Biomechanical Comparison of Vertbroplasty, Kyphoplasty, Vertebrae Stent for Osteoporotic Vertebral Compression Fractures -A Finite Element Analysis

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Research Article

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Abstract

Vertebroplasty (VP), balloon kyphoplasty (BKP), and vertebral stent (VS) are usually used for osteoporotic compression fracture. However, these procedures may pose risks of secondary adjacent level fractures. This study simulates finite element models of osteoporotic compression fractures treated with VP, BKP, and VS. Vertebral resection method was used to simulate vertebra fracture with Young's modulus set at 70 MPa to replicate osteoporosis. A compressive force of 1000N was applied on the T11 vertebra while the L1 vertebra were fully constrained as boundary condition. Moment loadings of 4.2 N-m in flexion, 1.0 N-m in extension, 2.6 N-m in lateral bending, and 3.4 N-m in axial rotation were applied. The VS model had the highest von Mises stresses on the bone cement under all different loading conditions (flexion/5.91 Mpa; extension/3.74 Mpa; lateral bending/3.12 Mpa; axial rotation/3.54 Mpa). The stress distribution and maximum von Mises stresses of the adjacent segments, T11 inferior endplate and L1 superior endplate, showed no significant difference among three surgical models. The postoperative T12 stiffness for VP, BKP, and VS are 2898.48 N/mm, 4123.18 N/mm, and 4690.34 N/mm, respectively. VS is the most effective surgical method to maintain vertebral body height without significantly increasing the risks of adjacent fracture.

Introduction

Osteoporosis is an increasingly prevalent disease globally. When the bone property becomes thin and brittle due to decreased bone density, it may lead to fracture especially at the forearm, femur and spine vertebrae. Vertebral compression fractures (VCF) occur due to axial loading force that results in vertebral body height decrease, usually located at the anterior column with an anterior wedge appearance. Regardless of the degree of vertebral height decrease, VCFs may elicit debilitating symptoms, including back soreness, severe pain, functional limitations, and decreased life quality.[1] Treatment options for vertebral compression fracture (VCF) consist of conservative and surgical treatments. At the acute stage of VCF, bed rest, brace support, and analgesics prescription are generally recommended. However, if the patients' symptoms persist after conservative treatment for several months, surgical treatment may be needed. Cement augmentation with vertebroplasty (VP), balloon kyphoplasty (BKP), or vertebrae stent (VS) (Spinejack system, Stryker Corp., Kalamazoo, MI) has been widely used procedures to treat the patient's pain and improve quality of life.[2–4] VP was performed after administration of a local anesthetic combined with intravenous narcotic or sedative drugs. The needle entry site over the pedicle was localized under fluoroscopic guidance, and then polymethylmethacrylate (PMMA) delivery into the vertebrae body was done to stabilize the fracture and alleviate pain. BKP uses a high-pressure balloon to prevent the collapsed vertebral body back to its original height by creating a cavity that is subsequently filled with the PMMA. In contrast, vertebrae stent (VS) (SpineJack) utilizes a cranio-caudal expandable implant to increase the body height followed by filling the intravertebral stent with the PMMA.[5]

In the past literature, there has been numerous clinical and biomechanical studies that compare the outcomes for both VP and BKP.[6–11] To our knowledge, comparative studies using finite element analysis for VP, BKP, and VS procedure are scarce and limited. The aim of this study was to simulate a finite element model of an osteoporotic compression fracture at the thoracolumbar region treated with these three surgical methods (VP, BKP, and VS). Stress distribution and stiffness of the treated vertebrae and the adjacent vertebral segments were simulated under compressive loading simulation to evaluate the possibility of developing secondary fracture. The findings of this study may guide future treatment decisions for surgeons to provide the most appropriate intervention.

Methods

Before study, this project was reviewed by the ethics committee/institutional review board (IRB) of Chang Gung Memorial Hospital. Because this study was a computer-simulation finite element study which did not involve human or animal species, therefore IRB approval and human informed consent were waived.

Models

Three models were established to simulate thoracolumbar osteoporotic compression fracture with different cement augmentations surgeries: 1) VP; 2) BKP; 3) VS). Radiographs representing these three types of surgical procedures are shown in Fig. 5.

Establishment of an intact normal thoracolumbar spine in FE model

An intact normal spine FE model was constructed by 1mm slice-interval cross-sectional computed tomography (CT) spine images of a 65-year-old male obtained from the Visible Human project of U.S. National Library of Medicine (NLM, NIH, Bethesda, MD). The process of creating a finite element model of T10 to L2 were briefly described as following. 1) CT scans were imported into Amira software (Visage Imaging, Carlsbad, CA). Vertebral boundaries of interest were identified with multiple images to form a three-node triangular surface model. 2) The surface model was imported into SolidWorks (SOLIDWORKS Corp., Boston, MA), to further create a three-dimensional solid model of the thoracolumbar spine. 3) The solid model of the thoracolumbar spine was imported into HyperWorks 10.0 (Altair Engineering, Inc., Troy, MI) to form an eight-node hexahedral FE model. CT images do not provide structural contours of the intervertebral discs. Therefore, the geometric characteristics of intervertebral discs were created according to data from Chosa et al.[23] The volume ratio of the annulus fibrosus to the nucleus pulposus was set 6:4, the thickness of the cortical bone was set to 1 mm, and the endplate was set to 0.5 mm, respectively. 4) Finally, FE model was imported into Abaqus FE analysis software (Abaqus/CAE v.6.10; Simulia Corp., Providence, RI) for further analysis.

