J. Biomed. Eng. Res.
Vol. 21, No. 3, 285-293, 2000

유한 요소법을 이용한 나이에 따른 척추의 형상 및 구조변화의 효과

김 용

선임 연구원 연구7팀, 단말기 사업부 현대전자

(2000년 1월 24일 접수, 2000년 6월 1일 채택)

Age-related Geometric Effects on the Human Lumbar Spineby the Finite Element Method

Y. Kim Ph D

Mechanical Engineer Sr. R&D Team 7. Hyundai Electronics Industries, Korea

(Received January 24, 2000. Accepted June 1, 2000)

요 약 : 나이에 의한 외부의 환경조건의 변화는 이에 적응하려는 척추의 구조적인 변화를 가져온다. 이러한 구조적인 변화는 척추의 biomechanical 거동에 영향을 미칠 것이다. 이러한 구조적인 변화의 효과를 연구하기 위하여, 나이에 의한 척추의 재료 및 기계적인 물성의 변화는 제외되었다. 유한요소법 (finite element method)에 의한 lumbar spine model (L3-L4)에 있어서, Annulus 의 유한요소 모델은 laminate composite elements로서 16개의 layer와 6개의 물성으로 구성되어있다. Spinal stiffness 와 facet reaction은 나이가 들수록 증가했다. 나이가 들수록 inner annulus의 fiber/layer tensile strains, cancellous bone stress 및 end-plate stress는 감소했다. Fiber/layer compressive strains, facet reaction, ligament reaction and end-plate rigidity는 나이에 의한 척추의 구조적인 변화에 의하여 증가했다. 따라서 나이에 의한 척추의 정상적인 쇠퇴과정에 있어서 척추의 구조적인 변화는 spinal stiffness를 증가 시켜서 척추 및 disc의 지나친 변형을 감소시킬 것이다.

Abstract : Age-related changes in the geometry of human lumbar spine would lead to changes of its mechanical behaviors. To investigate the effects of the geometric changes, no age-related changes in the material/mechanical properties were considered. Using the finite element method, two age-related models of lumbar spine segments (L3-L4) were constructed. The annulus of the models was modeled as laminate composite elements with 16 layers and 6 materials. The spinal stiffness and facet reaction of the lumbar spine increased with the age-related geometric changes in various combined loadings. Fiber and transverse tensile strains of the inner annulus, cancellous bone stress and end-plate stress decreased with the age-related geometric changes whereas fiber/layer compressive strains of the annulus, facet reaction, ligament reaction and end-plate rigidity increased. Consequently, it appears that in the normal age-related deterioration of discs, the age-related geometric change contributes to the increase of spinal stiffness (the decrease in range of the motion segment), preventing an excessive deformation of the disc.

Key words : Intervertebral disc, Vertebral body, Annulus, Range of motion)

INTRODUCTION

Most of materials of lumbar spine deteriorate with aging, decreasing their mechanical properties. In particular, the materials of intervertebral disc degenerate with aging, leading to disc prolapse. These changes of the materials would reduce spinal stiffness. That is, based on degeneration of the materials, spine segments is likely to be more compliant with aging. In general, however, spinal stiffness increases(or range of motion of spine segments decreases) with aging. Although the minimum and maximum ranges of motion of lumbar spine segments even in the same age and sex group indicate wide variations, a decrease of the mean values in all ranges of motion has been observed for all groups after maturity(Taylor and Twomey 1980, Sullivan et al. 1994). Taylor and Twomey (1980) measured the range of motion of human cadaveric lumbar spine in a force of 3.5kg(corresponding to 34.5 N)

통신저자 : 김 용, (143-130) 서울 광진구 화양동 15-51
Tel. 016-244-2156
Email. ykim8@hotmail.com

to produce a full range of motion without damage to the specimens. Under the same loading, the decline in the range of motion with aging means a stiffness increase of the lumbar spine. On all movements of lumbar spine the oldest group (60-80 years) is significantly stiffer than all younger age groups (Netzer and Payne 1993). Degenerated material properties of lumbar spine with aging would lead to a decrease of its stiffness. Tears or fissures in annulus induced by age-related material degeneration(such as dehydration of the disc) would lead to irregular distributions of the annulus fibers. These tears would not contribute to the increase of spinal stiffness. Furthermore, the material data with aging are still unclear for computer simulation, requiring further experimental study. In this study, therefore, no age-related changes of the material properties were considered.

