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Original Article

Dynamic characteristics of osteoporotic lumbar spine under vertical vibration after cement augmentation

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Abstract: Being beneficial in restoring stability and stiffness of osteoporotic vertebraes, cement augmentation techniques including vertebroplasty (VP) and kyphoplasty (KP) have been demonstrated to be effective for the treatment of patients with osteoporotic vertebral compressive fractures (OVCFs). However, it is unclear the influence of cement augmentation on the dynamics of pathologic and adjacent vertebraes under vibration condition. In this study, we developed a three-dimensional (3D) finite-element (FE) model of the spinal T12-Pelvis segment by using CT scan data of lumbar spine of an adult woman with no physical abnormalities. By modulating model parameters we further simulated osteoporotic conditions of the T12-Pelvis FE model with or without polymethyl methacrylate (PMMA) augmentation. Dynamic characteristics of the osteoporotic T12-Pelvis model were detected at the first order of vertical resonant frequencies (FOVRFs) under vertical vibration, which included vertical axial displacements, anteroposterior (AP) displacements and rotational angles of each vertebrae and intervertebral disc (IVD). The results showed that axial and AP displacements of both vertebraes and IVDs decreased in some point after PMMA augmentation. Axial displacements of the L4-L5 motion segment decreased most significantly and the changing ratios ranged from 20% to 30%. AP displacements of L5, D_{1-2} (the IVD between vertebraes L1 and L2) and D_{3-4} reduced most obviously after 1, 2 or 3 levels PMMA augmentation. No significant difference of axial or AP displacements of each vertebrae and IVD was observed between one-level and multilevel PMMA augmentation. Thus, we demonstrated that PMMA augmentation could reduce vertical axial and AP deformations of the osteoporotic lumbar motion segments under vertical vibration, especially for the inferior adjacent motion segments. However, the influence of the number of vertebraes with PMMA augmentation on the dynamics of osteoporotic lumbar spine was indistinctive.

Keywords: Osteoporosis, PMMA augmentation, FE model, dynamics, vertical vibration

Introduction

As one of the most common bone diseases in the aged population, osteoporosis could lead to painful OVCFs and decreased quality of life without proper prevention and treatment [1]. In recent years, cement augmentation techniques including VP and KP have become increasingly popular for the treatment of painful OVCFs [2]. Numerous studies have demonstrated that injection of PMMA, one of the most frequently used bone filling materials, could achieve significant promotion of stiffness and strength of the pathologic vertebraes [3-6]. In clinic, however, altered loads transfer and failure of adjacent vertebraes have also been occasionally observed after PMMA augmentation [7, 8]. As far as we know, the number of vertebraes processed for augmentation, the amount of cement injected and the environment the spinal system exposed to could all play a role in the prognosis of patients treated with VP or KP.

Investigations have shown that dynamic loads are more dangerous and could increase stresses and displacements of spinal components in comparison to static states [9, 10]. This might be one of the reasons why long-term whole body vibration (WBV) could cause health risks for the lumbar spine, especially for the lower lumbar motion segment L3-L5 [11]. To investigate quantitively the dynamic mechanical behavior of the spine system under chronic WBV, a growing number of researchers, in recent years, have developed diverse FE models and simulated different spinal conditions. By generating a 3D FE model of the spinal L3-L5 segment, Guo et al [12] showed that posterior

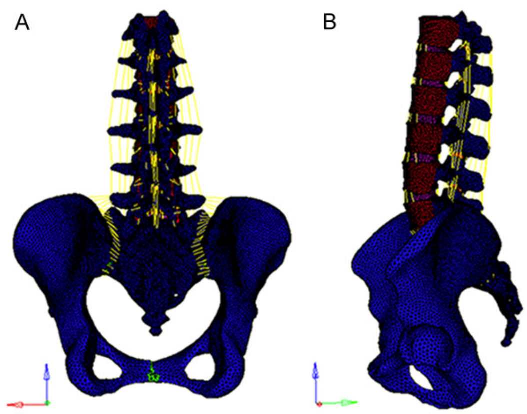

Figure 1. The normal 3D T12-Pelvis FE model. A. The coronal plane. B. The sagittal plane.

regions of the lumbar spine were more vulnerable to injuries during long-term WBV compared to anterior regions, which might result in disorders of the lumbar spine. Goel et al [9] developed a nonlinear 3D FE model of the ligamentous L4-S1 segment and found that chronic vibration exposure could lead to deformations of distinct spinal components.

