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Finite Element Analysis of Mechanical Stress Distribution in Titanium and PEEK Rod Constructs for Isthmic L5–S1 Spondylolisthesis

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ABSTRACT

AIM: To compare the biomechanical behavior of titanium and polyetheretherketone (PEEK) rods using finite element analysis (FEA) in a Grade I L5-S1 isthmic spondylolisthesis model.

MATERIAL and METHODS: An anatomically accurate 3D finite element model of the L3–S1 spine was created from CT data of a healthy 30-year-old male. A unilateral pars defect at L5 simulated Grade I spondylolisthesis. Instrumented models with titanium and PEEK rods were subjected to five physiological loading conditions. Von Mises stresses and displacement vectors were analyzed and stress distributions on bone, screws and rods were measured.

RESULTS: Titanium rods absorbed significantly higher loads across all loading conditions (e.g., 117 N vs. 34.5 N in compression; $p < 0.01$), while PEEK constructs allowed greater load sharing with the bone. Screws in titanium systems experienced higher stresses, particularly in posterior shear and axial rotation. Both materials effectively reduced stress at the pars defect.

CONCLUSION: Titanium constructs offer high rigidity but concentrate stress on implants, potentially increasing complication risk. PEEK rods demonstrated a more physiological load distribution, reducing implant stress without compromising stability. PEEK rods may serve as a biomechanically advantageous alternative to titanium in select spondylolisthesis cases. Further clinical validation is warranted.

KEYWORDS: Spondylolysthesis, Finite element analysis (FEA), Titanium rods, PEEK rods

ABBREVIATIONS: 3D: Three-dimensional, **ASD:** Adjacent segment disease, **CT:** Computed tomography, **DICOM:** Digital imaging and communications in medicine, **FE:** Finite element, **FEA:** Finite element analysis, **N:** Newton, **PEEK:** Polyetheretherketone, **SPSS:** Statistical package for the social sciences, **TLIF:** Transforaminal lumbar interbody fusion, **σ:** Normal stress, **σ_1, σ_2, σ_3:** Principal stresses (maximum, intermediate, minimum), **τ:** Shear stress

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INTRODUCTION

Spondylolisthesis is defined as the anterior displacement of one vertebra relative to the adjacent one, most frequently occurring at the L5-S1 level. The Wiltse classification categorizes spondylolisthesis into five etiological types: dysplastic (congenital), isthmic, degenerative, traumatic (13). Also, Meyerding developed a five-grade system used to quantify the degree of anterior vertebral slippage in spondylolisthesis, with Grade I representing 0–25% slip and Grade V indicating complete subluxation (4). In patients where the slippage progresses, when the symptoms persist, or neurological deficits occur, surgery is indicated. Posterior lumbar pedicle screw and rod fixation is the standard surgical approach aimed at stabilizing the motion segment and promoting arthrodesis (8). Titanium alloy rods have preferably been seen as the gold standard in posterior instrumentation surgery due to their high tensile strength, corrosion resistance, and biocompatibility. However, stabilizing the spine with titanium rod constructs may interfere with physiological load transmission, potentially leading to reduced mechanical stimulation of bone grafts, impaired fusion, and an increased risk of adjacent segment disease. Furthermore, it may exacerbate implant-related complications such as screw loosening or rod fractures (7). Because of this, alternative biomaterials with more favorable elastic properties have been developed, like polyetheretherketone (PEEK), which is a thermoplastic polymer increasingly used for spinal stabilization surgery, allowing a more physiological distribution of mechanical loads (14). Despite growing interest in PEEK as a rod material, evidence for its efficacy in spondylolisthesis is limited.

In this study, we developed a detailed three-dimensional FE model of the lumbosacral spine to compare the biomechanical behavior of PEEK and titanium rod constructs in the setting of Grade I L5-S1 spondylolisthesis. The findings may contribute to informed decision-making in implant selection for optimizing clinical outcomes in spondylolisthesis surgery.

MATERIAL and METHODS

This finite element analysis (FEA) was performed at *Gzm Teknoloji Tasarım San. ve Tic. Ltd. Şti. (Istanbul, Turkey)* to evaluate mechanical behavior in the lumbar spine under instrumented and non-instrumented conditions. The model was based on a 30-year-old male volunteer with no history of spinal trauma, tumor, infection, or fractures. Lumbar imaging (L3–S1) was acquired using a 256-slice computed tomography (CT) scanner with 1 mm slice thickness (*Siemens Healthineers AG, Erlangen, Germany*). The DICOM-format data were used to construct a high-fidelity anatomical model for finite element simulation.

