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Biomechanical Comparison of Nucleotomy with Lumbar Spine Fusion versus Nucleotomy Alone: Vibration Analysis of the Adjacent Spinal Segments

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This study aimed to investigate the effect of transforaminal lumbar interbody fusion (TLIF) with bilateral pedicle screw fixation (BPSF) on dynamic responses of the adjacent spinal segments to whole body vibration (WBV) after nucleotomy. A previously validated finite element model of an intact L1-sacrum lumbar spine was modified to simulate nucleotomy with and without TLIF and BPSF at L4-L5. Transit dynamic analyses were conducted on the nucleotomy alone and the fusion models under a vertical vibration load. The computed dynamic responses for the two models at adjacent levels were recorded and compared. The results showed that at level (L5-S1) below the denucleated disc, maximum response values of the disc bulge, annulus stress and intradiscal pressure decreased due to the fusion by 5.6%, 5.2% and 7.2%, and their vibration amplitudes decreased by 30.5%, 25.7% and 24.3%. At levels (L1-L2, L2-L3 and L3-L4) above the denucleated disc, maximum response values and vibration amplitudes of the strains and stresses also produced 5.2-8.9% and 25.9-29.7% deceases due to the fusion. It implies that after nucleotomy, application of the TLIF with BPSF might be helpful to prevent negative effects of the vertical WBV on adjacent disc levels.

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1. Introduction

Lumbar intervertebral disc herniation caused by disc degeneration is one of the most common causes of low-back pain and imposes a great burden on both the patient and society.[1] Nucleotomy is a common surgical procedure for the treatment of lumbar disc herniation. Although the nucleotomy may offer good short-term effects of pain relieve, the total or partial removal of the nucleus pulposus may also change biomechanics of the spinal motion segments, and lead to some long-term complications such as accelerated degeneration in the operated disc and decreased segmental stability.[2-5] Lumbar spine fusion is often the only option for the treatment of recurrent disc herniation,[6] so the fusion surgery is frequently performed after the nucleotomy.[7] There are various surgical options for interbody fusion of the lumbar spine, such as anterior lumbar interbody fusion (ALIF), posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF).[8] Furthermore, to enhance stability of the fused segment, the intebody fusion is commonly supplemented with bilateral pedicle screw fixation (BPSF).[9-11]

Numerous experimental and numerical studies have been conducted to evaluate the efficacy of the lumbar spine fusion. For example, an in vivo study by Takeshima et al. reported that for the patients with lumbar disc herniation, disc excision with fusion produced a greater reduction in low-back pain compared disc excision alone (82% of the fusion group versus 73% of the nonfusion group), but there were more intraoperative blood loss and operation time and cost in the fusion group than in the nonfusion group.[12] Niemeyer et al. conducted an in vitro comparative analysis of two different lumbar interbody fusion techniques (ALIF and TLIF) using fresh-frozen human lumbar spine specimens (L1-S1), and found that with BPSF, the ALIF provides a higher segmental stability than the TLIF under flexion-extension and axial rotation.[13] Ambati et al. developed a finite element (FE) model of lumbar L3-L5 motion segment to simulate the TLIF with screw fixation at L4-L5 level, and the results showed that the L4-L5 range of motions for flexion, extension, lateral bending, and axial rotation were significantly decreased after the fusion.[9] In addition, some in vivo/vitro and FE studies have also found