Establishment of T12 injured vertebra FE model

Vertebral resection method was used to simulate vertebra fracture in this study. One-half of the sponge bone of the T12 vertebra was removed to weaken the vertebral strength. Structure of the posterior part was reserved to simulate thoracolumbar compression fracture.

Material parameter setting

Material parameters of the normal thoracolumbar models established in this study were assigned according to Qiu et al..[24] Young's moduli and Poisson's ratios of endplate, intervertebral disc, posterior bone element, cortical bone, and cancellous bone were set respectively. Young’s modulus of the osteoporotic cancellous bone was set at 70 MPa according to the research by Homminga et al..[25] These models are assumed to be linear elastic, isotropic, and homogeneous. Table 2 summarizes the material parameters of this study.

Establishment of VP model in T12 compression fracture

For compression fractures, VP procedure uses bone cement PMMA as a filler, find the injectable point under fluoroscope guide, and inject the bone cement with a percutaneous needle to restore the original height of the vertebral body. Kim et al. proposed that under the same compressive load, the rigidity of the treated vertebral segment will be closest to the normal uncompressed vertebra when the bone cement accounts for 30% of the original spongy bone space.[26] In this study, 30% of the cancellous bone space in the T12 vertebral body was removed, and PMMA bone cement (Young's modulus: 3000 MPa, Poisson's ratio: 0.41) was added to simulate the finite element model of osteoporosis after vertebroplasty; bone cement is directly contacted with the spongy bone in the vertebral body and then solidified. The element type of bone cement is set in the same way as the spongy bone element.

Establishment of BKP model in T12 compression fracture

The difference of BKP from VP is that before the bone cement is delivered, the collapsed vertebral body is expanded to the expected height with a special balloon, and then the bone cement is injected into the opened cavity. In this study, 50% volume in the cancellous bone space of T12 vertebral body was excavated in the shape of sphere; then bone cement elements conforming to the spherical shape were created and put into the cavity to simulate bone cement injection, and bone cement with 40% volume of the injured vertebra was used to augment the T12 body, which is similar to that proposed by Purcell et al..[27]

Establishment of VS model with bone cement augmentation in T12 compression fracture

The VS in this study refers to a commercialized implantable titanium vertebral augmentation device (using SpineJack system) for treating VCF. From the collected and compiled SpineJack related literature and data, a 3D model of SpineJack implanted model was created by using Solidworks CAD software. In this study, 50% of the volume in the cancellous bone space of T12 vertebral body was excavated; SpineJack was assumed to restore 45% of the damaged T12 vertebra and bone cement was added to strengthen it.

Figures 6 demonstrated finite element photos of these three models.

Loading and boundary condition settings

The loading conditions are set as follows: (1) A compressive force of 1000N was applied on the top surface of the T11 vertebra (85% on the vertebral body and 15% on the posterior bone elements). The nodes on the bottom surface of the L1 vertebra were fully constrained as boundary condition. (2) Moment loadings of 4.2 N-m in flexion; 1.0 N-m in extension; 2.6 N-m in lateral bending; and 3.4 N-m in axial rotation were applied respectively. The stress distributions on the implant-cancellous bone interfaces were compared under different loading conditions, so as to assess the location of the fracture that may occur again in the treated segment. Under different loading conditions, the stress distributions on the adjacent segments (T11 and L1) after implantation were compared for different cement augmentation treatments. It was aimed to observe whether there is a "load shift" phenomenon that may cause high stress site to transfer to the internal vertebral body of adjacent segments, thereby posing a risk of secondary fracture in the adjacent segments.

Results

The biomechanical performance of the surgical segment and adjacent vertebral bodies were investigated, including von Mises stress distribution and compressive stiffness, in order to understand the effects of different loading conditions and to evaluate the risk of secondary fracture.

Maximum bone cement stress

From Figs. 1A-1D, the maximum stresses in the bone under flexion loading for each surgery models are: 3.9 MPa for VP model, 3.59 MPa for BKP model, and 5.91 Mpa for VS model; when under extension loading for VP model is 2.37 MPa, 3.61 MPa for BKP model, and 3.74 MPa for VS model; when under lateral bending condition for VP model is 2.48 MPa, 2.73 MPa for BKP model, and 3.12 MPa for VS model; when under axial rotation condition for VP model is 2.13 MPa, 1.85 MPa for BKP model, and 3.54 MPa for VS model.

Maximum adjacent segment interfacial stress distribution

The interfacial stress distributions at the adjacent lower T11 and upper L1 endplates were investigated to evaluate the risk of adjacent level fracture.