A decline in stature of the spine is one of the remarkable age-related changes in old age. The decline is attributed to a loss in average vertebral height and a change in vertebral body shape in old age (Twomey and Taylor 1987). They showed that little change occurs in mean height of the disc with aging. The lumbar vertebral bodies consequently become more concave and generally increase their mid-height in old age. The decline in stature of the spine would lead to a decrease of facet gap distance. The anteroposterior diameter of the disc increases by 15% in old age (Amonoo-Kuofi 1991), increasing the cross-section area of the disc. Pedicle diameter enlarged by 10% in old age (Amonoo-Kuofi 1995). These geometric changes may assist in an increase of stiffness(or a decrease of range of motion) of lumbar spine.

The purpose of this study is to investigate the effects of the age-related geometric changes on the lumbar spine segments(L3-L4) through a finite element analysis, which can provide unique and insightful information.

METHOD

Spine model (L3-L4)

In order to investigate age-related geometric effects of lumbar spine segments, the spine segments (L3-L4) were classified into two types with age: Model A for the young adults with ages ranging from 18 to 35 years, Model B for older than 60 years of age (Figure 1, Table 1). The geometric data for the modeling were based on the recent studies (Panjabi et al. 1992, 1993, Grobler et al. 1993, Marchnad and Ahmed 1990). Model A and Model B were distinguished by the age-related geometric factors shown in Table 1. The functional annulus regions of both models were determined by the layer thickness and the total layer number observed by Marchand and Ahmed (1990). An increase of disc area was assumed to be 10%

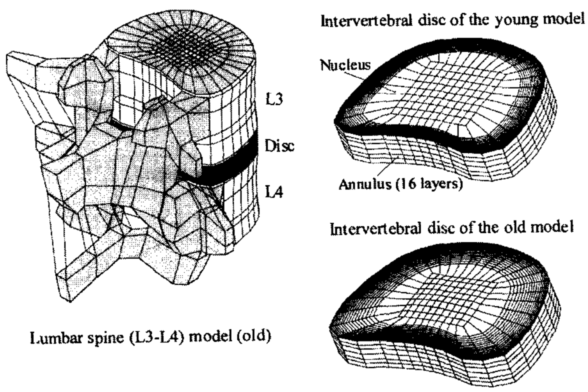


Fig. 1. The young and old models. The annulus is composed of composite elements with 16 layers. The left plots represent the layer thickness to the normal surfaces in both models. The nucleus occupies the core region of the intervertebral disc

Table 1. Age-related parameters of the young and old spine segments (L3-L4)

Model	Age (year)	Posterior facet gap (mm)	Disc height (mm) anterior/mid/posterior	Area ratio (nucleus/disc,mm^2)	Pedicle diameter (mm)*
Model A (Young)	18-35	0.6	9.6/10.7/8.5	52.2% (819/1568)	L3:H10.3, V16.8 L4:H11.7, V17.0
Model B (Old)	over 60	0.4	9.3/11.3/8.1	30.8% (531/1725)	L3:H12.1 V17.5 L4:H12.6, V17.8
Reference		Shirazi-Adl 1994	Twomey and Taylor 1987	Adams et al. 1996, Nachemson 1960, Amonoo-Kuofi 1991	Amonoo-Kuofi 1995

* H: Horizontal diameter, V: Vertical diameter

with aging (Nachemson 1960, Amonoo-Kuofi 1991). The material/mechanical properties of the models are shown in Tables 2 and 3. An alternate orientation of 60° of annulus fibers to the vertical axis was assumed to be unchanged with aging (Hickey and Hukins 1982). The inclination of the posterior facets of both models is 8.0° to the vertical axis(Sharma et al. 1998).

ANSYS(Ver. 5.5, Swanson Analysis Systems, Inc., Houston. PA), a commercial finite element program, was used for this study. In formulation of the three-dimensional finite element model of the lumbar spine segments (L3-L4), the end-plate, the cancellous bone, the cortical bone and the posterior bony elements were modeled as isoparametric eight-node elements with 6 degrees of

Table 2. The mechanical properties of the spine model. 6 tensile Young's moduli of annulus fibers with respect to the anatomic region represent 6 different materials of the annulus according to the literature (Skaggs et al. 1994)

