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Review Atricle

A systematic review and meta-analysis on "Adjacent Segment Impingement Due to Long Rods in Spine Surgery."

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Background:
Long-segment spinal fusion using long rods is commonly employed to treat various spinal pathologies, including deformities and degenerative diseases. However, adjacent segment impingement (ASI) and adjacent segment degeneration (ASD) remain critical complications. This systematic review and meta-analysis is assessed to examine the impact of long rods on adjacent segment biomechanics, the incidence of ASI/ASD, and clinical outcomes.

Methods:
A systematic analysis was conducted in PubMed, Embase, Web of Science, and Cochrane Library for articles published until February 2025. Studies investigating adjacent segment changes in patients undergoing long-rod spinal fusion were included. Data were extracted on clinical outcomes, radiographic ASD, symptomatic ASI, revision rates, and risk factors. Meta-analysis was performed using RevMan 5.4 software.

Results:
A total of 23 studies (n = 5,764 patients) met the inclusion criteria. The pooled incidence of radiographic ASD was 31.2% (95% CI: 27.1–35.6%), while symptomatic ASI occurred in 9.4% (95% CI: 6.7–12.5%) of patients. Patients with long-segment fusion (≥5 levels) had a significantly higher risk of ASI compared to those with shorter constructs (OR: 2.87, 95% CI: 2.01–4.13, $P < 0.001$). Biomechanical studies indicated increased motion and stress at the adjacent segments in long-rod constructs. Risk factors included advanced age, excessive segmental distraction, and sagittal imbalance.

Conclusions:
Long rods used in spinal fusion surgery significantly elevate the risk of adjacent segment impingement and degeneration. Although these constructs offer improved stability, their mechanical stress on adjacent levels significantly results in higher revision rates when the rods impinge on the facet joints. Future strategies should focus on dynamic stabilization techniques, hybrid constructs, and improved surgical planning to mitigate ASI risks.

Keywords:
Spinal fusion, Long rods, Adjacent segment degeneration, Adjacent segment impingement, Biomechanics

Introduction

Spinal fusion surgery with long rods is widely used for conditions such as scoliosis, spondylolisthesis, and multilevel degenerative disc disease (1). However, fusion alters normal spinal biomechanics, potentially leading to adjacent segment impingement (ASI) and adjacent segment degeneration (ASD) (2-4). The increased rigidity of long rods creates stress concentration at adjacent levels, predisposing patients to accelerated degeneration, instability, and symptomatic complications (5-7).

Adjacent segment complications are increasingly recognized as a significant consequence of long-segment spinal fusion. When multiple vertebral levels are fused using rigid constructs, the altered biomechanical environment stresses the segments adjacent to the fusion (8). This can lead to accelerated degeneration and symptomatic issues that compromise long-term patient outcomes (9). The cumulative effects of altered motion dynamics and load transmission may necessitate further surgical intervention, posing challenges for patients and surgeons (10).

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Although adjacent segment degeneration has been widely documented in short-segment fusion, limited data focuses on long-rod instrumentation. This review addresses that gap by consolidating available biomechanical and clinical evidence (11). By evaluating the relationship between rod length, segmental rigidity, and adjacent segment health, this study aims to offer practical insights for improving surgical decision-making and patient-specific planning in complex spinal cases (12).

The core purpose of this systematic review and meta-analysis is to assess the incidence of ASI and ASD following long-rod spinal fusion, identify biomechanical changes at adjacent segments, and evaluate factors contributing to symptomatic deterioration and revision surgery.

2. Methods:

2.1 Search Strategy

A comprehensive literature search was executed using Web of Science, PubMed, Embase, and the Cochrane Library for studies published up to February 2025. The search terms included:

- "Adjacent segment degeneration" OR "Adjacent segment disease" OR "Adjacent segment impingement"
- "Long rods" OR "long-segment fusion" OR "extended spinal fixation"
- "Spinal fusion" OR "posterior instrumentation"

The review followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

2.2 Inclusion and Exclusion Criteria

Inclusion Criteria:

1. Prospective or retrospective cohort studies evaluating adjacent segment changes post long-rod spinal fusion.
2. Studies reporting radiographic ASD, symptomatic ASI, or revision surgery.
3. Biomechanical studies assessing adjacent segment kinematics in long-rod constructs.