A three-dimensional (3D) mesh of the lumbar spine was created using Blender 4.2 (Blender Foundation, Amsterdam, Netherlands) and further refined in SolidWorks (*Dassault Systèmes, Vélizy-Villacoublay, France*). These tools enabled segmentation and reconstruction of vertebral bodies, intervertebral discs, and posterior elements. To simulate a Meyerding Grade I spondylolisthesis caused by a unilateral pars defect, the left pars interarticularis of L5 was virtually removed, and L5 was translated 20% anteriorly over S1. This created a biomechanically realistic model of spondylolytic instability at the L5-S1 junction (Figure 1).

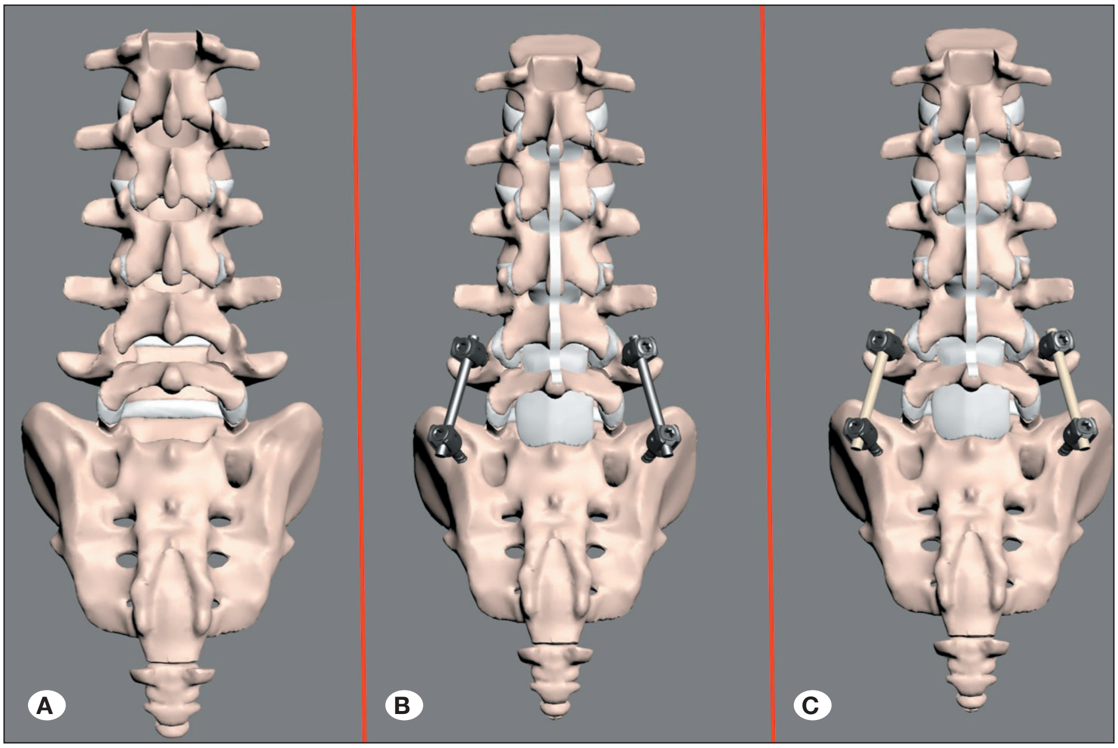


Figure 1: Three dimensional (3D) model of the lumbasacral area. **A)** Without instrumentation, **B)** with titanium rods, and **C)** with PEEK rods.

The models were exported in .obj format and imported into 3DEXPERIENCE SIMULIA (*Dassault Systèmes, Vélizy-Villacoublay, France*) for meshing and mechanical analysis. SIMULIA supports advanced FE simulation and was used to define contact interfaces, apply loads, and solve for mechanical stresses and displacements. All solid components, including cortical and cancellous bone, intervertebral discs, and implants, were treated as linear, homogeneous, isotropic materials, consistent with accepted practices in spine FEA. Material properties such as Young's modulus, Poisson's ratio, density, and tensile strength were assigned based on validated literature data.

Mesh convergence testing was performed to ensure accurate and stable results. Finer mesh densities were applied in regions of interest (e.g., screw entry points, rod-bone interfaces, and the pars interarticularis defect).

