Biomechanical Effects of Polyetheretherketone and Titanium Rods in Transforaminal Lumbar Interbody Fusion: A Finite Element Analysis

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Abstract

Background: Currently, the comprehensive biomechanical evaluation of polyetheretherketone (PEEK) rods in transforaminal lumbar interbody fusion (TLIF) is limited. The purpose of this study was to compare the biomechanical differences between titanium alloy (Ti) rods and PEEK rods in TLIF.

Methods: L3-5 lumbar models were developed using the finite element method. Four surgical models of TLIF were constructed by simulating different fusion methods and rods: cage fusion with Ti rods, cage fusion with PEEK rods, bone graft alone with Ti rods, and bone graft alone with PEEK rods. The range of motion (ROM) and stress distribution of the surgical and adjacent segments were then compared.

Results: Compared to the Ti rods, the PEEK rods increased the ROM by 0.7–20% at the L4/5 segment and decreased the ROM by 0.8–15.1% at the L3/4 segment. The disc stresses at the L3/4 level were similar among the surgical models (0.79–1.80 MPa). The peak stresses of the screws, rods, and bone-screw interfaces in the PEEK rod models were 0–1.2 times, 1.6–4.4 times, and 0–1.4 times lower than those of the Ti rod models, respectively. PEEK rods increased the average strain of the bone graft by 0.5–61.6% and the stresses of the cage by 0.9–44.1% and endplates by 2.1–52.9%.

Conclusion: In TLIF, PEEK rods played a positive role in restoring the ROM. They also increased the strain of the bone graft, stresses of the endplates and cages, and the risk of rod fracture and reduced the stress of the screw-rod system. Bone grafts alone combined with PEEK rods had acceptable biomechanical behavior in TLIF.

Introduction

Transforaminal lumbar interbody fusion (TLIF) is performed in clinics for the treatment of lumbar degenerative diseases and is favored by spine surgeons [1–3]. In contrast to posterior lumbar interbody fusion, the unilateral transforaminal approach is used in TLIF to decrease the risk of nerve root and dural injury and to prevent the destruction of the normal structure of the spine [4–6]. Studies on clinical results, radiography, and biomechanics have shown that patients who undergo TLIF have relatively good clinical outcomes [2, 7–9]. However, spinal fusion alone cannot provide sufficient strength and stability for the surgical segment, which may lead to spinal instability or even surgical failure [6, 10]. Therefore, a supplemental posterior pedicle screw fixation system was introduced to improve the biomechanical stability of the spine and surgical success rates [11, 12].

Currently, titanium alloy (Ti) is the preferred material for pedicle-based screw fixation systems because of its excellent strength, fatigue resistance, and biocompatibility [13, 14]. The superior construct stiffness of the Ti fixation system ensures spine stability and promotes solid fusion [11, 15, 16]. However, as a stress shielding effect and abnormal motion are caused by excessive rigidity of the fixation system, it is difficult to avoid adjacent segment disease (ASD) and instrumentation failure [17–19]. Some studies have reported that the reoperation rate due to ASD was at least 20% within 10 years [20]. In TLIF with

traditional rigid fixation, related ASD and screw loosening events have also been reported [21, 22]. Therefore, researchers look forward to finding new substitute materials to address this issue.

Novel polyetheretherketone (PEEK) rods, whose elastic modulus is close to that of bones, are used in clinical practice as an alternative to Ti rods in an effort to reduce the incidence of adverse events [13, 15, 23]. The biocompatibility, toxicity, and imaging characteristics of PEEK rods are better than those of Ti rods, which are the basis of their being potential clinical substitutes [24, 25]. Importantly, studies have revealed that PEEK rods can not only provide sufficient strength and stability but also reduce stress shielding, which may contribute to overcoming ASD and instrumentation failure [19, 26, 27]. However, most of these studies did not consider interbody fusion when constructing models of semi-rigid fixation with PEEK rods [18, 28–30]. Overall, there is a shortage of a comprehensive biomechanics evaluation of PEEK rods in TLIF.

The purpose of this study was to compare the biomechanical differences between Ti rods and PEEK rods in TLIF, which may provide some theoretical evidence for their use in clinical treatment.

Materials And Methods

Study design and setting

This was a finite element (FE) analysis study, which aimed to compare the biomechanical differences between Ti rods and PEEK rods in TLIF, performed in a laboratory setting.

