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Lumbar spine 의 뼈와 Interbody cage의 접촉면에서 기계공학적 민감성 고찰

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The Mechanical Sensitivity at Interfaces between Bone and Interbody Cage of Lumbar Spine Segments

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요 약 : 뼈의 성장에 미치는 많은 요소들 중에서 implant의 상대적인 미세운동(relative micromotion)은 뼈의 implant와의 접합을 방해하는 것으로 알려져 왔다. 그런데 이러한 상대적인 운동 및 spinal stability에 직접적으로 영향을 주는 하중조건, spinal material의 물성치, spinal geometry 및 뼈와 implant의 접촉면에서의 마찰계수를 고려하기 위하여, 하나의 titanium interbody cage 가 삽입된 human lumbar segments (L4-L5)의 유한요소 모델이 개발되었다. 이러한 유한요소 모델의 해석을 통하여 상대적인 미세운동, posterior의 수직적인 변위, von Mises 응력 및 마찰력이 예측되었다. Cancellous bone, annulus fibers 및 ligaments의 기계적인 물성치의 감소 또는 접촉면에서의 마찰계수의 감소는 상대적인 미세운동 (relative micromotion or slip distance)을 증가 시켰다. 접촉면에서의 normal force는 뼈의 밀도 (cancellous bone density) 가 감소하거나 접촉마찰계수가 증가하면 감소했다. 특히 하중조건에 있어서, compressive preload에 대한 torsion의 추가는 접촉면의 anterior부위에서 상대적인 미세운동을 증가 시켰다. 하지만 디스크면적이 증가할수록 상대적인 미세운동은 감소했다. 결론적으로, 접촉면의 기계공학적 거동 (Relative micromotion, stress response, posterior axial displacement and contact normal force)은 접촉면의 마찰계수, 뼈의 밀도, 하중조건 및 노화에 따른 형상/물성의 변화에 매우 민감함을 보이고있다.

Abstract : It is known that among many factors, relative micromotion at bone/implant interfaces can hinder bone ingrowth into surface pores of an implant. Loading conditions, mechanical properties of spinal materials, friction coefficients at the interfaces and geometry of spinal segments would affect the relative micromotion and spinal stability. A finite element model of the human lumbar spine segments (L4-L5) was constructed to investigate the mechanical sensitivity at the interfaces between bone and cage. Relative micromotion, posterior axial displacement, bone stress, cage stress and friction force were predicted in changes of friction coefficients, loading conditions, bone density and age-related material/geometric properties of the spinal segments. Relative micromotion (slip distance in a static loading means relative micromotion in routine activity) at the interfaces increased significantly as the mechanical properties of cancellous bone, annulus fibers or/and ligaments decrease or/and as the friction coefficient at the interfaces decreases. The contact normal force at the interfaces decreased as cancellous bone density decreases or/and as the friction coefficient increases. A significant increase of slip distance at anterior annulus occurred with an addition of torsion to compressive preload. Relative micromotion decreased with an increase of disc area. In conclusion, relative micromotion, stress response, posterior axial displacement and contact normal force are sensitive to the friction coefficient of the interfaces, bone density, loading conditions and age-related geometric/material changes.

Key words : lumbar spine, interbody cage, friction coefficient and finite element analysis

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INTRODUCTION

During the past few years, the development of cage

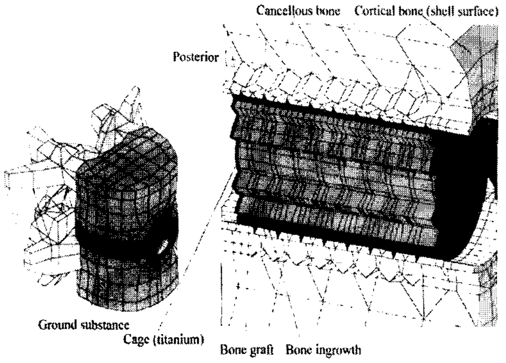

Fig. 1. A finite element model for a one-cage spine model (L4-L5)

