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Original Article

Biomechanical evaluation and comparison of polyetheretherketone rod system to traditional titanium rod fixation on adjacent levels

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ABSTRACT

Purpose: Adjacent segment degeneration or fracture of the vertebral body was commonly reported in rigid fusion. Use of semirigid instruments such as PEEK rod system could be an alternative treatment. However, the biomechanical implications of using PEEK rod systems are not well understood. Purpose of this study was to compare a PEEK rod fixation system to traditional titanium rod fixation via a finite element analysis.

Methods: A lumbar spine model from L2–L5 vertebral bodies was constructed. A fusion model, created by modifying the intact lumbar model, was used to simulate anterior interbody and posterolateral lumbar fusion. Loading was applied through flexion, extension, lateral bending, torsion.

Results: The greatest increase in stress was estimated at the upper disc adjacent to the titanium rod with interbody fusion. The lower increase in stress on adjacent segments occurred with PEEK rod fixation without fusion and noninstrumented posterolateral lumbar fusion models. With the same fusion or nonfusion procedures, the stress on discs and facet joints of adjacent segments in the PEEK rod group decreased by 5–25% of that in the titanium rod group for all loading conditions.

Conclusion: In comparison with rigid fixation, some potential advantages of using PEEK rod systems include a reduced stress on adjacent segment disc and facet joint, and the elastic ability of PEEK rod fixation allows for a greater range of motion, which may reduce the incidence of clinical complications seen with rigid fusion devices.

1. Introduction

Spinal fixation devices are typically used as a rigid construct to replace bone, restore alignment, maintain position, and prevent motion in the treatment of fractures, degenerative disease, and congenital deformities. Most fixation devices are used to promote fusion through bone grafting. However, this has resulted in a noticeable incidence of adjacent segment disease, especially when compared with the slower disease progression seen in patients who underwent a posterolateral lumbar fusion without instrumentation. For permanent stabilization, spinal bony fusion is required. After instrumented rigid-construct fusion, the biomechanical behavior of the spinal structure may be altered. A redistribution of stress in the unfused segments has been reported. Some studies[1,2] indicated that the high stiffness of the instrumented levels relates to increased stress on adjacent discs and facet joints. These increased loads over time may lead to segment hypermobility, facet hypertrophy, and degeneration of adjacent segments. Lehmann et al[3] reported accelerated degeneration of the adjacent segment and segmental instability above the fusion site in 45% of their patients. In a biomechanical study of simulated lumbosacral fusion, Lee and Langrana[4] demonstrated that stress was increased on the adjacent unfused segments. Furthermore, some studies have indicated that spinal fusion caused additional stresses on the motion segment above the fusion site.[5–7] Other reports[8,9] indicated that the modulus of titanium rod fixation is extremely supraphysiologic when compared with the normal bone structure. The high-stiffness construct resulted in abnormal load

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transfer and stresses that may accelerate degeneration of adjacent levels.

Recently, rods made of polyetheretherketone (PEEK) have been introduced as a semirigid alternative to traditional titanium rods. Because the PEEK's modulus of elasticity is between that of cortical and cancellous bone, the use of this polymer as part of a pedicle screw fixation would offer adequate rigidity for fusion but would avoid the stresses created by a titanium construct. Ahn et al[10] created an L3-L4 finite element model to investigate changes in load-sharing characteristics following PEEK rod fixation (dynamic system for nonfusion). It was shown that the PEEK rod reduced the compressive load transmitted through the fixation systems. The lower elastic modulus of PEEK rods could avoid the effects of stress shielding for applications in spinal surgery. Highsmith et al[11] observed that PEEK rods can reduce stress at the screw/bone interface, may allow some loading of the interbody construct, and can also theoretically increase fusion rates by allowing more contact between the endplate and graft. De Iure et al[12] reviewed 30 cases in which posterior fusion was supported by PEEK rods, analyzing early complications, rates of fusion, and clinical outcomes. At a follow-up of 18 months, both clinical and radiographic results were all satisfactory. It has been suggested that PEEK rod fixation systems may be a superior surgical alternative to the conventional titanium rod system for the patients with chronic low back pain,[10–12] but little information is available on how stresses on adjacent levels may be influenced. Therefore, the purpose of this study was to compare a PEEK rod system to traditional titanium rod fixation in a finite element model and calculate maximum von Mises stress on the disc and facet joint at adjacent segment levels. The lumbar spine will be modeled with anterior interbody fusion, posterolateral lumbar fusion and nonfusion conditions.

