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ORIGINAL ARTICLE

Biomechanical analysis of lumbar interbody fusion supplemented with various posterior stabilization systems

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Abstract

Purpose Biomechanical comparison between rigid and non-rigid posterior stabilization systems following lumbar interbody fusion has been conducted in several studies. However, most of these previous studies mainly focused on investigating biomechanics of adjacent spinal segments or spine stability. The objective of the present study was to compare biomechanical responses of the fusion devices when using different posterior instrumentations.

Methods Finite-element model of the intact human lumbar spine (L1–sacrum) was modified to simulate implantation of the fusion cage at L4–L5 level supplemented with different posterior stabilization systems including (i) pedicle screw-based fixation using rigid connecting rods (titanium rods), (ii) pedicle screw-based fixation using flexible connecting rods (PEEK rods) and (iii) dynamic interspinous spacer (DIAM). Stress responses were compared among these various models under bending moments.

Results The highest and lowest stresses in endplate, fusion cage and bone graft were found at the fused L4–L5 level with DIAM and titanium rod stabilization systems, respectively. When using PEEK rod for the pedicle screw fixation, peak stress in the pedicle screw was lower but the ratio of peak stress in the rods to yield stress of the rod material was higher than using titanium rod.

Conclusions Compared with conventional rigid posterior stabilization system, the use of non-rigid stabilization system (i.e., the PEEK rod system and DIAM system) following lumbar interbody fusion might increase the risks of cage subsidence and cage damage, but promote bony fusion due to higher stress in the bone graft. For the pedicle screw-based rod stabilization system, using PEEK rod might reduce the risk of screw breakage but increased breakage risk of the rod itself.

Keywords Biomechanics · Finite element · Lumbar interbody fusion · Rigid stabilization system · Non-rigid stabilization system

Introduction

Over the last several decades, there has been an increasing interest in using interbody fusion technique for treating degenerative spinal disorders [1–3]. It has been reported that the annual number of spinal fusion surgeries increased by 77 percent between 1996 and 2001 [4]. Anterior, posterior, transforaminal and lateral lumbar interbody fusion are some of the most often used surgical techniques for lumbar arthrodesis, and placement of the intervertebral cage combined with rigid posterior stabilization system such as pedicle screw-based titanium rod fixation has been considered as a gold standard for these fusion approaches [5, 6]. Although the lumbar interbody fusion is an effective treatment option to stabilize degenerative motion segment, restore lordosis and correct deformity [7], adjacent segment degeneration (ASD) has been generally regarded as a long term complication following the fusion surgery.

Studies in the literature have shown that the conventional rigid posterior fixation instrumentation may grossly alter physiologic load transfer at the instrumented level [8], and many researchers believe that the altered biomechanics may play an important role in ASD development [9, 10]. To

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avoid the adverse effects, several surgeons have attempted to introduce the compliant non-rigid posterior stabilization system, which could provide motion segment with flexibility and induce more uniform load distribution across spine, as an alternative to the rigid system in clinical practice [11–13]. Some in vitro experimental and finite element (FE) studies have also been conducted to compare the biomechanical effects of rigid and non-rigid posterior fixations [14–17]. For example, Kang et al. [16] investigated the effects of variations in material properties of the connecting rods used in pedicle screw-based stabilization system on biomechanics of the adjacent spinal segments after interbody fusion, and the results showed that disc pressure and facet joint contact force in the adjacent segments were lower when using flexible rods made of more compliant materials (e.g., PEEK) than using rigid titanium rods. Considering the fact that pedicle screw-based stabilization technique comes at costs of invasiveness, surgical time and potential nerve root injury, the non-rigid (dynamic) interspinous spacers have also been used by several surgeons as stabilization devices in lumbar interbody fusion [18, 19], and in vitro data from biomechanical tests suggested that the interspinous stabilization devices provided the fused lumbar spine similar stability as the pedicle screw-based stabilization devices [20, 21].

However, most of the previous studies mainly focused on comparing the differences in biomechanics of adjacent spinal segments or spine stability between using rigid and non-rigid posterior fixations, and very few quantitatively dealt with biomechanics of the fusion devices (intervertebral cage or stabilization system itself). Several postoperative complications associated with the fusion devices are recognized, such as cage subsidence/migration or posterior hardware failure [22, 23], and it is believed that a better understanding of biomechanics of the fusion devices is helpful for avoiding these implant-related complications. This study was designed to quantify and compare biomechanical responses of the fusion devices to bending moments at different physiological planes when instrumenting rigid and no-rigid posterior stabilization systems using three-dimensional FE model of lumbar L1–sacrum segment. The von-Mises stresses in implants and endplate were used as risk parameters associated with subsidence and mechanical failure of the fusion devices [24].

