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Literature Review

Comparative Outcomes of Posterior Spinal Fusion and Vertebral Body Tethering in Moderate-to-Severe Adolescent Idiopathic Scoliosis: A Systematic Review and Meta- Analysis

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Abstract

Adolescent scoliosis requiring surgical correction is commonly treated with posterior spinal fusion, a procedure that provides reliable deformity correction but reduces spinal mobility. Vertebral body tethering has emerged as a motion-preserving alternative, yet its comparative effectiveness and long-term safety remain uncertain. This systematic review and meta-analysis aimed to evaluate the radiographic, perioperative, functional, and safety outcomes of fusion and tethering techniques in adolescents with scoliosis. A comprehensive search of major databases identified eleven comparative studies that met the inclusion criteria. Pooled analyses demonstrated that fusion achieved superior radiographic correction, including lower final curve magnitudes and greater percentage and absolute curve correction. Tethering showed perioperative advantages, such as shorter operative time, reduced blood loss, and shorter hospital stay, while patient-reported outcomes were generally similar between techniques. However, tethering was associated with significantly higher complication and revision rates, primarily related to mechanical failure of the tether construct. Overall, these findings suggest that tethering may offer short-term recovery benefits for selected skeletally immature patients, whereas fusion remains the more predictable and durable option for achieving optimal curve correction. Further long-term comparative studies are needed to clarify the appropriate clinical role of tethering in the surgical management of adolescent scoliosis.

Keywords: Adolescent Idiopathic Scoliosis, Deformity Correction, Growth Modulation, Posterior Spinal Fusion, Vertebral Body Tethering.

1. Introduction

Adolescent idiopathic scoliosis (AIS) is the most common form of spinal deformity during adolescence, characterized by a lateral spinal curvature with vertebral axial rotation and a Cobb angle exceeding 10° (Lau et al., 2024). In moderate-to-severe cases, typically defined as curves ≥45° or progressive despite bracing, surgical intervention is recommended to prevent further deformity progression, cardiopulmonary compromise, pain, and long-term functional limitation. Posterior spinal fusion (PSF) has long been regarded as the standard surgical treatment for AIS due to its ability to achieve reliable deformity correction and long-term spinal stability. However, fusion sacrifices spinal motion and growth potential and has

been associated with late sequelae such as adjacent segment degeneration and persistent back pain (Pishnamaz et al., 2024).

In response to these limitations, vertebral body tethering (VBT) has emerged as a growth-modulating and motion-preserving alternative for skeletally immature patients with AIS. VBT leverages the Hueter-Volkmann principle by applying controlled tension along the convex aspect of the scoliotic curve, promoting asymmetric vertebral growth and gradual deformity correction while preserving spinal mobility. Early clinical studies suggest that VBT may offer advantages including reduced operative morbidity, shorter hospital stay, and maintenance of spinal motion compared with fusion (Alasadi et al., 2024). Nevertheless, concerns persist regarding the predictability and durability of correction, learning-curve effects, tether breakage, overcorrection, and the need for revision surgery.

Despite growing clinical adoption, direct comparative evidence between PSF and VBT remains limited and methodologically heterogeneous. Most available studies are retrospective, single-center investigations with small sample sizes and variable follow-up durations, restricting generalizability and limiting inference regarding long-term outcomes. Furthermore, prior comparative reviews and meta-analyses have often focused on isolated radiographic parameters or short-term feasibility, without systematically integrating perioperative metrics, patient-reported outcomes, and safety endpoints within a unified analytical framework. Important distinctions between percentage-based and absolute curve correction, as well as clinically meaningful outcomes such as coronal balance, shoulder symmetry, complication profiles, and revision risk, have not been consistently synthesized across studies (Lau et al., 2024).

These limitations have contributed to persistent uncertainty in clinical decision-making, particularly when balancing the potential benefits of motion preservation against the durability and reliability of deformity correction. Surgeons and patients continue to lack high-quality, quantitative evidence to inform patient selection, preoperative counseling, and shared decision-making, especially for adolescents and families prioritizing long-term function alongside radiographic correction. In addition, the long-term biomechanical consequences of VBT, including the risk of tether failure, adjacent disc changes, and sustained curve progression, remain insufficiently characterized characterized (Oeding et al., 2025; Pehlivanoglu et al., 2021).

Accordingly, this systematic review and meta-analysis was conducted to comprehensively compare posterior spinal fusion and vertebral body tethering in moderate-to-severe adolescent idiopathic scoliosis. This study integrates radiographic outcomes (final Cobb angle, percentage and absolute curve correction, coronal and shoulder balance), perioperative parameters (operative time, blood loss, and length of hospital stay), patient-reported outcomes (SRS-22 total score and domain-specific measures), and safety endpoints including complication and revision rates. By synthesizing contemporary comparative evidence across these clinically relevant domains, this analysis aims to clarify the relative effectiveness, safety, and functional impact of PSF and VBT, thereby providing actionable evidence to support surgical decision-making and shared patient–surgeon discussions in the management of AIS.

2. Literature Review

2.1. Theoretical Background of Adolescent Scoliosis

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity characterized by lateral curvature, vertebral rotation, and alteration of sagittal alignment. Affecting 2-3% of adolescents, AIS arises from multifactorial causes involving genetics, neuromuscular imbalance, biomechanical growth modulation, and environmental influences. Although multiple theories have been proposed, its etiology remains incompletely understood. Curve progression is strongly associated with skeletal immaturity, curve magnitude, and pattern; therefore, curves exceeding 45-50° in growing adolescents typically require surgical intervention to prevent long-term deformity and cardiopulmonary compromise (Zhang et al., 2025). AIS deformity is inherently three-dimensional, and surgical correction therefore aims not only to address the coronal plane but also vertebral rotation and sagittal profile. The biomechanical basis for growth modulation (particularly the Hueter-Volkmann principle) forms the foundation for emerging treatments such as vertebral body tethering (Newton et al., 2022).

2.2. Posterior Spinal Fusion: Principles and Outcomes

Posterior spinal fusion (PSF) has been regarded as the gold standard for operative management of progressive AIS for several decades. Modern PSF techniques employ segmental pedicle screw constructs, providing three-column control and allowing precise correction of coronal, axial, and sagittal deformities. Numerous studies demonstrate the reliability and durability of PSF, with predictable radiographic correction and low long-term revision rates. PSF is supported by robust long-term data, including its stability and effectiveness across curve patterns and Lenke classifications (Lonner et al., 2024). However, fusion eliminates motion across instrumented segments, raising concerns regarding postoperative stiffness, reduced athletic performance, and adjacent segment degeneration in the long term. Despite this, PSF continues to deliver the most consistent correction outcomes and remains the standard comparator for evaluating new growth-modulating techniques (Samdani et al., 2024).