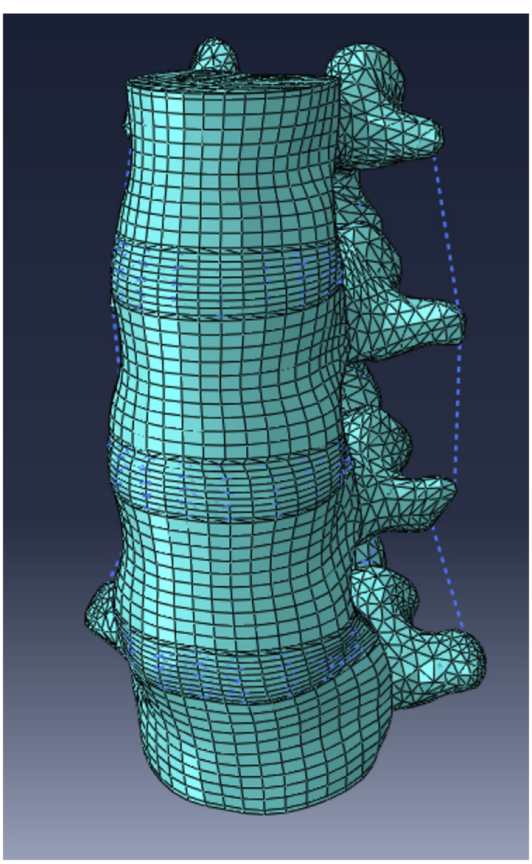

Fig. 1. Finite element model of the L2–L5 lumbar spine.

Table 1
Material properties specified in the finite element models.

	Young's modulus (MPa)	Poisson ratio	Cross-sectional area (mm^2)
Bony structure			
Cortex	12,000	0.3	—
Trabecular bone	100	0.2	—
Posterior element	3500	0.25	—
Endplate	3000	0.25	—
Intervertebral disc			
Nucleus pulposus	1	0.49	—
Ground substance	4.2	0.45	—
Annular fiber	750	—	0.76
Ligaments			
Anterior longitudinal ligament	7.8	—	63.7
Posterior longitudinal ligament	10	—	20
Intertransverse ligament	10	—	1.8
Ligamentum flavum	15	—	40
Interspinous ligament	10	—	40
Supraspinous ligament	8	—	30
Capsular ligament	7.5	—	30
Implants			
Bone graft	3500	0.3	—
Titanium alloy	110,000	0.3	—
PEEK	1300	0.2	—

PEEK = polyetheretherketone.

2. Materials and methods

2.1. Intact model

A finite element model of L2–L5 was reconstructed from computed tomography (CT) scans from a 60-year-old man with no pathologies (144 slices at a thickness of 1.25 mm) (Fig. 1), and the material properties were adopted from literature[13–18] (Table 1). Convergence for L2/3, L3/4, and L4/5 models was reached at 5778, 5342, and 5770 elements, respectively (Fig. 2). The finite element model of the ligamentous lumbar spine consisted of vertebrae, intervertebral discs, superior and inferior facet articulating surfaces, and a number of ligaments: supraspinous, interspinous, ligamentum flavum, transverse, posterior longitudinal, anterior longitudinal, and capsular. Cable elements were used to simulate ligaments and the annulus fiber of the disc, which were active only in tension. Three-dimensional contact elements were used to simulate the contact characteristics of the facet articulation.

2.2. Implanted (or fused) models

The model was modified in order to compare several surgical techniques with regard to stress transfer and structural support.