Maximum interfacial stress at lower T11 endplate

From Figs. 2A-2D, the maximum interfacial stress at the Lower T11 endplate under flexion loading for VP model is 19.52 MPa, 18.46 MPa for BKP model, and 20.97 MPa for VS model; under extension condition for VP model is 13.41 MPa, 13.99 MPa for BKP model, and 12.25 MPa for VS model; under lateral bending condition for VP is 11.61 MPa, 10.91 MPa for BKP model, and 12.19 MPa for VS model; under axial rotation condition for VP model is 8.74 MPa, 9.13 MPa for BKP model, and 8.63 MPa for VS model.

Maximum interfacial stress at upper L1 endplate

From Figs. 3A-3D, the maximum upper L1 endplate interfacial stress under flexion condition for VP model is 13.74 MPa, 13.79 MPa for BKP model, and 13.5 MPa for VS model; under extension condition for VP model is 13.41 MPa, 13.52 MPa for BKP model, and 14.27 for VS model; under lateral bending condition for VP model is 11.34 MPa, 11.36 MPa for BKP model, and 11.17 MPa for VS model; under axial rotation condition for VP model is 8.1 MPa, 9.13 MPa for BKP model, and 8.63 MPa for VS model.

Surgical segment vertebra stiffness

The postoperative T12 stiffnesses (slopes of the force-displacement curves) of the three different surgical interventions are shown in Fig. 4. The stiffness values could help understanding the biomechanical behavior of the injured vertebra under 1000 N compressive force. The stiffness for the VP, BKP, and VS groups are: 2898.48 N/mm, 4123.18 N/mm, and 4690.34 N/mm, respectively.

Table 1 summarized maximal stress on T12 cement surface, T11 lower endplate and L1 upper endplate in these three models.

Discussion

VP and BKP are common interventions for the treatment of osteoporotic compression fracture of the spine vertebrae. VS can achieve controlled anatomical restoration before bone cement augmentation and has gained popularity recently. Although the height restoration and augment material property may vary, these interventions use bone cement to stabilize fracture cracks. The aim of this study was to investigate the biomechanical effects on osteoporotic compression fracture of these different interventions.

Clinical studies of different cement augmentation procedures have been encouraging. Several studies have suggested both VP and BKP not only improved quality of life, pain relief, improved functionality, and restored vertebral body height.[12] A meta-analysis by Zhao et al. showed patients treated with BKP are more effective for long term VAS, ODI, improved kyphosis angle, mean vertebral body height, and significantly reduced risk of cement leakage.[13] Clinical outcomes of VKP and VS (SpineJack) cement augmentations were also compared in previous studies. Noriega et al. demonstrated both procedures were safe and led to significant clinical improvement for patients with osteoporotic vertebral compression fractures.[5] In 2019, a prospective, international, randomized study compared an implantable titanium vertebral augmentation device versus BKP in the reduction of vertebral compression fractures and found non-inferiority of the titanium augmentation device with an excellent risk/benefit profile for results up to 12 months.[14] Furthermore, *in vitro* biomechanical cadaver studies demonstrated height restoration was significantly better in the VS (SpineJack) group compared with the BKP group.[15] The clinical implications include a better restoration of the sagittal balance of the spine and a reduction of the kyphotic deformity. From our results, the VS group has the highest von Mises stress among the three surgical interventions of

5.94 MPa. The usual maximum compressive strength of PMMA is 93MPa, which is far more than the measured maximum stress in the VS group.[16] Therefore, it is reasonable that the compressive strength of PMMA is well within the safe range for all three surgical procedures.

The effect of cement augmentation on the adjacent vertebral body has been debated. Many studies have reported the incidence of adjacent level fractures, but the results were not consistent. Ma et al. conducted a Meta-analysis which encompasses 12 studies with 1,081 patients.[17] They concluded that BKP and VP are both safe and effective procedures for treating osteoporotic vertebral compression fractures. There were no statistical differences in visual analog scale, Oswestry Disability Index, cement leakage rates, and adjacent vertebral fracture rates. Similarly, Zhao et al. found both VP and BKP had a similar effect on short-term pain relief, posterior vertebral body weight, and adjacent-level fractures.[13] In this study, the stress distributions of the adjacent lower T11 and upper L1 endplate also showed no significant difference among the surgical intervention groups, implying no significant effect on the risks of adjacent fracture.

This study also showed that compression fracture treated with VS have the highest stiffness of 4690.34 N/mm. According to a study on the stress burden of the spine after VP and BKP by Rohlmann et al., the stiffness and strength of the vertebrae increase as the bone cement volume increases.[8] Their probabilistic and sensitivity study suggested that in cement augmentation procedures, the maximum stresses moderately depend on the injected cement volume. The VS group has the most amount of cement augmentation and VP has the least amount. According to Rotter et al., during intraoperative period, VS (SpineJack) could preserve the maximum height gain significantly better than BKP, which creates cavity absence of load-bearing after balloon deflation and before cement injection.[18] Furthermore, the additional support of titanium alloy implant also contributes to a higher stiffness for the VS group. Interestingly, the results of this biomechanical study also suggest a superior body height maintenance ratio for the VS surgical model due to a higher stiffness.