Materials and methods

An intact L1–sacrum lumbar FE model, consisting of five vertebrae (including cancellous bone, cortical shell and endplate), five intervertebral discs (including annulus ground substance, annulus fibers, nucleus pulposus) and seven spinal ligaments, was used. The detailed procedures for model development and validation have been shown in the previous works [25, 26]. The L4–L5 segment was chosen as fusion level due to its higher prevalence in individuals suffering from disc degeneration [27], and instrumented with PEEK cage and posterior stabilization system. Anterior lumbar interbody fusion was simulated by removing anterior longitudinal ligament, anterior portions of the annulus and entire nucleus pulposus at L4–L5 level [28], and then a cage was placed within the intervertebral space and was filled with cancellous bone to simulate the embedded bone graft [24], as shown in Fig. 1a. The interface between graft and endplate, as well as cage and endplate, was defined as surface-to-surface contact, and the assigned friction coefficient for graft–endplate and cage–endplate interfaces was 0.3 and 0.8, respectively [29, 30]. Further, the following three kinds of stabilization system were considered. (i) pedicle screw-based fixation using rigid connecting rods (titanium rods), (ii) pedicle screw-based fixation using flexible connecting rods (PEEK rods) and (iii) dynamic interspinous spacer (DIAM), as shown in Fig. 1b–d, respectively. For the pedicle screw-based stabilization systems, four 6-mm-diameter, 45-mm-length pedicle screws were inserted into L4 and L5 vertebral bodies and were interconnected with 6-mm-diameter titanium or PEEK rods. The DIAM system, consisting of a “H”-shape silicone core with a polyester cover, was implanted between spinous process of L4 and L5 where the interspinous ligament was removed for DIAM insertion. For these posterior stabilization systems, a tie constraint was assigned to the implant-bone interfaces via node sharing [16, 31]. Material properties and element types given to components of the FE models are shown in Table 1 [8, 16, 24, 30–34].

Subsequently, caudal part of the L1–sacrum model was fully fixed with application of a 400 N compressive follower preload. Further, additional flexion, extension, lateral bending and axial rotation moments of 7.5 Nm was each imposed on superior surface of L1 vertebral body. Biomechanical responses of the models to the moments were computed using FE static analysis. The parameters in terms of von-Mises stresses in L4 inferior endplate, cage, bone graft and posterior stabilization system were used as the comparison indices. In addition, the final mesh sizes for the models were determined after a mesh sensitivity analysis. The mesh refinement was performed to consecutively generate mesh resolutions until achieving a convergence towards aforementioned parameters, with a tolerance of less than 5% between two consecutive mesh resolutions [35]. The commercial FE analysis software ABAQUS/Standard (Dassault Systems Simulia Corp., Providence, RI, USA) and pre-processing software ANSA (BETA CAE Systems S.A., Thessaloniki, Greece) were employed in this study.

