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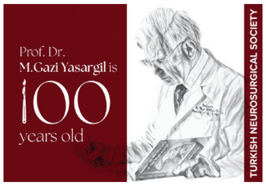

Impact of Rod Material and Spinopelvic Parameters on Distal Junctional Failure Following Lumbar Fusion: A Comparative Study of Semirigid PEEK and Rigid Titanium Alloy Rods

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ABSTRACT

AIM: To investigate the incidence of distal junctional failure (DJF) in patients undergoing posterior lumbar fusion with either semirigid polyether ether ketone (PEEK) or rigid titanium alloy rods, focusing on the impact of preoperative and postoperative spinopelvic parameters on DJF development.

MATERIAL and METHODS: A retrospective analysis was conducted on patients who underwent short-segment posterior transpedicular stabilization with semirigid PEEK or rigid titanium ally rods between 2015 and 2021. Preoperative and postoperative pelvic parameters, including pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL), PI-LL mismatch, and lower instrumented vertebra (LIV) were evaluated.

RESULTS: The total cohort consisted of 61 patients with a mean age of 55.85 ± 11.97 years. DJF occurred in 18.03% of patients in the PEEK group (6.67%) compared to the rigid rod group (29.03%) ($p<0.05$). Postoperative PI-LL mismatch was a critical factor in DJF development ($p<0.05$). Among patients with a preoperative PI-LL mismatch greater than 10°, non-DJF patients achieved a correction of -55.50°. Postoperative reductions in LL were also associated with an increased risk of DJF ($p<0.05$). In the PEEK group, DJF patients experienced -19.35° reduction in LL, whereas -11.02° in the rigid rod group.

CONCLUSION: PEEK rods were associated with a lower incidence of DJF compared to rigid titanium rods. Postoperative PI-LL mismatch and changes in lumbar lordosis and PI-LL mismatch are key predictors to prevent DJF.

KEYWORDS: Distal junctional failure, Lumbar fusion, PEEK rods, Rigid titanium rods, Spinopelvic parameters

ABBREVIATIONS: DJF: Distal junctional failure, **LL:** Lumbar lordosis, **PI:** Pelvic incidence, **PT:** Pelvic tilt, **SS:** Sacral slope, **LIV:** Lower instrumented vertebra, **PEEK:** Polyetheretherketone, **ROC:** Receiver operating characteristic

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INTRODUCTION

Lumbar fusion is a widely employed surgical intervention for managing degenerative lumbar spine conditions. Among the various techniques for achieving stability in lumbar fusion, rigid fixation with titanium alloy (Ti-6Al-4V) rods is a well-established method, known for providing robust stabilization and promoting fusion of spinal segments. However, the rigidity of these rods can alter the natural biomechanics of the spine, potentially contributing to complications such as distal junctional failure (DJF) over time (3). DJF is characterized by structural failures occurring at the distal end of the instrumented segment, including vertebral body fractures, loosening or breakage of pedicle screws, rod breakage, narrowing of the foraminal or spinal canal, and pseudoarthrosis (14).

Recent advancements in spinal surgery have introduced semi-rigid fixation systems using polyether ether ketone (PEEK) rods as an alternative to rigid titanium rods (12). PEEK rods, recognized for their biocompatibility and mechanical properties—such as high strength and flexibility—seek to strike a balance between providing stability and preserving the natural mobility of the spine (17). Despite their potential to reduce complications associated with rigid fixation, such as DJF, the evidence directly comparing the effectiveness of PEEK rods to titanium rods in terms of long-term outcomes remains limited (4,9).

The occurrence of DJF following lumbar fusion may be influenced by several factors, including the alignment of spinopelvic parameters such as pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), and lumbar lordosis (LL) (8). These parameters are critical for maintaining sagittal balance and influencing spinal load distribution (10). Variations in these parameters preoperatively, or changes observed postoperatively, may significantly impact the risk of DJF. Understanding how different fixation systems, such as PEEK and titanium rods, affect these spinopelvic parameters could provide valuable insights into optimizing surgical techniques and improving patient outcomes (2,6).

The aim of this study is to investigate the incidence of DJF in patients undergoing posterior lumbar fusion using either PEEK rods or rigid titanium rods. Specifically, we seek to determine whether differences in preoperative and postoperative spinopelvic parameters contribute to the development of DJF and if the type of rod used influences this risk. By elucidating the relationship between fixation methods, spinopelvic alignment, and DJF development, this study aims to provide evidence that may inform surgical decision-making and potentially reduce the risk of this complication.

MATERIAL and METHODS

Study Design

This retrospective study analysed cases of short-segment posterior transpedicular stabilisation of the lumbar spine performed at two spinal centre between 2015 and 2021. This study was approved by the Ethics Committee of Tekirdag Namik Kemal University (No: 2021.02.01.02). Due to the retrospective nature of the data analysis, informed consent was not required from the patients. The files of the operated patients were retrospectively analysed with the help of digital fixed data. The medium- and long-term outcomes of the included patients were evaluated for 3 years. Two groups took part in the study: Patients using PEEK rods, i.e. semi-rigidly stabilised, and patients using rigid rods. The development of DJF was evaluated in both groups and patients were assessed according to whether they developed DJF or not.

Inclusion and Exclusion Criteria

Patients aged 18 years and older with no previous stabilisation surgery, no known oncological disease or immunosuppression were included in the study. Only posterior stabilisation procedures with rigid rod and peek rod were included in the study. Surgeries performed with other dynamic systems were not included. Anterior surgery, anterior fixation, fixation with pedicle hooks, magnetic or growing rods and interbody fusion procedures were excluded. In addition, patients with known oncological conditions, patients on immunosuppressive therapy, osteoporosis, and patients under 18 years of age were excluded. Surgical indications included recurrent disc herniations, patients with foraminal and spinal stenosis without listhesis, and patients with pars defects. Patients with scoliosis, i.e. coronal balance <10 degrees, were included in the study; patients with coronal balance >10 degrees were excluded.