The final mesh consisted of:

- *Control (non-instrumented) model:* 2,454,046 elements and 598,057 nodes
- *Instrumented model (pedicle screws and rods):* 5,315,855 elements and 1,271,869 nodes

Physiological loading conditions, including vertical compression, anterior-posterior shear, lateral bending, and axial rotation, were simulated by applying distributed forces to nodal points on the superior endplate of L3. The inferior surface of S1 was fully constrained in all degrees of freedom to anchor the model and replicate in vivo boundary conditions. Bonded (rigid) contact definitions were used at screw-rod and screw-bone interfaces to mimic rigid fixation. All materials were modeled as linear, homogeneous, and isotropic to simplify computational complexity and ensure mesh convergence across loading scenarios. While this approach does not capture the anisotropic or nonlinear characteristics of biological tissues—particularly the fiber-reinforced nature of the annulus fibrosus and the differentiation between cortical and cancellous bone—it is consistent with several validated spine models in the literature (10,11).

Ligaments and facet joint articulations were not included in this model. While these structures are important for spinal load-sharing and kinematic behavior, their exclusion was based on the primary focus of this study—comparative analysis of mechanical stress distribution within instrumentation constructs (PEEK vs. titanium rods) under standardized conditions. Excluding these anatomical features also reduced model complexity and allowed more precise isolation of implant-specific biomechanical effects. This modeling approach has been used in previous validated finite element studies examining posterior instrumentation systems (9). These simplifications allow for comparative analysis of stress distribution across instrumentation constructs, which was the primary objective of this study. Nevertheless, we acknowledge that such assumptions may affect absolute stress magnitudes, especially under complex loading conditions such as axial rotation or shear.

The software computed multiple stress parameters:

- **Normal stresses (σ):** Represent tensile (positive) and compressive (negative) forces along anatomical axes.
- **Shear stresses (τ):** Represent tangential sliding forces within the material structure.
- **Principal stresses (σ_1, σ_2, σ_3):** Quantify the maximum, intermediate, and minimum normal stresses in the element, with σ_1 representing peak tensile and σ_3 peak compressive stress.
- **Von Mises stress:** A critical measure for identifying the likelihood of yield in ductile materials like titanium; widely used to predict mechanical failure under complex multiaxial loading.
- **Displacement vectors (X, Y, Z):** Indicate deformation magnitudes in three anatomical planes under load.

This FE model provided a detailed simulation of biomechanical responses in both instrumented and non-instrumented spondylolytic spines. Importantly, it enabled quantitative comparisons of stress distribution on rods, screws, vertebral bodies, and the pars defect under identical loading conditions, offering critical insights into how implant material and construct design affect spinal stability and the potential for mechanical failure.

This study is a computer-based finite element analysis and does not involve any experimental intervention on human participants or animals. The three-dimensional lumbar spine model used in this study was reconstructed from anonymized computed tomography (CT) imaging data solely for the purpose of anatomical modeling and biomechanical simulation. No identifiable patient information, clinical data, or treatment outcomes were used.

Since the study consisted exclusively of computational modeling and simulation, it does not meet the definition of human subject research. Therefore, ethics committee approval was not required.

RESULTS

The FEA evaluated mechanical load distributions in titanium and PEEK rod constructs at the L5-S1 segment under five physiologic loading conditions: vertical compression, anterior shear, posterior shear, lateral bending, and axial rotation. Load contributions were quantified separately for rods and screws (Figures 2–4).

Rods

The mechanical properties of the titanium and PEEK rods used in the simulation were based on the properties of the implants *from Osimplant Spinal Restoration Technologies (Istanbul, Turkey).* Titanium alloy (Ti-6Al-4V) was modeled with an elastic (Young's) modulus of 110 GPa, Poisson's ratio of 0.30, and density of 4.43 g/cm³. PEEK was modeled with a Young's modulus of 3.6 GPa, Poisson's ratio of 0.36, and density of 1.32 g/cm³. Both materials were assumed to be linear, homogeneous, and isotropic.