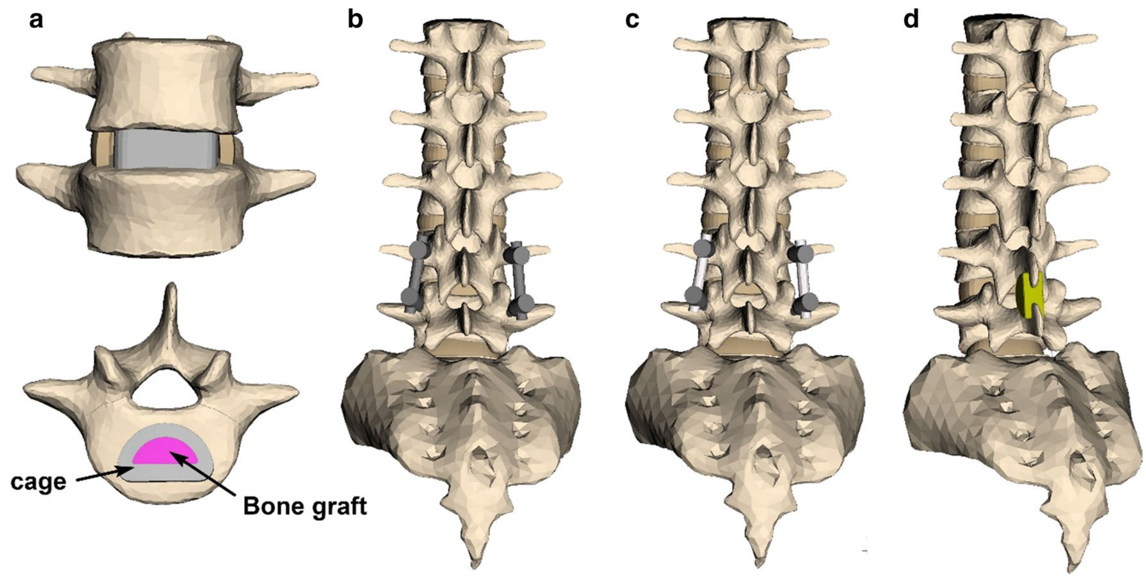

Fig. 1 Investigated L1–sacrum FE models: **a** Anterior lumbar interbody fusion; **b** The interbody fusion with pedicle screw-based titanium rod fixation; **c** The interbody fusion with pedicle screw-based PEEK rod fixation; **d** The interbody fusion with DIAM interspinous spacer

Table 1 Material properties and element types for the investigated FE models

Component	Element type	Young's modulus (MPa)	Poisson's ratio	Cross-sectional area (mm^2)	References
Bone					
Cortical bone	S3	12,000	0.3		[24]
Cancellous bone	C3D4	100	0.2		[24]
Endplate	S3	23.8	0.4		[31]
Posterior bony elements	C3D4	3500	0.25		[31]
Intervertebral disc					
Annulus ground substance	C3D8	Hyperelastic, Mooney–Rivlin $C_{10}=0.18$, $C_{01}=0.045$			[32]
Nucleus pulpous	C3D8	Hyperelastic, Mooney–Rivlin $C_{10}=0.12$, $C_{01}=0.03$			[32]
Annulus fibers	T3D2	360–550	0.3		[30]
Ligaments	T3D2				[8]
Anterior longitudinal		7.8 (< 12.0%) 20.0 (> 12.0%)		63.7	
Posterior longitudinal		10.0 (< 11.0%) 20.0 (> 11.0%)		20	
Ligamentum flavum		15.0 (< 6.2%) 19.5 (> 6.2%)		40	
Supraspinous		8.0 (< 20.0%) 15 (> 20.0%)		30	
Interspinous		10.0 (< 14.0%) 11.6 (> 14.0%)		40	
Intertransverse		10.0 (< 18.0%) 58.7 (> 18.0%)		1.8	
Capsular		7.5 (< 25.0%) 32.9 (> 25.0%)		30	
Implants					
Cage (PEEK)	C3D8	3600	0.25		[34]
Pedicle screws (titanium)	C3D4	110,000	0.3		[16]
Titanium rods	C3D4	110,000	0.3		[16]
PEEK rods	C3D4	3600	0.25		[34]
DIAM (Silicone core covered by polyester)	C3D4	2100	0.35		[33]

S3 3-node triangular elements, *C3D4* 4-node tetrahedral elements, *C3D8* 8-node hexahedral elements, *T3D2* 2-node truss elements

Results

Figures 2, 3, 4 demonstrate stress contour plots in L4 inferior endplate, cage and bone graft, respectively, for the investigated models. It was observed that the stress was concentrated and correlated with the motion direction. For example, in extension the stress was concentrated at posterior side of the endplate, cage and bone graft for all the models; in lateral bending theses, stresses were all concentrated at the same side as lateral bending direction. Also, it was observed from the contour plots that the titanium rod system generated less stress concentration in endplate, cage and bone graft. This was due to the fact that using a rigid fixation transferred the load posteriorly; hence, the anterior support undertook less load and hence less stress concentration. Further, the peak stresses under the different loading conditions are shown in Fig. 5. Compared with using titanium rod system, when using PEEK rod and DIAM systems the peak endplate stress was increased by 2.1–33.3% and 6.3–73.3%, respectively (Fig. 5a), the peak cage stress was increased by 6.9–29.4% and 8.8–64.7%, respectively (Fig. 5b), the peak bone graft stress was increased by 4.9–19.0% and 4.9–44.2%, respectively (Fig. 5c). For the pedicle screw-based rod stabilization system, the stresses in pedicle screws and rods, as well as the ratio of peak stress in the rods to yield stress of the rod material (titanium, 750 MPa; PEEK, 100 MPa) under the different loading conditions are listed in Table 2. It was found that compared with using titanium rod system, when using PEEK rod system the screw stress was decreased by 23.1% in flexion, 12.0% in extension, 24.2% in lateral bending and 36.7% in axial rotation. The ratio range was 5.1–11.1% for titanium rod system and 10.2–15.7% for PEEK rod system, respectively.