Radiological Evaluations

Preoperative indications for surgery were determined by lumbar MRI and lateral lumbar radiographs. Lateral lumbar radiographs are routinely performed in the first week after surgery. For postoperative pelvic parameters, lumbar radiographs or scoliosis radiographs were used. Patients are followed clinically for an average of 3 years to determine whether DJF has occurred and are checked with lumbar MRI and CT in case of clinical complaints (back and leg pain, neurological deficits). Various criteria were used to define DJF:

- DJF was defined as failure of the vertebra at or immediately caudal to the last instrumented level. DJF was considered if one or more of the following conditions were present:

  i) Pulling the pedicle screws,

  ii) Mechanical breakage of the rods in the caudal half of the fixation or breakage of one or more of the caudal pedicle screws,

  iii) Vertebral fracture,

  iv) Intervertebral disc degeneration with a Pfirrmann score of 4 or higher.

- For the diagnosis of DJF, disc degeneration was detected using lumbar MRI, while pedicle screw malposition and bone fractures were assessed using lumbar CT scans.

Pelvic Parameter Assessment

Pelvic parameters were primarily assessed using scoliosis radiographs. However, in cases where scoliosis radiographs were unavailable, standing lateral lumbar radiographs were also utilized. Measurements from these imaging studies were conducted using Surgimap software. Parameters such as PI, PT, SS, and LL were measured by an experienced spine surgeon and analyzed for their association with DJF development.

Grouping and Analysis

The included patients were divided into two groups: those who received semirigid PEEK rods and those who received rigid titanium rods. Patients were randomised 2:1.The development of DJF in both groups was monitored based on the aforementioned radiological criteria. Additionally, the potential influence of patients' pelvic parameter values on DJF development was analyzed.

Statistical Analyses

The statistical analyses were conducted to compare preoperative and postoperative pelvic parameters and the incidence of DJF between patients treated with PEEK rods and rigid rods. The normality of data distribution was assessed using the Shapiro-Wilk test. Parametric tests, such as the Student's t-test, were applied for normally distributed continuous variables, while the Mann-Whitney U test was used for non-normally distributed variables. For categorical variables, the chi-square test or Fisher's exact test was employed, as appropriate.

To evaluate the predictors of DJF, logistic regression analysis was performed, assessing the impact of preoperative and postoperative pelvic parameters on the development of DJF. Additionally, Receiver Operating Characteristic (ROC) curve analysis was conducted to determine the predictive power of different pelvic parameters, with Area Under the Curve (AUC) values calculated to assess the accuracy of these predictors.

Statistical significance was defined as $p<0.05$. All analyses were performed using SPSS (Statistical Package for the Social Sciences) version 26.0 software.

RESULTS

A comparative analysis between the PEEK and rigid rod groups revealed notable differences and similarities. The total cohort had a mean age of 55.85 ± 11.97 years, ranging from 23 to 80 years, with a statistically significant age difference between the groups ($p<0.05$). The overall incidence of DJF was 18.03%, with the PEEK group showing a lower incidence (6.67%) compared to the rigid rod group (29.03%), a difference that was statistically significant ($p<0.05$). Preoperative and postoperative parameters, including LL, PT, PI, and SS, did not show significant differences between the groups ($p>0.05$). the total postoperative LL was 47.18 ± 11.98 degrees, while postoperative PT and PI were 16.87 ± 8.87 and 53.24 ± 10.57 degrees, respectively. Regarding the postoperative PI-LL mismatch, the PEEK group presented a mean value of 7.10 ± 7.15, whereas the rigid rod group exhibited a mean of 10.60 ± 7.46, with the difference approaching statistical significance (p=0.0661). Additionally, changes in LL, PT, PI, SS, and PI-LL mismatch did not differ significantly between the groups ($p>0.05$) (Table I). while L5 was the most commonly instrumented vertebra in both groups, S1 was more frequently instrumented in the rigid rod group (16.13%) (Figure 1).

The analysis of preoperative and postoperative parameters between PEEK and Rigid rod groups, subdivided into DJF and non-DJF categories, revealed several notable differences. The mean age of patients in the PEEK DJF group was higher compared to the non-DJF group (64.00 ± 7.07 vs. 51.32 ± 10.09, p=0.0940), while no significant age difference was observed between DJF and non-DJF patients in the Rigid rod group (p=0.9564) (Table II). Preoperative LL was notably higher in the DJF groups for both PEEK (57.65 ± 11.81) and Rigid rods (56.50 ± 13.64) compared to their respective non-DJF groups (p=0.2409 and $p<0.05$). Postoperative PI-LL mismatch was significantly elevated in the DJF groups, with the PEEK DJF group showing a mean of 16.45 ± 3.18 compared to 6.43 ± 6.89 in the non-DJF group ($p<0.05$), and the Rigid DJF group exhibiting a higher mismatch (17.31 ± 3.70) than the non-DJF group (7.85 ± 6.86, $p<0.05$) (Figure 2). The LL difference also varied significantly between DJF and non-DJF patients in both groups, being negative in the DJF groups (indicating a decrease in lordosis postoperatively) and positive in the non-DJF groups ($p<0.05$ for PEEK and $p<0.05$ for Rigid) (Figure 3). In terms of PI difference, the Rigid rod group and PEEK rod group did not show significant differences (p=0.4716, 0.0631, respectively). Additionally, the PI-LL mismatch difference was considerably higher in the DJF groups for both PEEK (10.50 ± 7.78, $p<0.05$) and Rigid rods (9.88 ± 7.04, $p<0.05$), highlighting the discrepancy in achieving alignment postoperatively between the two groups.

Results by Rod Type:

Rigid Rod and PEEK Rod Analysis: For the Rigid Rod group and the PEEK Rod group, a significant difference was found in postoperative PI-LL mismatch between DJF and non-DJF patients ($p<0.05$). This indicates a strong association between higher postoperative PI-LL mismatch and the occurrence of DJF in patients treated with rigid rods and peek rods.