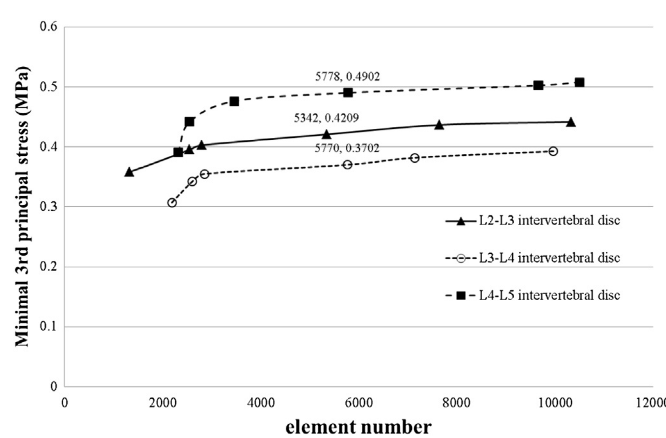

Fig. 2. Convergence test for the intact spine model.

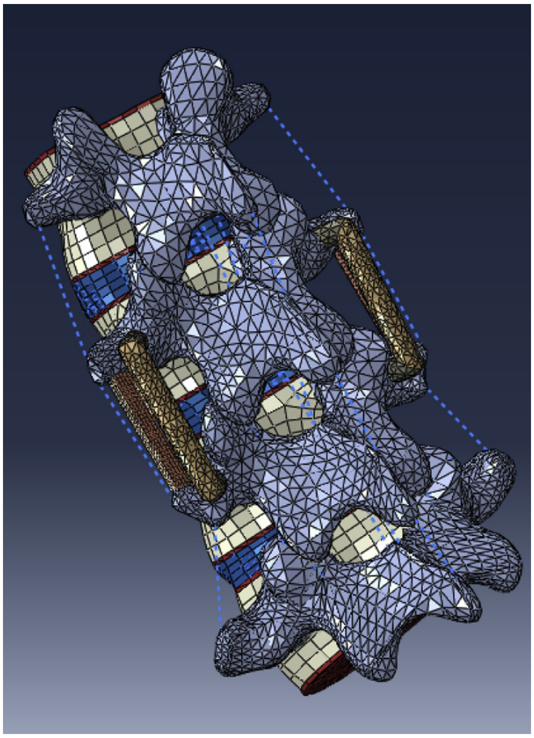

Fig. 3. Illustration of motion segment stabilized with posterior instrumentation and posterolateral fusion.

The implanted (or fused) models of L3/L4 were constructed after modifying the intact model to simulate postoperative changes with these kinds of devices: (A) only interbody fusion with PEEK spacer; (B) titanium rod fixation without fusion; (C) PEEK rod fixation without fusion; (D) titanium rod fixation with PEEK spacer and interbody fusion; (E) PEEK rod fixation with PEEK spacer and interbody fusion; (F) noninstrumented posterolateral fusion; (G) PEEK rod fixation with posterolateral fusion; and (H) titanium rod fixation with posterolateral fusion (Fig. 3).

2.3. Loading and boundary conditions

ABAQUS (SIMULIA, Dassault Systèmes, Providence, RI) was used for simulation. In the four-level finite element model, the degrees of freedom of inferior surfaces of the L5 vertebral body were completely fixed in all directions. To validate the model, loading conditions comparable to those detailed by Chen et al[8] were applied; 10 Nm flexion, 10 Nm extension, 10 Nm torsion, and a 10 Nm lateral bending moment were applied on the L2 vertebral body following a 150 N preload. Results were expressed in terms of von Mises stresses. An estimation of the rate of stress increase on the adjacent disc and facet joint (L2/L3 and L4/L5) was calculated from the following equation:

$$\text{Stress increase rate}(S_{\text{implanted}} - S_{\text{intact}})/(S_{\text{intact}})(\%)$$

where $S_{\text{implanted}}$ and S_{intact} represent the maximum von Mises stress of the adjacent disc and facet joint in the implanted model and the intact model, respectively.