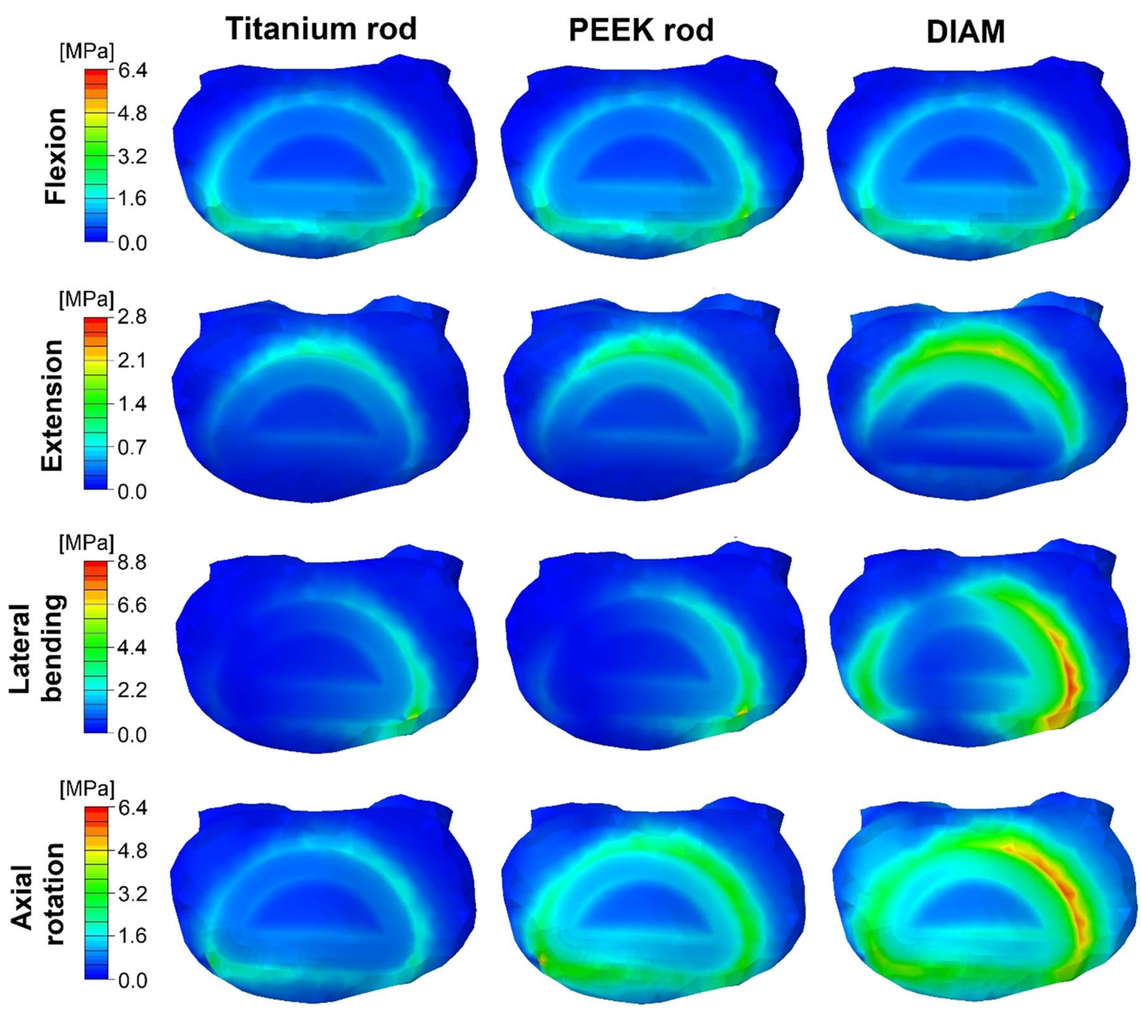

Fig. 2 Contour plots of von-Mises stress in L4 inferior endplate under flexion, extension, lateral bending and axial rotation when using the titanium rod, PEEK rod and DIAM systems