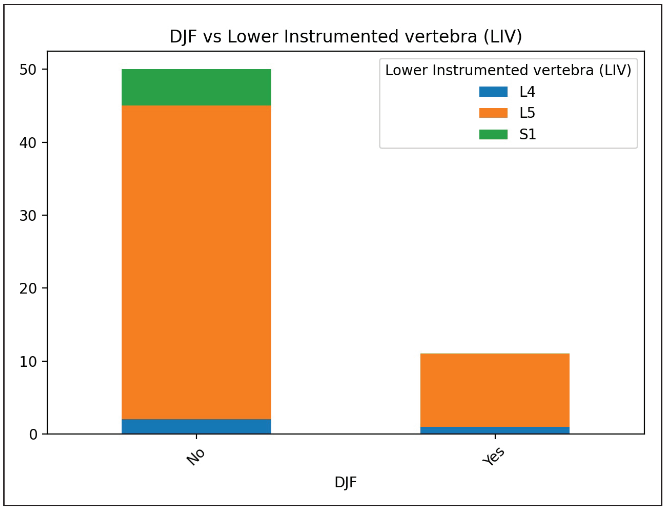

Figure 1: Distribution of DJF Based on Lower Instrumented Vertebra (LIV).

Table I: Comparison of Demographic and Surgical Parameters Between PEEK Rod and Rigid Rod Groups

Parameter	PEEK Rod n=30 (49.18%)	Rigid Rod n=31 (50.82%)	Total	p-value
	n (%)/ M ± SD [min - max]			
Age	52.17 ± 10.33 [33.00 - 71.00]	59.42 ± 12.52 [23.00 - 80.00]	55.85 ± 11.97 [23.00 - 80.00]	**<0.05***
DJF	2 (6.67%)	9 (29.03%)	11 (18.03%)	**<0.05***
Lower instrumented vertebra	L5: 26 (86.67%)	L5: 18 (58.06%), S1: 5 (16.13%), L4: 1 (3.23%)	L5: 44 (72.13%), S1: 5 (8.20%), L4: 1 (1.64%)	**<0.05***
Preoperative LL	45.52 ± 14.93 [15.70 - 75.70]	47.56 ± 15.27 [18.30 - 73.90]	46.56 ± 15.01 [15.70 - 75.70]	0.5991
Postoperative LL	45.70 ± 11.81 [20.10 - 66.60]	48.60 ± 12.16 [29.00 - 87.70]	47.18 ± 11.98 [20.10 - 87.70]	0.3489
Preoperative PT	20.26 ± 9.19 [4.30 - 36.80]	19.67 ± 10.96 [0.40 - 43.60]	19.96 ± 10.05 [0.40 - 43.60]	0.8221
Postoperative PT	16.55 ± 8.12 [2.30 - 41.10]	17.18 ± 9.67 [3.40 - 40.10]	16.87 ± 8.87 [2.30 - 41.10]	0.7839
Preoperative PI	51.92 ± 9.76 [31.60 - 68.60]	54.23 ± 10.10 [34.90 - 80.20]	53.10 ± 9.92 [31.60 - 80.20]	0.3673
Postoperative PI	51.82 ± 9.61 [31.80 - 68.30]	54.63 ± 11.41 [35.30 - 83.30]	53.24 ± 10.57 [31.80 - 83.30]	0.3034
Preoperative SS	31.65 ± 10.45 [14.90 - 51.00]	34.91 ± 10.87 [8.30 - 49.90]	33.31 ± 10.70 [8.30 - 51.00]	0.2385
Postoperative SS	35.21 ± 9.92 [19.20 - 56.30]	37.66 ± 6.85 [26.60 - 50.20]	36.45 ± 8.52 [19.20 - 56.30]	0.2646
Preoperative PI-LL mismatch	11.57 ± 8.61 [0.00 - 34.00]	12.22 ± 9.95 [1.20 - 45.30]	11.90 ± 9.24 [0.00 - 45.30]	0.7875
Postoperative PI-LL mismatch	7.10 ± 7.15 [0.50 - 34.40]	10.60 ± 7.46 [1.60 - 29.50]	8.88 ± 7.46 [0.50 - 34.40]	0.0661
LL difference	0.18 ± 11.88 [-22.60 - 21.90]	1.04 ± 14.16 [-22.60 - 24.50]	0.62 ± 12.99 [-22.60 - 24.50]	0.7995
PT difference	-3.71 ± 9.73 [-20.80 - 13.80]	-2.50 ± 9.83 [-23.60 - 14.60]	-3.10 ± 9.72 [-23.60 - 14.60]	0.6291
PI difference	-0.10 ± 0.47 [-1.60 - 0.70]	0.39 ± 3.90 [-6.00 - 19.80]	0.15 ± 2.79 [-6.00 - 19.80]	0.4910
SS difference	3.55 ± 9.68 [-13.80 - 21.20]	2.75 ± 9.58 [-13.90 - 23.10]	3.15 ± 9.55 [-13.90 - 23.10]	0.7462
PI-LL mismatch difference	-4.47 ± 8.61 [-22.50 - 16.00]	-1.62 ± 10.66 [-22.40 - 16.50]	-3.02 ± 9.73 [-22.50 - 16.50]	0.2550

***DJF:** Distal junctional failure, **LL:** Lumbar lordosis, **PT:** Pelvic tilt, **PI:** Pelvic incidence, **SS:** Sacral slope, **PI-LL mismatch:** Pelvic incidence-lumbar lordosis mismatch, **M:** Mean, **SD:** Standard deviation, **min:** Minimum, **max:** Maximum. p<0.05* indicates statistical significance.*

Postoperative PI-LL Mismatch and DJF Development: The analysis highlighted that patients with DJF, both in the Rigid Rod and PEEK group, tended to have higher postoperative PI-LL mismatch values. This finding emphasizes the importance of addressing PI-LL mismatch during the postoperative period, especially when using rigid fixation systems (Figure 2).

Correction of Preoperative PI-LL Mismatch > 10°: Among patients with a preoperative PI-LL mismatch greater than 10°, the analysis of changes revealed that:

- The average reduction of PI-LL mismatch in the DJF group was -4.40°, while in the non-DJF group, it was -10.57°. This suggests that more aggressive correction was performed in patients without DJF.
- In terms of percentage change:
  - DJF patients exhibited an average correction of -15.44%.
  - Non-DJF patients had a more substantial correction of -55.50%.