Though diverse experimental studies and mechanical analysis have investigated the effect of WBV on human skeleton system under normal or injured conditions, little attention has been paid to the role of cement augmentation in the dynamic behaviors of osteoporotic spinal segment under vertical vibration. In the present study, we developed a normal 3D FE model of the whole lumbar spine including its adjacent motion segments, and further simulated osteoporotic conditions of the lumbar spine with or without PMMA augmentation by modifying assigning parameters. The aim of this study was to explore the influence of cement augmentation on the dynamics of osteoporotic lumbar spine under vertical vibration, which could help people better understand the motion mechanism of the lumbar spine under osteoporotic condition and appreciate the effect of cement augmentation on the augmented vertebraes and non-augmented adjacent spinal components under long-term WBV.

Materials and methods

A normal 3D FE model of the T12-Pelvis segment was developed by using CT scan data of lumbar spine of an adult woman (58 years old) with no physical abnormalities. Informed consent was received from the patient prior to her participation in the study. This study was approved by the Ethics Committee of the First Affiliated Hospital of Soochow University. The CT scan data was imported into the software Mimics 15.0 and transformed into a 3D model, and then substantialized by using the software Solidworks. With the help of software HyperMesh, structures including vertebraes, endplates, annulus fibrosus, nucleus pulpous, ligaments and facet joints were meshed and reconstructed. The 3D FE model of human T12-Pelvis segment with a seating posture was finally generated (**Figure 1**). The model was comprised of 115524 nodes and 441897 elements. The assignment of element types and parameters of material property was acquired from previous studies [9, 13-17]. To simulate the osteoporotic condition, the Young's Modulus and density of cortical bone (including endplate and bony posterior element) were reduced by 33 percent. Similarly, those of cancellous bone were reduced by 66 percent [18, 19]. Other parameters of the model stayed unchanged (**Table 1**). The osteoporotic T12-Pelvis models with PMMA augmentation were assumed that all the cancellous bone of the augmented vertebrae was replaced by PMMA, which was designed with 3000 MPa of Young's Modulus and 0.41 of Poisson's Ratio [7].

As a whole, the normal T12-Pelvis FE model consisted of 7 vertebraes and 6 IVDs. There were cortical bones, cancellous bones, annulus fibrosus, nucleus pulpous, bony posterior element, ligaments and facet articulations at each segmental level. In detail, the nucleus pulpous was modeled as a cavity with incompressible fluid filled. The annulus fibrosus was modeled as a matter reinforced by annulus fibers, which was assumed as a composition of three radial consecutive laminar layers. The fibers in each layer were in a crisis-cross pattern and assumed to have an incline of 30° to the adjacent endplates [12, 19, 20]. The cross-section area of nucleus was assumed as 40% of disc area and the total volume of the annulus fibers was assumed as 19% of the annulus volume [16, 21]. The pelvis was assumed to be fixed on the ground. As an assignable factor, the upper body weight was simulated based on published data by imposing a preload of 400 N on the top surface of the vertebrae T12 [9, 12, 18]. Stress analysis was performed by using the software ABAQUS after modeling. By modifying assign-

Table 1. Assigning parameters of different spinal components in the osteoporotic T12-Pelvis FE model

Materials	Element types	Young's Modulus (Mpa)	Poisson's Ratio	Density ($\times 10^{-6}$ kg/mm^3)	References
Cortical bone	C3D6	8040 (normal#: 12000)	0.3	4.69 (normal#: 7)	[15, 17-21]
Cancellous bone	C3D6	34 (normal#: 100)	0.2	0.37 (normal#: 1.1)	
Bony posterior element	C3D6	2345 (normal#: 3500)	0.25	0.94 (normal#: 1.4)	
Endplate	C3D6	335 (normal#: 500)	0.25	0.8 (normal#: 1.2)	
Annulus	C3D6	4.2	0.45	1.05	
Nucleus pulpous	C3D6	1.0	0.49	1.02	
Annulus fiber	3D-cable	500		1.0	
Anterior longitudinal ligaments	2-node truss T3D2	7.8		1.0	
Posterior longitudinal ligaments	2-node truss T3D2	10		1.0	
Interspinous ligaments	2-node truss T3D2	10		1.0	
Supraspinous ligaments	2-node truss T3D2	8		1.0	
Intertransverse ligaments	2-node truss T3D2	10		1.0	
Ligamentumflavum	2-node truss T3D2	15		1.0	
Capsular ligaments	2-node truss T3D2	7.5		1.0	
Iliolumbar ligaments	2-node truss T3D2	10		1.0	
Anterior sacroiliac ligaments	2-node truss T3D2	20		1.0	
Posterior sacroiliac ligaments	2-node truss T3D2	20		1.0	

Normal#: The 3D FE model with normal bone mineral density (BMD).