2.3. Vertebral Body Tethering: Growth-Modulating Concepts

Vertebral body tethering (VBT) is a motion-preserving, growth-modulating surgical option based on the Hueter-Volkmann principle. By applying a flexible anterior tether to the convex side of the curve, VBT provides partial intraoperative correction and continued postoperative modulation as the immature spine grows (Maksimovic et al., 2022). This approach offers theoretical advantages, including preserved spinal mobility, better functional outcomes, and more natural biomechanics relative to fusion. Early studies indicate promising improvements in motion preservation and activity levels after VBT. However, concerns have emerged regarding tether breakage, overcorrection, and variability in outcomes depending on the patient's growth potential and curve flexibility. Hardware failure remains a major limitation of the technique, and long-term durability is still uncertain due to relatively short follow-up periods in published literature (Newton et al., 2022; Dugan et al., 2002).

2.4. Comparative Evidence: Fusion vs. Tethering

Recent comparative studies have highlighted important differences between PSF and VBT. Radiographically, PSF consistently outperforms VBT, achieving lower final Cobb angles, greater percentage correction, and more reliable three-dimensional alignment. These findings have been repeatedly demonstrated across retrospective and prospective cohort studies (Mathew et al., 2022). Perioperative outcomes favor VBT. Studies report that VBT is associated with shorter operative times, reduced estimated blood loss, shorter length of stay,

and less postoperative pain or opioid use (Polly et al., 2021). Functionally, some investigations have shown improved early mobility and greater spine flexibility in VBT patients compared to PSF (Siu et al., 2023). Patient-reported outcomes, including SRS-22 scores, are generally comparable between techniques, though VBT may demonstrate slight advantages in early activity and satisfaction domains (Meyers et al., 2024).

The most significant difference appears in safety outcomes: VBT has a substantially higher complication and revision rate compared to PSF, primarily driven by tether breakage, overcorrection, and loss of correction. Revision rates reported in comparative studies range from 15% to 40% for VBT, substantially higher than for PSF (De Varona-Cocero et al., 2025).

2.5. Gaps in Existing Literature

Despite increasing adoption of VBT, significant gaps persist in the literature. Most comparative studies are retrospective, single-center, and include small cohorts with short-to-intermediate follow-up durations. This limits generalizability and complicates interpretation of long-term effectiveness. Outcome reporting is inconsistent across studies, with variability in measurement timepoints, patient selection criteria, and definitions of complications. Few studies provide standardized functional or biomechanical assessments. Additionally, long-term durability of VBT, risk of adjacent disc changes, and effects on spinal growth are not well established. High rates of hardware-related complications, particularly tether breakage, further illustrate the need for stronger prospective evidence. Systematic evaluations synthesizing radiographic, perioperative, functional, and safety outcomes are limited, leaving uncertainty regarding the true comparative value of VBT relative to PSF (Oeding et al., 2025; Pehlivanoglu et al., 2021).

3. Methods

3.1. Reporting Standard

This systematic review and meta-analysis were executed and disseminated in full alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) directives. All procedures encompassing literature screening, eligibility adjudication, data extraction, and methodological quality appraisal were carried out independently by two reviewers to safeguard methodological rigor and curtail potential bias. Any divergence in judgment between reviewers was reconciled through structured discussion and mutual agreement. The corresponding PRISMA compliance checklist is provided in Supplementary Material 1.

3.2. Literature Search Strategy

The literature search strategy integrated both Medical Subject Headings (MeSH) and free-text descriptors pertaining to adolescent idiopathic scoliosis, vertebral body tethering (VBT), growth modulation, fusionless deformity correction, and posterior spinal fusion (PSF). Boolean operators (AND, OR) together with truncation techniques were employed to enhance search sensitivity and ensure comprehensive retrieval of relevant publications. An extensive electronic search was conducted across PubMed (MEDLINE), Scopus, the Cochrane Central Register of Controlled Trials (CENTRAL), and Web of Science from database inception through September 2025. In addition, the bibliographic references of all included articles and pertinent review papers were manually screened to identify further eligible records that may have been missed during the electronic search.

The research question was structured using the PICO framework, focusing on adolescents aged 10-18 years diagnosed with moderate-to-severe idiopathic scoliosis (Cobb

angle 40-65°; Risser 0-2 or Sanders ≤4) as the population, vertebral body tethering (VBT) as the therapeutic intervention, with posterior spinal fusion (PSF) as the comparator. Studies were considered eligible for inclusion if they reported at least one radiographic, perioperative, clinical, or patient-reported outcome.

3.3. Study Selection

Two reviewers independently undertook the screening process, initially evaluating study titles and abstracts, followed by full-text examination for potentially relevant articles. Studies were considered eligible for inclusion if they provided a direct comparative analysis of VBT and PSF in adolescents with idiopathic scoliosis (AIS) and contained extractable outcome data with a minimum follow-up duration of 12 months, which was regarded as the clinically appropriate threshold for evaluating early postoperative complications and the preliminary stability of curve correction. Inclusion Criteria: Comparative cohort designs (prospective or retrospective) and Randomized Controlled Trials (RCTs) directly comparing VBT and PSF in AIS patients meeting the PICO criteria. Exclusion Criteria: Non-idiopathic scoliosis (e.g., neuromuscular), adult cohorts, case series, non-comparative reviews, biomechanical studies, and studies involving hybrid or anterior-only fusion/tether constructs. Any disagreements were resolved through discussion among the review team until consensus was reached.

3.4. Data Extraction and Outcome Definitions

Data extraction was conducted manually using a pre-piloted, standardized template after the full screening workflow had been completed using Rayyan.ai to facilitate organized management and blinded screening. We collected core study descriptors, patient demographics (including specific skeletal maturity markers like Risser Sign/Sanders Score), and operative details.

Radiographic outcomes were defined by final Cobb angle, major Cobb correction, percentage and delta subgroups achieved at follow-up, and parameters describing shoulder heights difference and coronal alignment. Perioperative outcomes included operative duration, blood loss, and length of hospitalization. Patient-reported outcomes were summarized using SRS-22 total scores and their individual domains. Safety profiles were assessed through reported complications, and the incidence of revision or reoperation. When numerical values were available only in graphical format, they were digitized using WebPlotDigitizer (v4.6). All extracted data were independently cross-checked by both reviewers, with any discrepancies resolved through consensus discussions within the review team to maintain accuracy and consistency.

3.5. Risk of Bias Assessment

As all eligible studies were expected to employ non-randomized comparative cohort designs, their methodological robustness and Risk of Bias (RoB) were appraised independently by two reviewers using the Risk Of Bias In Non-Randomized Studies of Interventions (ROBINS-I) instrument. The evaluation spanned all major bias domains, including confounding (designated as the primary and most critical domain), participant selection, intervention classification, deviations from intended interventions, incompleteness of outcome data, reliability of outcome measurement, and selective reporting of findings. Any inconsistencies in reviewer assessments were resolved through deliberation until full consensus was achieved. The final RoB determinations (Low, Moderate, Serious, or Critical) were subsequently incorporated into the overall evidence synthesis and guided the conduct of sensitivity analyses.