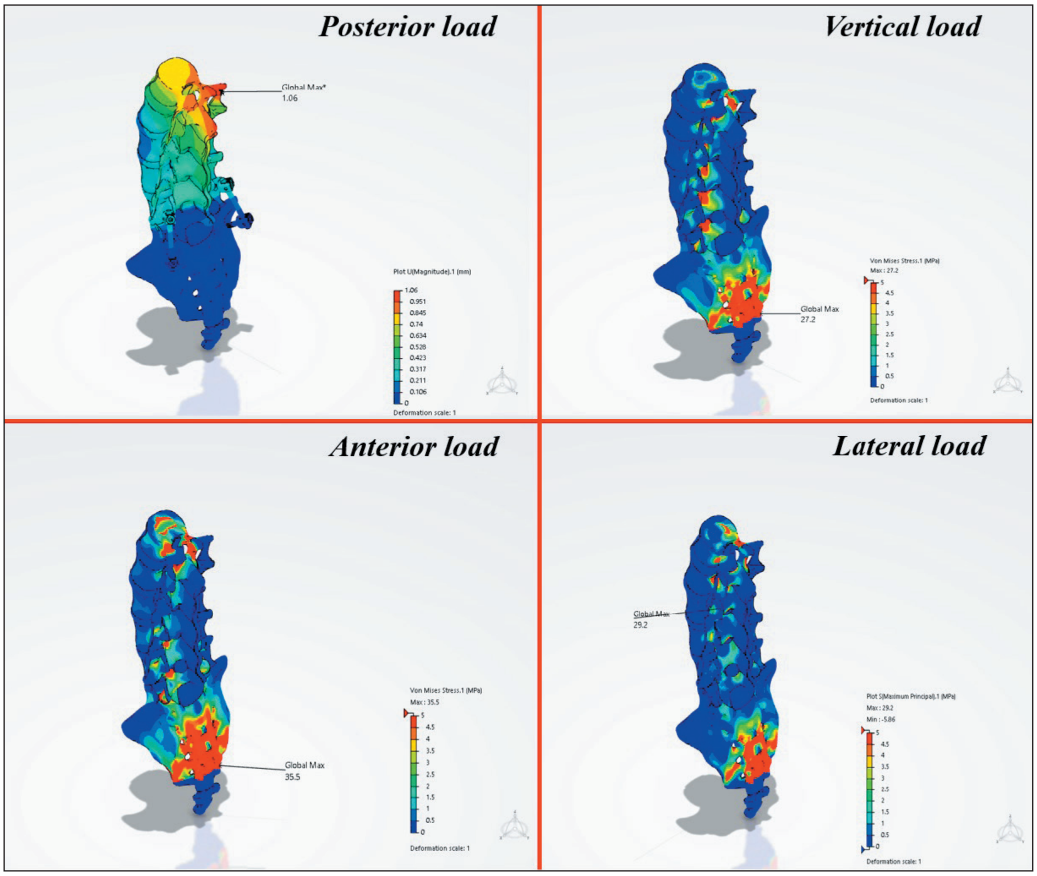


Figure 2: Stress contribution under several loading conditions of the lumbosacral area without instrumentation (control group).

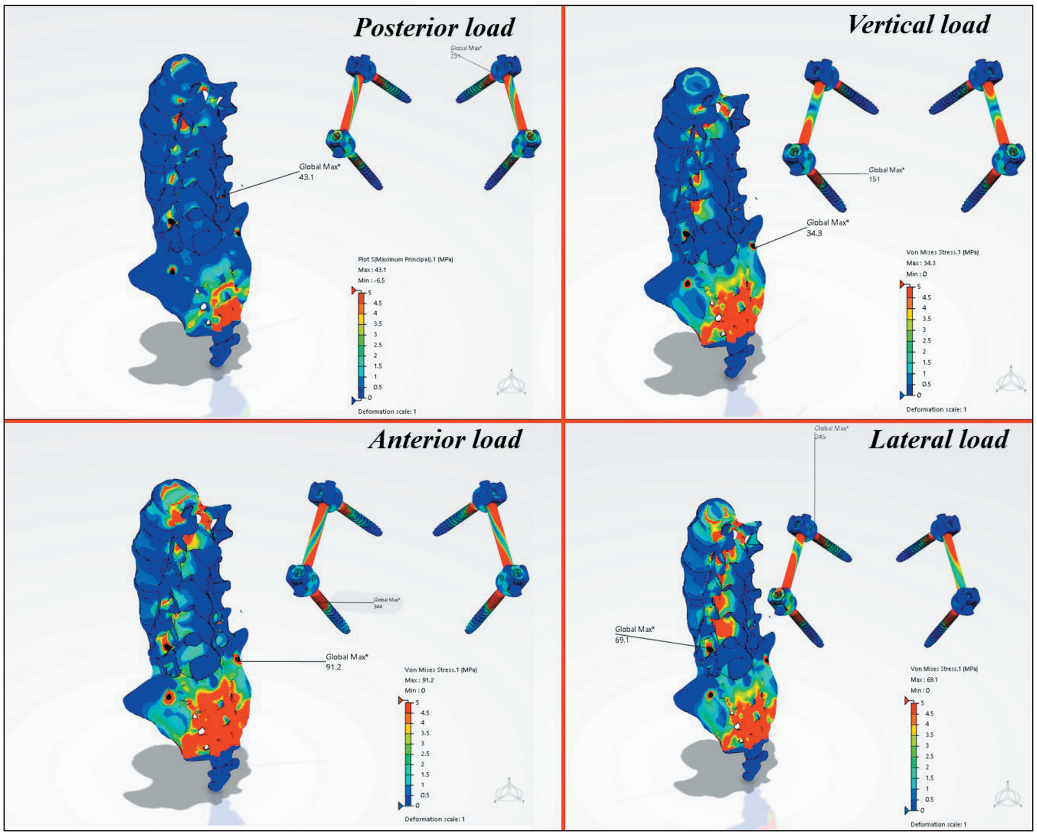


Figure 3: Stress contribution under several loading conditions of the lumbosacral area and the screws with titanium rods.