Materials	Young's modulus (MPa)	Poisson's ratio	Reference
Cortical bone	12000	0.3	
Cancellous bone	120	0.2	Mosekilde et al. 1987
Posterior bone	3500	0.25	
End-plate	120	0.4	Mosekilde et al. 1987
Annulus layer (fiber dir.)			Acaroglu et al. 1995
Anterior (inner/mid/outer)	76/106/136	1.5/1.35/1.2	Marchand and Ahmed 1990,
Lateral	76/106/136	1.5/1.35/1.2	Skaggs et al. 1994
Posterolateral	59/71/82	1.7/1.5/1.3	
Posterior	59/71/82	1.7/1.5/1.3	
Nucleus (fluid)	1.667e9 (bulk modulus)	0.4999	
Ligaments		Cross-sec. Area, mm^2	White and Panjabi 1990
Anterior longitudinal	7.8	22.4	Nachemson and Evans
Posterior longitudinal	10	7.0	1968
Ligamentum flavum*	17	14.1	
Transverse ligament	10	0.6	
Capsular ligament	7.5	10.5	
Intraspinous	10	14.1	
Supraspinous	8.0	10.5	

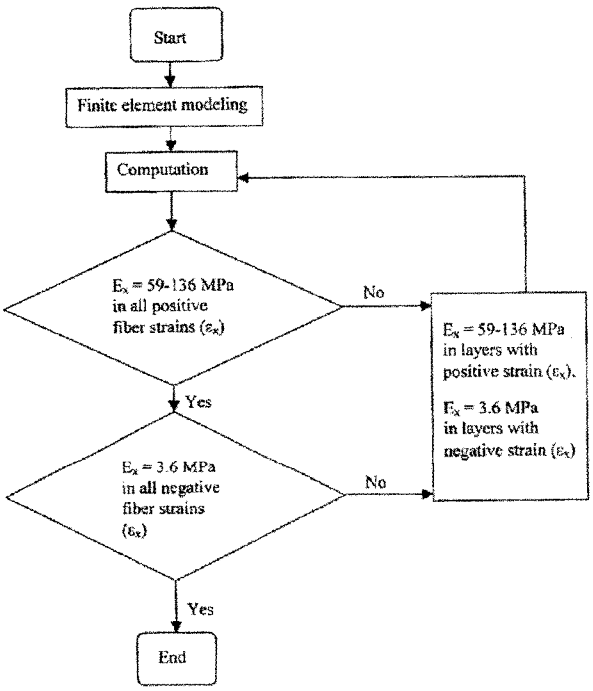
*prestrain 5% (Nachemson and Evans 1968)

Table 3. The mechanical properties of the annulus of the model to the principal direction

Young's modulus, MPa		FEM	Reference (FEM)	Reference (experimental)
Fiber direction	Tensile	59-136	Kim and Goel 1988	Skaggs *et al.* 1994
	Compressive	3.6	Goel et al. 1995	Umehara *et al.* 1996
Transverse direction	Tensile	3.0		
	Compressive	3.0		Umehara *et al.* 1996
Normal direction	Tensile	3.0	Shirazi-Adl 1994	Fujita *et al.* 1997, Marchand and Ahmed 1989
	Compressive	3.0		Best *et al.* 1994, Houben *et al.* 1997
Shear modulus, MPa		2.1		
Poisson's ratios (major)		Vxy=1.2-1.7 Vyz=0.7* Vxz=0.5*		Acaroglu *et al.* 1995

* Major Poisson's ratios were determined by restrictions of orthotropic materials.

freedom including 3 translations and 3 rotations. These bones are assumed to be isotropic materials. The cortical bone on the surface of the vertebral body was modeled as plate shell elements with 6 degrees of freedom. The annulus of the intervertebral disc was assumed to be 6 composite materials(Table 2). The annulus was modeled with eight-node laminate composite elements with 3 translational degrees of freedom. Interpolation elements established the transition between these elements(6 DOF elements and 3 DOF elements). The fibers of ligaments are bilinear isotropic elastic materials that have large stiffness in tension and are very compliant in compression. The stiffness of ligaments was removed if their element goes into compression. The fibers of the ligaments were then modeled as cable elements supporting tension only. Compliant articular cartilage layers of the posterior facets were modeled as spring elements with 75 MPa spring constant(Shirazi-Adl 1994, Sharma et al. 1998). The gap between the articular cartilage layers was modeled with gap elements which can support a compressive normal load to the surface. The gap distance of the facet articulation in Models A and B was assumed to be 0.6



-chart for computation of the finite ele-
moduli of annulus fibers were updated
to approach the material non-linearity
ensile and compressive elastic moduli
1 3

and 0.4mm, respectively(Shirazi-Ad
of the nodes and the elements in the
3324 and 3135, respectively. The inferi
finite element models (L3-L4) were
Muscle activation around the spine was i
study.