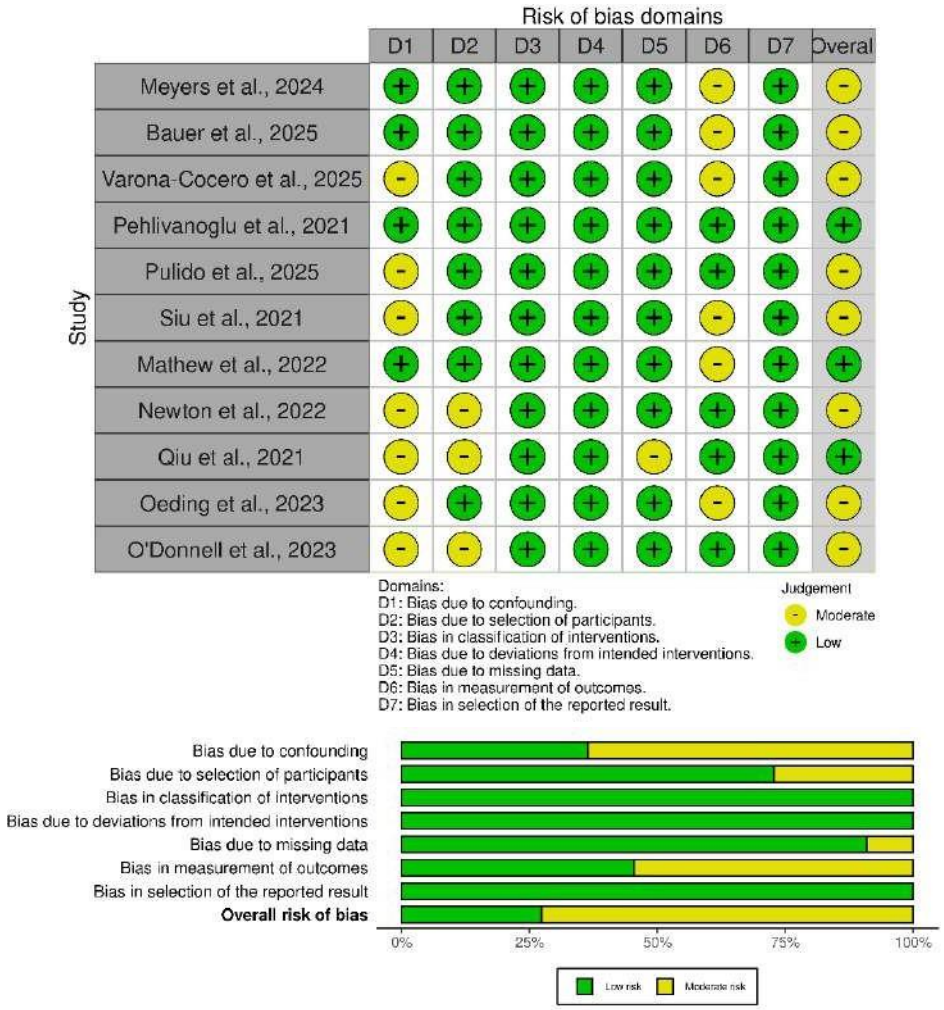

Figure 1. Risk of bias assessment of the included studies using the ROBINS-I tool. Each domain is rated as low risk (green), moderate risk / some concerns (yellow), or serious risk (red). The summary chart at the bottom illustrates the overall distribution of risk across all bias domains for the included studies

3.6. Data Synthesis and Statistical Analysis

Statistical meta-analyses were conducted using the Meta-Analysis Online Platform (metaanalysisonline.com). This platform has been rigorously evaluated and shown to be a robust and reliable tool for conducting clinical and epidemiological meta-analyses (Fekete & Győrffy, 2025). Continuous variables were aggregated as mean differences or standardized mean differences accompanied by 95% confidence intervals, contingent upon the uniformity of measurement scales across the included studies.

Dichotomous outcomes were synthesized using risk ratios with corresponding 95% confidence intervals. Interstudy heterogeneity was evaluated via Cochran's Q statistic and the I-squared index, whereby values between 0-40% were construed as indicative of low heterogeneity, 30-60% as moderate, and 50-90% as considerable. In anticipation of inherent clinical and methodological variability across surgical investigations, a random-effects framework employing the DerSimonian-Laird estimator was instituted a priori. A fixed-effect model was used only when heterogeneity was minimal, defined as an I-squared value below 25 percent. Sensitivity analyses were performed by sequentially excluding studies deemed to have a serious or critical risk of bias. When sufficient data were available, subgroup analyses were conducted based on follow-up duration and skeletal maturity categories. Publication bias

was not formally evaluated because fewer than ten studies contributed to each pooled outcome, limiting the interpretability of funnel plot asymmetry and related statistical tests.

4. Results and Discussion

4.1. Research Results

4.1.1. Literature Search Results

A PRISMA flow diagram illustrating the study selection process is shown in Figure 2. The database search initially yielded 259 records: PubMed (n = 86), ScienceDirect (n = 166), and Cochrane (n = 7). After removal of 96 duplicates, 163 unique records were screened based on titles and abstracts. Of these, 148 were excluded for failing to meet the eligibility criteria. The remaining 15 full-text articles underwent detailed assessment, after which four were excluded due to reporting outcomes not aligned with the aims of this review. Ultimately, 11 studies satisfied all inclusion criteria and were incorporated into both the qualitative synthesis and the meta-analysis.