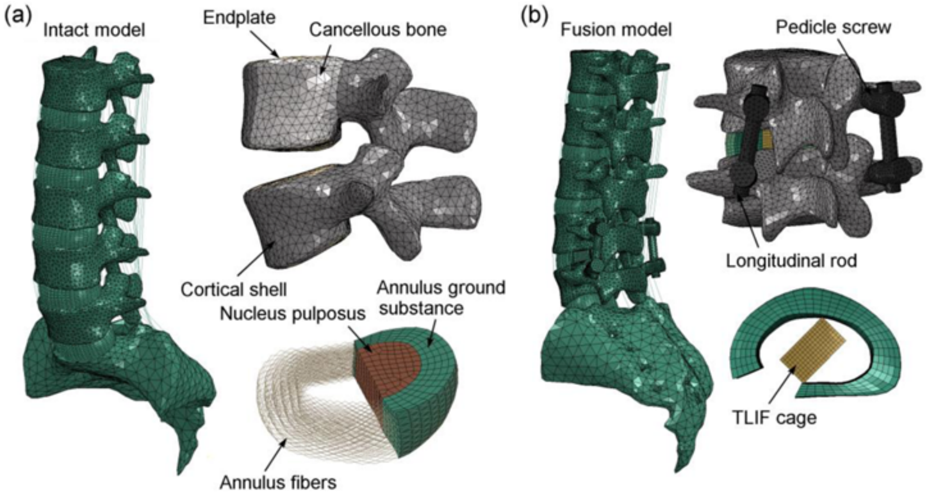

Fig. 1 (a) FE model of the intact lumbar spine, and (b) FE model of the fused lumbar spine

Table 1 Material properties and element types used in the FE model

Component	Young's Modulus (MPa)	Poisson's Ratio	Cross-sectional Area (mm^2)	Density (Kg/mm^3)	Element Type
Bone					
Cortical bone	12000	0.3		1.7e-6	S3
Cancellous bone	100	0.2		1.1e-6	C3D4
Endplate	23.8	0.4		1.2e-6	S3
Posterior bone elements	3500	0.25		1.4e-6	C3D4
Intervertebral disc					
Annulus ground substance	Hyperelastic, Mooney-Rivlin C_{10}=0.18, C_{01}=0.045			1.05e-6	C3D8
Nucleus pulpous	Hyperelastic, Mooney-Rivlin C_{10}=0.12, C_{01}=0.03			1.02e-6	C3D8
Annulus fibers	360-550	0.3		1.0e-6	T3D2
Ligaments					T3D2
Anterior longitudinal	7.8(<12.0%), 20(>12.0%)		63.7	1.0e-6	
Posterior longitudinal	10.0(<11.0%), 20(>11.0%)		20	1.0e-6	
Ligamentum flavum	15.0(<6.2%), 19.5(>6.2%)		40	1.0e-6	
Supraspinous	8.0(<20.0%), 15(>20.0%)		30	1.0e-6	
Interspinous	10.0(<14.0%), 11.6(>14.0%)		40	1.0e-6	
Intertransverse	10.0(<18.0%), 58.7(>18.0%)		1.8	1.0e-6	
Capsular	7.5(<25.0%), 32.9(>25.0%)		30	1.0e-6	
Implants					
Cage (PEEK)	3600	0.25		1.32e-6	C3D8
Screws and rods (Ti)	110000	0.28		4.5e-6	C3D4

S3 3-node triangular elements, *C3D4* 4-node tetrahedral elements, *C3D8* 8-node hexahedral elements, *T3D2* tension-only 2-node truss elements, *PEEK* Polyetheretherketone, *Ti* Titanium

that the spine fusion may lead to degenerative changes at adjacent segments.[14-16] There is no doubt that these previous studies have offered valuable insights into the biomechanical effect of the fusion on lumbar segments. However, to the best knowledge of the authors, there is a lack of studies to evaluate the effect of interbody fusion with rigid fixation on biomechanical behavior of the lumbar spine under whole body vibration (WBV) that is typically present when driving a car or riding on a bus.

There is a strong link between WBV exposure and lumbar disc degeneration.[17,18] The cyclic loading encountered during WBV has been implicated as a risk factor for lumbar degenerative diseases.[19] After lumbar disc herniation surgery, most patients can inevitably be exposed to WBV caused by vehicles during work and daily life. Therefore, it is important to understand vibration characteristics of the lumbar spine after the surgery. The aim of this study was to investigate the effect of TLIF with BPSF on dynamic responses of the adjacent spinal segments to WBV after nucleotomy using the FE method.

