Cureus
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Open Access Review Article

Prevention of Revision-Requiring Proximal Junctional Failure Following Long Thoracic-to-Pelvis Fusion for Adult Spinal Deformity: A Systematic Review and Meta-Analysis

Review began 10/11/2026
Review ended 11/06/2026
Published 11/11/2026

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DOI: 10.7759/cureus.119480

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Abstract

After surgery for adult spinal deformity (ASD), proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) are common complications. Previous assessments of preventive measures have included heterogeneous fusion constructs and PJK/PJF definitions. A systematic review and meta-analysis was conducted to assess preventive strategies for PJF-related revision surgery in thoracic-to-pelvis ASD reconstructions. The PubMed/MEDLINE, Embase, Scopus, and CENTRAL databases were comprehensively searched for relevant publications released prior to August 8, 2026. Adult patients undergoing spinal fusion of five or more levels, extending to the pelvis and incorporating a thoracic upper instrumented vertebra (UIV), were included in the analysis. The revised Cochrane risk-of-bias tool for randomized trials (RoB 2) and the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) were used to assess risk of bias, and the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) was used to determine certainty of evidence. A study-stratified binomial model was used to pool revision-PJF data; hook-related radiographic PJK was pooled using restricted maximum likelihood (REML) random-effects models with Hartung-Knapp inference. Of 3,458 search records identified, 17 studies were included. Fewer revision-PJF events were observed with ligament/tether augmentation across three studies examining 227 patients (1/121 vs 23/106 events; OR 0.0309, 95% CI 0.00171-0.15142; P<0.001). Hook use was not associated with a consistent decrease in radiographic PJK in five studies (596 patients) (RR 0.91, 95% CI 0.47-1.78; P=0.729; I^2=49.7%). The role of modified proximal fixation remained unclear. In a single randomized trial, teriparatide showed a possible benefit for trial-defined PJF when compared to denosumab (1/29 vs 6/27; RR 0.16, 95% CI 0.02-1.21). This endpoint indicated a need for revision without separately confirming that each operation occurred. Available evidence suggests that ligament/tether augmentation is associated with fewer revision-requiring PJF events, but certainty is very low because the estimate derives from three retrospective single-center cohorts with sparse events. Proximal hooks did not show a consistent reduction in radiographic PJK, and evidence for modified proximal fixation remains insufficient. Perioperative teriparatide showed a favorable but imprecise randomized signal in osteoporotic postmenopausal women. Revision-defined PJF is recommended as a primary endpoint for future comparative studies.

Categories: Quality Improvement, Orthopedics, Neurosurgery
Keywords: adult spinal deformity, hook, meta-analysis, proximal junctional failure, proximal junctional kyphosis, teriparatide, tether

Introduction And Background

Adult spinal deformity (ASD) involves abnormal spinal curvature or alignment that may cause pain and functional limitation. For these patients, spinal reconstruction surgery effectively re-establishes sagittal alignment and spinal biomechanics. Despite the advantages, long fusion constructs create a stiffness gradient at the proximal junction, where adjacent segments are vulnerable to degeneration and failure [1]. Proximal junctional kyphosis (PJK) can be described as a radiographic phenomenon, commonly defined by a proximal junctional angle of at least 10° and an increase of at least 10° from baseline, as opposed to proximal junctional failure (PJF), the clinical complication of structural collapse, instability, neurological deficit, or junctional event that may require revision. PJF does not invariably result in an operation; the primary endpoint of this review requires surgery actually performed. In their systematic review of 53 studies, Lau et al. observed PJK rates ranging from 5% to 46%. Revision rates for PJK show substantial variation, contingent on definitions and its actual clinical manifestation [2].

The Hart-International Spine Study Group PJK Severity Scale was later used to demonstrate the clinical importance of this varied diagnostic spectrum. Those with higher scores had worse Oswestry Disability Index scores, pain, and Scoliosis Research Society outcomes. Higher scores were also associated with revision surgery, although these cohort-specific findings do not establish universal surgical thresholds [3].