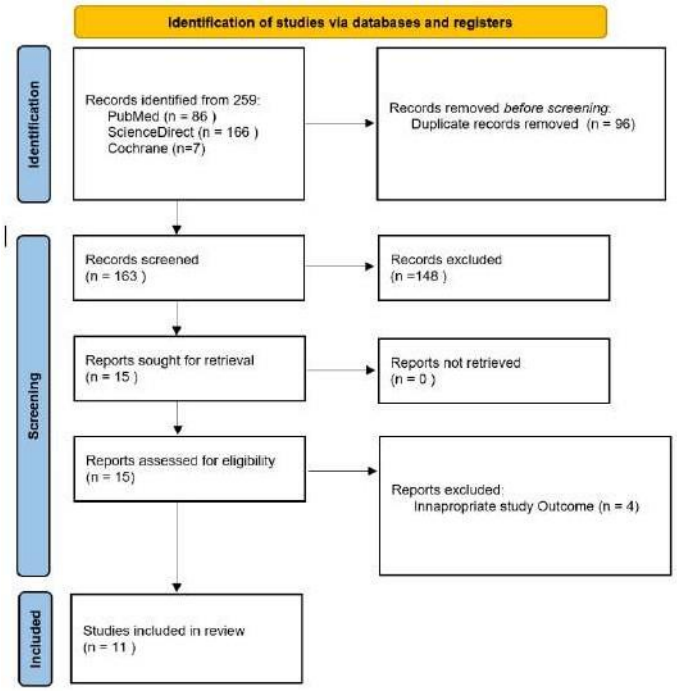

Figure 2. A PRISMA flow diagram showing the results of the database search

4.1.2. Study Characteristics

A total of eleven comparative studies satisfied the eligibility criteria and were incorporated into the qualitative synthesis. The principal characteristics of these investigations, including study design, cohort size, demographic profiles, evaluated outcome domains, and duration of follow-up, are detailed in Table 1. Notably, the majority of studies were published within the past five years, indicating representation of contemporary surgical practice and mirroring the recent surge in clinical adoption of VBT as a potential fusion-sparing alternative for skeletally immature patients with moderate-to-severe AIS (Newton et al., 2022; Pehlivanoglu et al., 2021; Qiu et al., 2021). Follow-up duration varied substantially across studies, ranging from short-term early recovery assessments (O'Donnell et al., 2023) to mid- term radiographic and functional evaluations extending beyond two years (Bauer et al., 2025; De Varona-Cocero et al., 2025; Meyers et al., 2024). Collectively, these studies provided

a heterogeneous but comprehensive dataset encompassing radiographic, perioperative, functional, and patient-reported outcomes.

Table 1. Summary of Study Characteristics of the Included Comparative Studies Evaluating Vertebral Body Tethering (VBT) versus Posterior Spinal Fusion (PSF) in Adolescent Idiopathic Scoliosis

No.	Study (year)	Study Design	Sample Size		Mean Age (SD)		Outcomes	Follow-Up
1	Meyers et al., 2024	Retrospective Review	45	46	13.5 (2.2)	12.8 (2.1)	Radiographic outcome (shoulder balance)	Mean 25.7 months (24–42)
2	Bauer et al., 2025	Prospective Study	24	24	14 (NR)	13.5 (NR)	Radiographic outcome (thoracic curve correction)	Minimum 2 years
3	Varona-Cocero et al., 2025	Retrospective Study	50	49	13.2 (1.9)	13.6 (1.4)	Radiographic outcome (fractional curve correction, L5 tilt); Comparative surgical outcome (PSF LIV vs 2RVBT)	Minimum 2 years
4	Pehlivanoglu et al., 2021	Retrospective Study	22	21	10.9 (1.5)	11.1 (1.5)	Range of motion, Flexibility and Quality of life	Mean 37–38 months
5	Pulido et al., 2025	Retrospective Study	89	109	14.8 (2)	12,2 (1.8)	Operative time, instrumented levels, inpatient/postdischarge opioid use (OME), PCA use	Perioperative/early postop only
6	Siu et al., 2023	Retrospective Study	24	23	13 (1.0)	12 (1.0)	Perioperative (EBL, operative time, LOS, transfusion), pain scores & opioid use, radiographic correction, revisions, costs	Minimum 2 years
7	Mathew et al., 2022	Prospective study with matched retrospective comparison group	26	26	13.4 (1.0)	13.2 (1.1)	Operative, Curve Correction, Complication, Growth Preservation	Minimum 2 years
8	Newton et al., 2022	Retrospective Study	237	237	13.4 (1.4)	12.1 (1.6)	Radiographic corection, Surgical and patient-reported outcomes	Mean 2.2–2.3 years
9	Qiu et al., 2021	Prospective Study	62	20	11.7 (0.9)	11.8 (1.9)	Baseline characteristics, radiographic flexibility, patient-reported outcomes (SRS-22)	Insufficient follow-up
10	Oeding et al., 2023	Retrospective Study	10	12	13.7 (1.6)	12.7 (1.4)	Compare patient-reported physical activity	Minimum 2 years
11	O'Donnell et al., 2023	Prospective Study	22	9	14.1 (1.6)	12.8 (1.2)	pain, mobility, and functional recovery during the first 6 weeks post-op.	6-week follow-up

The included studies varied in design, sample size, and follow-up duration, ranging from early postoperative assessments to mid-term evaluations beyond two years. Although methodological heterogeneity was present, most studies provided comparable baseline characteristics and reported outcomes relevant to radiographic correction, perioperative parameters, functional measures, and patient-reported results. This overview highlights the need for quantitative pooling to clarify consistent patterns across endpoints.

4.1.3. Summary of Systematic Review Findings

The principal findings of each included study are summarized in Table 2, outlining the radiographic, functional, perioperative, and patient-reported differences between VBT and PSF across diverse study designs and follow-up durations. Recent comparative evidence highlights consistent patterns: PSF provides more reliable and durable curve correction (Bauer et al., 2025; Meyers et al., 2024; Newton et al., 2022), whereas VBT offers advantages in spine mobility, functional recovery, and reduced perioperative burden (O'Donnell et al., 2023; Pehlivanoglu et al., 2021). Several studies also emphasized higher rates of tether-related complications and reoperations in VBT cohorts (De Varona-Cocero et al., 2025; Siu et al., 2023), although early postoperative symptoms such as pain and opioid use were consistently lower in VBT groups (Mathew et al., 2022; Pulido et al., 2025). Collectively, these findings provide a comprehensive and balanced overview of the comparative performance of the two procedures across short- and mid-term follow-up.

Table 2. Summary of Key Findings and Conclusions from Included Comparative Studies Evaluating Vertebral Body Tethering (VBT) versus Posterior Spinal Fusion (PSF)

No.	Study (Year)	Study Design	Summary of Result	Conclusion
1	Meyers et al., 2024	Retrospective Review	PSF produced greater correction of proximal thoracic, main thoracic, and thoracolumbar curves at two years. Shoulder imbalance was slightly more pronounced following PSF, although T1 tilt and clavicular angles were similar between groups. Other radiographic parameters showed no major differences.	PSF offers stronger radiographic correction, while VBT provides marginally better shoulder balance. Differences are statistically significant but clinically small.
2	Bauer et al., 2025	Prospective Study	Coronal correction at two years was comparable between groups; however, PSF demonstrated superior coronal balance and greater improvements in lumbar lordosis. VBT had a markedly higher reoperation rate, mostly related to tether failure, whereas PSF revisions were rare.	PSF yields more stable sagittal alignment and fewer reoperations, while VBT shows similar early correction but a higher risk of revision.
3	Varona-Cocero et al., 2025	Retrospective Study	PSF achieved greater correction of main and secondary curves, whereas VBT provided better L5 tilt correction. Complication and revision rates were low and comparable between groups, with tether breakage occurring only in VBT patients.	PSF offers greater Cobb correction, whereas VBT benefits distal compensation; overall complication rates are comparable
4	Pehlivanoglu et al., 2021	Retrospective Study	Curve correction was similar between groups at final follow-up. VBT preserved superior lumbar range of motion, trunk strength, endurance, and produced higher SRS-22 and SF-36 scores compared with PSF.	VBT is associated with reduced surgical burden and narcotic requirements compared with PSF.