2. Materials and Methods

2.1 FE modeling

A previously validated three-dimensional, osteoligamentous FE model of an intact L1-sacrum human lumbar spine (Fig. 1(a)) was

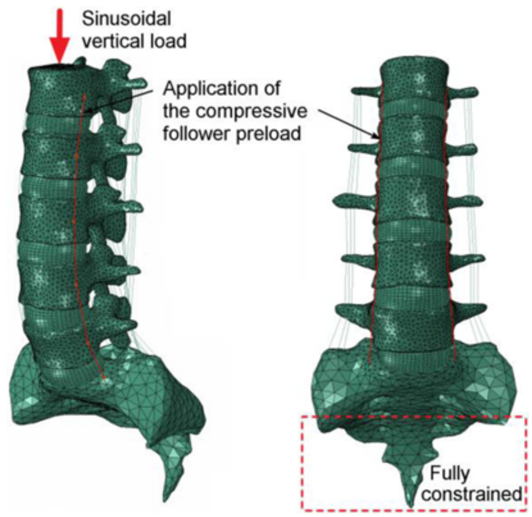

Fig. 2 Illustration of the boundary and loading conditions

employed in this study. Details for development and validation of the model have been reported elsewhere.[20] Material properties and element types used in the model are listed in Table 1. The intact model was modified to simulate nucleotomy and TLIF with BPSF at L4-L5 level. This level was chosen due to its higher prevalence in individuals suffering from disc degeneration.[21,22]

The nucleotomy was simulated by deleting nucleus pulposus of the L4-L5 disc. After the nucleotomy, the TLIF surgical procedure at L4-L5 level was simulated by the application of unilateral facetectomy and partial annulotomy as described by Ambati et al.[9] and the TLIF cage (10 mm height, 16 mm length, 9 mm width) with a flat box shape was placed between L4 and L5 verterbral bodies, as shown in Fig. 1(b). The BPSF system was composed of four pedicle screws and two longitudinal rods. The screws (6 mm diameter, 45 mm length) were inserted into L4 and L5 vertebral bodies and were interconnected by the rods (6 mm diameter). The bone-cage and bone-screw interfaces, as well as connections between screws and rods were simplified by assigning the contact surfaces to be completely bonded via node sharing.[23,24] Material properties and element types for the implants are also listed in Table 1.

2.2 Boundary and loading conditions

Transient dynamic analyses were performed on the model for nucleotomy alone (NA) and the model for nucleotomy with TLIF and BPSF, respectively, using the Abaqus/Standard 6.10 software (Dassault Systèmes Simulia Corp., Providence, RI, USA). The boundary and loading conditions are illustrated in Fig. 2. In the NA and fusion models, caudal part of the sacrum was fully constrained. The models were loaded with a sinusoidal vertical load of ±40 N and a compressive follower preload of 400 N. The sinusoidal load with a frequency of 5 Hz was applied on superior endplate of the L1 vertebra to simulate vibration loading of the human body.[25,26] The follower preload, representing the physiologic compressive load induced by muscle activities, was applied along a path approximating the tangent to the spinal curve using placed bilaterally thermo-isotropic truss elements.[27] To include the effect of human upper body mass, a mass point of 40 kg was assigned to the top of the L1 vertebra by 1 cm anterior to the L3-L4 vertebral centroid.[26,28,29] An equivalent damping ratio of 0.08 was adopted in the models.[30]

2.3 Model outputs

Dynamic responses (obtained from the transient dynamic analyses) of the adjacent disc levels for the NA and fusion models, including disc bulge, von-Mises stress (VMS) in annulus ground substance and intradiscal pressure (IDP), were collected and plotted as a function of time. Maximum and minimum values and vibration amplitudes (maximum minus minimum, i.e. peak-to-bottom variations) of the obtained response plots were also tabulated. In this study, disc bulge is defined as lateral deformation of the annulus; Annulus VMS is defined as the average value of the stresses in the elements used to model the annulus ground substance; IDP is defined as the average value of the pressures in the elements used to model the nucleus.