technology has increased due to less blood loss and quick recovery to work. A thread insert (a titanium cage) is a hollow screw device usually placed in the disc space between the vertebrae. Experimentally, Rapoff *et al.* (1995) compared the biomechanical characteristics of two types of the interbody cage. They showed that insertion of the interbody cages increases the stiffness of the motion segment up to 30% of that of a normal spine in compression. Also, Tencer *et al.* (1995) reported that insertion of the cages increases vertebral motion segment stiffness and decreases laxity by distracting intervertebral structures. Little is known, however, about the mechanical sensitivity at the contact interfaces of the lumbar spine segments with an anterior interbody cage to bone density, friction coefficients of the interfaces, age-related material/geometric properties and loading conditions.

In orthopedics, implant interfaces with bone have always been a biomechanical challenge for long term fixation and stability. Uhthoff and Germaine (1977) and Brunski *et al.* (1979) reported that formation of fibrous tissue is governed by relative motion of the screw fixation or implants. They assumed that bone fibrous tissue was caused by relative motion between the bone tissue and the implants. Dalenberg *et al.* (1993) showed that after implanting stiff screws in dogs, bone resorption on the interfaces between bone and the implants occurs during the first post operative three months. They observed bone loss that was considered to be a result of stress shielding. Pilliar *et al.* (1981) reported that relative movement greater than 0.15mm can hinder bone ingrowth into porous surfaced implants. Kim and Vanderby (2000) showed in a one-cage finite element model that relative micromotion and/or stress shielding could hinder bone ingrowth and that the one-cage spine could be more vulnerable to relative micromotion than the two-cage spine in lateral bending. These studies suggest that relative motion and altered stress/strain levels on the interfaces can be problematic. Interface mechanics may then provide insight and interpolation for the observed performance of current designs and may provide a point of departure for the design improvement of spinal implants.

The objective of the present paper is to evaluate analytically mechanical parameters such as relative micromotion, contact normal force and stress at the contact interfaces and to investigate the mechanical sensitivity at the interfaces to the friction coefficient, cancellous bone density, age-related geometric/material properties and loading conditions.

MATERIALS AND METHODS

A human lumbar spine model of L4-L5 vertebrae with an interbody cage was used for this study (Fig. 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). All materials including cancellous bone were considered a continuum.

Using a finite element package (ANSYS, version 5.5, Swanson Analysis Systems, Inc., Houston, PA), in formulation of the finite element model, cortical bone and cancellous bone were modeled as three-dimensional isoparametric eight-node elements. The cortical bone, cancellous bone and titanium cage were assumed to be isotropic and homogeneous. The intervertebral disc was modeled as 6 composite materials with a series of fiber bands and a ground substance around the nucleus, similar to the recent studies (Lim *et al.* 1994, Shirazi-Adl 1994, Goel *et al.* 1994), considering the mechanical properties of the annulus fibrosis according to the studies (Marchand and Ahmed 1990, Skaggs *et al.* 1994). The nucleus of the intervertebral disc was ignored because it is likely to be significantly compromised by the surgical procedure, and the stiffness of the remaining tissue is very low relative to the cage.

The cage is a hollow threaded titanium cylinder with several holes through its wall (Fig. 1). A model of the interbody cage was added to a normal model (L4-L5) to simulate the InterBody Fusion Device (IBFD; Sofamor-Danek, Memphis, Tennesee). Inside the cylindrical interbody cage, bone graft (formed from morselized cancellous bone packed) and bone ingrowth (through the holes in the cage) were assumed to have the properties of the

Table 1. Material properties of human lumbar spine (L4-L5)