According to the experimental studies (Pa
1994, Schultz et al. 1979, Tencer et al. 1
nonlinear effect of the lumbar specimen decreases
preload increases. Under the preload of 100 N, material nonlinearity is more apparent than the linea of the materials(Panjabi et al. 1994). However, under th preload of 823 N, the material linearity is striking(Tencer et al. 1982). Since axial compression due to body weight is pronounced on the human lumbar spine, 823 N preload is equivalent to body weight of 65 kg, provided that axial compression on the L3 body is 1.3 times of the body weight. 823 N preload was uniformly applied to the superior surface of the models. Then, various angular displacements (torsion, extension, flexion and lateral bending) were superposed on the 823 N preload.

In the annulus principal strains were based on a local layer coordinate system in order to investigate annulus fiber behavior exactly. Orientations of the principal strain were classified into the deformed fiber, transverse(to the fiber direction) and normal(to the layer surface) directions. The posterior reaction force is a vector summation of all the forces on the posterior facets.

In the current study, the assumption that annulus is composed of linearly orthotropic laminate materials(that is, the compressive elastic modulus of annulus fibers is the same as the tensile elastic modulus of annulus fibers) re-

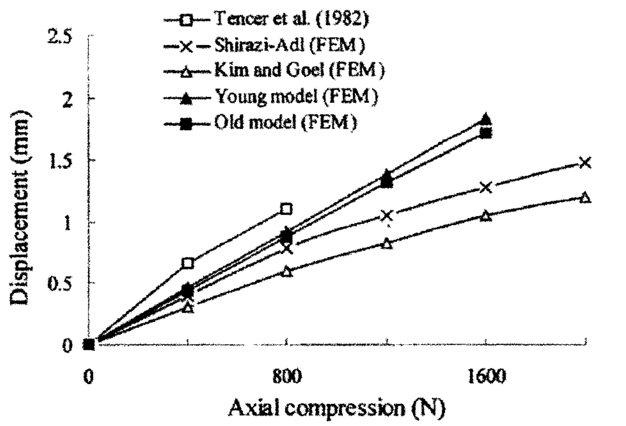


Fig. 3. The force-displacement curves of the lumbar spine segments (L3-L4) in axial compression. The o model is a little stiffer than the young model

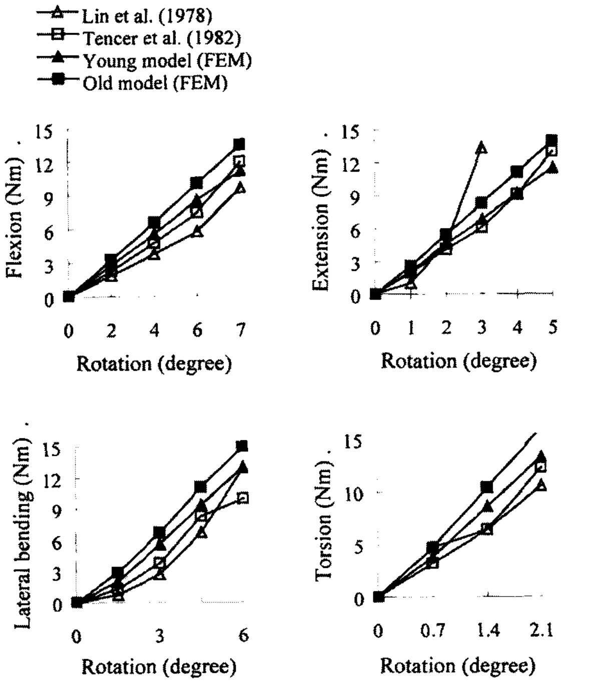


Fig. 4. The moment-angular displacement curves of the lumbar spine segments (L3-L4) under combined various loadings

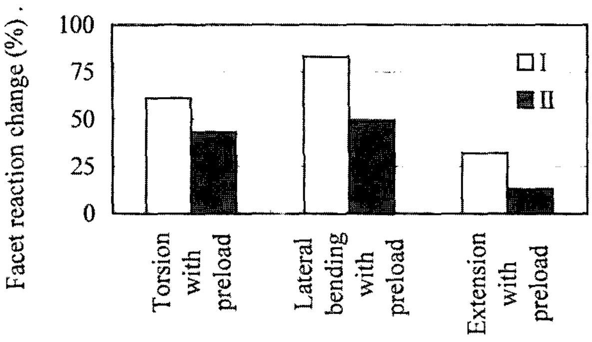


Fig. 5. Facet reaction increases with age-related geometric changes. A reduction of facet gap distance plays an important role in increasing the facet load of the spine segments (I: change of the old model to the young model, II: change of a case of the young model with 0.4 mm (instead of 0.6 mm) gap distance to the young model)

quired further consideration in computation of the model. Tensile elastic moduli of the fibers are 59-136 MPa while compressive elastic moduli of the fibers are less than 4 MPa(Tables 2 and 3). In order to overcome this problem of the assumption, an iterative scheme was introduced as shown in Figure 2. Through the scheme, the elastic moduli of the fibers were updated until the elastic moduli were defined properly.