3. Results

Figs. 3-5 show the computed time-domain dynamic responses in adjacent disc levels of the NA and fusion models to the vertical vibration, and their corresponding maximum and minimum values and vibration amplitudes are listed in Table 2. It was observed that plots of all the dynamic responses revealed cyclic characteristics with time, and maximum response values and vibration amplitudes of the computed strains and stresses in the fusion model were decreased compared with these in the NA model.

At the proximal adjacent level (L3-L4), the maximum values of disc bulge, annulus VMS and IDP in the fusion model were decreased by 5.7% (from 0.704 mm to 0.664 mm), 7.6% (from 0.198 MPa to 0.183 MPa) and 8.5% (from 0.609 MPa to 0.559 MPa) respectively compared with these in the NA model, and their vibration amplitudes decreased by 25.9%, 29.7% and 29.5% respectively. At the distal adjacent level (L5-S1), the maximum values of disc bulge, annulus VMS and IDP in the fusion model were decreased by 5.6% (from 1.187 mm to 1.120 mm), 5.2% (from 0.268 MPa to 0.254 MPa) and 7.2% (from 0.704 MPa

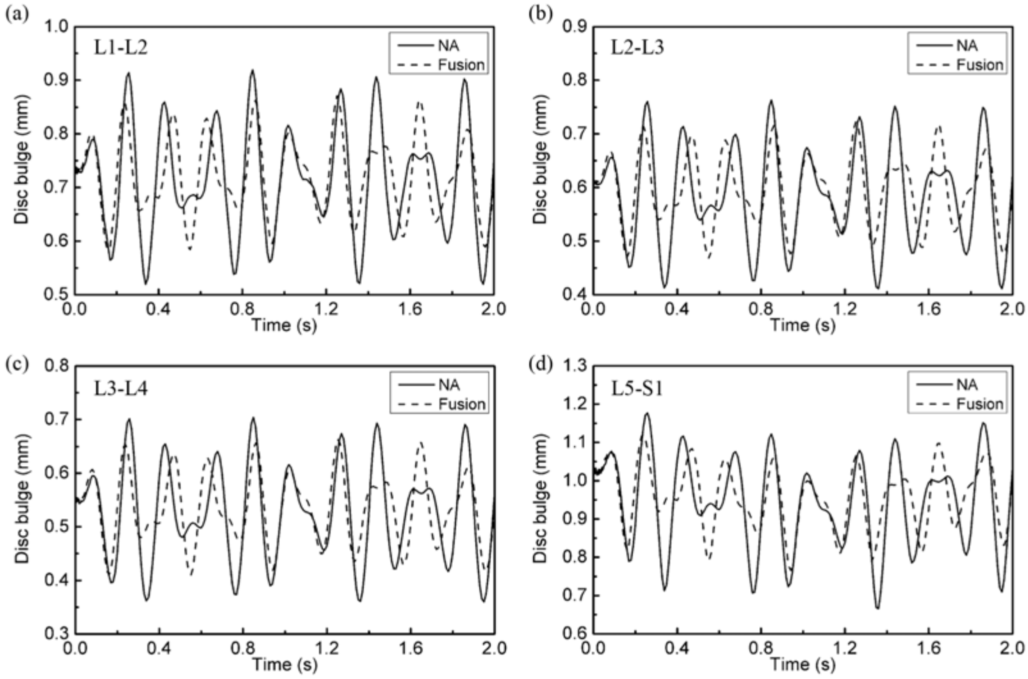

Fig. 3 Dynamic responses of the disc bulge to the vertical vibration for the NA and fusion models: (a) Level L1-L2, (b) Level L2-L3, (c) Level L3-L4, (d) Level L5-S1