Table II: Comparison of Preoperative and Postoperative Radiographic Parameters Between DJF and Non-DJF Patients in PEEK and Rigid Rod Groups

Parameter	PEEK DJF (n=2 (6.67%))	PEEK Non-DJF (n=28 (93.33%))	PEEK p-value	Rigid DJF (n=9 (29.03%))	Rigid Non-DJF (n=22 (70.97%))	Rigid p-value
	n (%)/ M ± SD [min - max]			n (%)/ M ± SD [min - max]		
Age	64.00 ± 7.07 [59.00 - 69.00]	51.32 ± 10.09 [33.00 - 71.00]	0.0940	59.22 ± 12.23 [34.00 - 80.00]	59.50 ± 12.91 [23.00 - 80.00]	0.9564
Preoperative LL	57.65 ± 11.81 [49.30 - 66.00]	44.65 ± 14.92 [15.70 - 75.70]	0.2409	56.50 ± 13.64 [36.30 - 73.90]	43.91 ± 14.62 [18.30 - 67.90]	**<0.05***
Postoperative LL	38.30 ± 7.21 [33.20 - 43.40]	46.23 ± 11.98 [20.10 - 66.60]	0.3681	45.48 ± 18.84 [29.00 - 87.70]	49.88 ± 8.38 [37.60 - 75.00]	0.3691
Preoperative PT	13.85 ± 6.43 [9.30 - 18.40]	20.72 ± 9.27 [4.30 - 36.80]	0.3155	20.79 ± 8.10 [9.30 - 31.40]	19.22 ± 12.08 [0.40 - 43.60]	0.7238
Postoperative PT	16.60 ± 5.66 [12.60 - 20.60]	16.54 ± 8.34 [2.30 - 41.10]	0.9925	21.03 ± 6.80 [12.60 - 30.70]	15.60 ± 10.35 [3.40 - 40.10]	0.1590
Preoperative PI	55.65 ± 5.02 [52.10 - 59.20]	51.65 ± 10.02 [31.60 - 68.60]	0.5850	60.21 ± 11.26 [47.70 - 80.20]	51.79 ± 8.71 [34.90 - 68.20]	**<0.05***
Postoperative PI	54.75 ± 4.03 [51.90 - 57.60]	51.61 ± 9.90 [31.80 - 68.30]	0.6630	59.80 ± 11.31 [48.00 - 80.30]	52.51 ± 11.00 [35.30 - 83.30]	0.1073
Preoperative SS	41.80 ± 11.46 [33.70 - 49.90]	30.93 ± 10.21 [14.90 - 51.00]	0.1587	40.56 ± 8.55 [28.60 - 49.90]	32.60 ± 11.04 [8.30 - 48.40]	0.0631
Postoperative SS	38.15 ± 9.69 [31.30 - 45.00]	35.00 ± 10.08 [19.20 - 56.30]	0.6719	38.82 ± 8.15 [28.30 - 49.60]	37.18 ± 6.39 [26.60 - 50.20]	0.5539
Preoperative PI-LL mismatch	5.95 ± 4.60 [2.70 - 9.20]	11.97 ± 8.74 [0.00 - 34.00]	0.3484	7.43 ± 8.49 [1.40 - 28.50]	14.17 ± 10.00 [1.20 - 45.30]	0.0868
Postoperative PI-LL mismatch	16.45 ± 3.18 [14.20 - 18.70]	6.43 ± 6.89 [0.50 - 34.40]	**<0.05***	17.31 ± 3.70 [12.40 - 24.10]	7.85 ± 6.86 [1.60 - 29.50]	**<0.05***
LL difference	-19.35 ± 4.60 [-22.60 - -16.10]	1.58 ± 10.98 [-18.20 - 21.90]	**<0.05***	-11.02 ± 12.30 [-22.60 - 13.80]	5.97 ± 11.88 [-13.90 - 24.50]	**<0.05***
PT difference	2.75 ± 0.78 [2.20 - 3.30]	-4.17 ± 9.92 [-20.80 - 13.80]	0.3397	0.24 ± 3.00 [-5.80 - 3.30]	-3.62 ± 11.41 [-23.60 - 14.60]	0.3291
PI difference	-0.90 ± 0.99 [-1.60 - -0.20]	-0.05 ± 0.39 [-1.30 - 0.70]	0.0631	-0.41 ± 0.71 [-1.60 - 0.30]	0.72 ± 4.60 [-6.00 - 19.80]	0.4716
SS difference	-3.65 ± 1.77 [-4.90 - -2.40]	4.07 ± 9.81 [-13.80 - 21.20]	0.2835	-1.73 ± 2.54 [-4.90 - 2.20]	4.59 ± 10.79 [-13.90 - 23.10]	0.0959
PI-LL mismatch difference	10.50 ± 7.78 [5.00 - 16.00]	-5.54 ± 7.71 [-22.50 - 11.40]	**<0.05***	9.88 ± 7.04 [-4.40 - 16.50]	-6.32 ± 7.98 [-22.40 - 6.80]	**<0.05***

***DJF:** Distal junctional failure, **LL:** Lumbar lordosis, **PT:** Pelvic tilt, **PI:** Pelvic incidence, **SS:** Sacral slope, **PI-LL mismatch:** Pelvic incidence-lumbar lordosis mismatch, **M:** Mean, **SD:** Standard deviation, **min:** Minimum, **max:** Maximum. p<0.05* indicates statistical significance.*

- These results indicate that greater correction of PI-LL mismatch might help reduce the risk of DJF.

Relationship Between LL and DJF:

Preoperative LL: In the total cohort, preoperative LL values did not show significant differences between DJF and non-DJF groups ($p>0.05$). However, when analyzing by rod type, a significant difference was found in the Rigid Rod group ($p<0.05$), where patients who developed DJF had higher preoperative LL compared to those without DJF. This suggests that higher preoperative LL in the Rigid Rod group may predispose patients to DJF (Figure 3).

Postoperative LL: Postoperative LL did not show statistically significant differences between DJF and non-DJF groups across the entire cohort ($p=0.3489$) or when analyzed separately for PEEK and Rigid Rod groups ($p>0.05$). This indicates that the absolute postoperative LL values may not be directly predictive of DJF risk.