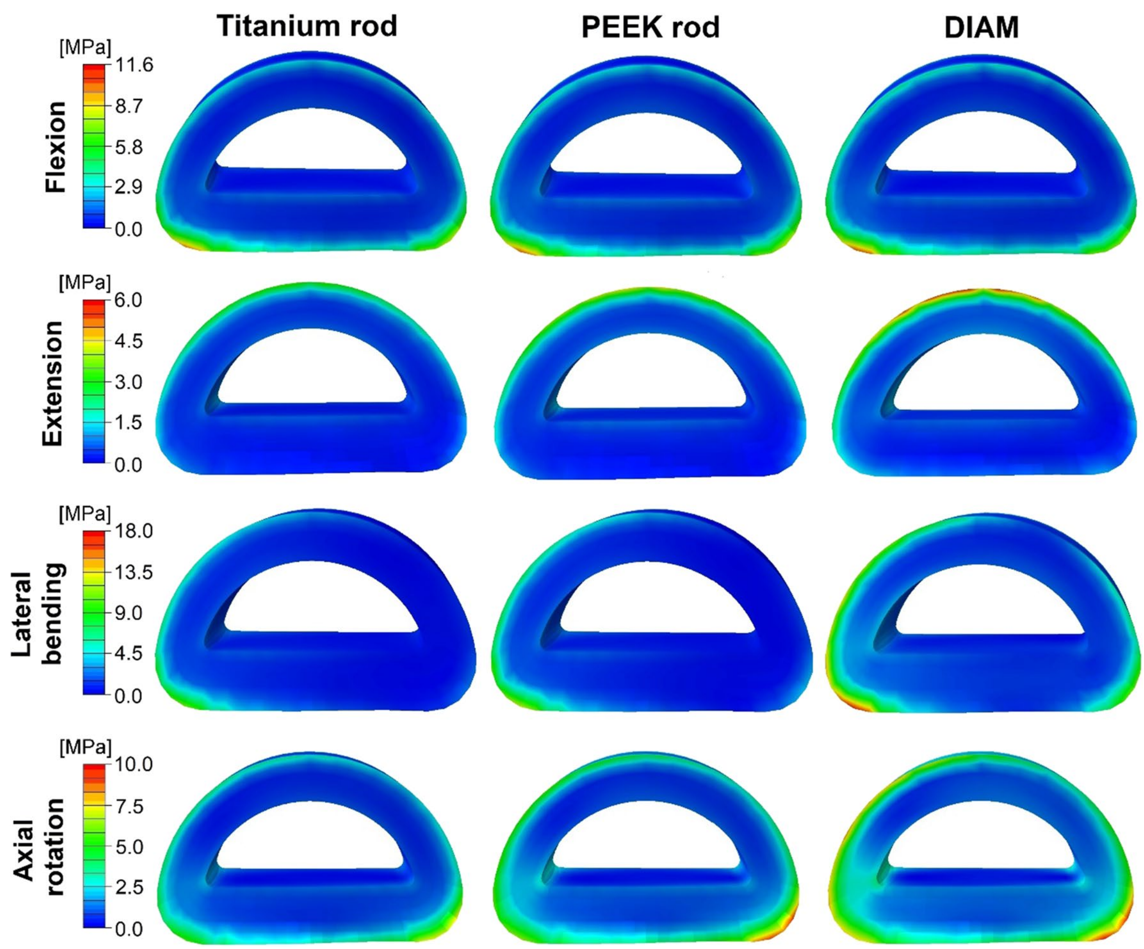

Fig. 3 Contour plots of von-Mises stress in fusion cage under flexion, extension, lateral bending and axial rotation when using the titanium rod, PEEK rod and DIAM systems

Discussion

To reduce ASD after lumbar interbody fusion with conventional rigid posterior fixation, non-rigid posterior stabilization systems have recently been employed to aid in spine fusion and stability. Biomechanical studies have demonstrated that the non-rigid fixation is helpful to restore segmental motion and load transfer of an intact lumbar spine after the fusion surgery [10]. However, there is a lack of studies in comparing the effect of rigid fixation and non-rigid fixation on biomechanics of fusion devices. In present study, a previously validated intact lumbar L1–sacrum FE model was used as a basis to mimic single-level (L4–L5) lumbar interbody fusion with various posterior stabilization systems. By means of these developed FE models, von-Mises stresses in implants and endplate under flexion, extension, lateral bending and axial rotation moments were computed and compared.

Pedicle screw-based flexible rod devices and dynamic interspinous spacers are two of the most used non-rigid posterior stabilization systems for lumbar interbody fusion according to the current literature [11–13, 16–21]. For the flexible rod system, nitinol and PEEK are some of the most common compliant materials in making of flexible rods, and we have compared biomechanics between the nitinol rod and conventional titanium rod systems in previous studies [28, 36]. For the commonly used interspinous spacers such as Coflex, DIAM, Wallis and X-STOP, previous study has shown that they have a similar effect on biomechanics of human lumbar spine in spite of their different designs [37]. Accordingly, the PEEK rod and DIAM systems were considered herein.

