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유한요소법을 이용한 진동요소의 요추에 미치는 영향해석

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EFFECT OF VIBRATION ON LUMBAR SPINE MECHANICS

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ABSTRACT

A three-dimensional finite element model of a ligamentous two motion segments (L4-S1) was developed to investigate its dynamic response. A number of parameters like the intradiscal pressure, forces in ligaments, and across facet joints in response to a sinusoidal axial compression force (-360 N to -440 N at 5 Hz) were predicted. The increase in the parameters varied from 12 % to as high as 50 % in comparison to response for a static load of 400 N. The predicted parameters also revealed a distortion and a phase shift in comparison to the applied sinusoidal signal. These changes may lead to degenerative changes seen clinically in persons exposed to a chronic vibration environment over time.

INTRODUCTION

Exposure of the human spine to a chronic vibration environment, is known to induce degenerative changes within the spinal structure. Earlier *in vivo* investigations have shown that the human spine resonates at about 5 Hz (3.5 to 8.5 Hz). It is not practical, however, to investigate the *in vivo* biomechanical response of the spine in terms of parameters like loads on various structures, stresses and straines, etc. *In vitro* and animal studies are mandated for this purpose. This paper deals with the response of the spine in a vibratory environment, using the finite element technique.

METHODS

A nonlinear three-dimensional finite element model of the L4-S1 ligamentous segment (RINT), based on the CT-based geometric data, was developed for the analysis, as shown in Figure 1. The vertebral bodies and posterior elements were modelled as homogeneous elements. For these bony element, three-dimensional isoparametric solid elements were adapted. The ground substance of the annulus was modelled with three-dimensional isotropic solid element. A tension-only, three-dimensional spar element proved suitable to model the annulus fibers. The nucleus pulposus was simulated with a three-dimensional incompressible fluid element. For facet articulation simulation, a three-dimensional interface element, capable of supporting only compression in the direction normal to the surface, and shear in the tangential direction was used. All ligaments sustain tensile forces only. The three-dimensional tension-only spar element, used in modelling the annulus fiber, proved suitable to model the ligaments. The types and number of elements used in finite element model are shown in Table 1. The material properties assigned to various structures were derived from the literature, as shown in Table 2.

A sinusoidal vertical vibration load of -360 to -440 N was applied to simulate the upper torso weight of 400 N combined with a vertical -40 to 40 N sinusoidal loading. The load was distributed appropriately at each nodal point on the superior body surface, with 90% of the load acting on the L4 upper vertebra surface and 10% of the load acting on the L4 superior facet element at 5 Hz sinusoidal vibration.

All node points located on the half-sagittal plane were restricted in the lateral direction, because of sagittal symmetry. The inferior surface of the S1 vertebral body and the S1 posterior elements were fixed in all directions. The input data were prepared for use with a commercially available finite element package (ANSYS, Swanson Analysis Systems). Computations were accomplished using a supercomputer (CRAY X-MP).

RESULTS and DISCUSSION

The static model predicted by the output corresponding to 400 N axial compression was in reasonable agreement with the experimental data reported in the literature.

The nodal point deformations (base values) in the cortical region (point a of Figure 1 B) and cancellous bone region (point b of Figure 1 B) of the L5 vertebra due to static upper torso weight of 400 N were -0.72 mm and -0.49 mm, respectively. The superimposition of sinusoidal load (±40 N at 5 Hz) resulted in the variations in the displacement over the vase values of ± 0.09 mm and ±0.07 mm. Likewise, the base von-Mises stresses in the cortical and cancellous bone elements of the L5 vertebra were 1.22 MPa and 0.18 MPa and the variations in stresses were ±0.16 MPa and ±0.02 MPa, respectively. The static intradiscal pressure at the L4-L5 nucleus was 315 KPa and variation in IDP was ±41 KPa, as shown in Figure 2. Transmission of force through the L4-L5 facet joint was 64.5 N initially, about 16.1% of the static axial compressive load due to upper body weight. During vibration, the maximum facet contact force ranged from a high of 77.6 N to 52.3 N, as shown in Figure 3. The percentage of facet contact force varies between 13.9 % to 18.3%. The ligaments located near the balance point of the model, namely, the AL, PL, LF, and TL ligaments, did not experience any force. However, because of the flexion-bending of the motion segment, the IS, SS, and CL ligaments experienced forces of 1.39 ±0.33 N, 1.32 ±0.21 N, and 1.47 ± 0.74 N, respectively. The first number represents the base value due to the static load of 400 N. The forces in the IS and CL ligaments were in-phase with the sinusoidal input load, but the SS ligament response showed a phase lag of appoximately 40 msec. The results indicate an increase in the computed parameters. However, the variations with time are distorted in shape and generally are not in phase with the sinusoidal input load. The phase difference and cyclic variations in the computed parameters may initiate degenerative changes clinically linked with the exposure of spine to a chronic vibration environment.