LL Difference (Change from Preoperative to Postoperative): A key finding was that the change in LL (LL difference) was

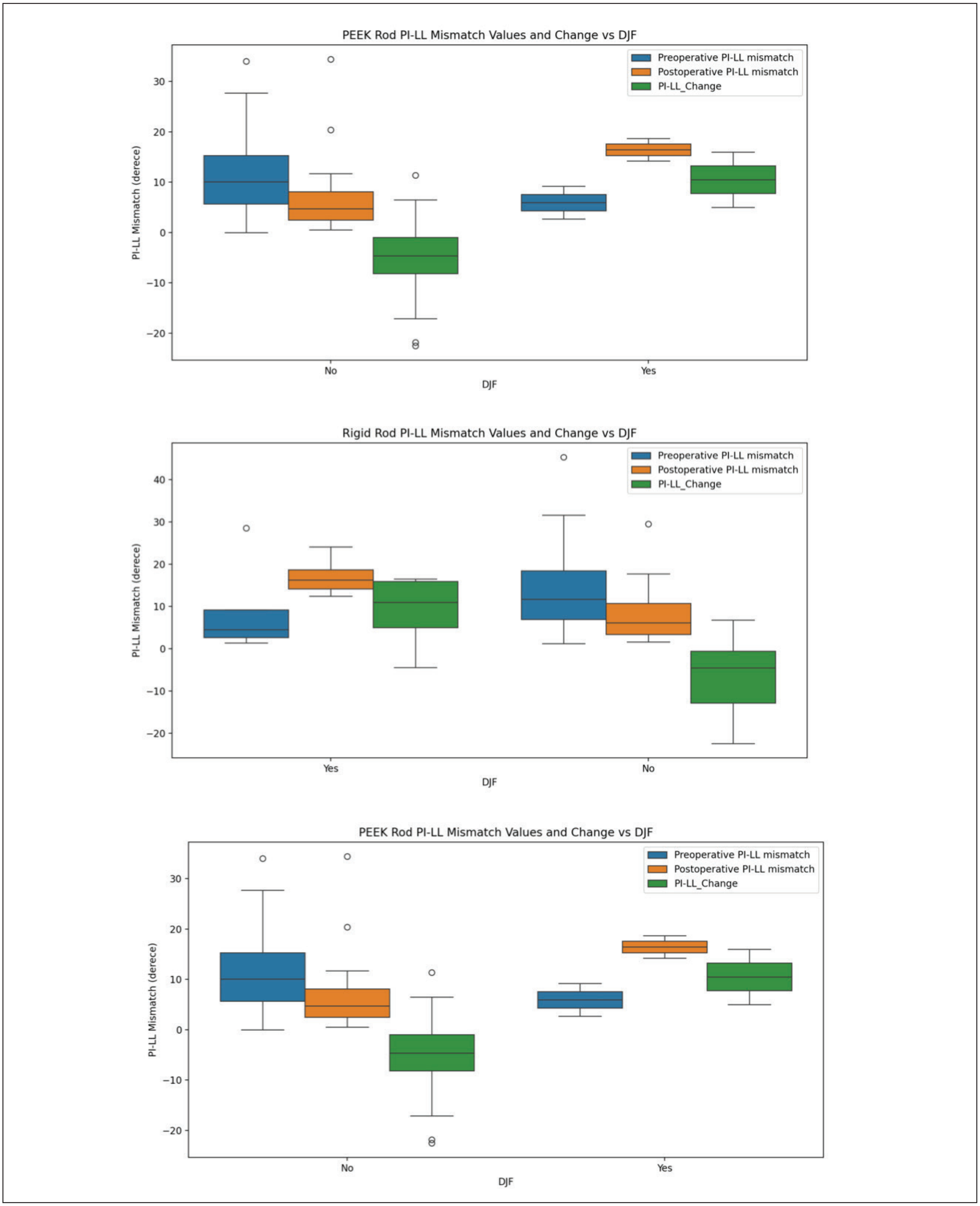

Figure 2: Comparison of PI-LL mismatch values and change in relation to DJF for different rod types. **DJF:** Distal junctional failure, **LL:** Lumbar lordosis, **PT:** Pelvic tilt, **PI:** Pelvic incidence, **SS:** Sacral slope, **PI-LL mismatch:** Pelvic incidence-lumbar lordosis mismatch.