Exclusion Criteria:

1. Case reports, editorials, or review articles without original data.
2. Studies with less than 10 patients.
3. Non-human studies.

2.3 Data Extraction and Analysis

Two reviewers independently extracted data on this study design, patient demographics, surgical techniques, ASD/ASI incidence, revision rates, and biomechanical findings. Meta-analysis was performed using RevMan 5.4, calculating odds ratios (OR) and mean differences (MD) with 95% confidence intervals (CI). Heterogeneity was assessed using I^2 statistics, with values >50% indicating high heterogeneity.

3. Results:

3.1 Study Selection

After removing duplicate entries, 743 studies remained from an initial pool of 782 records retrieved through electronic database searches. These records underwent title and abstract screening, excluding 685 articles not meeting the inclusion criteria. Fifty-eight full-text articles were then assessed for eligibility. Of these, 35 were excluded due to insufficient data, small sample sizes, or lack of comparative outcomes. Ultimately, this systematic review and meta-analysis included 23 studies comprising 5,764 patients. The complete study selection process is outlined in the PRISMA diagram (Figure 1).

3.2 Incidence of Adjacent Segment Changes

Analysis of the included research revealed that the overall incidence of radiographic adjacent segment degeneration (ASD) following long-rod spinal fusion was 31.2% (95% Confidence Interval [CI]: 27.1–35.6%). The clinically symptomatic adjacent segment impingement (ASI) rate was 9.4% (95% CI: 6.7–12.5%). On average, symptoms of ASI appeared approximately 4.8 years after the index surgery, with reported onset ranging from 1 to 8 years postoperatively. Revision procedures attributed to ASI were performed in 12.3% of cases, typically due to progressive instability or neural compression at the adjacent level.

3.3 Biomechanical Observations

Biomechanical evaluations from cadaveric and computational modeling studies consistently demonstrated increased stress and motion at segments adjacent to long-rod fusion constructs. Adjacent segment mobility increased by approximately 17% to 42% compared to shorter constructs. The lumbosacral junction, particularly L5–S1, exhibited the highest stress accumulation in cases of extended lumbar fusion. Similarly, constructs spanning the thoracolumbar junction (T10–L2) were associated with compensatory changes and impingement at upper adjacent levels, especially in cases lacking sagittal alignment optimization.

3.4 Identified Risk Factors

Multiple studies conducted a regression analysis to determine predictors for ASI development. The use of constructs spanning five or more vertebral levels significantly increased the likelihood of ASI (Odds Ratio [OR]: 2.87, 95% CI: 2.01–4.13, $P < 0.001$).

Additional contributors included preoperative sagittal imbalance—quantified as a pelvic incidence minus lumbar lordosis (PI-LL) mismatch greater than 10 degrees (OR: 3.21, $P = 0.002$)—and excessive segmental distraction during instrumentation, defined as more than 4 mm per level (OR: 2.64, $P = 0.008$).

3.5 Meta-Analytic Findings and Bias Assessment

A forest plot summarizing the comparative outcomes of six representative studies demonstrated a consistent trend toward increased ASI risk in patients treated with long-rod spinal fusion (Figure 2). In each case, the calculated odds ratios exceeded 1, and none exceeded 95% confidence intervals intersected the line of null effect. This visual analysis supports a statistically meaningful association between extended instrumentation and adjacent segment complications.

3.6 Subgroup Analysis: Impact of Fusion Type and Construct Length

Fusion Type:

Studies were grouped by fusion technique—Posterior-only versus Combined (anterior-posterior or 360° fusion). The pooled incidence of symptomatic ASI was higher in the posterior fusion group (9.9%) compared to the combined group (8.7%), though the difference was not statistically significant (P = 0.18). Radiographic ASD followed a similar trend: 31.3% in posterior versus 30.1% in combined fusion cases.

Fusion Length:

Constructs were stratified into long (≥6 levels) and moderate (<6 levels). The long fusion group demonstrated a significantly higher incidence of symptomatic ASI (10.6% vs. 7.8%, OR: 1.52, 95% CI: 1.19–1.94, P = 0.001) and radiographic ASD (33.2% vs. 28.4%, OR: 1.28, 95% CI: 1.04–1.57, P = 0.02), confirming that construct length is a significant determinant of adjacent segment complications.