However, several previous articles have reported the possible risk factors for recollapse of cemented vertebrae after percutaneous cement augmentation. In 2011, Chen et al. retrospectively reviewed 1,800 patients with a 2-year follow-up. The incidence of refracture of the same vertebra after VP with an incidence rate of 0.56%.[19] Osteonecrosis, greater anterior vertebral height restoration, lesser kyphosis angle correction and cystic filling pattern were found to be significant risk factors for recollapse. As for BKP, Lavelle et al. reported a 10% incidence recurrent fracture after BKP of a previously operated vertebra primarily within the first 90 days after surgery.[20] The study by Kim et al. demonstrated the presence of intervertebral cleft and non-PMMA-endplate-contact may contribute to future recompression of BKP treated vertebrae.[21] Li et al. conducted a risk factor analysis for re-collapse of cemented vertebrae after percutaneous VP or BKP.[22] Low bone mineral density, percutaneous BKP, and low volume cement injection were found to be associated with high risk of recollapse. Therefore, cautious interpretation of patients with the above risk factors is imperial to prevent deterioration of fracture condition.

There are several limitations to this study that need to be considered. The creation of a finite element model requires several simplifications and assumptions, including a homogeneous cement filling model and orthotropic material simulation. Physiological boundary conditions, cortical and trabecular bone region distinction, subsequent bone remodeling and pre-existing damage may be neglected. Furthermore, as of many other biomechanical studies, our finite element analysis was limited to a single thoracic vertebral segment and may not be generalized to other vertebrae. Despite the shortcomings mentioned above, this is the first study comparing the stress distribution and maximum von Mises stresses on the treated and adjacent vertebrae among VP, BKP, and VS using finite element analysis. This biomechanical study can improve the understanding of cement augmentation on vertebral compression fracture. To make the results from this finite element analysis clinically applicable, we encourage future multicenter studies with long term follow up to confirm these findings.

Conclusions

Compared to VP and BKP, treating compression fracture with VS (SpineJack) is the most effective surgical method to maintain vertebral body height without significantly increasing the risks of adjacent secondary fracture.

Declarations

Data Availability

The data used to support the finding of this study are available from the corresponding author upon request.

Author Contribution

Jen-Chung Liao designed the study and wrote the manuscript. Michael Jian-Wen Chen wrote the manuscript. Jen-Chung Liao and Tung-Yi Lin applied the fund. Wen-Pin Chen reviewed and edited the manuscript.

Conflicts of Interest

The authors declare that there no conflicts of interest regarding the publication of this paper.

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All methods were carried out in accordance with relevant guidelines and regulations.

All experimental protocols were approved by a named institutional and/or licensing committee.

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Tables

Table 1. Maximum von Mises stress of three surgical models (MPa)

	Flexion	Extension	Lateral bending	Axial rotation
Bone cement				
VP	3.90	2.37	2.48	2.13
BKP	3.59	3.61	2.73	1.85
VS	5.91	3.74	3.12	3.54
Lower T11 endplate				
VP	19.52	13.41	11.61	8.74
BKP	18.46	13.99	10.91	9.13
VS	20.97	12.25	12.19	8.63
Upper L1 endplate				
VP	13.74	13.41	11.34	8.1
BKP	13.79	13.52	11.36	5.84
VS	13.50	14.27	11.17	8.32

VP, vertebroplasty; BKP, Balloon kyphoplasty; VS, vertebrae stent.

Table 2. Material Properties of the Finite Element Model

Component	Young's modulus (MPa)	Poisson ratio (υ)	Density (tonne/mm3)	Element type
Cortical Bone	34	0.3	1E-9	Tetrahedral
Cancellous Bone	34	0.3	1E-9	Tetrahedral
Posterior element	2345	0.25	1E-9	Tetrahedral
Endplate	670	0.3	1E-9	Tetrahedral
Annulus substance	5	0.45	3E-9	Hexahedral
Nucleus	9	0.4	3E-9	Hexahedral
Annulus Fiber	455	0.3	1E-9	Surface
Cement	3000	0.41	1E-9	Tetrahedral
Vertebrae stent (SpineJack)	113800	0.34	1E-9	Tetrahedral
Rigid body	10	0.4	1E-9	Pentahedron