Materials	Young's modulus (MPa)	Yield strength (MPa)	Poisson's ratio	Ash density (g/cm³)
Cortical bone [5]	12000	173	0.3	
Cancellous bone[13]	100	3.4	0.2	0.11-0.2
Posterior bone [5]	3500	173	0.25	
Cartilaginous endplate	24		0.4	
Ground substance	6		0.49	
Annulus fiber[1,12,21]	59-136	3.6-10.3		
Titanium cage[25]	110,000	848.4	0.3	4.85
Bone graft	100	--	0.2	0.17
Ligaments[15,24]		Cross-sec. area(mm^2)		
Anterior longitudinal	7.8	22.4		
Posterior longitudinal	10	7.0		
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 3.5% (Nachemson and Evans 1968)

cancellous bone (Closkey *et al.* 1993). Bone ingrowth was assumed to occupy the holes on the contact surfaces between vertebral bodies and the cage. The cage, bone graft and bone ingrowth were modeled with three-dimensional solid elements. The elements of the bone ingrowth were, however, excluded in computation. The interfaces between vertebral bodies and the cage were meshed as contact elements. The friction coefficient of the interfaces was assumed to be 0.4 according to Shirazi-Adl *et al.* (1993). An initial gap distance of the contact elements was assumed to be zero due to pre-tension of the annulus and ligaments induced by insertion of the cage (Kim 2000, Rapoff *et al.* 1995). In Table 1 the ash density of cancellous bone was assumed to be 0.11, 0.17 or 0.2g/cm³ (Mosekilde *et al.* 1987), which represents 40, 100, 120 MPa Young's modulus, respectively. Age-related changes in disc area (Nachemson 1960), pedicle diameter (Amonoo Kuofi 1995), elastic modulus of annulus fibers (Acaroglu *et al.* 1995) and elastic modulus of ligaments (Nachemson and Evans 1968) and changes in the friction coefficient and facet gap distance were considered to investigate the mechanical behavior of the interfaces.

When inserting the interbody cage into the lumbar spine, some researchers (Kim and Vanderby 2000, Rapoff *et al.* 1995) observed pretension of the annulus fibers and ligaments. However, with rare information of the pretension it was assumed that the insertion of the interbody cage causes to 1~2% tensile prestrain of the annulus fibers and 1% tensile prestrain of the ligaments. Moreover, ligamentum flavum is known to be pretensioned as much as 5 N in a normal old spine (the equivalent prestrain of the pretension is 2.5% based on its mechanical properties) (Nachemson and Evans 1968, White and Panjabi 1990). Consequently, ligamentum flavum was assumed to have 3.5% prestrain in the one cage model. However, the effects of the tensile prestrains were ignoble under compresssion (Kim and Vanderby 2000). The finite element modeling of the present study was detailed and validated in Kim and Vanderby (2000).

The inferior surface of the L5 vertebra was fixed. The loading conditions on the superior surface were chosen to be within a normal physiologic range (White and Panjabi 1990), using a compressive load of 1200 N, torsion of 10 Nm or 1.5 degrees, lateral bending of 5 Nm, and extension/flexion of 10 Nm or 7.0 degrees.

RESULTS

In general, the predicted parameters were proportional to the applied loads. Due to the near linear relationship between the parameters and loads, the data in the following paragraphs are based on the applied loads of the loading conditions.

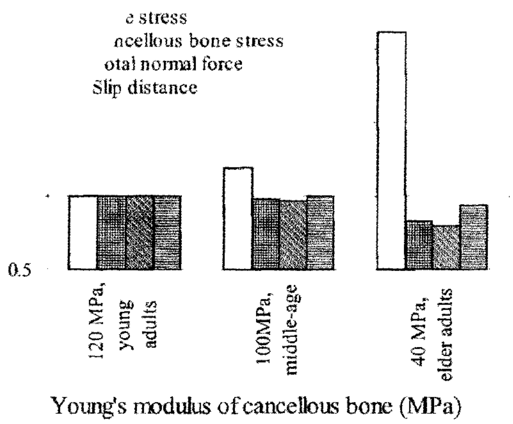

Fig. 2. The effects of the variations of the Young's modulus of cancellous bone at the contact interfaces under 1200 N compression. The results were normalized by the corresponding values of 120 MPa Young's modulus of cancellous bone