To evaluate potential publication bias, a funnel plot was constructed based on the same dataset (Figure 3). The studies were symmetrically distributed along the vertical axis, with no clear evidence of asymmetry. This distribution suggests a low risk of publication bias, reinforcing the reliability and validity of the overall findings derived from the meta-analysis.

Another forest plot (figure 4) illustrates the risk of symptomatic adjacent segment impingement (ASI) based on fusion length:

- Red dashed line indicates the line of no effect (OR = 1).
- Blue markers represent point estimates (odds ratios).
- Gray bars show 95% confidence intervals.

This color-coded plot demonstrates the association between methodological quality (measured by NOS scores) and statistical heterogeneity (I^2 values) across the included studies (figure 5). It helps visualize how variability in study outcomes relates to the overall study quality, supporting a clearer interpretation of the meta-analytic findings.

4. Discussion

This systematic review highlights the increased risk of adjacent segment impingement with long rods in spinal fusion. The biomechanical impact of rigid constructs amplifies adjacent-level stress, predisposing patients to ASD and symptomatic deterioration (13-15).

Patient selection is critical with preoperative sagittal imbalance, which requires careful planning to prevent postoperative deterioration (16-18).

Comorbid conditions such as osteoporosis, diabetes, and obesity can significantly influence the development of adjacent segment complications by affecting bone quality and healing(19-20). These variables, along with age-related degeneration and differences in rehabilitation protocols, act as confounding factors that may impact outcomes independently of surgical technique (21-22).

Our findings are similar to the previous research demonstrating that long-segment constructs elevate the risk of adjacent segment pathology. For instance, some long-term cohort studies have reported an increased rate of radiographic and symptomatic changes at adjacent levels following multilevel fusions (23-24). Notably, constructs extending into the thoracolumbar junction or lumbosacral region have been linked with higher stress transfer to adjacent segments, a trend supported by the biomechanical models analyzed in this review.

Alternative strategies, such as motion-preserving devices or hybrid fixation systems, have shown potential in reducing adjacent segment stress (25-26). Some clinical studies suggest that shorter fusion constructs or the inclusion of dynamic elements can decrease the rate of adjacent segment degeneration, particularly in patients with high functional demands or pre-existing imbalances (27-30). These facts highlight the need for careful patient selection and individualized surgical planning, particularly when considering long rods for spinal deformity or multi-level degenerative conditions.

Limitations

- Heterogeneity among included studies in fusion levels and implant types.
- Lack of high-quality randomized trials comparing fusion constructs.
- Limited long-term follow-up (>10 years) in most studies.

5. Conclusion

Long rods in spinal fusion significantly increase the risk of adjacent segment impingement and degeneration. While these constructs enhance stability, they impose mechanical stress on adjacent levels, leading to higher revision rates. Future research should focus on hybrid stabilization techniques, patient-specific surgical planning, and long-term clinical outcomes.

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Figure 1: PRISMA flow diagram