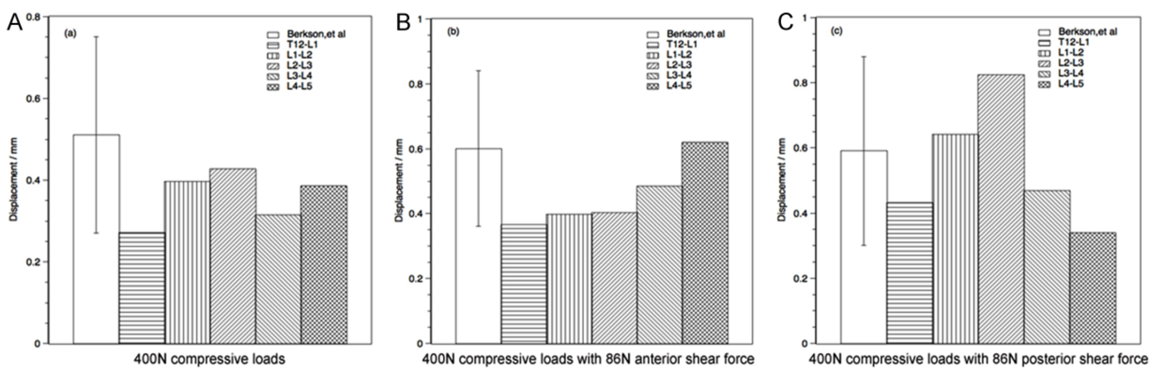

Figure 2. Validation of axial displacements of different motion segments of the T12-Pelvis FE model against experimental data. A. Axial displacements of each motion segment of the T12-Pelvis model under 400 N compressive loads. B. Axial displacements of each motion segment of the T12-Pelvis model under 400 N compressive loads with 86 N anterior shear force. C. Axial displacements of each motion segment of the T12-Pelvis model under 400 N compressive loads with 86 N posterior shear force.

ing parameters we further developed osteoporotic T12-Pelvis FE models. The Pre-PMMA model was to represent the osteoporotic T12-Pelvismodel without PMMA augmentation, while Case 1 simulated the condition of PMMA augmentation of the vertebrae L3, Case 2 simulated the condition of PMMA augmentation of both vertebraes L2 and L3, and Case 3 simulated the condition of PMMA augmentation of vertebraes L2, L3 and L4.

Resonant frequencies and vibration modes were often described to analyze the dynamic characteristics of the spine system under vertical vibration. In this study, for the availability of comparison we specifically detected the FOVRFs of the osteoporotic T12-Pelvis models under vertical vibration [20]. Vibration modes including axial displacements, AP displacements and rotational angles were detected with models vibrated at the FOVRFs. To make an accurate prediction of the dynamic characteristics of the lumbar spine under different conditions we firstly carried out validation of the normal T12-Pelvis model against previous experimental data. Namely, vertical axial dis-