Intact FE model

Computed tomography (CT) data of the L3-5 vertebrae were obtained from a healthy male (29 years old, 176 cm height, 60 kg weight, with no history of spine-related diseases, and trauma). This study was approved by the Ethics Committee of our hospital, and informed consent was obtained from the volunteer. The procedure for lumbar model reconstruction was similar to that used in previous studies[31]. Thin-layer (0.625 mm) CT data were saved in DICOM format and imported into Mimics (Materialise Inc., Leuven, Belgium) to generate a surface model. The solid model was constructed using 3-Matic software (Materialise Inc.) and meshed using HyperMesh (Altair Engineering, Inc., Troy, Michigan, USA). The definition of material properties, model assembly, and analysis were performed using Abaqus (Hibbitt, Karlsson, and Sorensen, Inc., Providence, Rhode Island, USA).

Consistent with a previous study on the lumbar FE model, the 1 mm thick cortical layers and the 0.5 mm thick endplates covered the surface of the vertebral body (Fig. 1a-c) [31]. The nucleus pulposus (NP) was simulated as an incompressible fluid element, which accounted for 40% of the intervertebral disc volume (Fig. 1d) [32]. The annulus fibrosus (AF) was constructed using a heterogeneous fiber-reinforced composite consisting of annulus fibers and a ground substance (Fig. 1e-f) [31, 33]. The ligaments were modeled as tension truss elements, including the anterior longitudinal, posterior longitudinal, flavum, supraspinous, interspinous, intertransverse, and capsular ligaments (Table 1). The facet articular

cartilage with a thickness of 0.2 mm was tied to the bone, and the friction coefficient between articular surfaces was 0.1 [8]. A convergence analysis was performed by ensuring that the strain energy error was less than 5% [27].

Table 1
Definition of materials properties in the finite element models.

Materials	Element type	Young's modulus (MPa)	Poisson's ratio (μ)	Cross-Sectional Area (mm ²)
Bone				
Cortical bone	C3D4	12,000	0.3	
Cancellous bone	C3D4	100	0.2	
Posterior elements	C3D4	3500	0.25	
Cartilage endplate	C3D8	24	0.4	
Intervertebral disc				
Nucleus pulposus	C3D8	1	0.49	
Annulus ground	C3D8H	Hyperelastic C10 = 0.18 C01 = 0.045		
Annulus fiber	T3D2	Hypoelastic		
		Layer 1/2 550 Layer 3/4 495 Layer 5/6 413 Layer 7/8 358		
Ligaments	T3D2			
Anterior longitudinal		7.8 (< 12%), 20 (> 12%)		63.7
Posterior longitudinal		10 (< 11%), 20 (> 11%)		20
Ligamentum flavum		15 (< 6.2%), 19.5 (> 6.2%)		40
Supraspinous		8.0 (< 20%), 15 (> 20%)		30
Interspinous		10 (< 14%), 11.6 (> 14%)		40
Intertransverse		10 (< 18%), 58.7 (> 18%)		1.8

C3D4: 4-node tetrahedral elements; C3D8: 8-node hexahedral elements; T3D2: 2-node truss elements.

Materials	Element type	Young's modulus (MPa)	Poisson's ratio (μ)	Cross-Sectional Area (mm ²)
Capsular		7.5 (< 25%), 32.9 (> 25%)		30
C3D4: 4-node tetrahedral elements; C3D8: 8-node hexahedral elements; T3D2: 2-node truss elements.				

Surgical FE models

In this study, the intact model was modified and four surgical models were constructed: TLIF with a cage and two Ti rods (Cage + Ti rods), TLIF with a cage and two PEEK rods (Cage + PEEK rods); TLIF with autogenous bone graft alone and two Ti rods (bone graft alone + Ti rods); and TLIF with autogenous bone graft and two PEEK rods (bone graft alone + PEEK rods).

To simulate the process of decompression and fusion, left L4-5 facetectomy was performed, and then the entire NP, left posterior part of the AF, and capsular and flavum ligaments were removed in all the surgical models (Fig. 2a-b) [34]. A banana -shaped PEEK cage was placed on the anterior part of the L4-L5 intervertebral space (height, 9.5 mm; length, 32 mm; width, 10 mm; and surface area, 1.86 cm²; BKMeditex USA, Las Vegas, NV, USA) (Fig. 2c) [35]. Cancellous bone was implanted in the inner and outer spaces of the cage to fill the intervertebral space. To remove the overlap between the cage and the endplates, a “Boolean calculation” was performed. Cage-bone graft interfaces were assigned a “tie” constraint, and cage-endplate interfaces were assigned a friction coefficient of 0.2 [34]. In the bone graft alone models, cancellous bone was used to fill in the L4/5 space. It was assumed that the surface of the bone graft was rigidly connected to the vertebral surface to simulate complete fusion.