No.	Study (Year)	Study Design	Summary of Result	Conclusion
5	Pulido et al., 2025	Retrospective Study	PSF required longer operative time, more instrumented levels, and substantially higher opioid use during both inpatient and outpatient periods. VBT patients required fewer opioids and had fewer refill needs, reflecting a less invasive recovery profile.	VBT provides a less invasive recovery profile with markedly reduced opioid needs and shorter surgical exposure.
6	Siu et al., 2021	Retrospective Study	PSF produced greater curve correction but was accompanied by higher blood loss, longer operative time, greater postoperative opioid use, and slightly longer hospital stay. VBT patients discontinued opioids earlier. Revision rates favored PSF, though differences were not statistically significant.	PSF delivers superior radiographic correction, whereas VBT results in lower perioperative morbidity and faster analgesic recovery.
7	Mathew et al., 2022	Prospective study with matched retrospective comparison group	VBT had shorter operative time, less blood loss, and shorter length of stay. PSF showed better curve correction and a higher rate of achieving Cobb < 35°. VBT preserved growth at instrumented levels but was associated with suspected tether breakage. Complication rates were similar.	PSF provides more consistent correction, while VBT offers lower perioperative morbidity and growth preservation but carries higher mechanical risks.
8	Newton et al., 2022	Retrospective Study	PSF achieved significantly greater thoracic correction at ≥2 years and a higher proportion of patients meeting Cobb < 35°. VBT preserved spinal growth but demonstrated higher revision and tether breakage rates. HRQoL was similar between groups, with PSF slightly better in self-image.	PSF remains more reliable in long-term correction and stability, while VBT emphasizes growth modulation but with higher mechanical failure.
9	Qiu et al., 2021	Prospective Study	Both groups showed comparable baseline characteristics and PROMs. VBT patients demonstrated greater preoperative flexibility, whereas pulmonary function and early PROMs remained similar between groups.	Baseline and early functional outcomes were comparable; VBT patients were more flexible at presentation.
10	Oeding et al., 2025	Retrospective Study	PSF provided superior curve correction and lower revision rates. VBT/PLST enabled faster return to physical activity, preserved flexibility, and showed similar satisfaction levels despite higher revision risk.	PSF excels in radiographic correction, while VBT/PLST enhances early functional recovery but increases revision likelihood.
11	O'Donnell et al., 2023	Prospective Study	VBT patients were younger and less skeletally mature. They experienced lower early postoperative pain, earlier return to independence, faster opioid cessation, and better early PROMIS pain and mobility scores. Global health outcomes were similar.	VBT offers superior early recovery and pain outcomes, though baseline maturity differences may influence comparability.

Overall, the comparative evidence shows a consistent trend: PSF achieves more reliable curve correction, while VBT offers advantages in motion preservation, early recovery, and reduced perioperative burden. Several studies reported higher tether-related complications with VBT, though patient satisfaction and early functional outcomes were generally favorable. These findings collectively support the need for meta-analytic synthesis to determine the magnitude of these differences.

4.1.4. Radiographic Outcomes

A. Final Cobb Angle

Five studies (De Varona-Cocero et al., 2025; Mathew et al., 2022; Meyers et al., 2024; Newton et al., 2022; Siu et al., 2023) evaluated final postoperative Cobb angles, and all consistently demonstrated smaller residual curves in the PSF group, as reflected by positive standardized mean differences favoring PSF. The pooled analysis confirmed a significant advantage for PSF (SMD 0.76, 95% CI 0.61-0.91; P < 0.0001), with no evidence of heterogeneity (I^2 = 0%), and the prediction interval (0.55-0.97) remained entirely positive. Overall, these findings indicate a robust and reproducible superiority of PSF in achieving lower residual postoperative curves. To visually summarize these results, Figure 3 presents the forest plot of the final postoperative Cobb angle.

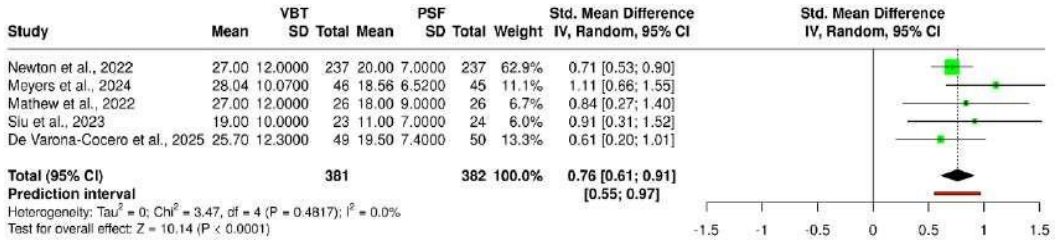

Figure 3. Forest plot of final cobb angle

B. Major curve correction, % subgroup

Three studies (Mathew et al., 2022; Newton et al., 2022; Oeding et al., 2025) reported percentage major curve correction. All effect estimates were negative, indicating superior correction in the PSF group. The pooled standardized mean difference showed a large and statistically significant advantage for PSF (SMD -1.57; 95% CI −2.35 to -0.79). Heterogeneity was high (I^2 = 84.6%), reflecting variability in the magnitude of benefit across studies, but the overall effect remained strongly in favor of PSF. These results are illustrated in Figure 4, which shows the forest plot of percentage major curve correction.

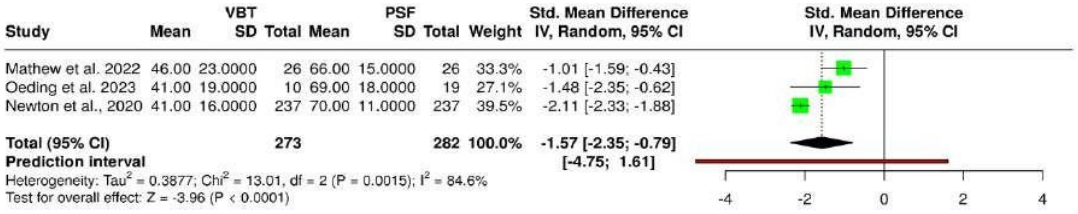

Figure 4. Forest plot of major curve correction (percentage)

C. Major curve correction, Δ subgroup

Three studies (Mathew et al., 2022; Newton et al., 2022; Oeding et al., 2025) reported the absolute change in major Cobb angle from pre- to postoperative follow-up. All studies showed greater absolute correction in the PSF group, reflected by consistently negative effect sizes favoring PSF. The pooled analysis demonstrated a significant advantage for PSF (SMD -1.26, 95% CI -1.51 to -1.01), with no observed heterogeneity (I^2 = 0%). The prediction interval (-1.81 to -0.71) remained entirely negative, indicating stable superiority of PSF across different settings and populations. These findings are depicted in Figure 5, which shows the forest plot of major curve correction (delta).