3. Results

3.1. Stress increase rate of the adjacent disc

The contours of stress distributions under flexion are demonstrated in Fig. 4. Under the different loading conditions, stresses on the L2/L3 and L4/L5 discs are shown in Figs. 5 and 6, respectively. The increase in stress on the upper disc was larger than that of the lower disc. The noninstrumented posterolateral fusion model (group H) showed the lowest increase in stress out of all groups. The titanium rod fixation model with PEEK spacer and interbody spacer fusion (group C) produced the greatest effect on adjacent discs (either upper or lower disc); and the adjacent disc L2/L3 showed the greatest increase at 41%. For the nonfusion condition, the increases in stress on the adjacent disc in the PEEK rod implanted model (group B) were all lower than the titanium rod implanted model (group A). The disc stress in group B decreased dramatically (27% in L2/L3 and 25% in L4/L5) compared to group A, especially in rotation movements. For the interbody fusion condition, the increase in stress on adjacent discs in the PEEK rod

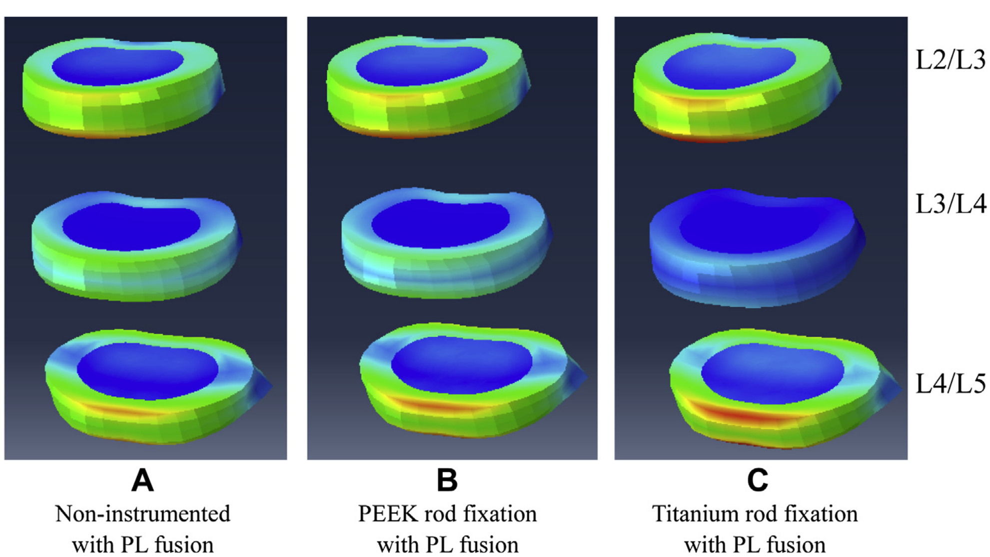

Fig. 4. Under 10 Nm flexion, the stress contours of the disc in the L2/L3, L3/L4, L4/L5 of (A) noninstrumented posterolateral (PL) fusion; (B) polyetheretherketone (PEEK) rod fixation with posterolateral fusion; and (C) titanium rod fixation with posterolateral fusion.