In terms of posterior fixation, the pedicle screw-based fixation system consisted of four screws (diameter, 6.5 mm; length, 45 mm) and two connecting rods. The screw was made of Ti-6Al-4V and inserted into the vertebra. The connecting rods were categorized as Ti-6Al-4V rods and PEEK rods. The rods were cylindrical with a diameter of 5.5 mm and length of 58 mm (Table 2). The bone-implant and screw-rod interfaces were defined in the “tie” contact condition.

Table 2
Definition of materials properties and dimensions of the implants.

Implants	Material	Element type	Young's modulus (MPa)	Poisson's ratio	Design	Diameter (mm)	Length (mm)
Screws	Ti-6Al-4V	C3D4	110,000	0.3	Cylindrical	6.5	45
rod	Ti-6Al-4V	C3D4	110,000	0.3	Cylindrical	5.5	58
	PEEK	C3D4	3600	0.25	Cylindrical	5.5	58
Cage	PEEK	C3D8	3600	0.25	Banana-shaped		
Graft bone	Cancellous bone	C3D4	100	0.2			
Ti: Titanium; Al: Aluminum; V: Vanadium; PEEK: polyetheretherketone; C3D4: 4-node tetrahedral elements; C3D8: 8-node hexahedral elements.							

Loading conditions

This study focused on the ranges of motion (ROMs) in all models under the loading conditions of flexion, extension, lateral bending, and rotation, as well as the maximum von Mises stress of the adjacent disc, endplates, cages, screw-rod system, and bone graft in the surgical model. The ROM was calculated based on a previous study [34]. By fixing the inferior surface of the L5 vertebrae to limit its degree of freedom, 400 N of vertical preload and 8 Nm of bending moments were applied on the L3 superior surface simultaneously to simulate physiological load and motion in coronal, sagittal, and axial planes, respectively. Additionally, the ROMs of the L3/4 and L4/5 segments were compared with those of previous studies to validate the intact model [34, 36, 37].

Results

Model validation

In this study, an intact spinal model of L3-5 was constructed and validated. Under extension, flexion, lateral bending, and axial rotation, the ROM was 2.84°, 3.96°, 2.36°, and 1.90° in the L4/5 segment, and 3.26°, 3.69°, 2.55°, and 2.45° in the L3/4 segment, respectively (Fig. 3). Under similar load conditions, the agreement of the ROMs between those of the current study and previous studies, including those tested on cadavers and FE studies, were acceptable, indicating that the current model could be used for further studies.

PEEK rods versus Ti rods

After validating the effectiveness of the intact model, four surgical models were constructed. Substantially, compared with the intact model, the ROMs of the L4/5 segment for all surgical models decreased (0.58°–1.62°), while the ROMs of the L3/4 segment increased (3.23°–6.20°) (Fig. 4a-b).

Whether in cage fusion or bone graft alone fusion, the ROMs of the L4/5 segment in the PEEK rods fixation models were greater than those in the Ti rods fixation models (0.83° – 1.62° vs. 0.58° – 1.57°). Correspondingly, the ROMs at the L3/4 segment were lower in the PEEK rod fixation models than in the Ti rod fixation models (3.23° – 6.17° vs. 3.60° – 6.20°).

The peak stresses of the cage in the PEEK rods fixation models were 7.2–30.4 MPa, which were greater than those of the Ti rods fixation models (6.6–25.3 MPa) under all loading conditions (Fig. 5a). The peak stresses of the disc at the L3/4 segment for all surgical models increased compared to those of the intact model (0.79–1.80 MPa vs. 0.64–1.46 MPa), while the disc stresses of the PEEK rod fixation models were similar to those of the Ti rod fixation models (0.79–1.79 MPa vs. 0.80–1.80 MPa) (Fig. 5b). Furthermore, the peak stresses of the endplates were 8.83–61.44 MPa in the models with PEEK rods, and were 7.96–50.82 MPa in the models with Ti rods (Fig. 5c). Compared to Ti rod fixation models, PEEK rod fixation models could reduce the peak stresses of screws (37.59–65.72 MPa vs. 39.08–122.96 MPa) (Fig. 5d). The largest stresses experienced by the PEEK rods were 7.36–37.40 MPa, which were much lower than those experienced by the Ti rods (20.84–124.06 MPa) (Fig. 5e). Furthermore, the peak stresses at the bone-screw interfaces in the PEEK rod groups were lower than those in the Ti rod groups (21.10–44.80 MPa vs. 26.47–105.48 MPa) (Fig. 5f).