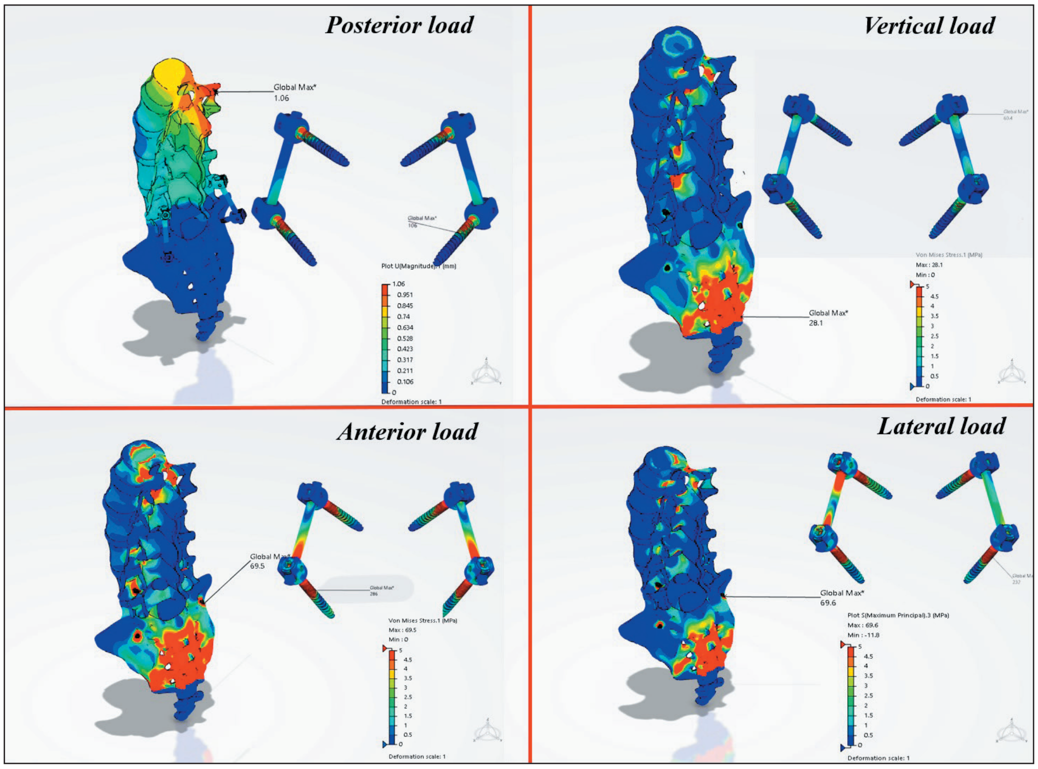


Figure 4: Stress contribution under several loading conditions of the lumbosacral area and the screws with PEEK rods.

Across all loading scenarios, titanium rods demonstrated markedly higher load absorption compared to PEEK rods. In vertical compression, titanium rods carried a load of 117 N, while PEEK rods absorbed only 34.5 N. Under anterior shear, the titanium rod experienced 94.4 N versus 44.7 N in the PEEK counterpart. The difference was even more pronounced in posterior shear, where the titanium rod carried 168 N compared to only 20 N in the PEEK rod. During lateral bending, titanium and PEEK rods bore 219 N and 64.4 N, respectively. Similarly, under axial rotation, the titanium construct withstood 153 N of load, whereas the PEEK rod carried 60 N.

These differences were statistically significant, as confirmed by a paired t-test comparing rod loads across materials (t(4) = 5.27, p = 0.006). These findings indicate that titanium rods, due to their higher stiffness, absorb and localize more mechanical load, while PEEK rods facilitate greater load sharing with surrounding biological structures, resulting in lower rod stress.

Screws

In both instrumented models, bilateral pedicle screws measuring 6.5 mm in diameter and 45 mm in length were placed at L5 and S1. The rods were 5.5 mm in diameter and matched in length across both material groups. Implant dimensions were kept identical for the titanium and PEEK groups to ensure that differences in stress distribution were solely attributable to material properties rather than geometric variations.