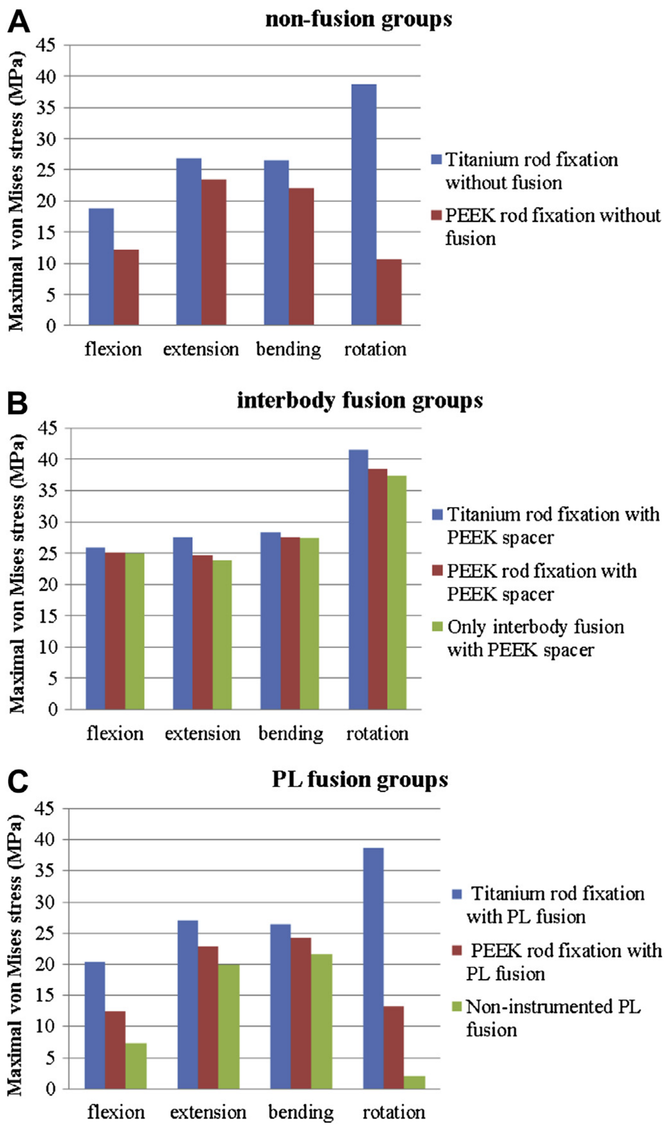

Fig. 5. Increasing rate of maximum von Mises stress on the upper adjacent disc L2/L3 in different loading conditions: (A) nonfusion groups, (B) interbody fusion groups, and (C) posterolateral (PL) fusion groups.

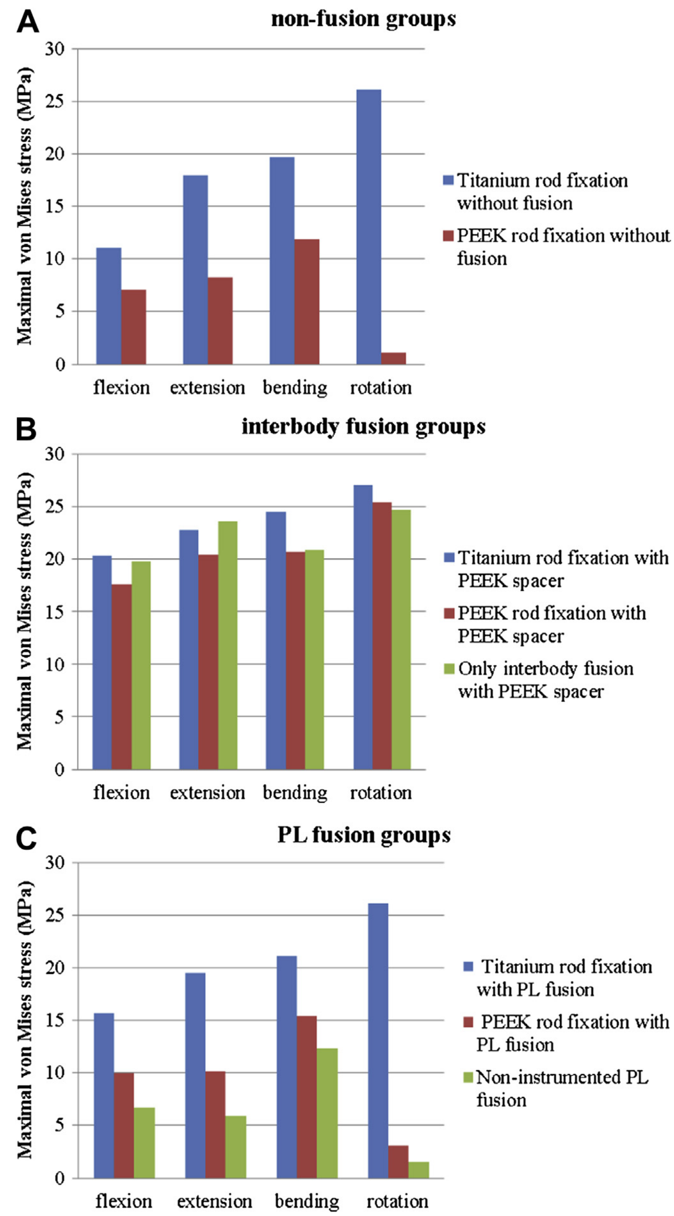

Fig. 6. Increasing rate of maximum von Mises stress on the lower adjacent disc L4/L5 in different conditions: (A) nonfusion groups, (B) interbody fusion groups, and (C) posterolateral (PL) fusion groups.

implanted model (group D) and titanium rod implanted model (group C) was within 5% of each other through each of the other motions. For the posterolateral fusion condition, the increases in stress on the adjacent disc in the PEEK rod implanted model (group G) were all lower than those in the titanium rod implanted model (group F). The increase in stress of group G decreased dramatically (26% in L2/L3 and 22% in L4/L5) compared with group F, particularly in rotation moments.