It was found that the average strain of bone graft in the PEEK rod fixation models was larger than that in the Ti rod fixation models (570.67–9570.85 μ E vs. 481.42–7433.68 μ E) (Fig. 6a-c). In addition, the average strain of the outer bone graft around the cage was much greater than that of the inner bone graft in the cage (1544.30–7519.96 μ E vs. 481.42–1298.92 μ E).

Cage fusion versus bone graft alone fusion

In the cage fusion models, the ROMs of the L4/5 and L3/4 segments were 0.58° – 1.49° and 3.51° – 6.20° , respectively. In the bone graft alone fusion models, the ROMs were 0.74° – 1.62° and 3.23° – 6.09° at the L4/5 and L3/4 segments, respectively. The peak stresses of the endplates were much lower in the bone graft alone models than in the cage fusion models (7.96–18.69 MPa vs. 18.34–61.44 MPa). The adjacent disc stresses were similar between bone graft alone models and cage fusion models (0.79–1.79 MPa vs. 0.79–1.80 MPa). Compared to bone graft alone fusion models, cage fusion models could reduce the peak stresses of screws (37.59–105.42 MPa vs. 40.63–122.96 MPa), rods (7.36–107.71 MPa vs. 9.29–124.06 MPa), and bone-screw interfaces (21.10–52.50 MPa vs. 31.43–105.48 MPa). The average strain of the bone graft in models without cages was much greater than that in models with cages (2202.99–9570.85 μ E vs. 481.42–7519.96 μ E).

Discussion

As a novel “compliant” material, PEEK rods are available as substitutes for traditional Ti rods [15]. Although some studies have demonstrated that PEEK rods have excellent performance, there is still a lack of sufficient biomechanical evidence to support the use of PEEK rods in TLIF. In our study, we found that PEEK rods in TLIF played a positive role in restoring normal motion and reducing stress shielding.

However, the PEEK rods also simultaneously increased the risk of rod fracture, endplates collapse, and cage failure.

The L4/5 segment was chosen for fusion and fixation because it has the highest clinical incidence (58.3%), which is determined by its anatomical structure and physiological function[38]. It is generally accepted that the aim of a lumbar surgery, including TLIF, is to provide stability after decompression, essentially sacrificing part of the ROMs for symptom improvement. In our study, the ROMs of the L4/5 segment for all surgical models were decreased by 41.1–69.5% compared to that of the intact model. Compared to the Ti rod rigid fixation models, the PEEK rod semi-rigid fixation models increased the ROM at the L4/5 segment by 0.7–20%. It was suggested that PEEK rods could not only stabilize the movement of the spine to a great extent but also allow for more ROMs than that of Ti rods. In cadaveric biomechanical testing, Gornet et al. also showed that there was no significant difference in stability between PEEK rods and Ti rods [14]. Yeager et al. concluded that the stability of PEEKs rod was similar to that of Ti rods in vitro [26]. Moreover, we found that the change in the ROMs caused by PEEK rods during lateral bending and rotation was greater than that created during flexion and extension. We inferred that the axial stiffness provided by PEEK rods was similar to that of Ti rods, but the bending stiffness of PEEK rod models was lower than that of Ti rod models. It is known that axial stiffness affects flexion and extension, whereas lateral bending stiffness affects rotation and lateral bending [26]. Therefore, axial stiffness is mainly provided by the anterior column, while the posterior internal fixation is important to bending stiffness [23, 26].