The load distribution on pedicle screws followed a similar pattern. In vertical compression, the screw load was 151 N in the titanium construct and 37.6 N in the PEEK construct. For anterior shear, both constructs exhibited high screw loading, with titanium and PEEK screws bearing 344 N and 286 N, respectively. Posterior shear resulted in a significant discrepancy: titanium screws experienced 231 N, while PEEK screws bore only 106 N. During lateral bending, the screw loads were relatively close (245 N for titanium, 232 N for PEEK), suggesting a more uniform load distribution in this condition. Axial rotation showed the greatest difference, with titanium screws carrying 233 N and PEEK screws only 59.7 N.

Paired t-test analysis demonstrated that these differences in screw loads were also statistically significant [t(4) = 3.47, p = 0.026], confirming that PEEK constructs exert less mechanical stress on pedicle screws, particularly in posterior and rotational loading scenarios.

Together, these results suggest that while titanium instrumentation offers increased structural stiffness and resistance to deformation, it also generates greater stress concentrations at both the rod and screw levels. In contrast, PEEK instrumentation distributes loads more evenly, reducing stress on the implants and potentially mitigating the risk of stress shielding, screw fatigue, or implant-bone interface failure. These findings underscore the biomechanical advantages of semi-rigid PEEK rods in reducing mechanical overload while maintaining stability in the fixation of L5-S1 spondylolisthesis.

In addition to evaluating implant stresses, the FEA also assessed stress distribution at the site of the pars interarticularis defect. The results demonstrated that both titanium and PEEK rod constructs effectively reduced the mechanical stress concentration on the pars region. This stress reduction suggests that posterior instrumentation contributes to mechanical stabilization of the defect site, potentially limiting further slippage and promoting fusion. While titanium provided greater immediate stiffness, PEEK offered comparable stress offloading with the added benefit of more physiological load distribution (Tables I-II).

DISCUSSION

This study employed an anatomically accurate FE model of the lumbosacral spine to compare the biomechanical behavior of titanium and PEEK rod constructs in the context of isthmic L5-S1 spondylolisthesis. Our findings revealed that titanium constructs consistently transmitted higher mechanical stress to both rods and screws compared to PEEK, with statistically significant differences across all test scenarios. These results support the hypothesis that the material properties of spinal instrumentation significantly influence stress distribution, construct behavior, and, ultimately, the biological and clinical outcomes of spinal fusion surgery.

Table I: Load Contribution on Rods and Screws

	Rods	
Load (Newton)	**Titanium**	**PEEK**
Vertical	117.0	34.5
Anterior	94.4	44.7
Posterior	168.0	20.0
Lateral	219.0	64.4
Rotation	153.0	60.0

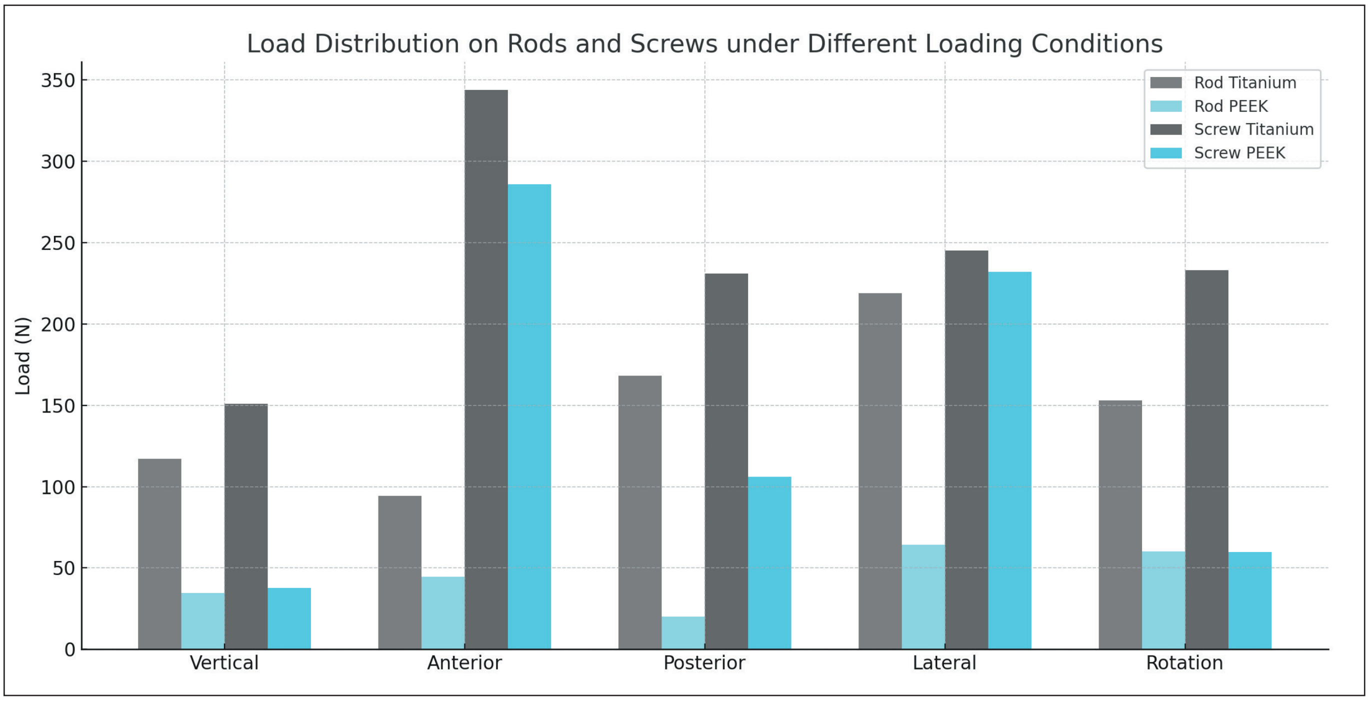
	Screws	
Load (Newton)	**Titanium**	**PEEK**
Vertical	151	37.6
Anterior	344	286.0
Posterior	231	106.0
Lateral	245	232.0
Rotation	233	59.7