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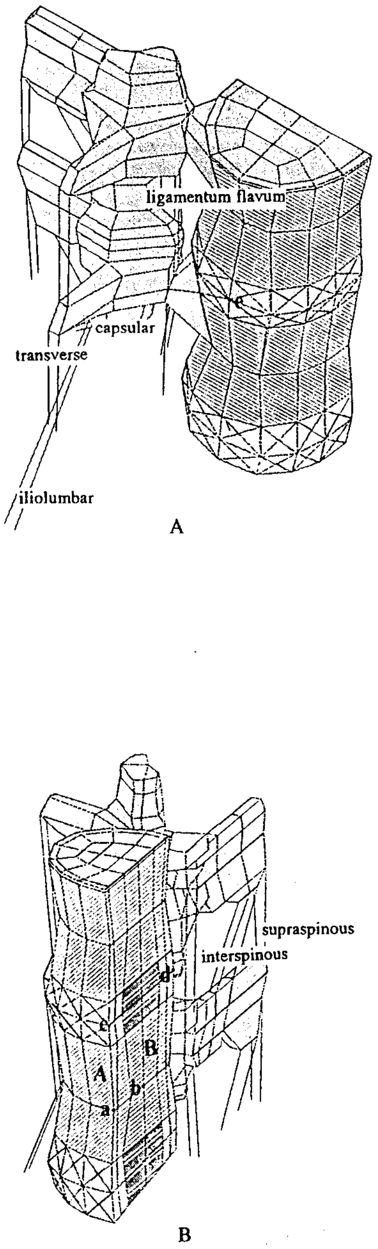

Figure 1 Refined finite element model (RINT): (A) oblique view, and (B) sagittal oblique view.

Table 1 Types and number of elements used in finite element model.

Spinal elements	Element type	RINT
Vertebral body L4	3-D 8 node solid	44
Posterior elements L4	3-D 8 node solid	30
Facet elements L4	3-D 8 node solid	18
Vertebral body L5	3-D 8 node solid	44
Posterior elements L5	3-D 8 node solid	32
Facet elements L5	3-D 8 node solid	19
Annulus (ground substance)	3-D 8 node solid	64
Annulus (fiber)	3-D cable	192
Nucleus	3-D fluid	24
Facet articulation	3-D gap	10
Ligaments		
AL	3-D cable	12
PL	3-D cable	8
LF	3-D cable	6
TL	3-D cable	4
CL	3-D cable	6
IS	3-D cable	5
SS	3-D cable	4
IL	3-D cable	2
Total Number of elements		524

Table 2 Material properties for different materials used in finite element model.

Materials	Young's modulus (MPa)	Shear modulus (MPa)	Poisson's ratio	Density (Kg/mm^3)	Cross sectional area (mm^2)*
Cortical bone	12,000	4,615	0.30	1.7×10^{-6}	-
Cancellous bone	100	41.7	0.20	1.1×10^{-6}	-
Bony posterior elements	3500	1,400	0.25	1.40×10^{-6}	-
Facet elements	3500	1,400	0.25	1.45×10^{-6}	-
Annulus (ground substance)	4.2	1.6	0.45	1.05×10^{-6}	-
Annulus (fiber)	175	-	-	1.0×10^{-6}	-
Nucleus pulposus	1,666.7**	-	-	1.02×10^{-6}	-
Ligaments					
AL	7.8(<12.0%) 20.0(>12.0%)	-	-	1.0×10^{-6}	63.7
PL	10.0(<11.0%) 20.0(>11.0%)	-	-	1.0×10^{-6}	20.0
LF	15.0(< 6.2%) 19.5(> 6.2%)	-	-	1.0×10^{-6}	40.0
TL	10.0(<18.0%) 58.7(>18.0%)	-	-	1.0×10^{-6}	3.6
CL	7.5(<25.0%) 32.9(>25.0%)	-	-	1.0×10^{-6}	60.0
IS	10.0(<14.0%) 11.6(>14.0%)	-	-	1.0×10^{-6}	40.0
SS	8.0(<20.0%) 15.0(>20.0%)	-	-	1.0×10^{-6}	30.0
IL	10.0(<18.0%) 58.7(>18.0%)	-	-	1.0×10^{-6}	26.4

* = Cross sectional area corresponding to a full model; ** = Bulk modulus;
AL = Anterial logitudinal; PL = Posterior longitudinal; LF = Ligamentum flavum;
TL = Transverse; CL = Capsular; IS = Interspinous; SS = Supraspinous;
IL = Iliolumbar.

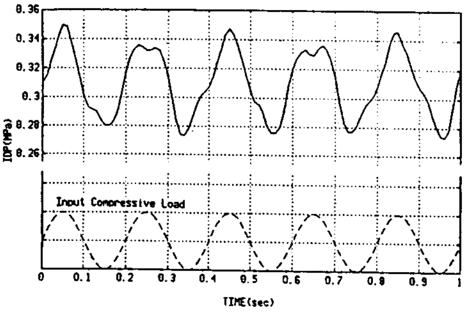

Figure 2 Variations of the intradiscal pressure during vibration.

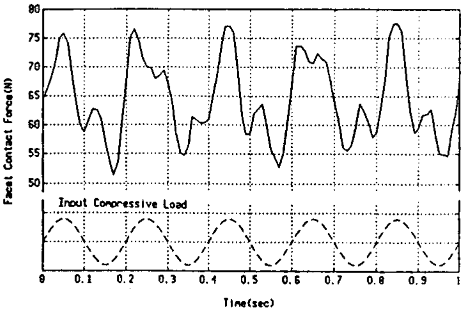

Figure 3 Variations of the facet contact force during vibration.