ASD is a common long-term complication of lumbar fusion. Abnormal motion (quality and quantity) and intervertebral disc pressure (IDP) of adjacent segments are closely related to ASD [39]. In this study, we found that, compared to the intact model, the ROMs and intradiscal peak stresses of the L3/4 segment of all the surgical models increased by 31.8–68.0% and 18.5–39.0%, respectively. Cunningham et al. found that spinal instrumentation increased proximal IDP by as much as 45% in in vitro biomechanical testing [40]. Jin et al. showed that although both PEEK rods and Ti rods increased the inter-segmental rotation and IDP in the upper adjacent segments, the PEEK rods generated fewer changes than those of titanium rods [41]. Similarly, Nikkhoo et al. demonstrated that there was no significant difference in the ROM of adjacent segments between the PEEK rod models and the intact models, and PEEK rods reduced the disc height loss, fluid loss, and disc stresses of adjacent segments under cyclic loading compared with those of Ti rods [30]. Additionally, during flexion, the increase in disc stresses at L3/4 was highest (29.7–39.0%), and this was similar to that reported by Hsieh et al. (50%) [23]. In fact, the structural stiffness provided by both rigid and semi-rigid fixation systems is significantly greater than that of the normal spinal unit, which further changes the ROM and IDP of adjacent segments [13, 41]. The ROM increases at the adjacent level may be derived from the non-physiological center of motion, which is a compensatory change to fixed segments [29, 42]. However, this adverse compensation makes the spine's originally complex but regular coupling movement to become irregular, resulting in facet hypertrophy, an IDP change, and altered biomechanics [42]. Remarkably, PEEK rods reduce the ASD incidence owing to their low structural stiffness and physiological load sharing [14, 17]. Furthermore, the biomechanical effect of the rigidity of the rod on the adjacent segments seems to be more important than the amount of fusion

mass [41]. Athanasakopoulos et al. reported a retrospective clinical study comprising 52 patients with posterior lumbar internal fixation using PEEK rods, and no ASD was observed after a mean follow-up period of 3 years [43]. However, although the disc stresses of the PEEK rod models at the adjacent level were better than those of the Ti rod models, the difference was not significant in our study. Generally, there is still a lack of high-quality clinical studies to verify the effect of PEEK rods on ASD.

The concept of flexible fixation is reflected not only in the partial restrictions on the ROM but also in reasonable load sharing [18]. Some researchers believe that low back pain is caused by abnormal load transfer rather than an abnormal ROM [17, 29]. As expected, the PEEK rods showed superior performance in terms of stress distribution. In our study, the peak stresses of screws, rods, and bone-screw interfaces in PEEK rod models were 0–1.2 times, 1.6–4.4 times, and 0–1.4 times lower than those of Ti rod models, respectively. Fan et al. showed that PEEK rods decreased the stress of pedicle screws by 12.0–36.7% and rods by 2.5–5.6 times compared to cases where Ti rods were used; however, the ratio of peak stress to yield stress of PEEK rods (10.2–15.7%) was greater than that of Ti rods (5.1–11.1%)[27]. The ratio in our study was 7.4% for PEEK rods and 2.8–16.5% for Ti rods, which also suggested that the fracture risk of PEEK rods was high. Theoretically, PEEK rods with low elastic modulus can reduce the structural stiffness and transfer loads to the anterior column. This could unload the stress of screws and bone-screw interfaces and is especially important for patients with osteoporosis [44]. Ahn et al. showed that the PEEK rod system transmitted 27.5% of the axial compressive load, while this ratio was 66.7% in the Ti rod system [18]. Gornet et al. proved that the PEEK rod loads were at least 6% less than the titanium rod loads under all loading conditions [14].

In addition, we found that PEEK rods increased the average strain of the bone graft by 0.5–61.6% and stresses of the cage by 0.9–44.1% and those of endplates by 2.1–52.9%. As noted earlier, this was because the PEEK rods transferred load to the anterior column. Furthermore, we found that the strain of the bone graft in the periphery of the cage was greater than that in the interior of the cage, suggesting that fusion may begin from the periphery. However, the bone graft of the anterior column experienced stress, which stimulated its growth and fusion according to Wolff's law. Wang et al. found that the PEEK rod group had better fusion than the Ti rod group after posterior bone graft fusion and internal fixation in canines [45]. However, PEEK rods simultaneously increased the risk of cage failure and endplate collapse. It is well known that cages are important than posterior fixation in maintaining spinal stability because the anterior column bears approximately 75% of the load [23].