Mechanical Load Distribution and Material Behavior

Titanium, with its high elastic modulus, provides a rigid and durable construct that resists deformation. As demonstrated in our study, this rigidity translates into higher stress concentrations at the rod and screw levels. Under posterior shear, for instance, the titanium rods bore 168 N—more than eight times the load of PEEK rods (20 N). Similarly, titanium screws carried approximately twice the load of PEEK screws in posterior shear and four times as much in axial rotation. This localized load concentration can lead to stress shielding, where reduced mechanical stimulation of surrounding bone tissue impairs bone remodeling and fusion. It may also increase the risk of implant-related complications, such as screw loosening, rod fatigue fracture, or bone resorption at the bone-implant interface (3).

PEEK, in contrast, exhibits an elastic modulus that is closer to cortical bone, enabling a semi-rigid construct that permits micro-motion and more physiological load sharing. In our model, PEEK rods consistently exhibited lower stress across all loading directions. For example, during axial rotation, PEEK rods carried 60 N versus 153 N in titanium rods. These results suggest that PEEK distributes loads more uniformly

Table II: Diagram of the Load Distributions under Different Loading Conditions



through the spine-implant system, reducing the stress borne by the hardware and potentially improving the mechanical environment for bone fusion (6).

Comparison with Prior Studies

Our results are consistent with previous computational and experimental research. Li et al. conducted an FEA comparing titanium and PEEK rods in a TLIF model and observed significantly reduced stress in PEEK rods compared to titanium rods under comparable loading conditions. They also reported increased strain on the interbody graft with PEEK, which may favor osteogenesis by enhancing mechanical stimulation at the fusion site (6). Similarly, a biomechanical study by Li et al. on long-segment posterior lumbar instrumentation showed that PEEK rods reduced the maximum stress on screws and better preserved adjacent segment motion. These constructs showed a more balanced stress distribution that could delay the onset of adjacent segment degeneration, a well-documented complication associated with rigid titanium constructs (5). In a recent meta-analysis, authors found that PEEK rod systems were associated with superior clinical outcomes compared to titanium, including reduced incidence of ASD, lower rates of implant failure, and improved fusion quality. The authors attributed these advantages to the semi-rigid nature of PEEK, which allows for better load-sharing without compromising mechanical stability (7).

These findings reinforce the notion that rigid titanium constructs, while biomechanically robust, may over-constrain spinal segments, leading to stress concentrations that compromise both hardware longevity and spinal health. PEEK rods, through their ability to approximate the mechanical properties of native bone, may mitigate these drawbacks by creating a more favorable environment for fusion and reducing the biomechanical burden on adjacent segments.

Clinical Relevance and Surgical Decision-Making

The results of this FEA demonstrate that both titanium and PEEK rod constructs effectively reduce mechanical stress at the pars interarticularis in L5-S1 spondylolisthesis, contributing to stabilization of the defect. However, the type of implant material significantly influences the distribution of stress across the instrumentation system. Titanium constructs transmitted significantly higher loads to rods and pedicle screws, particularly under posterior shear and rotational loads. These focal stress concentrations may accelerate implant fatigue and predispose patients to mechanical complications such as screw loosening, rod breakage, or bone–implant interface failure (6).