3.2. Stress increase rate of the adjacent facet joint

Under the different loading conditions, the stresses on the adjacent facet joint of L2/L3 and L4/L5 are shown in Figs. 7 and 8, respectively. Similarly, the increase in stress on the upper facet was larger than that of the lower one. All implanted models showed a greater increase in stress on the adjacent facet joint when subjected to lateral bending. For the nonfusion, interbody fusion, and posterolateral fusion conditions, the increases in stress on the adjacent level in the PEEK rod-implanted model were all lower than those in the titanium rod implanted model; the differences were within 5% for each other motion.

3.3. Range of motion of the instrumented level

Under the different loading conditions, the decrease in range of motion (ROM) permitted at the fusion site in each group is shown in Table 2. Comparing the results of the intact, nonfusion models, the ROM of the PEEK rod-implanted model decreased by 80% in flexion, 67% in extension, 70% in bending, and 49% in rotation. The ROM of the titanium rod-implanted model decreased by 95% in flexion, 93% in extension, 92% in bending, and 93% in rotation. For posterolateral fusion, the ROM in the noninstrumented model decreased by 76% in flexion, 68% in extension, 63% in bending, and 26% in rotation. The ROM of the PEEK rod-implanted posterolateral

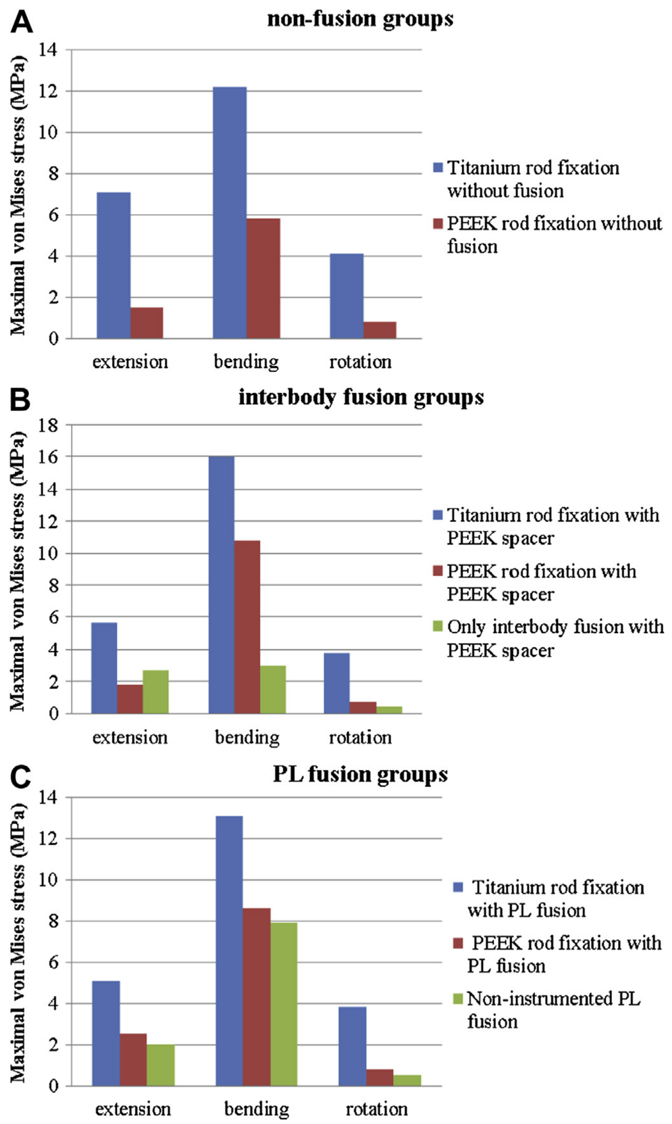

Fig. 7. Increasing rate of maximum von Mises stress of the upper adjacent facet joint L2/L3 in different conditions: (A) nonfusion groups, (B) interbody fusion groups, and (C) posterolateral (PL) fusion groups.