The results illustrated in Figs. 2 and 5a indicate that when using non-rigid fixation, the peak stress in L4 inferior endplate was higher than using rigid fixation. Previous biomechanical studies have shown that a higher stress in the endplate adjacent to the interbody cage might result in greater cage subsidence [24, 38]. Therefore, the present findings imply that application of the non-rigid fixation for lumbar interbody fusion might increase the risk of cage

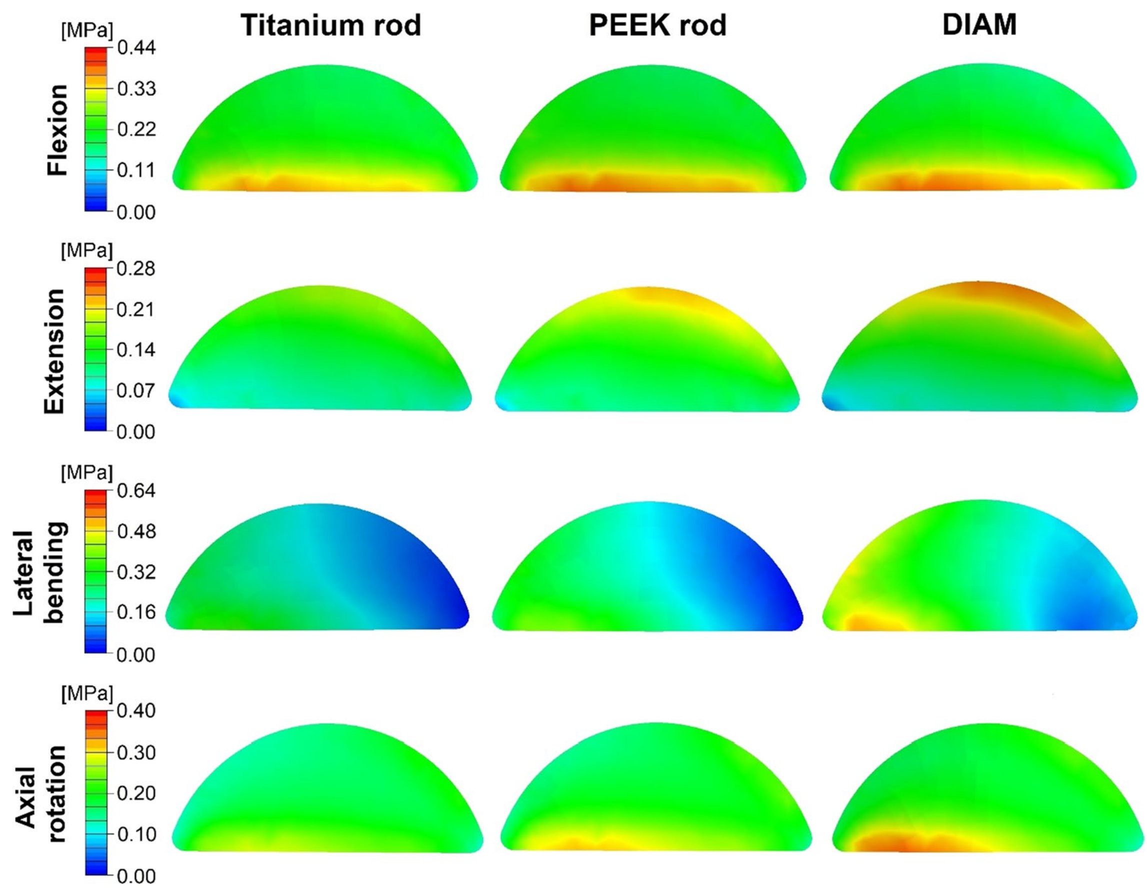

Fig. 4 Contour plots of von-Mises stress in bone graft under flexion, extension, lateral bending and axial rotation when using the titanium rod, PEEK rod and DIAM systems

subsidence. Because cage subsidence occurs most commonly at the lower endplate of upper vertebra [39], only the stress in L4 inferior endplate was computed. The results illustrated in Figs. 3 and 5b indicate that when using non-rigid fixation, the peak cage stress was higher than using rigid fixation, which implies that application of non-rigid fixation for lumbar interbody fusion might increase the risk of cage damage. The results illustrated in Figs. 4 and 5c indicate that when using non-rigid fixation, the peak bone graft stress was higher than using rigid fixation, and based on Wolff's law this higher stress might be better for promoting bony fusion. To sum up, the present results indicate that the load transmitted through the anterior spinal column was increased when using non-rigid fixation, which supports the prediction of Ponnappan et al. [14] who reported that the non-rigid fixation might provide better anterior column load-sharing profile than rigid fixation. It also confirmed in vitro experimental results of the literature [40, 41], which showed that non-rigid fixation led to less stress-shielding effect.