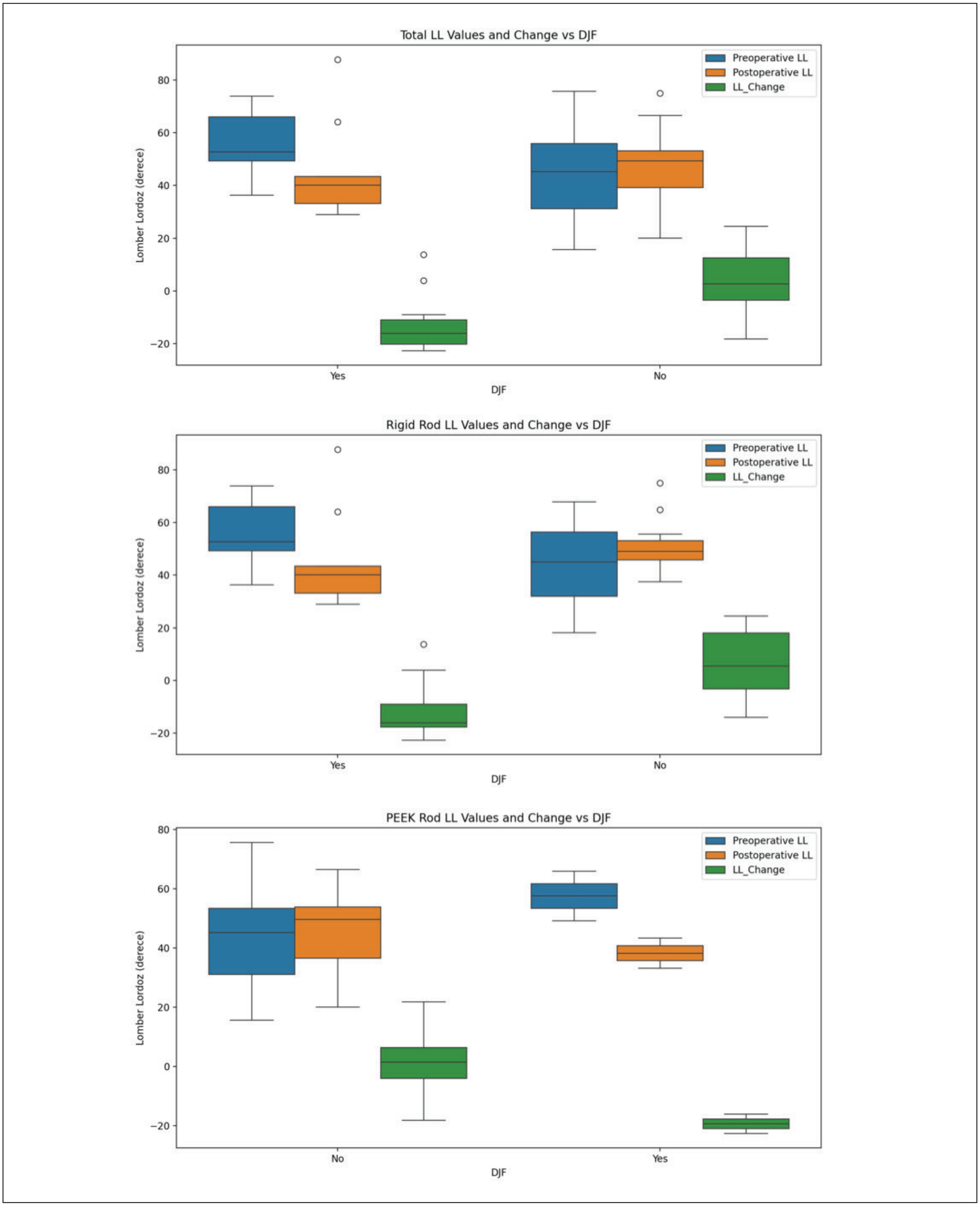

Figure 3: Comparison of lumbar lordosis (LL) values and change in relation to DJF for different rod types. **DJF:** Distal junctional failure, **LL:** Lumbar lordosis, **PT:** Pelvic tilt, **PI:** Pelvic incidence, **SS:** Sacral slope, **PI-LL mismatch:** Pelvic incidence-lumbar lordosis mismatch.

significantly different between DJF and non-DJF groups across both rod types: In the PEEK Rod group, DJF patients experienced a greater reduction in LL (-19.35°) compared to those without DJF (1.58°), with a statistically significant difference ($p<0.05$). Similarly, in the Rigid Rod group, DJF patients had a mean LL change of -11.02°, indicating a reduction, while non-DJF patients saw an increase in LL (5.97°), with a highly significant p-value ($p<0.05$). These results suggest that a reduction in LL postoperatively, particularly a significant loss of LL, may contribute to the development of DJF, especially in patients treated with PEEK rods.

ROC curve analysis provides insights into the predictive power of various preoperative and postoperative parameters in identifying the risk of DJF. Here's how we can interpret the findings based on the AUC values presented (Figure 4):

1. Postoperative PI-LL Mismatch (AUC = 1.00): The AUC value of 1.00 indicates perfect discrimination, meaning that this parameter can perfectly distinguish between patients who develop DJF and those who do not. This result suggests that postoperative PI-LL mismatch is a critical factor in determining the likelihood of DJF, making it the most reliable predictor among the measured parameters.
2. Preoperative SS (AUC = 0.82): An AUC of 0.82 indicates a good level of discrimination. This implies that preoperative SS is a relatively strong predictor of DJF risk, and higher preoperative SS values may be associated with a greater risk of DJF.
3. Preoperative LL (AUC = 0.71): An AUC of 0.71 indicates moderate predictive power. Preoperative LL has some value in identifying patients at risk of DJF.

DISCUSSION

Our study provides valuable insights into the role of different rod types (PEEK vs. rigid titanium) in the development of DJF following lumbar fusion, with a particular focus on their impact on spinopelvic parameters such as PI, PT, SS, and LL. The results align with, but also differ from, various findings in the current literature, offering a comprehensive understanding of how these fixation systems influence postoperative outcomes.

The occurrence of DJF is a significant complication following lumbar fusion, particularly when spinopelvic parameters are not adequately balanced postoperatively (11). Pelvic parameters like PI, PT, SS, and LL are crucial for maintaining sagittal balance and proper load distribution across the spine. In cases where these parameters are not optimized, mechanical complications such as DJF can arise. This observation is consistent with the work of Le Huec et al., who highlighted the importance of sagittal alignment in predicting clinical outcomes after spinal fusion surgery (8). The alignment of these parameters plays a central role in reducing biomechanical stress on the distal segments, minimizing the risk of hardware failure and vertebral fractures (15).