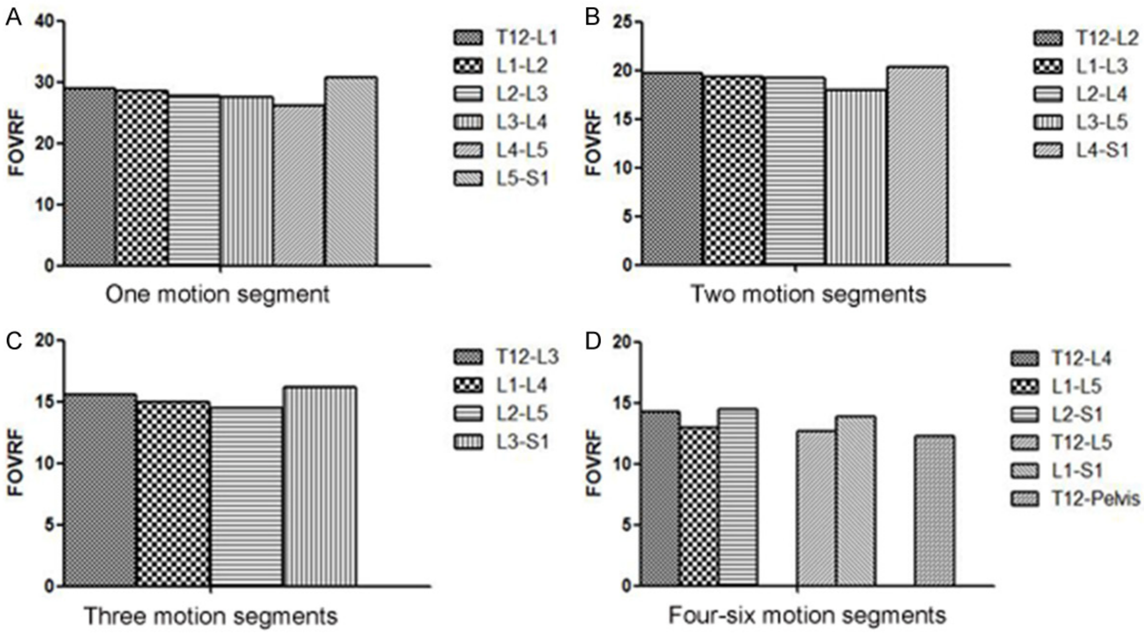

Figure 3. Validation of the FOVRFs of different motion segments of the T12-Pelvis FE model. A. The FOVRFs of one motion segment. B. The FOVRFs of two motion segments. C. The FOVRFs of three motion segments. D. The FOVRFs of four, five and the intact T12-Pelvis segment.

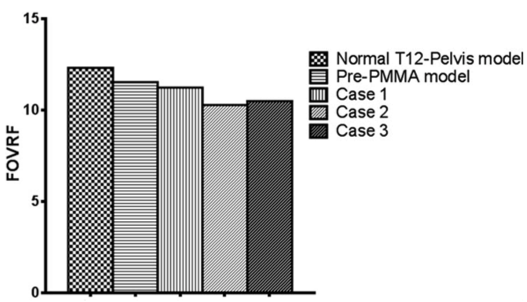

Figure 4. The FOVRFs of the intact T12-Pelvis segment in normal and osteoporotic FE models.

placements and the FOVRFs of different motion segments of the T12-Pelvis model were analysed under 400 N compressive loads with or without shear force. Thereafter, we examined dynamic characteristics of the osteoporotic T12-Pelvis models with or without PMMA augmentation at the FOVRFs under 400 N compressive loads. Deformations of vertebraes and IVDs were tested respectively.

Results

Validation of the normal T12-Pelvis FE model

According to the results of experimental studies, vertical axial displacements of one motion segment of the lumbar spine were 0.51±0.24 mm under 400 N compressive loads, 0.60±0.24 mm under 400 N compressive loads with 86 N anterior shear force and 0.59±0.29 mm under 400 N compressive loads with 86 N posterior shear force [22]. In this study, vertical axial displacements of all the motion segments from T12-L1 to L4-L5 of the T12-Pelvis FE model fell within the experimental deviation described above under corresponding conditions (**Figure 2A-C**).

Figure 3 showed the FOVRFs of different motion segments of the T12-Pelvis FE model under vertical vibration, which got reduced while the number of motion segments increased. The results showed that the FOVRFs were in the range of 26.19-30.68 HZ for one motion segment (**Figure 3A**), in the range of 18.01-20.33 HZ for two motion segments (**Figure 3B**), in the range of 14.47-16.18 HZ for three motion segments (**Figure 3C**) and in the range of 12.96-14.45 HZ for four motion segments (T12-L4, L1-L5, L2-S1 in **Figure 3D**). The FOVRFs of the T12-L5, L1-S1 and intact T12-Pelvis segments were 12.63 HZ, 13.85 HZ and 12.31 HZ respectively (**Figure 3D**). According to Goel et al [9], the FOVRF of L4-L5 segment was 27.7 Hz and that of the L4-S1 segment was 17.5 Hz. Guo et