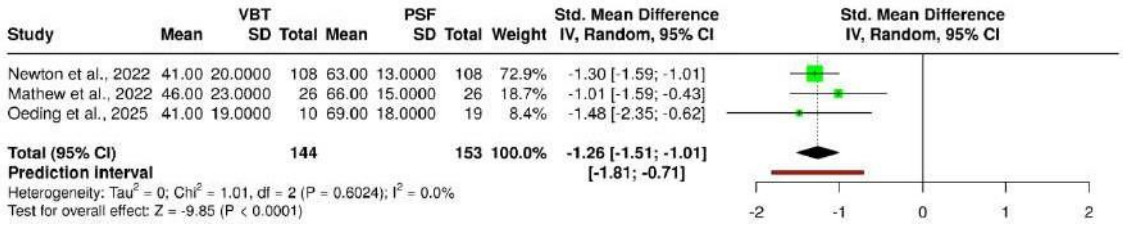

Figure 5. Forest plot of major curve correction (delta)

D. Shoulder Height Difference

Three studies (Meyers et al., 2024; Newton et al., 2022; Siu et al., 2023) reported postoperative shoulder height difference, with all effect sizes favoring VBT. The pooled analysis showed a small but statistically significant advantage for VBT (SMD -0.38; 95% CI -0.54 to -0.22), with no heterogeneity (I^2 = 0%) and a consistently negative prediction interval. Overall, VBT produced slightly better shoulder height symmetry, though the magnitude of difference was modest. The modest yet consistent advantage of VBT is depicted in Figure 6 through the forest plot of shoulder height difference.

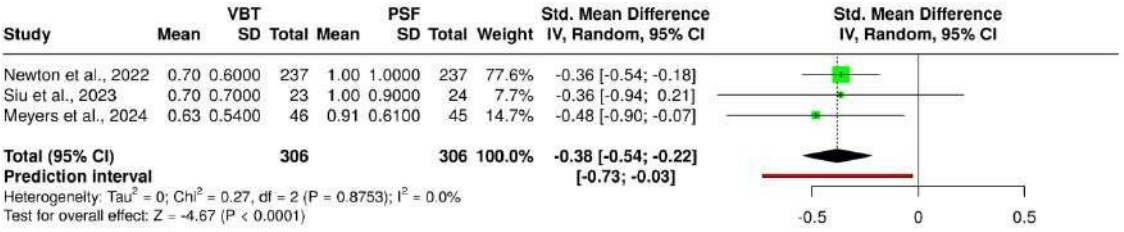

Figure 6. Forest plot of shoulder height difference

E. Coronal Balance

Three studies (Bauer et al., 2025; Pehlivanoglu et al., 2021; Siu et al., 2023) reported coronal balance. Individual results varied, with two studies favoring VBT and one showing no difference. The pooled effect slightly favored VBT but was not statistically significant (SMD 0.84, 95% CI -0.03 to 1.70) and showed high heterogeneity (I^2 = 82.9%), indicating inconsistent findings across studies. This pattern of inconsistent results across studies is summarized in Figure 7, where the forest plot of coronal balance is presented.

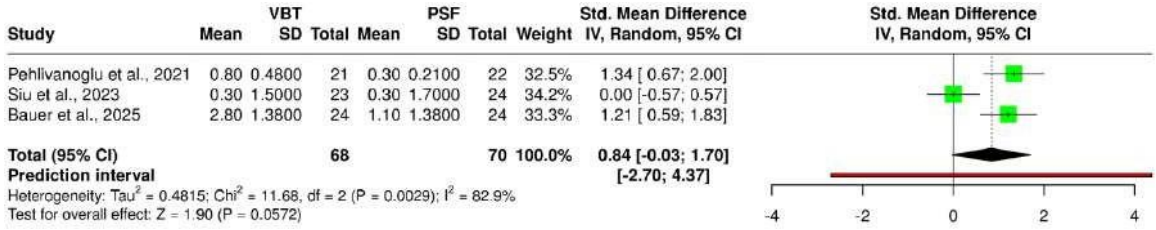

Figure 7. Forest plot of coronal balance

4.1.5. Perioperative Outcomes

A. Operative Time

Three studies (Mathew et al., 2022; Pulido et al., 2025; Siu et al., 2023) showed consistently longer operative times for PSF compared with VBT. The pooled estimate favored VBT (SMD -2.24; 95% CI -4.61-0.13), although the result did not reach statistical significance and heterogeneity was very high (I^2 = 98%). Overall, VBT tended to require shorter operative

duration, but the true effect remains uncertain due to wide variability between studies. The wide variability in operative time across studies is depicted in Figure 8 through the forest plot of operative time.

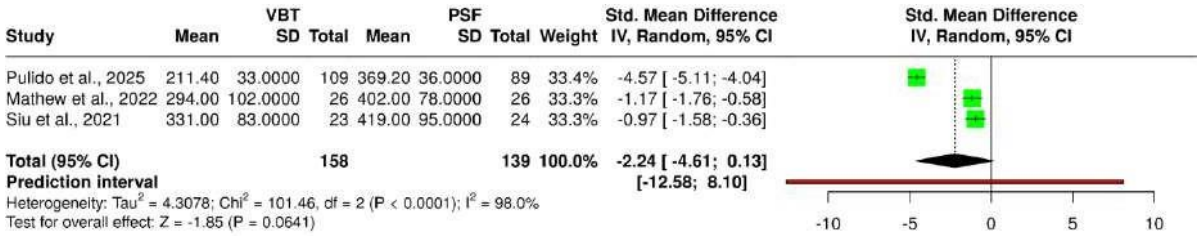

Figure 8. Forest plot of operative time

B. Estimated Blood Loss

Two studies (Mathew et al., 2022; Siu et al., 2023) reported estimated blood loss, and both showed markedly lower blood loss with VBT compared with PSF, with large negative effect sizes favoring VBT. The pooled analysis demonstrated a significant reduction in blood loss with VBT (SMD -1.52; 95% CI -1.98 to -1.07) and no heterogeneity (I^2 = 0%). The prediction interval (-4.46 to 1.41) suggests that although individual study effects may vary, the overall direction consistently favors VBT. This overall pattern of reduced blood loss with VBT is summarized in Figure 9, where the forest plot of estimated blood loss is presented.