RESULTS

In general, the predicted parameter increased in proportion to the applied loads as shown in Figures 3 and 4. Due to the near linear relationship between the parameters and load, the data in the following paragraphs are based on the maximum load of each applied loading condition (Figures 3 and 4).

Spinal stiffness and facet reaction

In Figure 3 the displacement-load curves of the two finite element models were compared with the experimental study (Tencer et al. 1982) and with the previous finite element studies (Shirazi-Adl et al. 1984, 1987, Kim and Goel 1988) in axial compression. The results of the current models are more linear than the previous finite element models. In Figure 4 the rotation-moment relationships under several moments with 823 N preload are in good agreement with Tencer et al. (1982). In compression, torsion, lateral bending and extension the spinal stiffness and the facet reaction increase with age-related geometric changes (Figures 4 and 5). No facet load was found in axial compression or/and in flexion moment. In order to investigate effects of a facet gap change, a case of the young model with 0.4 mm in facet gap distance (instead of 0.6 mm) was considered. This reduction of facet gap distance increased the facet reaction (Figure 5).

Intervertebral disc

The annulus was mechanically analyzed. The principal strains of the annulus layers with respect to the principal direction were shown in Figure 6. In Figure 6, the negative strains of fiber direction predict compressive fiber behavior. The positive strains of fiber direction predict tensile fiber behavior. The negative strains of transverse

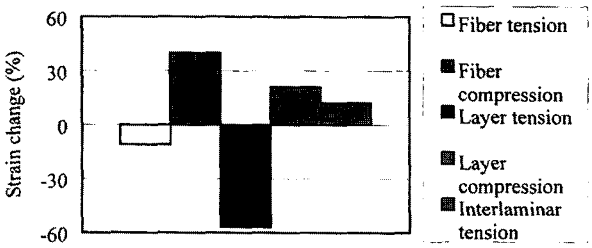


Fig. 6. The changes of the old model to the young model in the principal strains of the annulus ((old-young)*100/young)

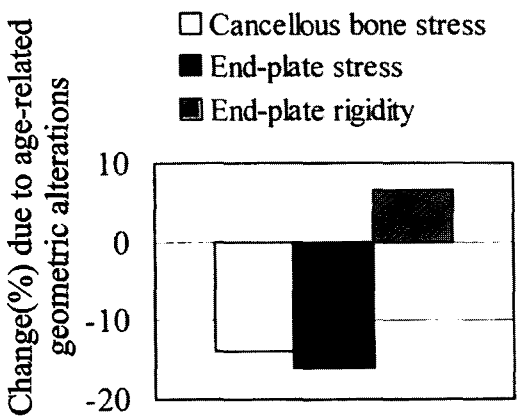


Fig. 7. The maximum von Mises stresses of the cancellous bone and end-plate of the young model decrease with the age-related geometric changes ((old-young)* 100/young)

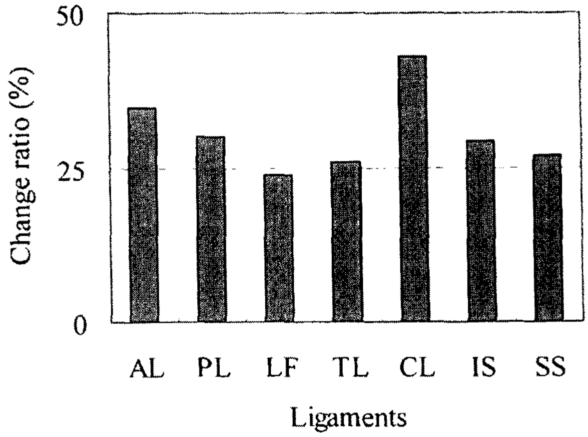


Fig. 8. The change ratio, (old-young)*100/young, of the average forces applied on ligaments in various combined loadings. The age-related geometric changes lead to 23-43% increase (AL: Anterior longitudinal, PL: Posterior longitudinal, LF: Ligamentum flavum, TL: Transverse ligament, CL: Capsular ligament, IS: Intraspinous, SS: Supraspinous)

direction to the fiber direction represent layer compression. The positive strains of the transverse direction represent layer tension. The positive strains of normal direction to the layer surface represent interlaminar tension. In axial compression, fiber and layer tensile strains decrease with the age-related geometric changes whereas fiber and layer compressive strains and interlaminar tensile strain increased (Figure 6).