This indicates radiographic PJK and revision necessitating PJF are not synonymous endpoints. A reduced proximal junctional angle does not appear to lead to fewer revisions or improved symptoms/function; therefore, preventative measures should be judged by clinical failure and revision rates.

Patient cohorts within present studies also vary considerably in terms of fusion length, the point of distal fixation, the upper instrumented vertebra (UIV), and how PJF is defined. Vercoulen et al. found that all 18 clinical prevention cohorts in their review were at severe or critical risk of bias, judging the heterogeneity too substantial for quantitative comparison [4]. Reduced rates of PJK or PJF with tethers, hooks, and cement augmentation have been described in meta-analyses, yet differences in construct length, UIV level, type of pelvic fixation, and endpoint definitions restrict their comparability [5-9]. Clinical relevance for their use in long thoracic-to-pelvis fusion is therefore unclear.

The design of this systematic review and meta-analysis was based on a clinically driven endpoint hierarchy, with a primary outcome measure of PJF requiring revision surgery actually performed. Author-defined PJF and radiographic PJK were reported separately. This systematic review aimed to evaluate the strategy-specific evidence for fewer clinically meaningful junctional failures during long-construct ASD surgery.

Review

Materials and methods

Study Design and Reporting

This systematic review and meta-analysis is reported in accordance with PRISMA 2020 [10]. A version-controlled protocol was prepared. The protocol included specification of population of interest, intervention categorizations, outcome hierarchy, cohort-overlap criteria, and statistical analysis plan. PubMed/MEDLINE, Embase, Scopus, and Cochrane Central Register of Controlled Trials (CENTRAL) databases were used for our final search query and amendment of bibliographic sources. The review was registered in the International Prospective Register of Systematic Reviews (PROSPERO; CRD420261479414) on August 16, 2026, after searching and screening were completed and before data extraction, risk-of-bias assessment, and evidence synthesis began, as documented in the registration record. AI-assisted tools were used for source checking, extraction review, statistical code preparation, numerical reanalysis, manuscript editing, and formatting. The authors are responsible for reviewing the final content.

Eligibility Criteria

Included studies enrolled adults aged 18 years or older who underwent primary or revision posterior instrumented fusion for ASD. Eligible constructs included fusion of at least five vertebral levels, extended distally to the pelvis through iliac or S2-alar-iliac fixation, and had a thoracic UIV; these criteria were intended to minimize construct-level heterogeneity. Mixed constructs that included both eligible and ineligible components were allowed if eligible primary subgroups could be identified and analyzed independently. Included studies needed to have ⩾6 months of follow-up for the cohort or subgroup to be analyzed/separately extracted. A specified period of observation was required for events to be counted. Studies simply reporting a mean follow-up of >6 months were not considered sufficient. Alluri et al. clearly reported thoracic-to-pelvis fusion, but the subtype of pelvic implant was not specified. This cohort was retained with this limitation acknowledged and then excluded in a sensitivity analysis.

Preventive strategies encompassed ligamentous tethering/bands, cement augmentation, semirigid proximal fixation, methods for construct stiffening, soft-tissue sparing procedures, bone-health maintenance, and predefined bone-health treatment algorithms. Surgery with planned changes to alignment or proximal geometry was assessed separately. Achieved alignment, overcorrection, pelvic incidence-lumbar lordosis (PI-LL) mismatch, UIV inclination, and subsequent surgical modifiers were classified as mediators or risk factors, rather than interventions. Both randomized and nonrandomized comparative studies were considered eligible for pooling of treatment effects. Data from single-arm studies were reported descriptively for information regarding technique safety and rare events.

The study excluded cases of pediatric or adolescent idiopathic scoliosis, neuromuscular or congenital deformity, and curves associated with tumors, infections, or acute trauma. Furthermore, the study excluded cases involving lumbar UIV, constructs not extending to the pelvis, biomechanical or finite-element studies, case reports, narrative reviews, and technical reports that did not present comparative clinical outcomes.