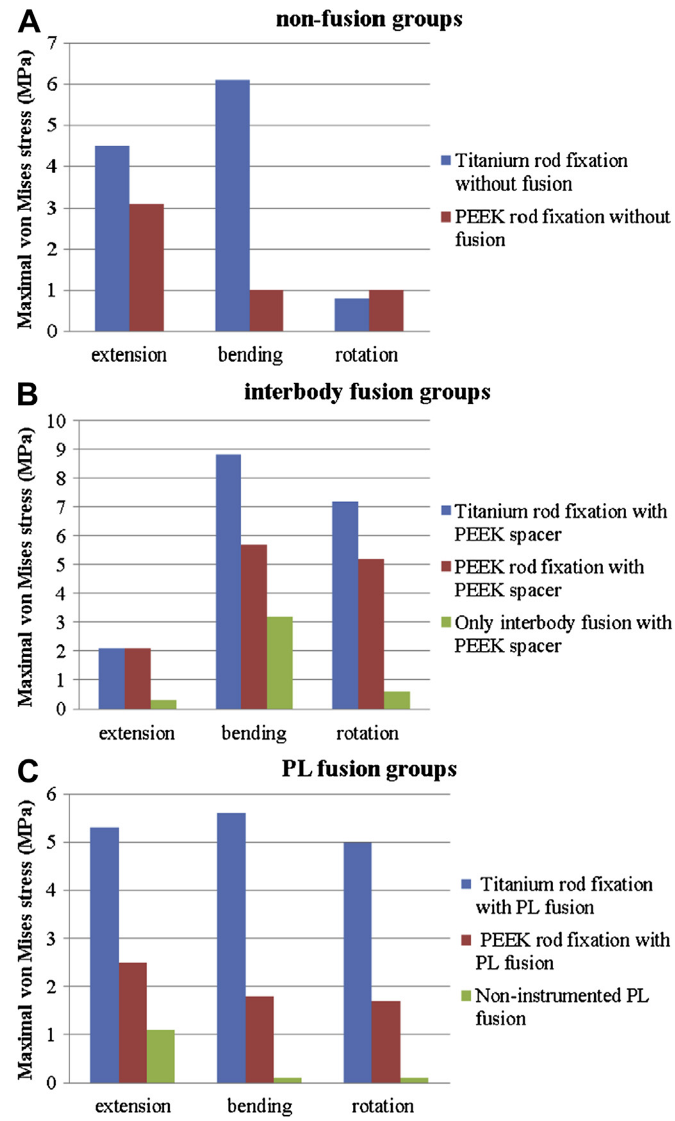

Fig. 8. Increasing rate of maximum von Mises stress of the lower adjacent facet joint L4/L5 in different conditions: (A) nonfusion groups, (B) interbody fusion groups, and (C) posterolateral (PL) fusion groups.

fusion model decreased by 86% in flexion, 79% in extension, and 53% in bending; the ROM of the titanium rod-implanted model was equal to that of the titanium rod without fusion model.

4. Discussion

The finite element method has long been used in biomechanical studies for research concerning clinical problems of the spine as well as for predicting the biomechanical characteristics. In this study, a four-level lumbar spine model was developed to investigate how stresses on the disc and facet joint were affected after implantation of a PEEK rod fixation system. As with all finite element model research, there are some inherent limitations to the models used: (1) the structure of the vertebral body was assumed as isotropic and homogenous, or (2) the loading conditions were not truly physiological, because this model did not account for the mechanical effects of muscle contraction. Although the finite element model of this study had assumptions and limitations, the results were comparable to previous publications.[8,19] A greater increase in stress was estimated at the upper disc adjacent to the fusion site than at the lower disc for each of the simulated fusion conditions. Cho et al[19] performed posterolateral fusion on 81 patients, and followed up for a minimum of 2 years. Degeneration of the upper adjacent segments (8 patients) was reported more often than in the lower adjacent segments (1 patient). A final limitation of this model concerns the variability of model validation. Due to the differences in geometries and conditions of soft tissues among cadaver and finite elements models introduced in previous biomechanical studies,[8] the validation results may differ even though the reported ROM may be similar. This research simulated different treatment options for spinal fixation to provide comparative information for the selection of a suitable fixation method.