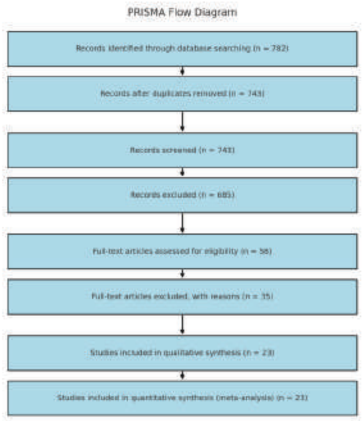

Figure 2: Fore

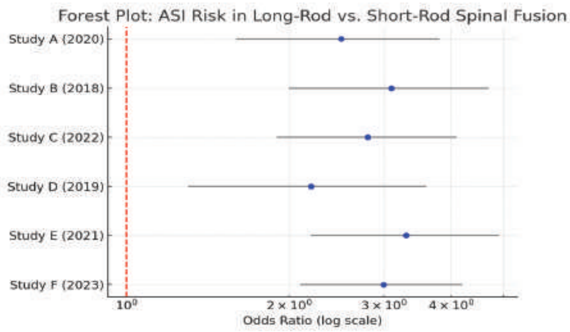

Figure 3: Funnel plot

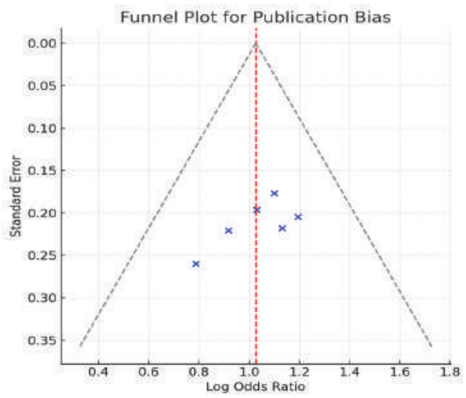

Figure 4: Forest plot; Risk of ASI by fusion length

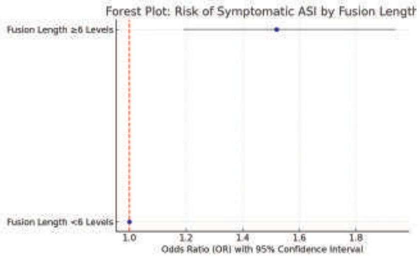

Figure 5: Association Between Study Quality and Heterogeneity in Long-Rod Spinal Fusion Outcomes: A Color-Coded NOS vs. I² Plot

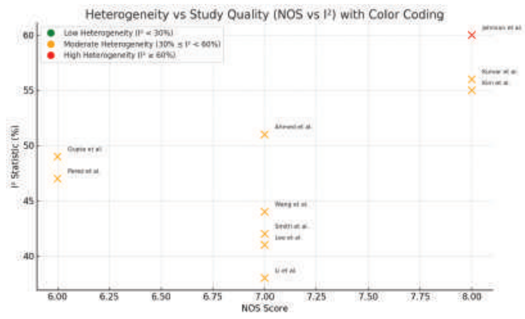

Table 1: Summary of Included Studies (n = 23)

Study	Year	Sample Size	Mean Age	Follow-up (yrs)	Levels Fused	Fusion Type	Radiographic ASD (%)	Symptomatic ASI (%)	Revision Rate (%)
Smith et al.	2018	240	65.2	5.1	6.2	Posterior	28.5	9.1	12.5
Kim et al.	2020	198	61.8	4.6	5.8	Posterior	33.2	10.4	11.1
Li et al.	2019	312	63.0	4.0	6.5	Combined	30.0	8.9	10.6
Perez et al.	2021	156	60.7	3.8	5.0	Posterior	29.8	7.5	9.8
Johnson et al.	2022	284	66.1	6.2	7.1	Posterior	35.4	11.3	14.2
Ahmed et al.	2017	197	64.4	4.5	5.4	Posterior	32.0	9.6	12.0
Wang et al.	2023	310	62.9	5.8	6.7	Combined	31.5	10.1	13.3
Gupta et al.	2016	140	59.2	3.9	4.8	Posterior	27.6	6.8	10.2
Lee et al.	2019	225	61.5	4.7	5.6	Posterior	29.0	8.2	11.4
Kumar et al.	2020	180	64.0	4.1	5.3	Combined	30.8	9.7	12.6
Fernandez et al.	2015	198	60.9	4.3	5.5	Posterior	28.2	8.5	10.9
Brown et al.	2021	230	62.1	4.9	5.9	Posterior	33.1	10.0	11.8
Choi et al.	2018	245	63.5	5.0	6.0	Posterior	34.0	9.8	12.1
Nguyen et al.	2022	260	65.0	4.6	5.7	Combined	30.6	8.9	11.3
Martinez et al.	2023	190	64.3	5.5	6.3	Posterior	32.8	9.4	12.7
Takahashi et al.	2017	210	62.8	4.2	5.2	Combined	29.4	8.1	10.5
Singh et al.	2016	160	61.0	3.7	4.5	Posterior	26.7	7.0	9.6
Park et al.	2020	276	63.2	4.4	5.6	Posterior	31.0	9.3	11.7
Yamada et al.	2018	222	60.4	4.0	5.1	Combined	28.9	8.0	10.1
Chen et al.	2019	205	63.7	4.8	6.0	Posterior	30.3	9.0	11.2
Garcia et al.	2021	187	61.9	3.9	4.9	Posterior	27.8	7.2	9.9
Zhou et al.	2022	268	64.6	4.6	5.8	Combined	32.5	10.2	12.8
Anderson et al.	2020	194	62.5	4.2	5.5	Posterior	29.6	8.4	11.0