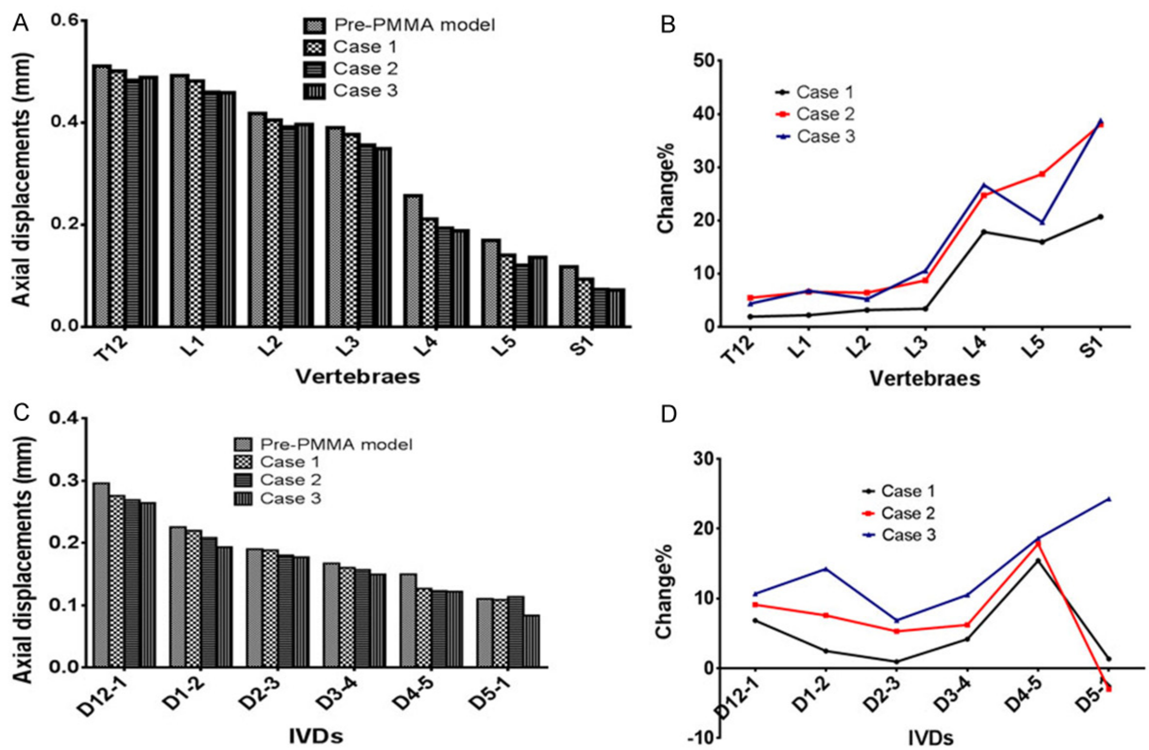

Figure 5. Axial displacements of lumbar vertebraes and IVDs in osteoporotic T12-Pelvis models under vertical vibration. A. Axial displacements of lumbar vertebraes in the Pre-PMMA model, case 1, case 2 and case 3. B. Changing ratios of axial displacements of each vertebrae in case 1, case 2 and case 3. C. Axial displacements of lumbar IVDs in the Pre-PMMA model, case 1, case 2 and case 3. D. Changing ratios of axial displacements of each IVD in case 1, case 2 and case 3.

al [23] reported that the FOVRFs of T12-L1 and L2-L3 segments were 26.7 Hz and 25.7 Hz respectively, and the FOVRFs of two motion segments (L3-L5), four motion segments (L1-L5) and five motion segments (L1-S1) were 19.6 Hz, 11.5 Hz and 9.12 Hz correspondingly. Thus the FOVRFs of different motion segments of this normal T12-Pelvis model were rather in agreement with those reported previously. Based on the validation of axial displacements and the FOVRFs of each motion segment, the T12-Pelvis FE model was appropriate for further studying the dynamic characteristics of human lumbar spine under osteoporotic conditions with or without PMMA augmentation.

The FOVRFs of lumbar spine in normal and osteoporotic FE models

The FOVRFs of the intact T12-Pelvis segment were 12.31 HZ, 11.526 Hz, 11.23 HZ, 10.278 HZ and 10.49 HZ in the normal T12-Pelvis model, the Pre-PMMA model, case 1, case 2 and case 3 respectively (**Figure 4**). It revealed that the FOVRFs of the lumbar spine got decreased after PMMA augmentation, which, however, existed no significant difference among conditions with 1, 2 and 3 levels augmentation.