Figures

Figure 1

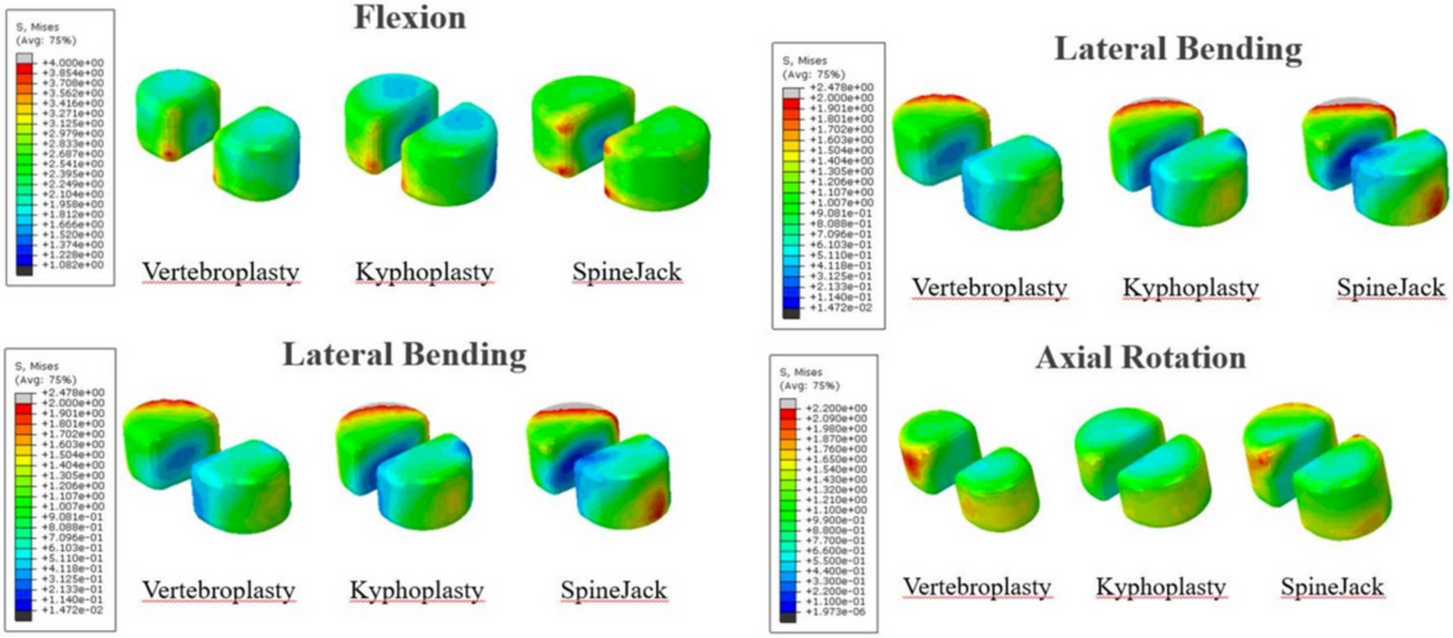

Figure 1

Finite element stress nephogram of bone cement. A: Flexion. B: Extension. C: Lateral bending. D: Axial rotation

Figure 2

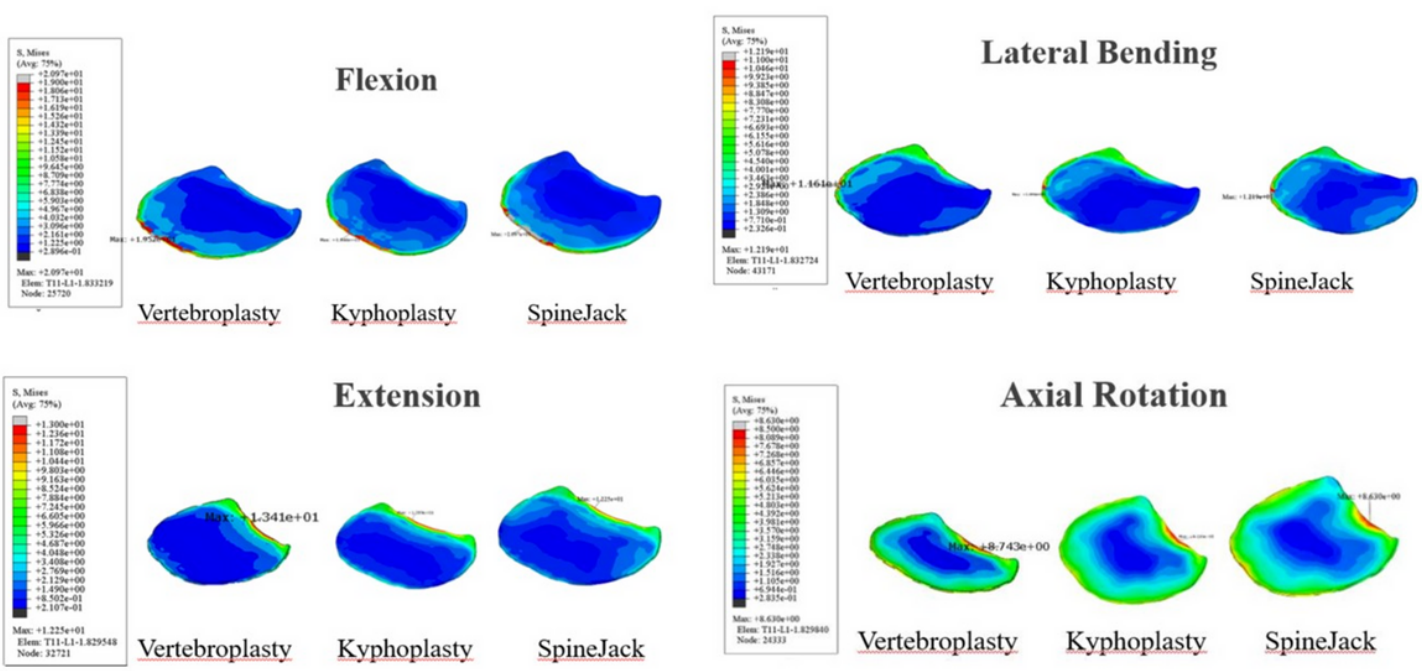

Figure 2

Finite element stress nephogram of interfacial stress at lower T11 endplate. A: Flexion. B: Extension. C: Lateral bending. D: Axial rotation