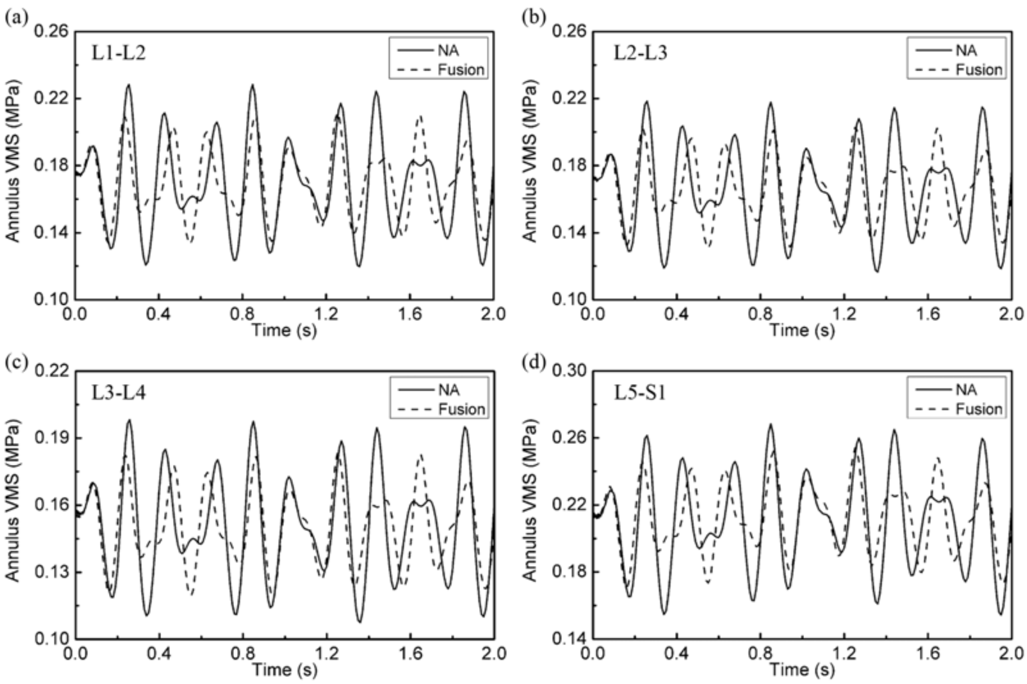

Fig. 4 Dynamic responses of the annulus VMS to the vertical vibration for the NA and fusion models: (a) Level L1-L2, (b) Level L2-L3, (c) Level L3-L4, (d) Level L5-S1

to 0.653 MPa) respectively compared with these in the NA model, and their vibration amplitudes decreased by 30.5%, 25.7% and 24.3% respectively. In addition, at other levels (L1-L2 and L2-L3), the maximum values and vibration amplitudes of the computed strains and stresses also produced also produced 5.2-8.9% and 26.9-29.4% deceases respectively due to the fusion.

4. Discussion

Previous studies have reported the effect of spine fusion on biomechanical response of the lumbar spine to static loadings after nucleotomy. However, very few have dealt with the WBV condition. In this study, a previously validated FE model of an intact L1-sacrum