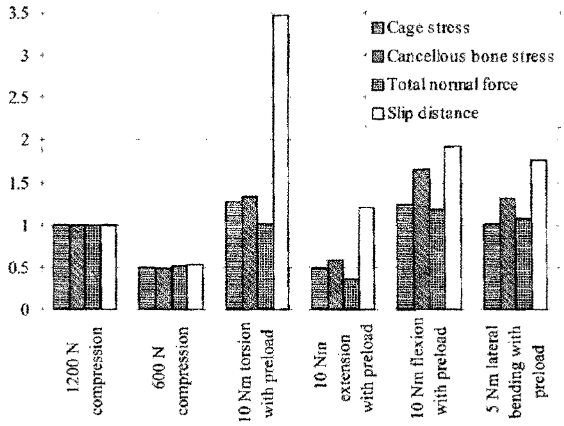

Fig. 3. The mechanical behavior in the contact surfaces depends strongly on the loading conditions. The results were normalized by the corresponding values of 1200 N compression

Figure 2 shows the mechanical variables normalized by those of 120 MPa Young's modulus of cancellous bone. A decrease of the Young's modulus increased relative micromotion (slip distance). In 40 MPa Young's Modulus, 110 % increase of relative micromotion was observed at the contact regions. However, the decrease reduced von Mises stress of cancellous bone and normal force of the interfaces. The maximum von Mises stress of the cage shows

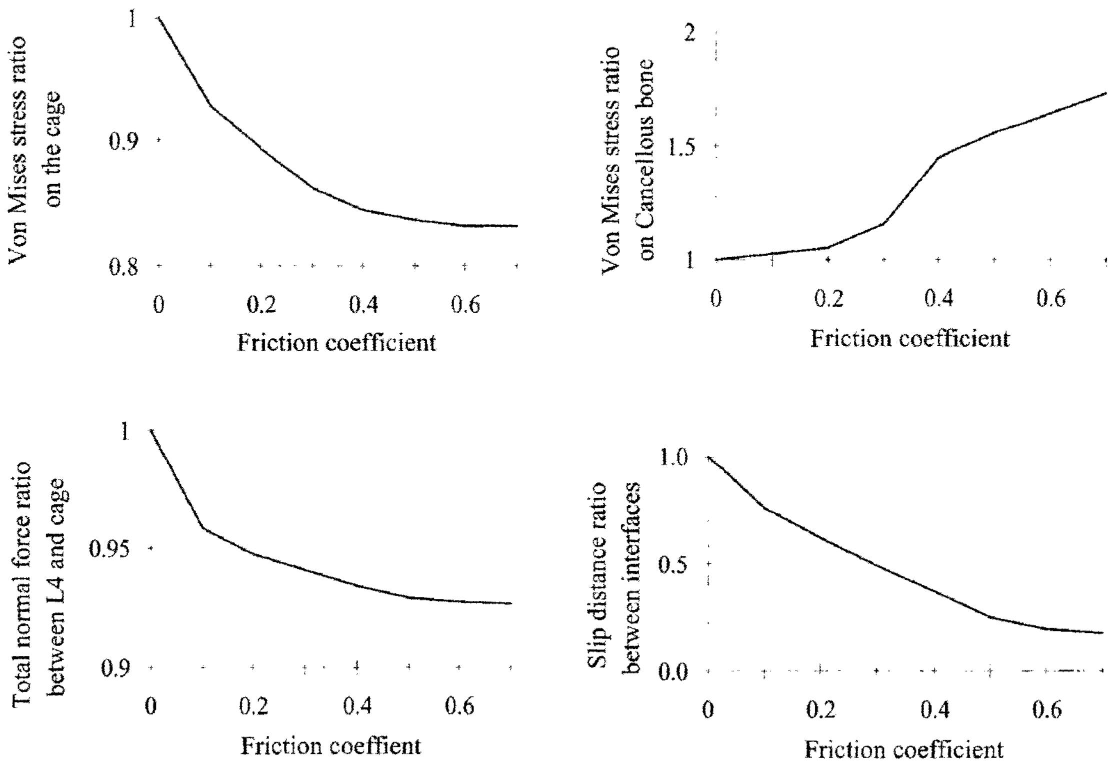

Fig. 4. The mechanical behavior is very sensitive to the friction coefficient in the interfaces. The me ~re normalized by the corresponding values of frictionless interfaces under 1200 N compression

slight changes.