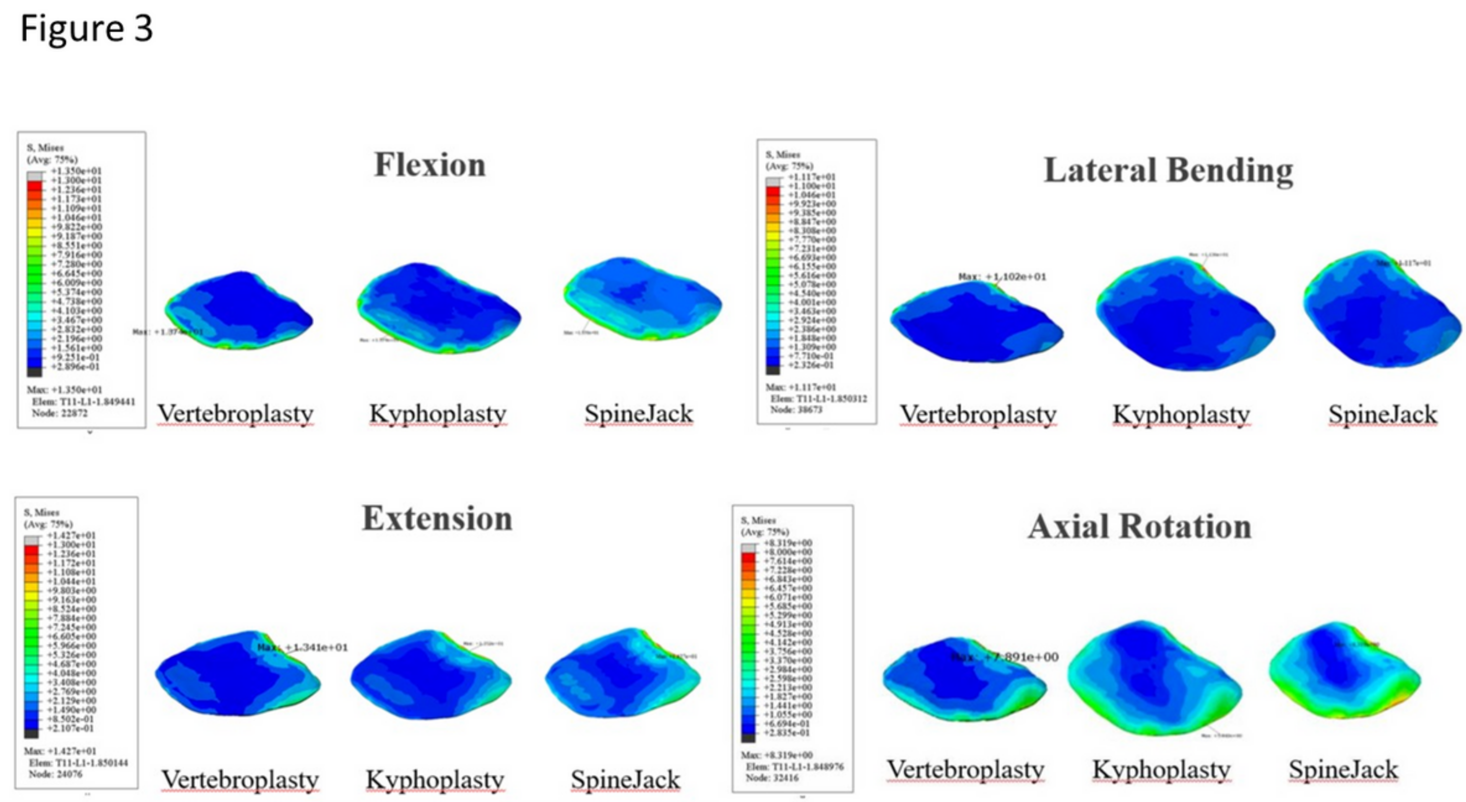

Figure 3

Finite element stress nephogram of interfacial stress at upper L1 endplate. A: Flexion. B: Extension. C: Lateral bending. D: Axial rotation