Dynamic changes of osteoporotic lumbar spine after cement augmentation

Figure 5 showed the axial displacements of lumbar vertebraes and IVDs at the FOVRFs under vertical vibration in osteoporotic T12-Pelvis models with or without PMMA augmentation. We could observe that axial displacements of both vertebraes (**Figure 5A**) and IVDs (**Figure 5C**) decreased gradually from the upper motion segments to the lower motion segments. Compared to the axial displacements of each vertebrae and IVD in the Pre-PMMA model, those in the augmentation models decreased correspondingly. **Figure 5B** and **5D** exhibited the changing ratios of axial displacements of vertebraes and IVDs in case 1, case 2 and case 3. It revealed that the changing trend was similar in these three augmentation models. Axial displacements of the inferior adjacent

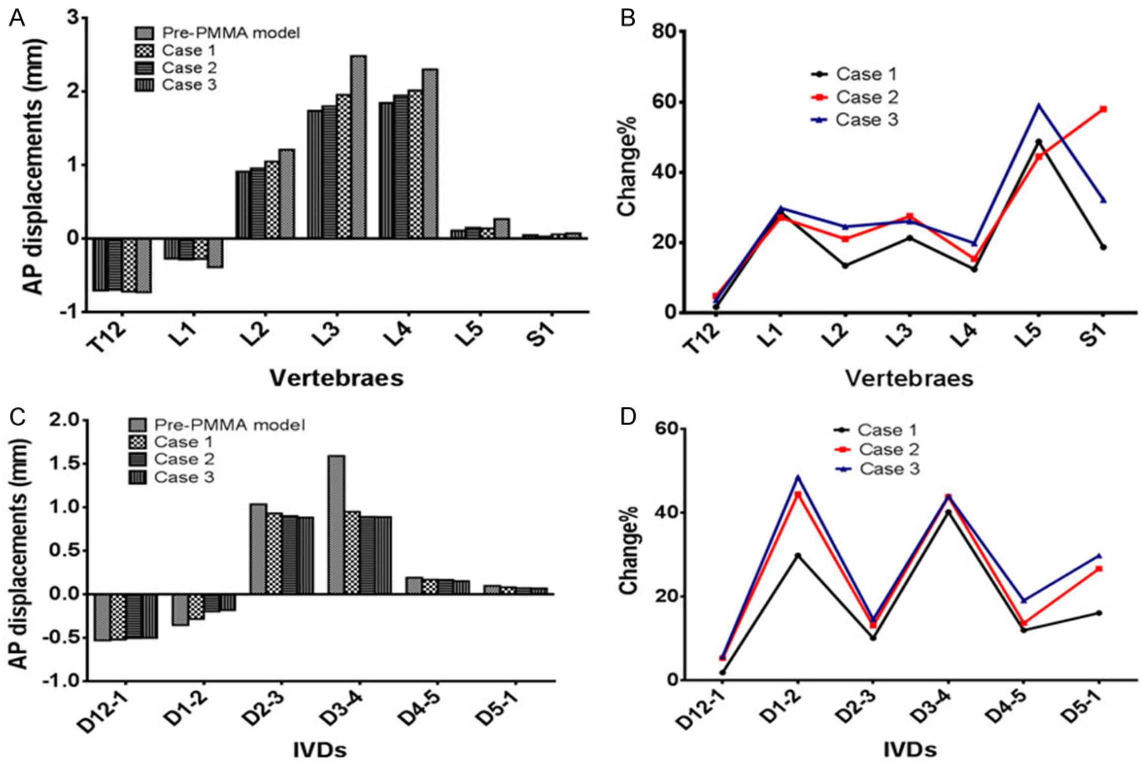

Figure 6. AP displacements of vertebraes and IVDs in osteoporotic T12-Pelvis models under vertical vibration. A. AP displacements of vertebraes in the Pre-PMMA model, case 1, case 2 and case 3. B. Changing ratios of AP displacements of vertebraes in case 1, case 2 and case 3. C. AP displacements of IVDs in the Pre-PMMA model, case 1, case 2 and case 3. D. Changing ratios of AP displacements of IVDs in case 1, case 2 and case 3.