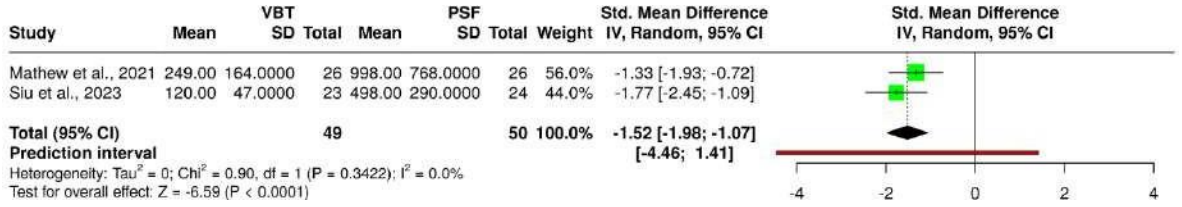

Figure 9. Forest plot of estimated blood loss

C. Length of Stay

Two studies demonstrated shorter hospitalization with VBT, while one showed only a small difference, all favoring VBT. The pooled analysis confirmed that VBT significantly reduced length of stay compared with PSF (SMD -0.78, 95% CI -1.30 to -0.25). Heterogeneity was moderate (I^2 = 71%), but the direction of effect was consistent across studies, indicating that VBT is generally associated with a shorter postoperative hospitalization. These results are shown in Figure 10, which displays the forest plot of length of postoperative hospital stay.

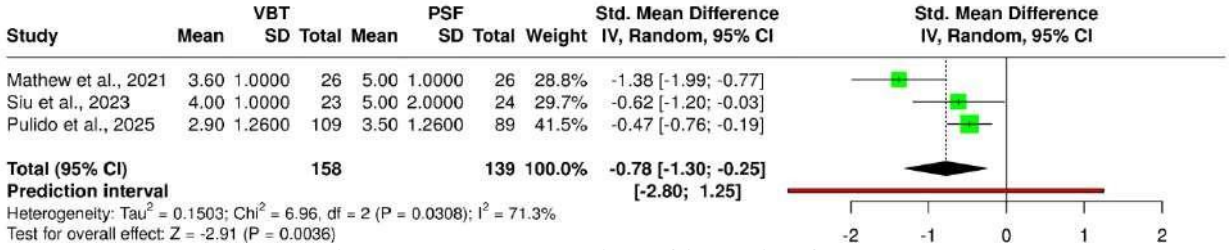

Figure 10. Forest plot of length of stay

4.1.6. Patient-reported Outcomes

A. SRS-22 Total

Two studies (Newton et al., 2022; Pehlivanoglu et al., 2021) reported SRS-22 total scores. Effect sizes varied, and the pooled estimate showed no significant difference between VBT and PSF (SMD = 0.48, 95% CI -0.55 to 1.52). Heterogeneity was high (I^2 = 89.7%), and the prediction interval (-10.74 to 11.71) was extremely wide, indicating substantial uncertainty and no reliable advantage for either technique. To illustrate these results, Figure 11 presents the forest plot of SRS-22 total scores.

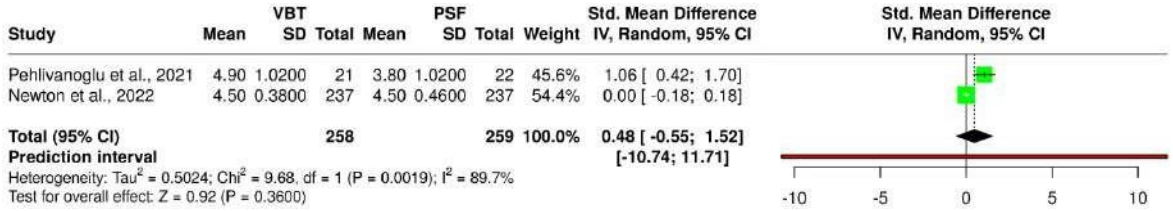

Figure 11. Forest plot of SRS-22 total scores

B. Activity/Function

Two studies reported SRS-22 activity/function scores, with inconsistent findings between VBT and PSF. Individual estimates varied widely, and the pooled result showed no significant difference between groups (SMD 0.69, 95% CI -0.70 to 2.08), with very high heterogeneity (I^2 = 90.8%). The wide prediction interval (-14.45 to 15.83) indicates substantial uncertainty, suggesting neither technique demonstrates a clearly superior effect on functional outcomes. These results are shown in Figure 12, which displays the forest plot of SRS-22 activity/function scores.

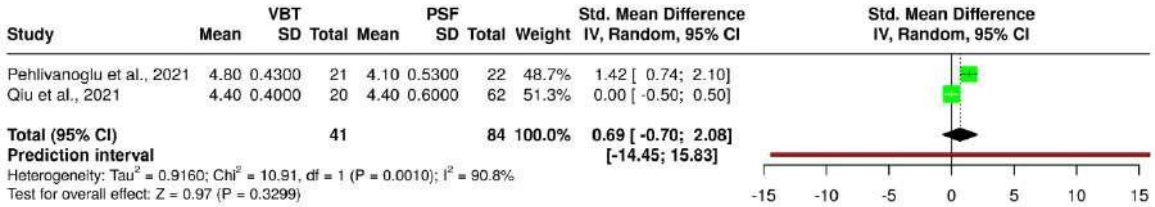

Figure 12. Forest plot of SRS-22 activity/function scores

4.1.7. Complications and Revisions

A. Complication Rate

Four studies (Bauer et al., 2025; De Varona-Cocero et al., 2025; Mathew et al., 2022; Siu et al., 2023) reported complication rates, with most showing numerically higher event frequencies in the VBT group. The pooled analysis demonstrated a significantly increased risk of complications with VBT compared with PSF (RR 2.09, 95% CI 1.11-3.93), with no heterogeneity (I^2 = 0%). Although the prediction interval (0.75-5.83) was wide, the overall effect indicates a reliably elevated complication risk associated with VBT. The increased complication risk associated with VBT is depicted in Figure 13 through the forest plot of complication rates.

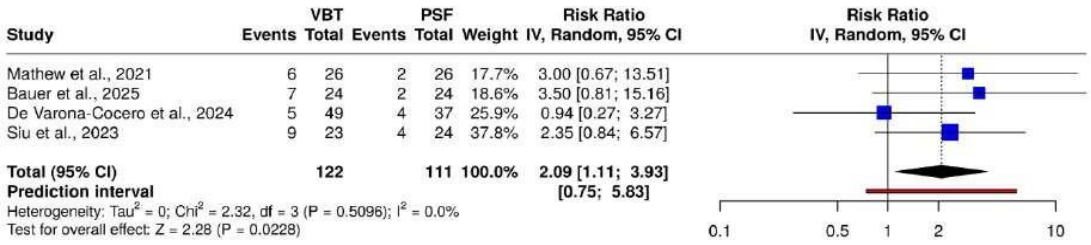

Figure 13. Forest plot of complication rate

B. Revision Rate

Six studies reported revision rates, and all but one showed higher revision frequencies in the VBT group compared with PSF. The pooled risk ratio indicated more than a threefold increased risk of revision after VBT (RR = 3.89, 95% CI 1.71-8.81). Heterogeneity was moderate (I^2 = 39.7%) and the prediction interval was wide (0.56-27.19), reflecting variability in individual study effects. Overall, the evidence consistently suggests higher revision risk with VBT. These results are shown in Figure 14, which displays the forest plot of revision rates.

