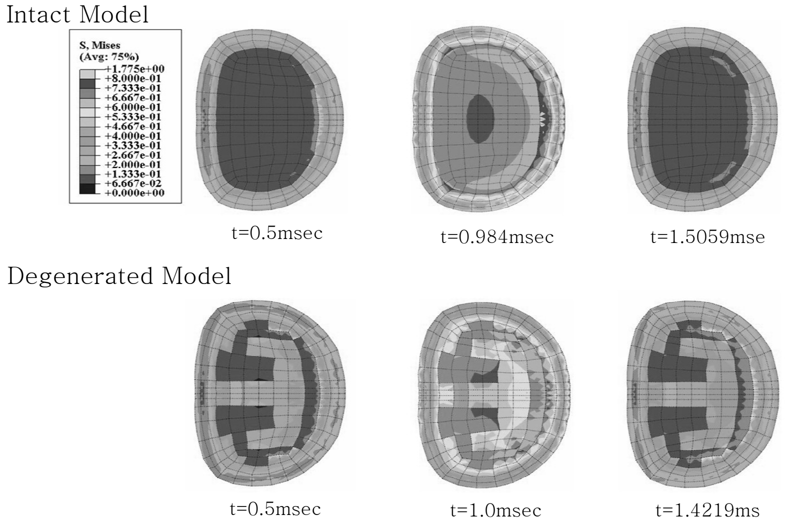


Fig. 5. Von Mises stress distribution at the center of the intervertebral disc.

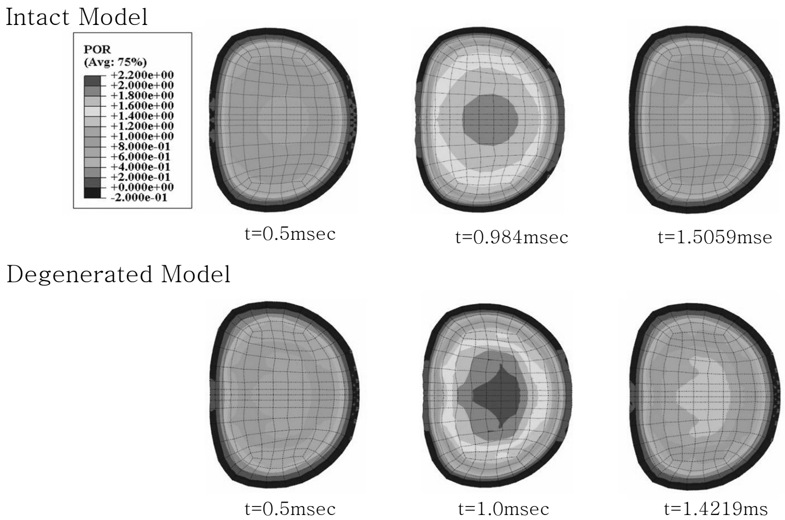


Fig. 6. Pore pressure distribution at the center of the intervertebral disc.

High stress concentrations were detected at the innermost layers of the anterior annulus, followed by outermost anterior and posterior region, for both models. Despite the irregular stress distribution in the degenerated model, pore pressure showed relatively uniform distribution.

Pore pressure distribution of the intact model indicated that high pore pressure was found at the center of the nucleus and its magnitude was uniformly decreased from the center.

4. Discussion

The degeneration effects on the mechanical response of an L3/L4 spinal motion segment under impact loading condition were studied by using a poroelastics 3-D FE model. Our previous method [11] for the degeneration process of IVD was adapted again by changing the void ratio, permeability and Young' modulus. Lotz et al.'s [13] experimental results indicated that all forms of fibrocartilage lamellas and fibers found in the nucleus pulposus had orginated and migrated from the cartilage endplate and proceeded in a centripetal direction, which is similar to our results as shown in Fig. 1. Based on observation of the frozen specimen, the nucleus and annulus became structurally similar with increasing disc degeneration [14]. This indicates that the Young's modulus of the nucleus was increased from the values of the healthy nucleus to the values of annulus ground substance, similar to our results.

The results in Fig. 3 suggest that the degenerated disc reduced its shock absorbing mechanisms. The difference of averaged von Mises stress at the center region of vertebral bodies (region A, A* in Table 2) of 0.3533 MPa for intact model decreased to 0.3301 MPa for the degenerated model. There was relatively small stress difference at the regions close to the endplate (region B, B* in Table 2). This finding indicated that a fracture will be initiated at the region close to the endplate center and disc degeneration did not significantly alter stress at this region for impact loading condition. Same clinical findings that the elderly experience more frequent central vertebral body fracture from a fall, verify this calculated result.

In our analysis, the degenerated disc did not accompany height loss; therefore, it reduced vertebral motion response. In vivo experimental result [5] showed that increased nucleus stiffness with degeneration reduced motion response. Miura et al. [15] also found that the range of motion was reduced for degenerated discs in flexion/extension and lateral bending, while it increased in axial rotation. The intact nucleus transmits compressive force to the peripheral annulus structure, while the degenerated nucleus sustains more compressive force. Reducing the water content of the nucleus makes the disc better adapted to withstand high compressive forces, because the nucleus is then less likely to be prolapsed through the posterior annulus [16]. These results could be conforming to the stress distributions in the cross sectional plane of the disc. As seen in the figure, high stress was concentrated at the inner wall of the annulus. Increasing stress brought about annulus disorganization in the inner and middle annulus [13], and then the mechanical property change will be accelerated at this region. Factors that might affect the stiffness and damping characteristics include the degenerative or hydration state of the disc, the cross-sectional size of the disc and the height of the disc.

As a result of the pore pressure distribution shown in Fig. 6, the flow movement through the outer peripheral surface of the annulus did not change, and remained at the same small value regardless of the disc degeneration. This prediction indicates that the fluid in the nucleus regardless of the disc degeneration provides initial impact resistance. However, the degenerated nucleus produced slightly higher pressure, and the stiffened nucleus did not effectively distribute the impact load to the surrounding annulus. Moreover, increased stress in the nucleus of a degenerated disc will create fissure at this region. This fissure will decrease disc height and induce consequent degeneration to the connected structure. The described methodology has a few limitations regarding the simulation of grades of disc degeneration. The effects of degeneration on the mechanical properties and geometrical changes of spinal ligamentous structure are still unknown [14]; furthermore, the effect of annulus tear seen during degeneration was not considered in this analysis. We intended to perform a first step into the simulation of motion segment degeneration under impact loading; nevertheless, the results of this study can only indicate trends.

5. Conclusion

The finite element technique was addressed to analyze the effect of degeneration of the SMS under impact in producing trauma to the SMS. Within the limitations of our model, our results suggest that fractures are more likely to occur in the degenerated SMS. Intact disc with pressure containing nucleus introduced load to the central part of the vertebra, so that the central portion of the endplate is highly stressed. A similar result was derived for the degenerated disc. For severely degenerated discs, when the nucleus loses its fluid-like properties accompanied with disc prolapse, this influence is obviously still more pronounced. Especially, the effect of these changes will be distinct in shock absorbing pattern. The authors are pursing these studies further, and hope to report their findings in the future.

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