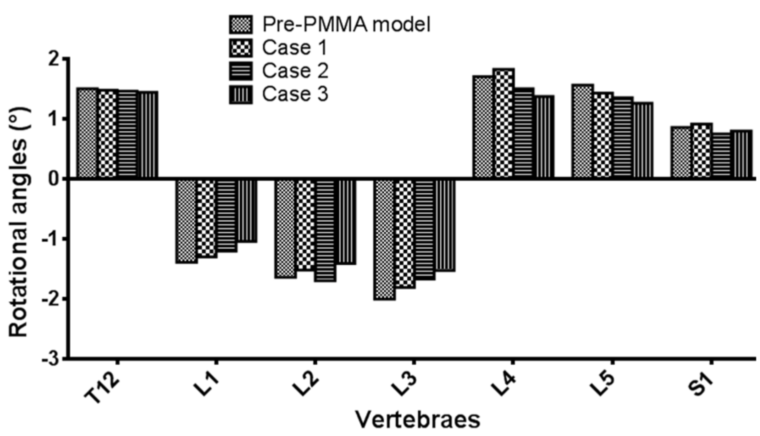

Figure 7. Rotational angles of vertebraes in osteoporotic T12-Pelvis models under vertical vibration.

segment L4-L5 (including L4, L5 and D_{4-5}) reduced by about 30% after 1, 2 or 3 levels augmentation, which was much more significant than other motion segments.

In addition to the vertical motion, the osteoporotic T12-Pelvis models also exhibited an extension-flexion motion trend at the FOVRFs under vertical vibration. The upper motion segments (T12-L1) of the T12-Pelvis segment performed a flexion while the lower motion segments (L2-S1) performed an extension. **Figure 6A** and **6C** showed that AP displacements of L3, L4 and IVD_{3-4} were maximal in the Pre-PMMA model. After PMMA augmentation all the vertebraes and IVDs displayed a decrease of AP displacements, and the changing ratios in case 1, case 2 and case 3 were shown in **Figure 6B** and **6D**. We could observe that AP displacements of L5, D_{1-2} and D_{3-4} reduced by more than 40% in all three augmentation models, which were most obvious through the whole lumbar spine. We also detected the angular rotation of the osteoporotic lumbar spine under vertical vibration. The results showed that rotational angles of each vertebrae varied in the range of 1°-2°, which presented no obvious difference among the Pre-PMMA model, case 1, case 2 and case 3 (**Figure 7**). While rotational angles of the L1-L3 segment were anticlockwise, those of other part (T12 and L4-S1) were clockwise, which were respectively maximal at vertebraes L3 and L4.

Discussion

Various studies have shown that low-amplitude high-frequency WBV could increase osteogenic capability of osteoblastic cells and is favorable for the maintenance of skeleton system, which has been more and more popular as prophylactic and rehabilitative treatments for patients with osteoporosis and other metabolic or degenerative bone diseases [24-27]. On the other hand, it is reported that long-term WBV may lead to high stress and large deformation in some spinal components, which can result in diverse spinal disorders [11, 20, 28]. Thus the outcome of WBV varies under different conditions. At present, it's unclear what role WBV plays in patients with cement augmentation. By using osteoporotic T12-Pelvis FE models we verified that both axial and AP displacements got decreased in each vertebrae and IVD after 1, 2 or 3 levels PMMA augmentation. Axial displacements of the L4-L5 motion segment and AP displacements of L5, D_{1-2} and D_{3-4} reduced most significantly. These results demonstrated that PMMA augmentation could reduce the deformation and increase the stiffness and stability of osteoporotic lumbar spine at the FOVRFs under vertical vibration, especially for the inferior adjacent motion segments.