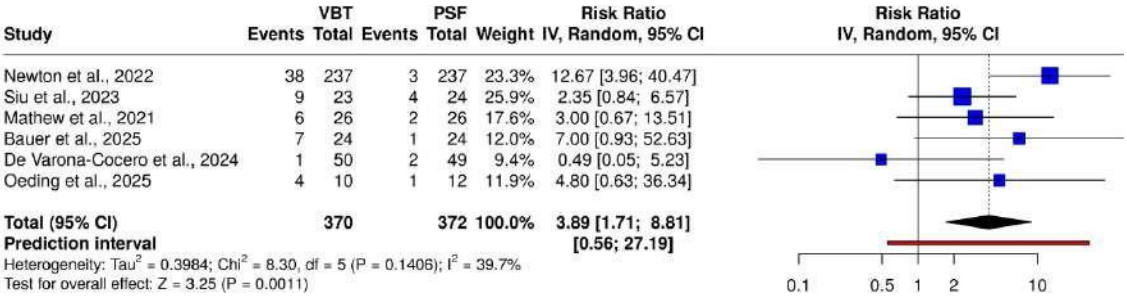

Figure 14. Forest plot of revision rate

4.2. Discussion

4.2.1. Radiographic Outcomes

This meta-analysis demonstrates a consistent radiographic advantage of posterior spinal fusion (PSF) over vertebral body tethering (VBT) in the correction of moderate-to-severe adolescent idiopathic scoliosis. Across five included studies, PSF achieved significantly smaller residual Cobb angles, greater percentage curve correction, and larger delta correction magnitudes. These findings align with the inherent mechanical stability and immediate corrective capacity of rigid fixation, which reliably restores coronal alignment regardless of curve flexibility.

Conversely, VBT's performance was more variable, reflecting its dependence on growth modulation, patient maturity, and tether integrity. Although VBT did not match PSF in primary curve correction, it showed tendencies toward improved shoulder height symmetry and comparable coronal balance. These subtler alignment advantages may relate to its preservation of spinal mobility and avoidance of thoracic stiffness. However, the lack of radiographic superiority and the wide prediction intervals indicate that VBT correction remains less predictable, particularly in older adolescents or curves exceeding recommended indications.

4.2.2. Perioperative Outcomes

In contrast to radiographic findings, perioperative metrics consistently favored VBT. Operative time, estimated blood loss, and hospital length of stay were significantly lower in the VBT cohort. These differences highlight the less invasive nature of anterior thoracic

tethering, which avoids extensive muscle dissection, multilevel instrumentation, and decortication inherent to PSF. Shorter hospital stays and reduced intraoperative morbidity may translate to faster early recovery trajectories, an advantage frequently cited by proponents of motion-preserving surgery. Nonetheless, the magnitude of benefit varied between studies, and the potential clinical significance must be interpreted alongside VBT's higher need for revision. While VBT offers clear perioperative advantages, these gains may be offset by long-term maintenance concerns, particularly when tether breakage or overcorrection develop during growth.

4.2.3. Patient-Reported Outcomes

Subjective outcomes, including SRS-22 total scores and activity/function domains, revealed no significant differences between PSF and VBT. This finding suggests that despite radiographic and perioperative contrasts, patient-perceived quality of life and functional well-being remain equivalent in the short to mid-term.

Comparable satisfaction across procedures may reflect the strong baseline health of AIS patients, the cosmetic benefits inherent to both surgeries, and adaptive functional recovery regardless of technique. However, most included studies provided early to mid-term follow-up; it remains uncertain whether long-term motion preservation with VBT translates into durable functional advantages into adulthood. Similarly, PSF's known long-term stability may result in equivalent or superior satisfaction as patients age.

4.2.4. Safety and Revision Profiles

Safety outcomes reveal the most clinically consequential divergence between VBT and PSF. VBT demonstrated significantly higher rates of overall complications and revisions—particularly tether breakage, overcorrection, and mechanical failure. These events commonly emerge 1-3 years postoperatively and are strongly associated with skeletal maturity at surgery, curve stiffness, and biomechanical loading across the construct.

In contrast, PSF displayed a markedly more favorable long-term safety profile, with low revision rates and predictable long-term stability. Given that many VBT revisions eventually convert to fusion, the procedure's intended motion-preserving benefit may be lost in a subset of patients. These findings reinforce the importance of strict patient selection, particularly favoring skeletally immature patients with flexible curves and avoiding those nearing growth cessation.

4.2.5. Overall Clinical Interpretation

Taken together, these findings highlight the trade-offs inherent in choosing between PSF and VBT. PSF remains the gold standard for achieving maximal and durable deformity correction with the lowest long-term complication burden. VBT, while appealing due to its less invasive nature and motion-preserving philosophy, currently demonstrates less predictable radiographic outcomes and a notably higher revision risk.

However, VBT may still hold value for selected patients prioritizing spine mobility, body image, or athletic performance, particularly those who fall within ideal indications (Risser 0-2, Sanders ≤4, flexible curves <65°). As technology evolves and tether materials improve, future iterations of growth modulation may offer enhanced reliability.

5. Conclusion

In this systematic review and meta-analysis, vertebral body tethering (VBT) demonstrated clear perioperative advantages, including shorter operative duration, reduced intraoperative blood loss, and faster postoperative recovery, while achieving patient-reported outcomes comparable to those of posterior spinal fusion (PSF). Nevertheless, VBT was associated with less consistent radiographic correction and substantially higher rates of postoperative complications and revision surgery, reflecting concerns regarding durability and long-term curve control.

From a clinical perspective, these findings suggest that PSF remains the most reliable surgical option for achieving predictable and durable deformity correction in moderate-to-severe adolescent idiopathic scoliosis, particularly in patients nearing skeletal maturity or prioritizing long-term stability. VBT may be considered in carefully selected skeletally immature patients who place a high value on motion preservation and are willing to accept an increased risk of reoperation. From a research standpoint, the observed heterogeneity in outcomes and limited long-term follow-up underscore the need for well-designed prospective studies with standardized indications, longer follow-up durations, and consistent reporting of radiographic, functional, and patient-reported outcomes to better define the optimal role of VBT in contemporary scoliosis management.

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