Cancellous bone, end-plate and ligaments

Figure 7 shows that the maximum von Mises stress of cancellous bone is higher at the young model as compared with the old model. The maximum stress of the young model was 2.9 MPa and the corresponding stress of the old model was 2.7 MPa. The maximum von Mises stress occurred at the posterocentral region of the cancellous bone adjacent to the disc in both finite element models.N

End-plate displacement occurs under axial compression. The centrahe annulus layers with respect to the principal direction were shown in Figure 6. In Figure 6, the negative strains of fiber direction predict compressive fiber behavior. The positive strains of fiber direction predict tensile fiber behavior. The negative strains of transverse direction to the fiber direction represent layer compression. The positive strains of the transverse direction represent layer tension. The positive strains of normal direction to the layer surface represent interlaminar tension. In axial compression, fiber and layer tensile strains decrease with the age-related geometric changes whereas fiber and

In addition, the average forces on ligaments increased by 23-43% with the age-related geometric changes in various combined loadings (Figure 8).

DISCUSSION

In Figure 3 the displacement-load curves of the current normal models was compared with the previous finite element and experimental studies (Tencer et al. 1982, Shirazi-Adl et al. 1984, 1987, Kim and Goel 1988). The literature provides a vast range of behaviors because the characteristics of experimental specimens vary with each individual, and because testing methods vary. The results of the present models are more linear than the previous finite element models. The reason is in axial compression that the present model shows no facet load transmission in agreement with the literature (Sharma et al. 1998, Lin et al. 1978, Tencer et al. 1982) while others showed 2~13% facet load transmission. In the current models (L3-L4 level), the facets were inclined at an angle of 82° to the transverse plane, while the corresponding angle is 72° for L3-L4 (Kim and Goel 1988) and 63° for L2-L3 (Shirazi-Adl et al. 1984 and 1987), respectively. The nonlinear curves of the experimental literature (Lin et al. 1978, Tencer et al. 1982) might attribute to material nonlinearity of the annulus fibers (Skaggs et al. 1994), not the facet load transmission because the same trend of the nonlinearity was observed without the posterior facets

(Lin et al. 1978). However, the literature (Kim and Goel 1988, 1995, Shirazi-Adl et al. 1984, 1987) and the current models do not include the material nonlinearity of the annulus fibers reported by Skaggs et al (1994). Instead of the material nonlinearity, with an iteration scheme in computation of the model, the current model of the annulus could approach closely their material non-linearity between tensile and compressive elastic moduli in annulus fibers, requiring 4-35 iterations with loading conditions.

Sullivan et al. (1994) reported in 1126 healthy subjects that total sagittal range of motion of lumbar spine declines with aging. Taylor and Twomey (1980) reported in vivo and ex vivo tests that the range of sagittal and horizontal plane movements decreases with aging. The decline angle in the sagittal range is 13° ex vivo and 12° in vivo (Taylor and Twomey 1980). In the current study, for study of this decrease of the range of motion (or the increase of spinal stiffness), many age-related factors were considered. According to Amonoo-Kuofi (1991 and 1995), there is an overall increase in the various dimensions of the disc with aging. He showed in the mean anteroposterior diameters of lumbar discs that male discs gained by 20-25%, while female discs increased by 11-17%. Nachemson (1960) classified 121 post-mortem discs with age and measured their cross-section area. From his measurement the mean disc area in range of 20-35 years age is 18.4 cm^2 while the corresponding area in range over 60 years age is 20.4cm^2. That is, an increase of the area between these two groups is about 11%. In the current study, with the above age-related geometric change the stiffness could increase significantly. Furthermore, an increase of spinal stiffness due to decrease of facet gap distance could occupy 15-39% of the total stiffness increase between the young and old adult in extension, lateral bending and torsion. This increase of spinal stiffness may be in part related with blocking by facet joints because facet reaction increases with aging. Taylor and Twomey (1980) showed in flexion that the decline angle is 10-20° with aging. If there is no facet reaction in flexion according to Sharma et al. (1998), the decrease of flexion motion range could be independent on posterior facet reaction and is likely to be attributed to the age-related geometric change. Therefore, the age-related geometric change of the spine segments could play a significant role in an increase of spinal stiffness (decrease of range of motion), responding to the changing needs of the body.