Previous studies suggested that vibration at a lower frequency could possibly have higher energy transmission, which might increase the vibration amplitude of the human body [20]. The spinal motion segments have the maximal vibration amplitude when exposed to vertical vibration at the FOVRFs. So we detected vertical and AP deformations of different motion segments of the osteoporotic T12-Pelvis models at the FOVRFs under vertical vibration to analyze efficiently the influence of WBV on the dynamics of osteoporotic lumbar spine. By using the normal T12-Pelvis model we observed that the FOVRFs were lower when the number of the motion segments was more. Guo et al also suggested that the FOVRFs got decreased with the increase of the number or the weight of the spine segments [12, 20]. It was reported that the FOVRFs of human spine system varied in the range of 3.5 HZ to 8.9 HZ with vertical accelerations of up to 2.6 g under vibration environment [29]. In this study, the FOVRF of the normal T12-Pelvis segment under 400 N compressive loads was 12.31 HZ. This discrepancy might due to the different data used for establishing FE models and distinct conditions the models simulated. Compared to the FOVRF of the T12-Pelvis segment in the normal T12-Pelvis FE model, those in the osteoporotic models had all reduced, especially for the PMMA augmentation models. Thus, the results demonstrated that the FOVRFs of the spine motion segments could be affected by their bone density and material property.

Vertical axial displacements of the upper motion segments under vertical vibration were much larger than those of the lower motion segments in all these osteoporotic models, which suggested that the upper part of osteoporotic lumbar spine might be more vulnerable to injuries during WBV. This was consistent with the clinical phenomenon that OVCFs occurred most frequently in the thoracic-lumbar spinal segment (T12-L2). In recent years, cement augmentation techniques including VP and KP have been increasingly demonstrated to be successful for the treatment of patients with OVCFs [5, 30]. Biomechanical and experimental studies validated that prophylactic or post-fracture augmentation could increase the stiffness of osteoporotic segments and maintain the height of the injured vertebraes [5, 31]. In this study, by using osteoporotic FE models we demonstrated that PMMA augmentation could obviously decrease vertical axial deformation of the augmented and adjacent non-augmented motion segments under vertical vibration. Axial displacements of the inferior adjacent vertebraes and IVDs decreased most obviously after augmentation, which suggested that PMMA augmentation could effectively decrease loads transfer to the inferior adjacent motion segments during WBV.

The osteoporotic lumbar spine also exhibited an extension-flexion motion trend besides the vertical motion at the FOVRFs under 400 N compressive loads. The upper motion segments displayed a flexion while the lower segments displayed an extension. AP displacements of the L3-L4 segment were maximal through the whole lumbar spine. These results were quite in accordance with the geometrical curvature feature of human lumbar spine, which had also been reported by Guo et al [20]. These vibration characteristics of osteoporotic lumbar spine under vertical compressive loads meaningfully explained the clinical phenomenon that degenerative spondylolisthesis occurred most frequently at the L2-L4 segment. In addition, the lumbar spine exhibited a sagittal rotation movement under vertical vibration, which rotated clockwise at T12 and L4-S1 and anticlockwise at L1-L3. Rotational angles of vertebraes L3 and L4 were maximal among all lumbar vertebraes in these osteoporotic models. Guo et al detected the dynamics of the lumbar spine under the condition of denucleation at the IVD_{4-5} and also found that the L1-L3 segment rotated clockwise while the L4-S1 segment rotated anticlockwise [20]. However, it was L2 and L5 that had the largest rotational angles under vertical vibration in their study. This inconsistency might result from the different conditions that the T12-Pelvis FE models had simulated. We assumed that the flexion-extension motion and angular rotation movement could cushion the loads transmission and maintain the balance of the lumbar spine under vertical vibration.

Previous studies suggested that cement augmentation could affect mechanical behaviors of the spine system by the number of vertebraes processed for augmentation and amount of cement injected. In the present study, we demonstrated that vertical axial and AP deformations of each motion segment existed no significant difference among cases of 1, 2 and 3 levels PMMA augmentation of the osteoporotic T12-Pelvis segment. It illuminated that PMMA augmentation could alter the dynamic characteristics of osteoporotic lumbar spine under vertical vibration regardless one-level or multilevel augmentation. In this study, we only analysed the dynamic changes of the osteoporotic lumbar spine at the FOVRFs under vertical vibration after PMMA augmentation. To obtain more details about the motion mechanism of osteoporotic lumbar spine with cement augmentation during WBV, studies by using other augmentation materials (such as modified PMMA with low-modulus) at various frequencies need to be performed in the near future.

Conclusions

PMMA augmentation could reduce vertical axial and AP deformations of the osteoporotic lumbar motion segments at the FOVRFs under vertical vibration, especially for the inferior adjacent motion segments. However, the influence of the number of vertebraes with PMMA augmentation on the dynamics of osteoporotic lumbar spine was indistinctive.

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Disclosure of conflict of interest

None.

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