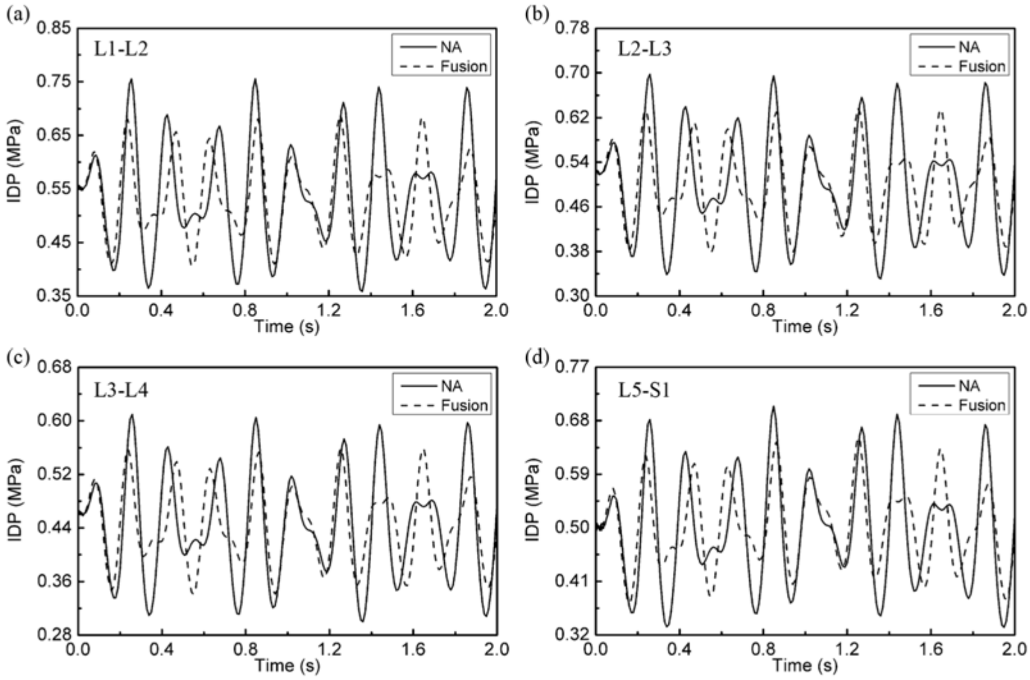

Fig. 5 Dynamic responses of the IDP to the vertical vibration for the NA and fusion models: (a) Level L1-L2, (b) Level L2-L3, (c) Level L3-L4, (d) Level L5-S1

Table 2 The maximum and minimum values and vibration amplitudes of the computed dynamic responses for the NA and fusion models

Dynamic responses	NA model			Fusion model			% change	
	Max	Min	VA[a]	Max	Min	VA[a]	*%[b]	**%[c]
Disc bulge (mm)								
L1-L2	0.919	0.519	0.400	0.871	0.583	0.288	-5.2	-28.0
L2-L3	0.763	0.411	0.352	0.723	0.468	0.255	-5.2	-27.6
L3-L4	0.704	0.361	0.343	0.664	0.410	0.254	-5.7	-25.9
L5-S1	1.187	0.676	0.511	1.120	0.765	0.355	-5.6	-30.5
Annulus VMS (MPa)								
L1-L2	0.228	0.120	0.108	0.212	0.133	0.079	-7.0	-26.9
L2-L3	0.219	0.117	0.102	0.203	0.131	0.072	-7.3	-29.4
L3-L4	0.198	0.107	0.091	0.183	0.119	0.064	-7.6	-29.7
L5-S1	0.268	0.155	0.113	0.254	0.170	0.084	-5.2	-25.7
IDP (MPa)								
L1-L2	0.756	0.359	0.397	0.689	0.405	0.284	-8.9	-28.5
L2-L3	0.697	0.331	0.366	0.637	0.377	0.260	-8.6	-29.0
L3-L4	0.609	0.300	0.309	0.559	0.341	0.218	-8.5	-29.5
L5-S1	0.704	0.334	0.370	0.653	0.373	0.280	-7.2	-24.3

Max, maximum; Min, minimum; VA, vibration amplitude.