The mechanical behavior at the interfaces varies with the loading conditions (Fig. 3). In Figure 3, the data of 1200 N compression normalized those of each loading applied. The ratios of the data in 600 N compression to those of 1200 N compression are seemed to be a half. In general, an addition of torsion, extension, flexion or lateral bending to the preload (1200 N compression) increases relative motion between the interfaces (i.e. at the anterior contact surfaces in torsion or/and flexion, at the posterior in extension and at the lateral in lateral bending). In particular, an addition of 10 Nm torsion to 1200 N compression leads to 250% increase of relative micromotion at the anterior region of the contact interfaces.

As shown in Figure 4, where the data were normalized by those of frictionless interfaces under 1200 N compression, slip distance, von Mises stresses and contact forces vary with the friction coefficient between the interfaces. With an increase of the friction coefficient, cage stress, contact normal force and slip distance decrease, whereas cancellous bone stress increases.

In compression of 1200 N an increase in pedicle diameter or in disc area decreases cage stress, bone stress and posterior axial displacement, whereas leads to little change of slip distance (Fig. 5). Relative micromotion (slip distance) increases slightly with an increase of pedicle diameter or with a decrease of elastic modulus of annulus fibers, whereas decreases with an increase of disc area in torsion with preload (Fig. 6).

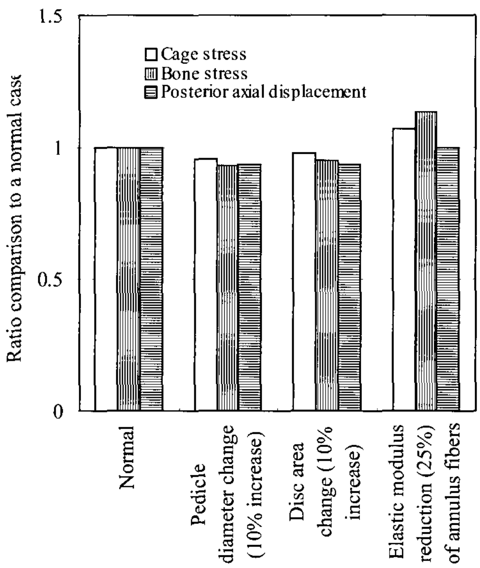

Fig. 5. The effects of the parameters of lumbar spine in 1200 N compression. The data were normalized by the one-cage model with normal geometric/material properties

DISCUSSION

This study investigated the mechanical sensitivity at bone/implant interfaces of the anterior lumbar fusion spine segments (L4-L5) to the friction coefficient of the interfaces, age-related material/geometric change and loading conditions. This study considered physiologic levels of axial, torsional and bending loads on the lumbar spine.

Actually the contact surfaces between the bone and cage are not uniform with non uniform vertebral geometry near the intervertebral disc. The bone/implant contact surfaces vary in accordance with spinal anatomy, placement and the insertion technique. In the present one cage model, complete contact of the interfaces between bone and cage was initially assumed. Thus, relative micromotion computed at the contact interfaces would be underestimated due to local bone failure resulted from incomplete contact and stress concentration at the interfaces. In addition, all materials in the one cage model were assumed to be linearly elastic and homogeneous. Experimentally, the material properties of cancellous bone are not uniform and intervertebral disc materials are nonlinear viscoelastic. Despite these simplifying assumptions, results from the current study demonstrate qualitative trends and useful mechanical insight into surgical alterations.