The application of the cage is to overcome issues related to intervertebral space reduction caused by autogenous bone due to its weak strength [46]. However, given the high elastic modulus of the cage and the small contact area, which should be > 30%, events of cage subsidence and endplate collapse are still worthy of careful evaluation [47]. In our study, we found that compared to cage fusion, bone graft alone fusion increased the ROMs of the fixed segment, reduced the peak stresses of the endplates, and increased the average bone graft strain. However, bone grafting alone also increased the peak stresses of screws, rods, and bone-screw interfaces. In a clinical study involving 23 patients who underwent TLIF with autologous bone graft fusion alone, Sleem et al. found that autologous bone grafts alone could also

achieve satisfactory clinical outcomes [48]. Interestingly, it was noticed that bone graft alone combined with PEEK rods had superior biomechanical characteristics, especially in terms of improving the bone graft strain, endplate stress, and rod stress. However, whether the model could provide sufficient stability and strength remains to be further studied because there is still no recognized ROM and load sharing.

This study has some limitations. First, muscles were not considered in the model. Undeniably, the role of muscles is complex and important. Second, our data were obtained from a healthy, young man. The human lumbar spine of each individual is unique and is also affected by the age, presence of disease, and other factors. Third, we only analyzed the biomechanical behavior of PEEK rods after rigid fusion without considering fusion failure. Fourth, we simplified the loading pattern, material properties, and interaction of the implants and the spine, but the actual situation was severely complicated.

Conclusion

In TLIF, PEEK rods could not only significantly restrain the ROM of surgical segments, but also allow more flexibility compared to those of Ti rods. Simultaneously, PEEK rods decreased the stresses of the screws and bone-screw interfaces and increased the strain of the bone graft and stresses on the endplates and cages. Although the PEEK rods reduced the stresses of the rods, the risk of rod fracture increased. The effect of PEEK rods on adjacent discs was similar to that of Ti rods. Moreover, bone graft alone fusion was superior to cage fusion in providing the ROM, increasing bone graft strain, and reducing endplate stresses, but it also increased the stresses of the posterior fixation system. Theoretically, bone graft alone combined with PEEK rods have acceptable biomechanical features in TLIF. Further studies are required to confirm the finding in the future.

Abbreviations

FE, finite element

AF, annulus fibrosus

ASD, adjacent segment disease

CT, computed tomography

IDP, intervertebral disc pressure

NP, nucleus pulposus

PEEK, polyetheretherketone

ROM, range of motion

Ti, titanium alloy

TLIF, transforaminal lumbar interbody fusion

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of our hospital, and informed consent was obtained from the volunteer

Consent for publication

Not applicable

Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

The study concept and design were performed by LT. The examinations and administrative support were completed by LHP and CS. Data analysis and interpretation were done by LJ and WJ. Writing the manuscript and critical revision of the manuscript were performed by LJ, ZGY, QH and LWD. All authors read and approved the final manuscript.

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Figures

Figure 1

The intact L3-L5 finite element model of the human spine. (a) front view, (b) lateral view, (c) axial view, (d) intervertebral disc, (e) annulus ground substance, and (f) annulus fibers.

Figure 2

The surgical model for transforaminal lumbar interbody fusion with a cage. (a) front view, (b) left posterior oblique view, and (c) axial view.

The intact model validation

Figure 3

Comparison of range of motion between the current intact model and the previous studies.

Figure 4

Range of motion in different surgical models at (a) L3/4 segment and (b) L4/5 segment. Ti: titanium alloy PEEK: polyetheretherketone Cage + Ti rod: cage fusion with Ti rods Cage + PEEK rod: cage fusion with PEEK rods Bone graft alone + Ti rod: bone graft alone fusion with Ti rods Bone graft alone + PEEK rod: bone graft alone with PEEK rods

Figure 5

Maximum von Mises stresses of the (a) cage, (b) adjacent disc, (c) endplates, (d) screws, (e) rods, and (f) bone-screw interface. Ti: titanium alloy PEEK: polyetheretherketone Cage + Ti rod: cage fusion with Ti rods Cage + PEEK rod: cage fusion with PEEK rods Bone graft alone + Ti rod: bone graft alone fusion with Ti rods Bone graft alone + PEEK rod: bone graft alone with PEEK rods

Figure 6

Average strain of the (a) inner bone graft of the cage, (b) outer bone graft of the cage, and (c) bone graft in bone graft alone models. Ti: titanium alloy PEEK: polyetheretherketone Cage + Ti rod: cage fusion with Ti rods Cage + PEEK rod: cage fusion with PEEK rods Bone graft alone + Ti rod: bone graft alone fusion with Ti rods Bone graft alone + PEEK rod: bone graft alone with PEEK rods