Figure 4

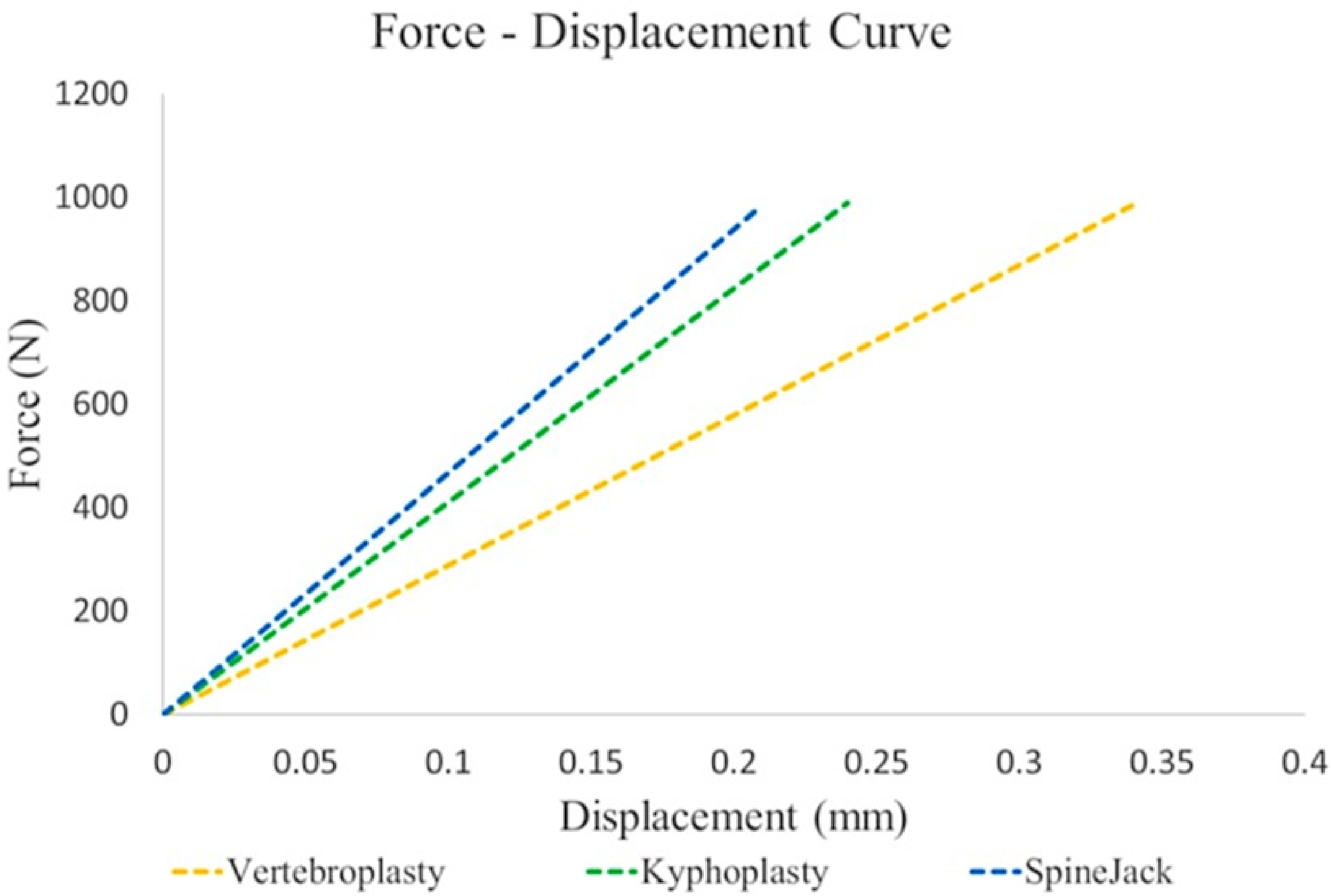

Figure 4

Force-displacement curve of the treated vertebrae after three different surgical procedures