In all implanted models, using the PEEK rod system with/without interbody spacer or posterolateral fusion could reduce the stress on adjacent segments in comparison to titanium rod systems. In the study by Abode-Iyamah et al,[18] a transforaminal lumbar interbody fusion at L5/S1 and fixation with PEEK or titanium rods from L3 to S1 were performed to evaluate the intradiscal pressure at adjacent levels. An increase in intradiscal pressure was reported adjacent to the instrumented vertebral segments, and the pressure difference was greater with the titanium rods. In a nonfusion

Table 2
Kinematics results of the fusion site for different conditions.

Groups	Motions			
	Flexion	Extension	Bending	Rotation
Intact model	9.48°	4.74°	5.62°	6.95°
Titanium rod fixation without fusion	0.43°	0.34°	0.47°	0.49°
PEEK rod fixation without fusion	1.85°	1.56°	1.71°	3.55°
Titanium rod fixation with PEEK spacer of interbody fusion	N/A[a]	N/A[a]	N/A[a]	N/A[a]
PEEK rod fixation with PEEK spacer of interbody fusion	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Only interbody fusion with PEEK spacer	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Titanium rod fixation with PL fusion	0.43°	0.34°	0.47°	0.49°
PEEK rod fixation with PL fusion	1.34°	1.01°	1.18°	3.26°
Noninstrumented PL fusion	2.25°	1.50°	2.09°	5.14°

[a] The PEEK spacer is simulated to bond with endplates; hence, there is no range of motion to the fused level in interbody fusion groups. PEEK = polyetheretherketone.

configuration, PEEK rods could allow some ROM and, hence, could provide uniform load sharing in all segments.

In a previous cadaver study, implantation with PEEK constructs demonstrated a significant increase in allowable ROM over titanium rods in all loading directions.[20] The use of PEEK rods without fusion may act as a tension band at implantation sites in the lumbar spine. This can be used to stabilize the spine in a patient with mobile or fixed low-grade spondylolisthesis and stenosis when combined with decompression. The posterior tension band may delay the progression of spondylolisthesis and improve the symptoms of back pain. In the instrumented lumbar interbody fusion models, the difference in stress at adjacent levels between PEEK rods and titanium rods was smaller than that in posterolateral fusion models. The implanted PEEK interbody spacer is an important factor to stress increase rate to adjacent levels. From the results of this study, interbody fusion without a pedicle screw resulted in greater stress transfer to adjacent discs. The elastics modulus of the PEEK spacer is greater than that of the intervertebral disc. Replacing the PEEK spacer with an intervertebral disc increased the stiffness of the motion segment, heightening stresses on the adjacent disc. This is because the adjacent disc is located between the fusion segment and normal motion segment. Because of the interbody spacer, the advantages in stress transfer to adjacent levels seen with the use of a PEEK rod were not better than when a titanium rod was used. Previous studies[20,21] demonstrated that PEEK rods more closely approximated the physiologic anteroposterior columnar load sharing and improved the interbody fusion rate. In the instrumented posterolateral spinal arthrodesis models, the biomechanical characteristics of instrumented PEEK rod fixation with posterolateral fusion were similar to noninstrumented posterolateral fusion, but superior to the implanted titanium rods with posterolateral fusion. PEEK rods permit greater stability[20] to reduce the risk of nonunion in noninstrumented fusion procedures. PEEK rods with posterolateral fusion could be used as an alternative technique to noninstrumented or instrumented titanium rod posterolateral fusion.

5. Conclusion

Clinical applications for PEEK rod systems in fusion surgery are still limited. This current study details a computational analysis for comparing traditional rigid titanium rod systems to more novel PEEK fixation. The PEEK rod system could provide potential advantages for reducing mild stress on adjacent-segment discs and facet joints. In addition, the elastic property of PEEK rod fixation allows for a greater range of motion than that of the titanium system. Therefore, it may reduce the incidence of complications seen with traditional rigid fusion devices. More clinical evidence and follow-up studies are needed to justify its benefits.

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