The present study showed that relative micromotion at the interfaces is sensitive to the friction coefficient. As the friction coefficient increases, relative micromotion and cage stress (von Mises) significantly reduce. The decrease of relative micromotion would enhance bone ingrowth into surface pores of the cage. However, an increase in

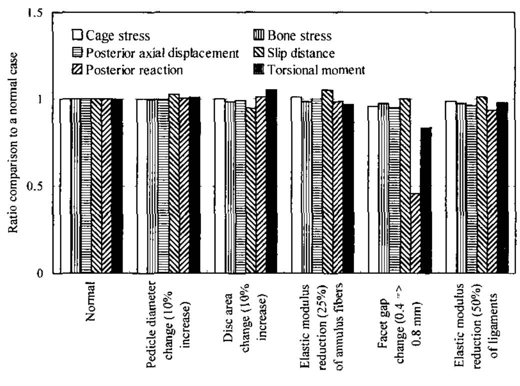

Fig. 6. The effects of parameters of lumbar spine in torsional rotation of 1.5 degrees with 1200 N compression. The data were normalized by the one-cage model with normal geometric/material properties

the friction coefficient tends to increase bone stress. Consequently, a reasonable improvement in the friction coefficient would lead to better spinal prosthesis stabilization and implant performance.

To loading conditions relative micromotion was also vary sensitive. In particular, an addition of torsion to compressive prelaod significantly increased slip distance at the anterior region of the interfaces because of cutting the anterior part of the disc and the anterior longitudinal ligaments as the implant was placed from the anterior. Also, an addition of extension, flexion or lateral bending to compression tends to increase relative micromotion at the interfaces. It would, therefore, be better to avoid cutting the anterior part of the disc and the anterior longitudinal ligament so that less slip occur at the anterior region and to avoid an excessive rotational loading.

It is known that the mechanical properties of bone, annulus fibers and ligaments decrease with aging (Mosekilde *et al.* 1987, Acaroglu *et al.* 1995, Nachemson and Evans 1968). In the present study, a significant increase of slip distance occurred as cancellous bone density decreases. According to Lund *et al.* (1998) and Jost *et al.* (1998), bone density of the adjacent vertebrae is a significant factor for stabilization. Low bone strength is attributed, in general, to low bone density (Mosekilde *et al.* 1987). When bone near implants has low bone strength, bone failure might occur even under physiologic loadings, adversely affecting the eventual success of the artroplasty. Furthermore, a change in age-related mechanical property of annulus fibers and ligaments would reduce stability of spine segments, causing more significant relative micromotion between bone and implants under various combined loads.

Among age-related geometric changes of spine segments an increase in disc area and/or in pedicle diameter would enhance spinal stability because relative micromotion, cage stress and bone stress near the contact interfaces decrease under compression and various combined loadings. In particular, to torsion with preload or to flexion with preload, an age-related change of disc area would contribute significantly to reduction of relative micromotion. Therefore, it is expected that larger disc area or/and larger pedicle diameter would establish more stable interbody fusion of spinal segments after the arthroplasty.

Since an interbody cage was simulated for the present study, the results from the one-cage model would not support enough a spine model with two cages or with other interbody devices. A biomechanical study revealed that an increase in extension stiffness (or decrease in laxity) occurred only with addition of posterior plates, compared with two-cage spinal segments (Tencer *et al.* 1995). According to them, the torsional stiffness of the specimen with two threaded inserts placed posteriorly was reduced significantly. These problematic loadings of torsion or extension may be substantially stabilized by using a translaminar screw fixation or a posterior plate (Ranthonyi *et al.* 1998, Tencer *et al.* 1995). Further study is necessary to estimate and investigate analytically the mechanical behavior of a stabilized spine with these interbody devices.

In a long-term follow up, age-related changes in the material properties would hinder bone ingrowth at the interfaces. An increase of spinal stiffness induced by the age-related geometric change would cause additional degeneration of adjacent intervertebral discs, which is called 'juxtafusion degeneration' In conclusion, the effects of the material/geometric properties, friction coefficients and loading conditions on the mechanical behavior of the contact interfaces are likely to provide useful insights to physicians in spinal surgery.

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