Information Sources and Search Strategy

PubMed/MEDLINE, Embase, Scopus, and CENTRAL were each searched on August 8, 2026, from inception to that date, using the search strings in Appendix A without database filters. The search approach focused on encompassing broad conceptual themes for ASD/spinal deformity and proximal-junctional conditions, intentionally avoiding the inclusion of a prevention term, pelvic-fixation restrictions, minimum fusion length, or UIV restriction. These terms were selectively applied during the screening process to avoid

restricting retrieval by construct characteristics. The initial database searches returned 929 PubMed, 1,431 Embase, 1,069 Scopus, and 29 CENTRAL records. Please refer to Appendix A for complete search strategies. Focused Source Audit (dated 10/26/20 26) reviewed disputed extractions/additional candidate reports. This was not a repeat of the database searches, nor did it alter the August 8, 2026 cutoff.

Study Selection Data Extraction and Cohort Overlap

Duplicate records were removed using Microsoft Excel (Microsoft Corp., Redmond, WA, USA). Two reviewers independently screened titles and abstracts and assessed reports, including journal publications, meeting abstracts, and trial-registry entries, against the eligibility criteria. Disagreements were resolved by a third reviewer. Abstracts that didn't offer sufficient detail regarding fusion length, distal fixation, UIV, or follow-up for immediate exclusion were progressed to full-text review. Eligible reports underwent a final review to ensure eligibility and identify any overlapping cohorts prior to data extraction. Citations and one primary exclusion reason per report are provided in Appendix G.

Two reviewers independently extracted data, with disagreements resolved by a third reviewer. Data were tabulated by study, arm, outcome, and effect. Characteristics reported at the study level included methodologic and clinical characteristics such as study design, date of enrollment, sample size, ASD criteria, construct characteristics, duration of follow-up, and availability of bone-health data. Information on comparator groups, co-interventions, and endpoint definitions was also tabulated. Event counts per patient were recorded at the outcome level along with the adjusted effect estimate, associated confidence interval, and covariates included in the model. Proximal structural failure that clearly led to revision surgery actually performed was the criterion for coding revision-requiring PJF. A stated need for revision without confirmation of surgery was recorded separately as author-defined PJF. Author-defined PJF included events defined as PJF by the original authors that did not meet this review’s definition of revision-requiring PJF. Radiographic PJK and clinically consequential non-revision PJF were coded distinctly. Original definitions, source locations, denominators, and outcome windows are provided in Appendix F.

Potential duplicate cohorts were assessed for differences in institution/consortium, enrollment dates, sample size, UIV/distal construct, intervention, authorship, follow-up, and outcome. The publication with the greatest number of directly eligible endpoints or longest continuous period of valid follow-up was prioritized to maximize the likelihood that our pooled estimate used data from only one source for each cohort/outcome window. Supplemental reports were used in this review solely for their unique content. The matched and full Safaee cohorts were used in separate analyses and were not counted together (Appendix E).

Risk of Bias and Certainty of Evidence

Two reviewers independently assessed risk of bias, with disagreements resolved by a third reviewer. Bias assessment for randomized trials was performed using the Cochrane risk-of-bias tool for randomized trials (RoB 2) [11]. The Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) for nonrandomized comparative studies was informed by an intervention-specific target trial framework [12]. Risk-of-bias assessment considered confounders including age, bone health, frailty/comorbidity, revision status, UIV level, severity of baseline deformity, preoperative sagittal alignment, planned correction, and surgical complexity. Studies with critical ROBINS-I risk of bias were excluded from the primary pooled estimate of treatment effect. The certainty of evidence was assessed using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) framework for risk of bias, inconsistency, indirectness, imprecision, and publication bias [13]. Matching and adjusted regressions were performed by the primary-study authors; pooling aggregate counts did not reproduce patient-level adjustment or matched-pair dependence. Reasons for downgrade due to specific outcomes are presented in Appendix E; domain-level information for outcomes is available in Appendix B. Sparse outcomes were accounted for as imprecision rather than as a separate domain of risk of bias. Assessments flagged as provisional in Appendix B remain classified as such.