[a]VA=Max-Min, [b]*% change=100*($Max_{(Fusion)}$-$Max_{(NA)}$)/ $Max_{(NA)}$, [c]**% change=100*($VA_{(Fusion)}$-$VA_{(NA)}$)/ $VA_{(NA)}$

human lumbar spine[20] was initially modified to simulate nucleotomy with and without TLIF and BPSF at L4-L5 disc level, respectively. Subsequently, the NA and the fusion models were used to investigate the effect of TLIF with BPSF on dynamic responses of the adjacent spinal segments to the vertical vibration after nucleotomy. For applying the physiologic compressive load to the whole lumbar spine without generating instability, the follower load technique[27,31] was employed and the two developed models were subjected to a compressive follower preload of 400 N.

Transient dynamic analyses were performed on the NA and fusion models under a sinusoidal vertical load of ±40 N with a frequency of 5 Hz. This vibration load mode was adopted due to the fact that when a person in a sitting posture was exposed to vertical vibration at 5 Hz, a cyclic axial load of about 40 N might be imposed on the top of the lumbar spine as reported by wilder.[32] Furthermore, the loading frequency (5 Hz) was considered to be related to human body vibrations and many transport vehicles.[25,33] The results obtained from the dynamic analyses are shown in Figs. 3-5. It was found that the computed strain and stress responses varied in different disc levels. These levels with larger response values might have a higher health risk than other levels under the vibration, because the high strains and stresses caused by the external loads could lead to the accelerated degeneration of spinal components as indicated in the literature.[34,35] An in vitro study by O'Connell et al. reported that the nucleotomy alters the internal radial and axial strains of the annulus fibrosus for the denucleated lumbar disc under axial compression, and thus might leave the annulus fibrosus vulnerable to damage and microfractures.[5] A more recent FE study also found that the nucleotomy increased dynamic responses of strain and stress to the vertical vibration load at the denucleated and its adjacent lumbar disc.[36] These findings imply that the lumbar spine with nucleotomy will face a higher risk of disc degeneration compared with the intact one under both the static and vibration loadings. At present, spine fusion is considered to be the only option for preventing an accelerated degeneration of the treated motion segment after the nucleotomy. But in the meantime, biomechanics of the spinal segments adjacent to the fused one can inevitably be altered.[14-16] The results of the present study showed that at adjacent levels (L1-L2, L2-L3, L3-L4 and L5-S1), maximum response values of disc bulge, annulus VMS and IDP produced 5.2-5.7%, 5.2-7.6% and 7.2-8.9% deceases respectively due to the fusion (TLIF with BPSF), and their vibration amplitudes produced 25.9-30.5%, 25.7-29.7% and 24.3-29.5% deceases respectively (Table 2). This implies that the fusion prevents negative effects of the vertical vibration on the adjacent disc levels after nucleotomy.

Several limitations of this study should be noted. First, the employed intact FE model was created on the base of one unique specimen with given geometry and material properties, so it means that these computed absolute values might be not representative of an average person. However, the principal effect of the nucleotomy and fusion on dynamic response of the lumbar spine to the vibration was not affected, since the NA and fusion models were developed based on the same intact model. Second, the degenerative changes due to osteophytes, sclerosis, and annular tears[37] were not accounted for in present FE models, and viscoelasticity of the disc were also neglected. Third, the muscles were not included in present model. Although the applied compressive follower preload can mitigate this limitation, the follower load technique can not completely simulate the complex contribution of muscles to the spinal response. In addition, the same follower preload was applied to the intact and modified models without consideration of some changes in muscle activities generated after the nucleotomy and fusion.

5. Conclusions

This study presented a quantitative investigation on the effect of TLIF with BPSF on dynamic responses of the adjacent spinal segments to WBV after nucleotomy using the previously developed and validated L1-Sacrum FE model. The results obtained from the transit dynamic analyses indicated that the TLIF with BPSF decreased maximum values and vibration amplitudes of the computed strain and stress responses at the adjacent disc levels under the vertical vibration. It implies that the applied TLIF with BPSF might be useful to prevent negative effects of the vertical WBV on the adjacent levels after nucleotomy. The present biomechanical study is helpful in understanding the role of nucleotomy and fusion in vibration response of the lumbar spine.

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