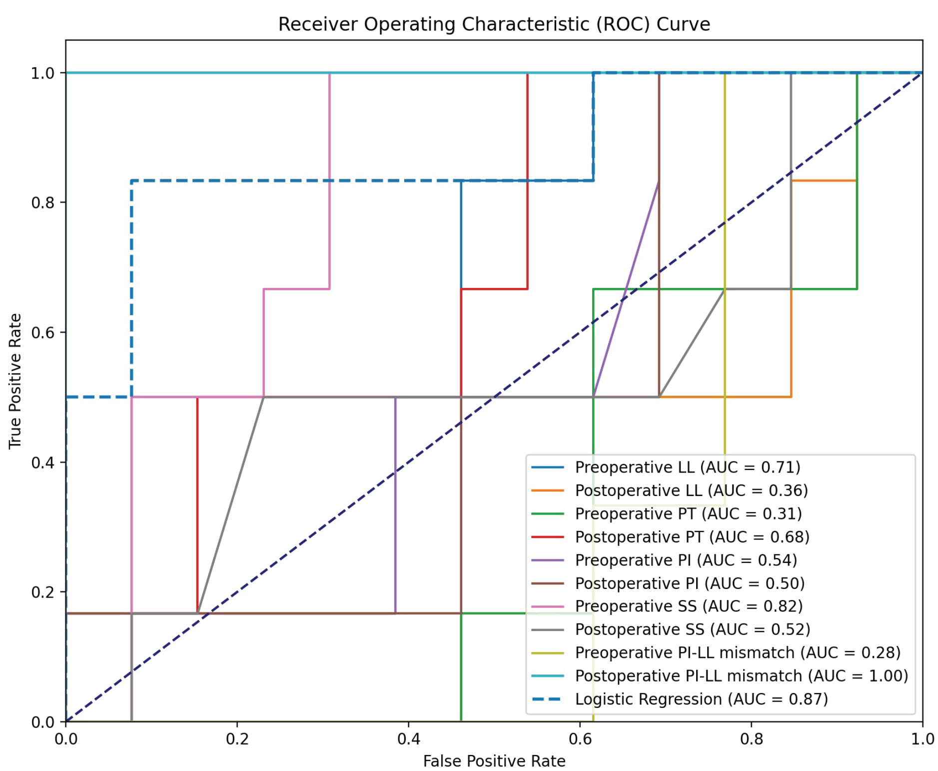

Figure 4: ROC curve analysis of spinopelvic parameters for predicting DJF. **DJF:** Distal junctional failure, **LL:** Lumbar lordosis, **PT:** Pelvic tilt, **PI:** Pelvic incidence, **SS:** Sacral slope, **PI-LL mismatch:** Pelvic incidence-lumbar lordosis mismatch.

In our study, we observed no significant differences between the PEEK and rigid rod groups in terms of preoperative and postoperative PI, PT, SS, and LL values. However, postoperative PI-LL mismatch emerged as a critical factor in the development of DJF. Patients with DJF had significantly higher postoperative PI-LL mismatch values, especially in the rigid rod group. This mismatch can be quantified, and maintaining a PI-LL difference of less than 10 degrees is often recommended to optimize surgical outcomes (16). This finding is consistent with previous studies, such as those by Lafage et al. and Schwab et al., which emphasized that maintaining a postoperative PI-LL mismatch within 10° to 15° is essential for achieving sagittal balance and reducing the risk of DJF (7,13) (Figure 5).

PEEK rods have been introduced as an alternative to rigid titanium rods due to their biomechanical properties, which include high flexibility and biocompatibility. These rods aim to provide sufficient stability while preserving the natural motion of the spine, reducing the biomechanical stresses on adjacent segments. Our findings, which showed a significantly lower incidence of DJF in the PEEK rod group (6.67%) compared to the rigid rod group (29.03%) ($p<0.05$), align with previous studies that suggest PEEK rods can mitigate the risk of DJF (6,9,12). The flexibility of PEEK rods allows for a more physiological transition of loads between fused and unfused segments, potentially reducing complications such as vertebral fractures and hardware failures (17).

In contrast, rigid titanium rods, while offering robust initial stability, have been associated with a higher risk of mechanical complications due to their increased rigidity. Studies like those by Biswas et al. and Yoon et al. have reported higher DJF rates in patients treated with rigid rods, attributing these complications to the increased stress placed on adjacent segments (1,18). Our study corroborates these findings, particularly in the rigid