These findings are consistent with prior clinical and experimental studies examining the mechanical and biological performance of PEEK rods in spinal fusion. Qi et al. reported that PEEK rods demonstrated comparable clinical and radiological outcomes to titanium alloy rods, with the added benefit of potentially reducing implant-related complications due to their semi-rigid nature and closer modulus of elasticity to bone tissue (12). Similarly, Huang et al. found that PEEK rod constructs were associated with favorable long-term radiological outcomes, including preservation of disc height and a low incidence of hardware-related complications at a minimum 5-year follow-up. These results reinforce the biomechanical hypothesis that PEEK rods may attenuate stress concentrations on implants and adjacent spinal segments, thereby decreasing the likelihood of screw loosening, rod breakage, and adjacent segment degeneration. When integrated with our finite element findings, the accumulating evidence supports the use of PEEK rods as a viable alternative to titanium in select spinal fusion cases, particularly where implant fatigue and load transmission balance are clinical concerns (2).

This more physiological load-sharing profile could minimize stress shielding, maintain intersegmental motion within acceptable ranges, and create a more favorable biomechanical environment for fusion. From a clinical perspective, these properties may translate into reduced implant failure rates, improved long-term stability, and potentially lower incidence of adjacent segment degeneration.

For spine surgeons, these findings are particularly relevant when selecting instrumentation in cases where biomechanical balance is critical—such as in younger patients, in long-segment fusions, or where preservation of adjacent segment function is desired. The results also provide quantitative biomechanical evidence to support the use of PEEK rods as a semi-rigid fixation alternative in posterior lumbar fusion. Incorporating such data into surgical planning may help personalize treatment, optimize construct longevity, and reduce the need for revision surgery (14). Conversely, titanium may be more suitable in cases requiring maximum initial rigidity, such as high-grade spondylolisthesis, severe instability, or osteoporotic bone, where immediate construct stability is critical. The choice between materials should thus be individualized, balancing the need for rigidity with the risks of overloading adjacent structures and hardware components (1).

The biomechanical findings of this study, particularly the significantly lower stress concentrations observed in PEEK rods and screws, may have important clinical implications. By reducing focal stress on implants, PEEK constructs could potentially lower the incidence of mechanical complications such as screw loosening or rod fracture, which remain leading causes of implant failure and revision surgery. Furthermore, more physiological load-sharing with PEEK rods may support better bone remodeling and fusion environment, possibly enhancing arthrodesis success and reducing the risk of adjacent ASD. While these implications are supported by previous studies and our finite element data, they remain speculative and require further validation through cadaveric biomechanical testing or prospective clinical cohort studies comparing outcomes of titanium versus PEEK rod instrumentation in spondylolisthesis patients.

Limitations

Despite the insights offered by this study, several limitations must be acknowledged. First, although the FE model was anatomically accurate and based on CT-derived geometry, it remains a simplified representation of in vivo conditions.

The simulations assumed linear, homogeneous, and isotropic material properties, which may not fully reflect the complex viscoelastic and anisotropic nature of biological tissues. Additionally, muscle forces and dynamic loading cycles were not incorporated, which may affect stress distribution patterns in real-life scenarios.

CONCLUSION

This FEA demonstrated that the material properties of spinal instrumentation significantly affect stress distribution and mechanical behavior in the surgical treatment of L5-S1 spondylolisthesis. Titanium rods, while providing superior stiffness and immediate stability, concentrated higher mechanical loads on both rods and pedicle screws, which may predispose to hardware-related complications and stress shielding. In contrast, PEEK rods allowed for a more physiological distribution of mechanical stress, reducing the force on implants and promoting a favorable biomechanical environment for spinal fusion. Both constructs effectively reduced the stress on the pars defect, indicating their capacity to stabilize the spondylolytic segment. However, the semi-rigid behavior of PEEK offers additional advantages in reducing focal stress concentrations and potentially preserving adjacent segment integrity. These findings support the consideration of PEEK rods as a potentially advantageous alternative to titanium in select clinical scenarios. Future in vivo studies and long-term clinical trials are necessary to validate these results and assess their impact on fusion rates, implant longevity, and patient outcomes.

Declarations

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Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

Disclosure: The authors declare no competing interests.

AUTHORSHIP CONTRIBUTION

Study conception and design: IA
Data collection: AYY
Analysis and interpretation of results: AAA
Draft manuscript preparation: IA
Critical revision of the article: KP
All authors (IA, AYY, AAA, KP) reviewed the results and approved the final version of the manuscript.

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