Figure 5

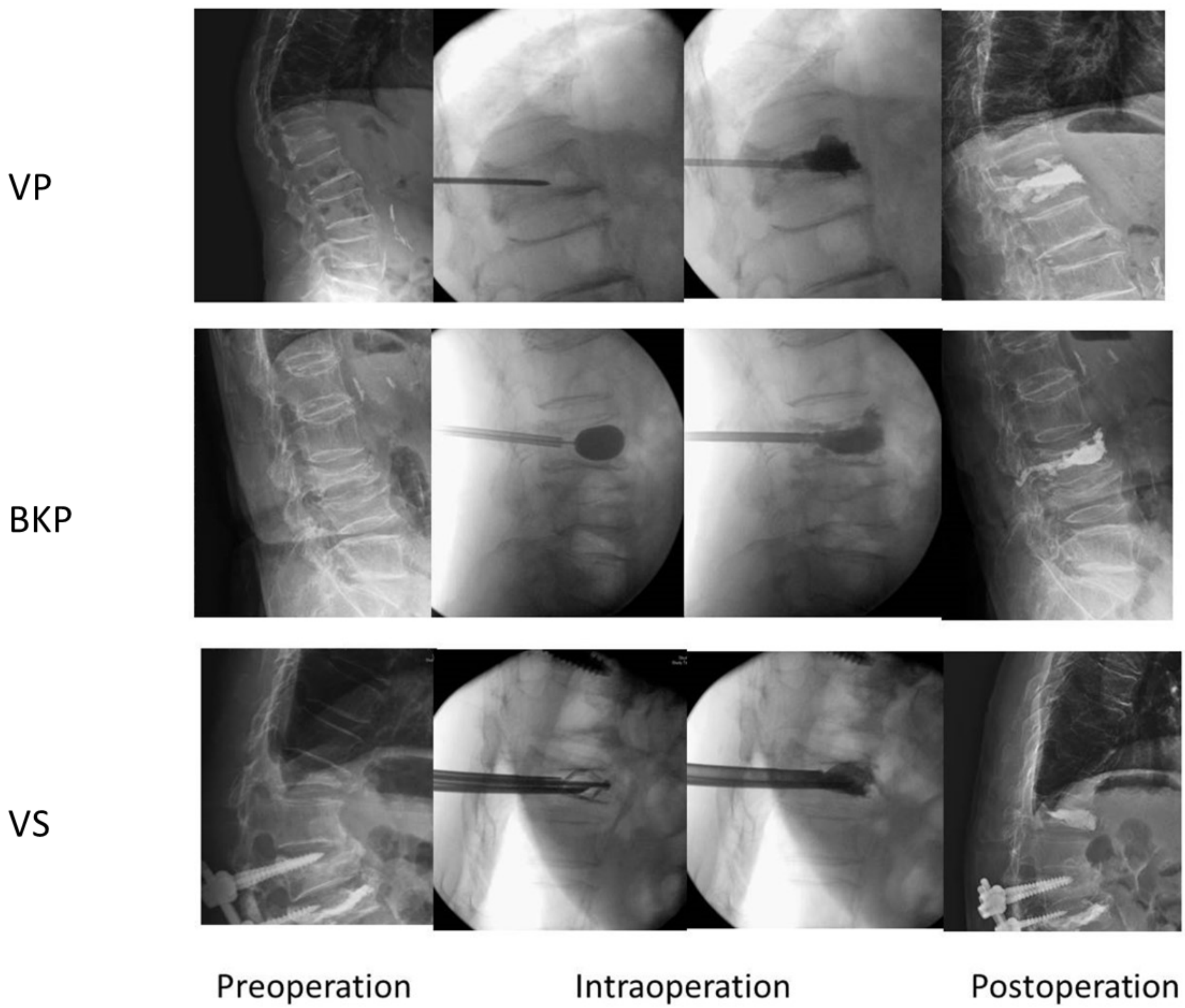

Figure 5

Radiographs representing three types of cement augmentation technique. VP: vertebropalsty, BKP: balloon kyphoplasty, VS: vertebrae stent

Figure 6

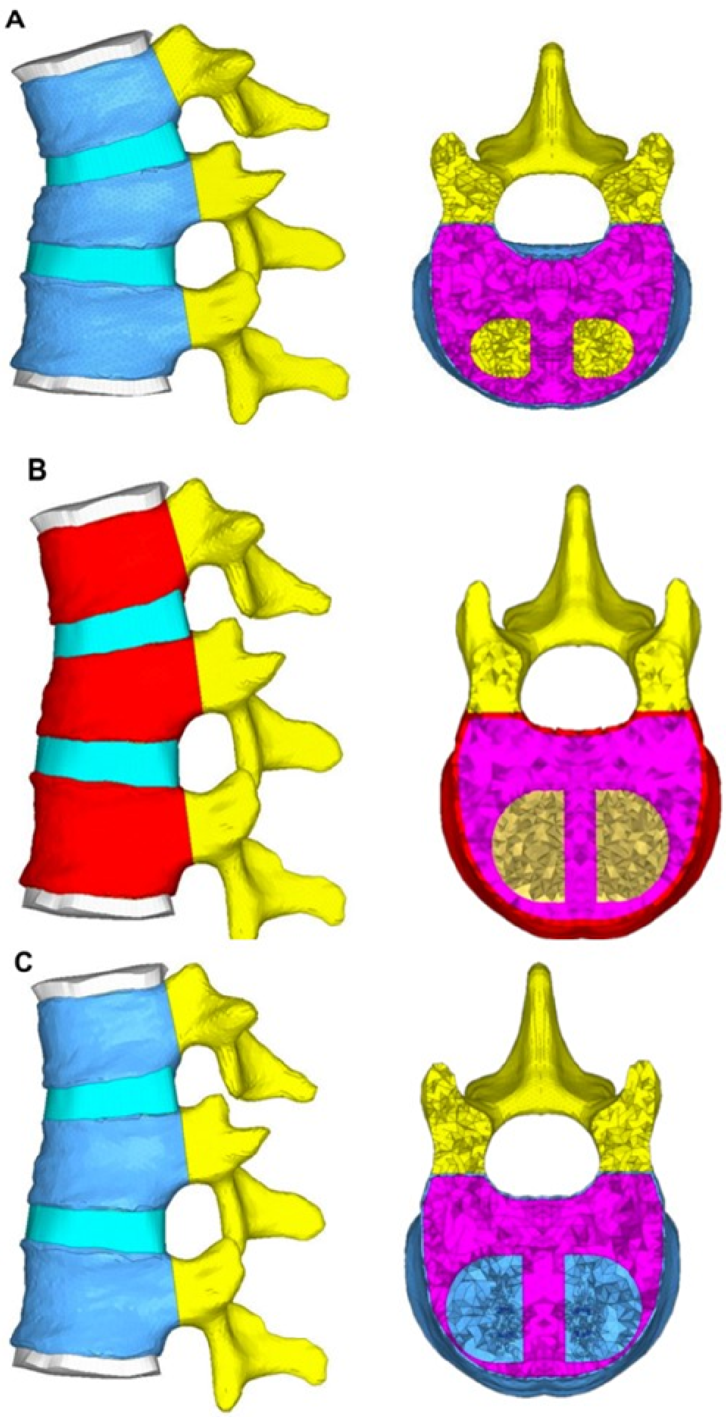

Figure 6

T11-L1 finite element model representing three types of cement augmentation technique. A: Vertebroplasty. B: Kyphoplasty. C: Vertebrae stent