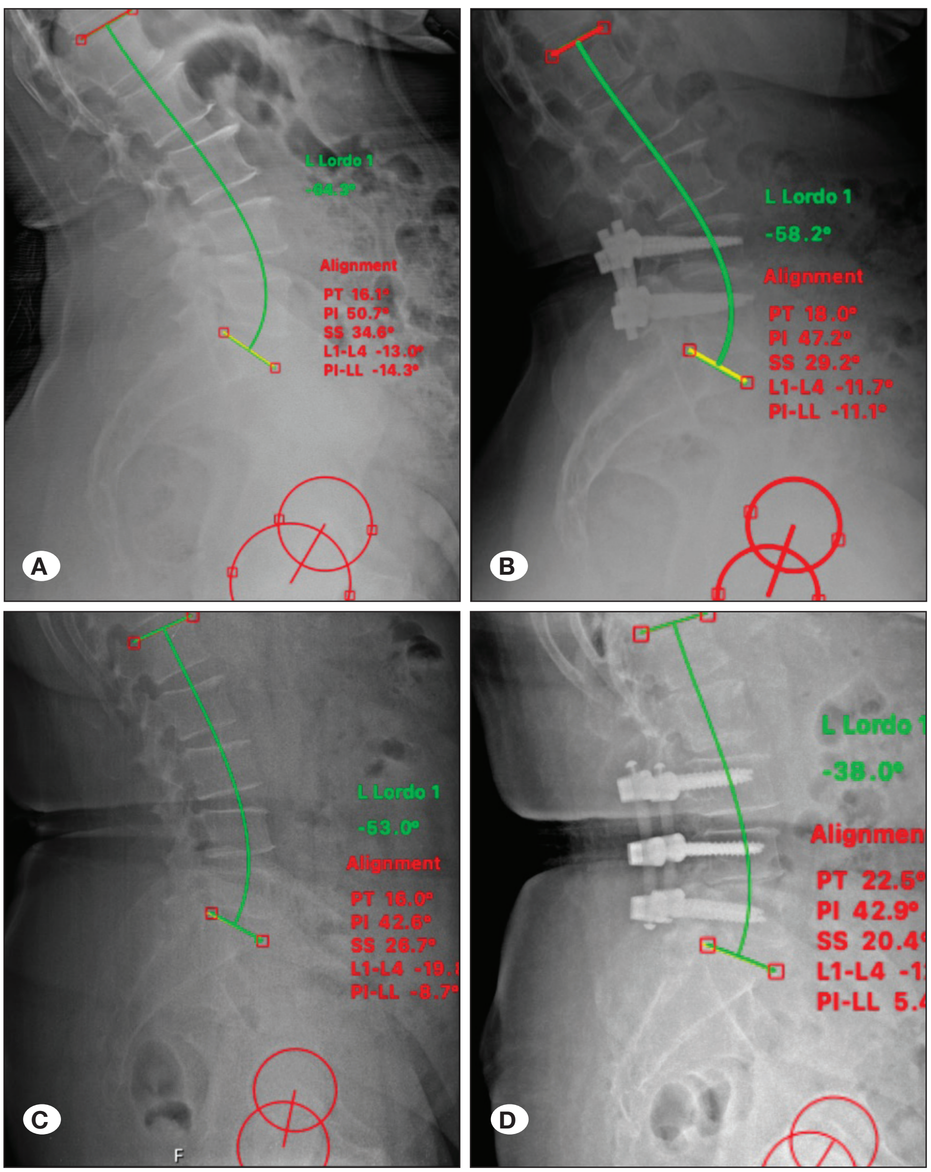

Figure 5: Preoperative and Postoperative Radiographs Showing Spinal Alignment in Patients Treated with PEEK and Rigid Rods. **A)** Preoperative image with severe lumbar lordosis (L1 Lordo -64.3°) and other alignment parameters PT 16.1°, PI 50.7°, SS 34.6°, L1-L4 -13.0°, PI-LL -14.3°. **B)** Postoperative image after surgery with Rigid rods, showing improved lumbar lordosis (L1 Lordo -58.2°) and reduced PI-LL mismatch (-11.1°). **C)** Preoperative image from a patient with lumbar lordosis (L1 Lordo -53.0°) and alignment parameters PT 16.0°, PI 42.6°, SS 26.7°, L1-L4 -19.1°, PI-LL -8.7°. **D)** Postoperative image after PEEK rod placement, showing further correction of lumbar lordosis (L1 Lordo -38.0°), with an increased PI-LL value of 5.4°.

rod group, where postoperative PI-LL mismatch was strongly associated with the occurrence of DJF. The higher stiffness of titanium rods may amplify mechanical stress at the distal end of the construct, contributing to complications such as screw pullout, rod breakage, and vertebral fractures.

Our results confirm that postoperative PI-LL mismatch plays a crucial role in DJF development. Patients with higher PI-LL mismatch values were significantly more likely to develop DJF. Similar findings have been reported that higher postoperative mismatch is associated with an increased risk of adjacent segment degeneration and DJF (5). Furthermore, in patients with a preoperative PI-LL mismatch of more than 10 degrees, i.e. patients with impaired pelvic parameters, only a 15% reduction in PI-LL correction is not sufficient and is a risk factor for DJF. In patients without DJF, PI-LL correction was found to be 55%. In other words, in patients with a high PI-LL mismatch, it is recommended to reduce this value between 15-55% to prevent DJF. This is one of the most important results in our study and one that can contribute to the literature.

Another important aspect of our study that distinguishes it from previous research is the introduction of a specific threshold for LL correction. Patients with DJF in both the PEEK and rigid rod groups experienced a significant reduction in LL postoperatively, with the loss of lumbar curvature being more pronounced in DJF patients. When a PEEK rod is inserted, LL reduction is only performed for the purpose of opening the foramen by distraction. In our study, if a manoeuvre performed with PEEK for this purpose causes a decrease in LL by -19 degrees, this is considered a risk factor for DJF. In addition, the risk of DJF may increase if the LL is reduced by more than 11 degrees in rigid rods. This aligns with previous research by Matsumoto et al., who reported that a postoperative decrease in LL is a major risk factor for DJF (10). The loss of LL can shift the center of gravity forward, increasing the mechanical load on distal segments and predisposing them to failure. Our findings suggest that maintaining or restoring adequate LL postoperatively is essential for reducing the risk of DJF, especially when using rigid fixation systems. By establishing a clear LL correction threshold, our study introduces a novel contribution to the literature and highlights the importance of managing LL correction carefully during surgery. Future studies should explore this threshold further and assess its applicability across different patient populations undergoing lumbar fusion.

In our study, L5 was the most commonly instrumented vertebra in both groups. However, we observed that S1 was more frequently instrumented in the rigid rod group (16.13%) compared to the PEEK group. This finding is significant because previous studies have suggested that the choice of LIV can influence the risk of DJF. For example, Matsumoto et al. reported that fusions extending to the sacrum (S1) are associated with a higher incidence of distal junctional complications due to the increased biomechanical demands on the lumbosacral junction (10). Our results support this observation, as the rigid rod group, with more frequent instrumentation of S1, exhibited a higher DJF incidence. The increased stiffness of titanium rods combined with the mechanical forces acting on the lumbosacral junction may explain the higher complication rates in these cases. The positive effects of PEEK rods on pelvic parameters stem from their material properties. Compared to traditional rigid titanium rods, PEEK rods have a lower elastic modulus, allowing them to provide dynamic stability to the spinal construct. This characteristic is particularly important in maintaining sagittal balance and optimizing PT, PI, and LL parameters. Literature indicates that the reduced rigidity of PEEK rods minimizes stress accumulation on proximal segments, thereby decreasing the risk of junctional failure. Additionally, these rods can be more easily modified to achieve patient-specific alignment of pelvic parameters.

Our study has several limitations that should be acknowledged. First, the retrospective design of the study may introduce inherent biases, including potential selection bias and limitations in the completeness of the available clinical data. Second, while we evaluated a considerable number of patients, the sample size may still be relatively small, particularly when stratifying groups based on the development of DJF and rod type. This may limit the generalizability of our findings. Third, the follow-up period, although covering a medium to long-term range (3 years on average), may not be sufficient to capture all cases of DJF, particularly those that develop later. Additionally, the study was conducted at two spine center, which may limit the external validity of the results. Future studies should aim for multicenter trials with larger cohorts and longer follow-up periods to validate these findings. Finally, while we employed rigorous statistical methods to analyze spinopelvic parameters, the complexity of spinal alignment and patient-specific variability may require more advanced modeling and biomechanical analysis to fully understand the mechanisms driving DJF.

CONCLUSION

In degenerative spine patients with normal coronal balance, and without listhesis undergoing short-segment stabilization, The PEEK rod is more effective in preventing the development of DJF in degenerative spine patients receiving short-segment stabilization who have normal coronal balance and no listhesis. Additionally, in patients with preoperative PI-LL mismatch, achieving sufficient correction is crucial to prevent DJF. Postoperative PI-LL mismatch and changes in lumbar lordosis also contribute to the development of DJF.

Declarations

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AUTHORSHIP CONTRIBUTION

Study conception and design: HSC, NK, EU, BP

Data collection: HSC, EU

Analysis and interpretation of results: MD, OCG, ATS, EB

Draft manuscript preparation: HSC, EU, NK

Critical revision of the article: NK

Other (study supervision, fundings, materials, etc...): MAK, EH, MA

All authors (NK, HSC, EU, BP, MAK, EH, MA, OCG, ATS, EB, MD) reviewed the results and approved the final version of the manuscript.

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