In summary, after skeletal maturity, the spinal structure undergoes slow alterations with aging and its change varies with individuals. The primary geometric changes after skeletal maturity include a loss of disc height with a decrease in facet gap distance (or increased concavity of end-plate into the vertebral body with a decrease in the height of the annulus) and an increase in diameter of disc and pedicle. These alterations could increase spinal stiffness(or decrease range of motion), ligament force and facet reaction. A decrease in the range of motion is likely to contribute to preventing an excessive deformation of the annulus. Furthermore, the age-related geometric changes would alter the loads applied to spinal facet joints, ligaments and the muscles near spinal segments. Also, it seems that there is a relationship between the geometric and material changes because they change together after maturity and because a geometric change (e.g., an increase in disc area) may lead to a coarse or more irregular distribution of annulus fiber. Geometric changes would occur to respond to the changing needs of the body while material property changes would induce disc degeneration. The relationship between the geometric and material changes is to be investigated in further study.

Consequently, the present study indicates that age-related changes in the geometry of the lumbar spine would be a primary factor in the decrease of range of motion(increase of spinal stiffness), and lead to alterations of facet reaction, ligaments force, stress/strain distribution in annulus and bone stress, based on an average young and old individual.

REFERENCES

1. E.R. Acaroglu, J.C. Latidis, L.A. Setton, R.J. Foster, V.C. Mow and M. Weidenbaum, *"Degeneration and Aging Affect the Tensile Behavior of Human Lumbar Annulus Fibrosus"*, Spine, Vol. 20, pp.2690-2701, 1995
2. M.A. Adams, D.S. McNally and P. Dolan, *"Stress distributions inside intervertebral discs; The effects of age and degeneration"*, J Bone Joint Surge (Br), Vol. 78(6), pp.965-972, 1996
3. H.S. Amonoo-Kuofi, *"Morphometric Changes in the Heights and Anteroposterior Diameters of the Lumbar Intervertebral Discs with Age"*, J Anat, Vol. 175, pp.159-168, 1991
4. H.S. Amonoo-Kuofi, *"Age-related Variations in the Horizontal and Vertical Diameters of the Pedicles of the Lumbar Spine"*, J Anat, Vol. 186, pp.321-328,