The stress data listed in Table 2 for the pedicle screw-based rod stabilization systems indicate that the PEEK rod led to lower peak screw stress than the titanium rod, implying that using PEEK rod could reduce the risk of screw breakage. This might also be attributed to the reduced stress shielding caused by PEEK rod, which decreased load through the posterior hardware. This finding also supports the prediction of Ponnappan et al. [14] about potential biomechanical advantages of the PEEK rod system. Furthermore, the stress data indicate that although the peak stress in PEEK rod was lower than that in titanium rod, the ratio of peak stress in the rods to yield stress of the rod material was higher for PEEK rod due to its significantly lower yield stress (yield stress of the rod material: PEEK, 100 MPa; titanium, 750 MPa), implying that the PEEK rod system might face a higher risk of rod breakage. Previous biomechanical studies reported that the rod system made of compliant material (nitinol) had a higher failure rate [36, 42], and the present results support this conclusion. To sum up, just like a coin which has two sides, the PEEK rod system has both advantages and disadvantages. Therefore, it should be carefully used in clinical practice.

Additionally, it is also observed from Fig. 5 that biomechanical differences between using the PEEK rod and DIAM systems are not obvious in all loading direction except under

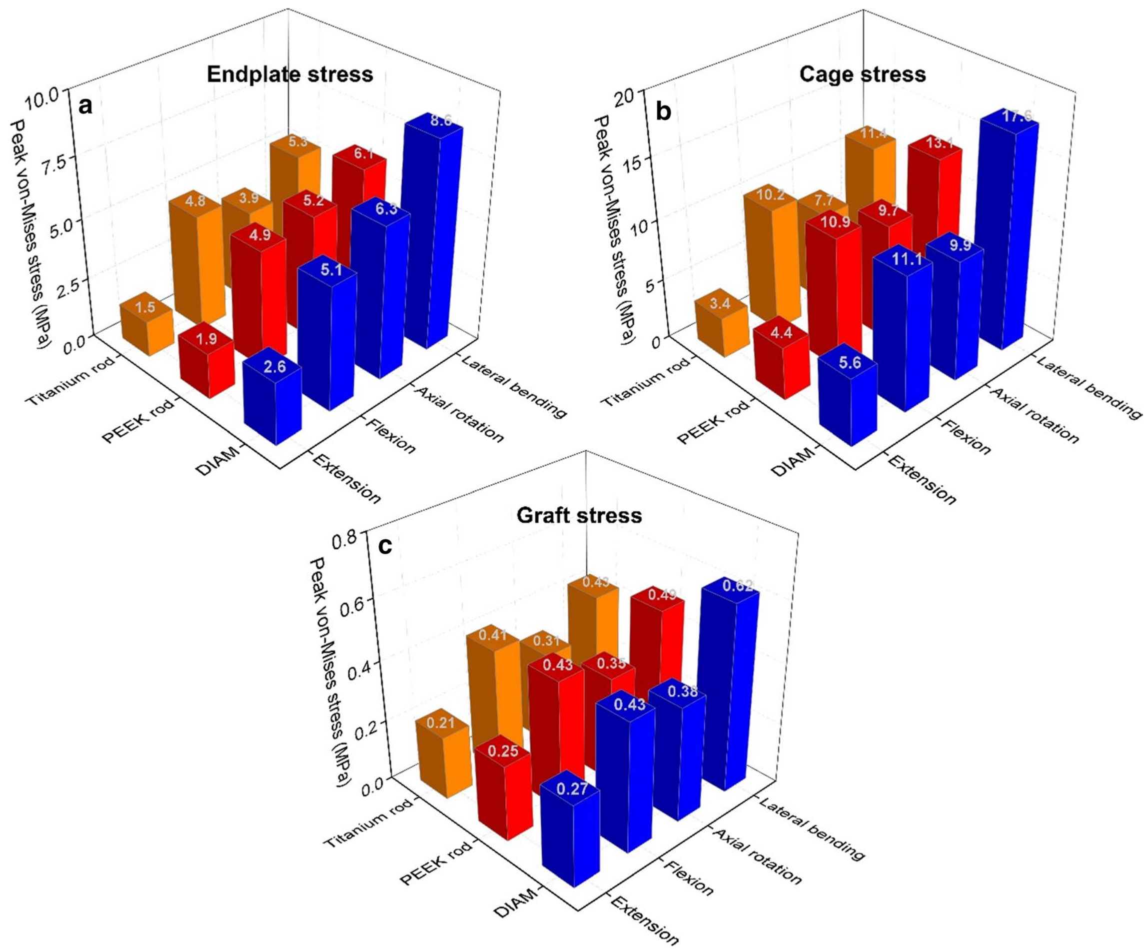

Fig. 5 Comparison of the peak von-Mises stress in anterior spinal column under flexion, extension, lateral bending and axial rotation when using the titanium rod, PEEK rod and DIAM systems. **a** Stress in L4 inferior endplate; **b** Stress in fusion cage; **c** Stress in bone graft

Table 2 Peak stress of pedicle screws and connecting rods, and the ratio of peak stress in the rods to yield stress of the rod material under flexion, extension, lateral bending and axial rotation when using the titanium rod and PEEK rod systems

Load case	Screw stress (MPa)		Rod stress (MPa)		Ratio (%)	
	Titanium	PEEK	Titanium	PEEK	Titanium rod	PEEK rod
Flexion	51.9	39.9	37.9	10.2	5.1	10.2
Extension	36.6	32.2	53.3	10.4	7.1	10.4
Lateral bending	52.4	39.7	83.5	12.6	11.1	12.6
Axial rotation	63.7	40.3	54.6	15.7	7.3	15.7

lateral bending. It implies that these two systems provide similar resistance to flexion, extension and axial rotation. The relatively obvious difference under lateral bending might be explained by the fact that the DIAM device was inserted close to the rotation axis for lateral bending and hence limited its resistance to this loading [43]. Overall, the loading–sharing characteristics of DIAM system were not significantly better than those of PEEK rod system according to the present results. However, several potential advantages of such an interspinous spacer were worth discussing based on basic principle of biomechanics. For example, the interspinous spacer usually has lower stiffness than the pedicle screw-based rod device; hence, the interspinous spacer might induce less mechanical and kinematic compensation to its adjacent spinal segment and hence might lead to lower stress and motion at the adjacent segment. It implies that likelihood of ASD might be relatively lower when using the interspinous spacer, which agreed with the clinical results regarding the incidence of radiographic ASD (1% and 10.5% in interspinous spacer group and pedicle screw-based flexible rod group, respectively) [44]. Moreover, the interspinous spacer has several clinical advantages over the pedicle screw-based rod device in terms of skin incision, muscle dissection and short operative time and less intra-operative estimated blood loss [18]. Therefore, interspinous spacer might be a promising candidate posterior stabilization device.

There were several limitations in this study. The geometry of human lumbar spine varies from individual to individual, but only one lumbar FE model derived from a unique specimen was used. Material properties in the models were assumed to be linear elastic. The complex interactions between posterior instrumentations and spine were simplified to be tie constraint. The devices were simulated with the simplest geometry, and no set was used to connect the screw to the rods. The muscles were not included in present models. Although using the follower load technique mitigates the effect of ignoring muscles, the complex contributions of muscles were unable to be entirely replaced. The screw loosening and the "distraction-compression" principle [45] were also neglected. In addition, limited by the available experimental data, only the intact model was validated, and the surgical models were developed using this intact model as a baseline. Overall, the obtained biomechanical data from this study should be viewed as a comparative analysis among different surgical cases due to these inherent limitations of the model.

Conclusions

This study was designed to quantitatively compare the effect of rigid and non-rigid posterior fixation instrumentations on biomechanics of the implants used for lumbar interbody fusion by means of FE method. The results indicated that the peak stresses in endplate, fusion cage and bone graft were higher when using pedicle screw-based PEEK rod and DIAM interspinous systems than using pedicle screw-based titanium rod system, implying that non-rigid fixation might increase the risks of cage subsidence and cage damage but promote bony fusion. Furthermore, it was found that biomechanical differences between PEEK rod and DIAM systems are not significant in all loading direction except under lateral bending. Because the interspinous implantation is a less invasive technique, which has several clinical advantages over posterior pedicle screw fixation, the interspinous spacer might be a promising candidate stabilization device for spine fusion. In addition, the results indicated that when using PEEK rod for the pedicle screw fixation, the peak screw stress was lower but the ratio of peak stress in the rods to yield stress of the rod material was higher than using titanium rod, implying that using PEEK rod might reduce the risk of screw breakage but increase breakage risk of the rod itself.

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Declarations

Conflict of interest The authors declared that they have no conflict of interest.

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