1995
5. B.A. Best, F. Guilak, L.A. Setton, W. Zhu, F. Saed-Nejad, A. Ratcliff, M. Weidenbaum and V.C. Mow, *"Compressive Mechanical Properties of the Human Annulus Fibrosus and Their Relationship to Biochemical Composition"*, Spine, Vol. 19, pp.212-221, 1994
6. D.S. Hickey and D.W.L. Hukins, *"Aging Changes in the Macromolecular Organization of the Intervertebral Disc: an X-ray Diffraction and Electron Microscopic Study"*, Spine, Vol. 7, pp.234, 1982
7. Y. Fujita, N.A. Ducan and J.C. Lotz, *"Radial tensile properties of the lumbar annulus fibrosus are site and degeneration dependent"*, J. Orthop Res, Vol. 15(6), pp.814-819, 1997
8. V.K. Goel, B.T. Monroe, L.G. Gilbertson and P. Brinckmann, *"Interlaminar Shear Stresses and Laminae Separation in a Disc"*, Spine, Vol. 20, pp.689-698, 1995
9. L.J. Grobler, P.A. Robertson, J.E. Novotny and M.H. Pope, *"Etiology of Spondylolisthesis: Assessment of the Role Played by Lumbar Facet Joint Morphology"*, Spine, Vol.18, No.1, pp.80-91, 1993
10. Houben GB, Drost MR, Huyghe JM, Janssen JD and Huson A, *"Nonhomogeneous permeability of canine annulus fibrosus"*, Spine, Vol. 22(1), pp.7-16, 1997
11. Y.E. Kim and V.K. Goel, *"Biomechanics of Chemonucleolysis"*, The winter annual meeting of the ASME 1988, Nov.27-Dec.2, BED-Vol. 9, pp.461-471, 1988
12. H.S. Lin, Y.K. Liu and K.H. Adams, *"Mechanical Response of the Lumbar Intervertebral Joint under Physiological (Complex) Loading"*, J. Bone & Joint Surg, Vol. 60, pp.41-54, 1978
13. F. Marchand, A.M. Ahmed, *"Investigation of the Laminate Structure of Lumbar Disc Annulus Fibrosis"*, Spine, Vol. 15, pp. 402-410, 1990
14. L. Mosekilde, L. Mosekilde and C.C. Danielson, *"Biomechanical Competence of Vertebral Trabecular Bone in Relation to Ash density and Age in Normal Individuals"*, Bone, Vol. 8, pp.79-85, 1987
15. A.L. Nachemson, *"Lumbar Intradiscal Pressure"*, Acta Orthop Scand, Suppl 43, pp.1-140, 1960
16. A.L. Nachemson and J. Evans, *"Some mechanical Properties of the Third Lumber Inter-laminar Ligament [ligamentum flavum]"*, J Biomech, 1968, Vol. 1, pp.211, 1968
17. O. Netzer and V.G. Payne, *"Effects of Age and Gender on Functional Rotation and Lateral Movements of the Neck and Back"*, Gerontology, Vol. 39(6), pp.320-326, 1993
18. M.M. Panjabi, T.R. Oxland, I. Yamamoto and J.J. Crisco, *"Mechanical Behavior of the Human Lumbar and Lumbosacral Spine as Shown by Three-Dimensional Load-Displacement Curves"*, J Bone & Joint Surg, Vol. 76-A (3), pp.413-424, 1994
19. M.M. Panjabi, V.K. Goel, K. Takata, J. Duranceau, M. Krag and M. Price, *"Human Lumbar Vertebrae-Quantitative Three-Dimensional Anatomy,"* Spine, Vol. 17, pp.299-306, 1992
20. M.M. Panjabi, T. Oxland, K. Takada, V.K. Goel, J. Duranceau and M. Krag, *"Articular Facets of the Human Spine: Quantitative Three-Dimensional Anatomy,"* Spine, Vol.18, No.10, pp.1298-1310, 1993
21. A.B. Schultz, D.N. Warwick, M.H. Berkson and A.L. Nachemson, *"Mechanical Properties of Human Lumbar Spine Motion Segments - Part I: Responses in Flexion, Extension, Lateral Bending, and Torsion"*, J Biomech Engr ASME, Vol. 101, pp.46-51, 1979
22. M. Sharma, N.A. Langrana and J. Rodriguez, *"Modeling of Facet Articulation as a Nonlinear Moving Contact Problem: Sensitivity Study on Lumbar facet Response. ASME, J. Biomechanical Engineering"*, Vol. 120, pp.118-125, 1998
23. A. Shirazi-Adl and G. Drouin, *"Load-bearing Role of facets in a Lumbar Segment under Sagittal Plane Loadings"*, J. Biomechanical Engineering, Vol. 20, pp.601-614, 1987
24. A. Shirazi-Adl, S.C. Shrivastva and A.M. Ahmed, *"Stress Analysis of the Lumbar Disc-body Unit in Compression"*, Spine, Vol. 9, pp.120-134, 1984
25. S.A. Shirazi-Adl, *"Nonlinear Stress Analysis of the Whole Lumbar Spine in Torsion-Mechanics of Facet Articulation"*, J Biomech, Vol. 27, pp.289-299, 1994
26. D.L. Skaggs, M. Weidenbaum, J.C. Latridis, A. Ratcliffe and V.C. Mow, *"Regional Variation in Tensile Properties and Biochemical Composition of the Human Lumbar Annulus Fibrosis"*, Spine, Vol. 19 (12), pp.1310-1319, 1994
27. M.S. Sullivan, C.E. Dickinson and J.D. Troup, *"The Influence of Age and Gender on Lumbar Spine Sagittal Plane range of Motion. A Study of 1126 Healthy Subjects"*, Spine, Vol. 19, pp.682-686, 1994
28. J. Taylor, L. Twomey, *"Sagittal and Horizontal Plane Movement of the Human Lumbar Vertebral Column in Cadavers and in the Living"*, Rheumato-

logy and Rehabilitation, Vol. 19, pp.223-232, 1980

29. A.F. Tencer, A.M. Ahmed and D.L. Burke, *"Some Static Mechanical Properties of the Lumbar Intervertebral Joint, Intact and Injured"*, J Biomechanics, Vol. 104, pp.193-201, 1982
30. L.T. Twomey and J.R. Taylor, *"Age Changes in Lumbar Vertebrae and Intervertebral Discs"*, Clin. Orth. And Related Research, Vol. 224, pp.97-104, 1987
31. S. Umehara, S. Tadano, K. Abumi, K. Katagiri, K. Kaneda and T. Ukai, *"Effects of degeneration on the elastic modulus distribution in the lumbar intervertebral disc"*, Spine, Vol. 21(7), pp.811-9, 1996
32. A.A. White and M.M. Panjabi, Clinical Biomechanics of the Spine. 2nd ed., J.B. Lippincott, Philadelphia, pp.20-28, 106-112, 1990