Statistical Analysis

A meta-analysis was conducted when two or more independent studies reported clinically comparable interventions and outcomes; biologically distinct prevention approaches were meta-analyzed separately. Revision-requiring PJF was analyzed using independent binomial arm counts, study-specific fixed intercepts and a common log odds ratio: $\text{logit}(p_{ij})=\alpha_i+\beta\times\text{treatment}_{ij}$. Maximum likelihood estimation yielded $\exp(\beta)$, with a 95% profile-likelihood interval using a likelihood-ratio cutoff of 3.841 and a two-sided likelihood-ratio test of $\beta=0$. No continuity correction, random-effect variance, or beta-binomial dispersion parameter was used. Sensitivities included Mantel-Haenszel pooling without correction, conditional-profile likelihood, leave-one-study-out analyses, and exclusion of the cohort allowing six-month follow-up. When both matched and unmatched cohort data were available for the same endpoint, the matched comparison was used for the primary analysis and the full cohort was retained for sensitivity analysis.

Study-level risk ratios for reported PJK outcomes were pooled using random-effects meta-analysis with restricted maximum likelihood (REML) and unmodified Hartung-Knapp confidence intervals using k−1

degrees of freedom. Tau^2 and I^2 were estimated to describe heterogeneity across studies. Hazard ratios were not pooled with odds ratios or risk ratios. No preoperatively adjusted observational estimates were pooled; estimates controlling for postoperative mediators were considered supportive evidence. Because hazard ratios and extractable Kaplan-Meier data were not consistently reported, a time-to-event meta-analysis was not feasible. Follow-up duration varied across studies, so pooled estimates reflect each study's follow-up period. Confidence intervals for teriparatide and the separate fixation comparisons were calculated using the log-RR Wald method. The trial-reported Pearson test and our Fisher's exact test are presented separately. Descriptive funnel plots were generated separately for tether augmentation and proximal hooks, using continuity-corrected estimates for the tether display. Meta-regression, funnel-asymmetry testing, and trim-and-fill analyses were not performed because too few studies were available. The aggregate dataset, analysis code (Python 3.12.14; NumPy 2.3.5; SciPy 1.17.0), and convergence diagnostics are provided in Appendix I.

Forest plots were drawn using the relative efficient information from each study for the main binomial model. Inverse variance weights were used to plot the remaining models. All other fixed-effect analyses were conducted using normal theory confidence intervals. A sensitivity analysis was also conducted by adding 0.5 to each of the 4 cells if a study had a 0 cell. The random effects model used an REML estimate with the Hartung-Knapp interval bounded at a minimum of 1 on the variance scale. The primary hook model used an unadjusted Hartung-Knapp interval. Cochran's Q, I^2, and τ^2 summarize heterogeneity in the inverse-variance analyses.

Results

Study Selection

The database searches identified 3,458 records. After removal of 1,871 duplicates and six registry/protocol records before screening, 1,581 records were screened, and 1,503 were excluded. Of 78 reports sought for retrieval, one was not retrieved, and 77 were assessed for eligibility. Sixty reports were excluded because they did not meet population, construct, or follow-up criteria (n=32); assessed ineligible interventions or comparators (n=10); had a noncomparative, technical, biomechanical, or case-based design (n=5); provided overlapping or superseded information without an independent contribution (n=12); or were published only as a conference abstract or meeting proceedings (n=1) (Appendix G). These 60 reports included two trial-registry entries. The final systematic review included 17 studies, including 16 comparative studies and one descriptive cohort study (Figure *1*). Targeted source review did not identify a mutually eligible stratum for Sargut, Rodnoi, Oh, Rodriguez-Fontan, or Viswanathan; Jain was excluded as the publicly available data did not identify a thoracic-to-pelvis subgroup [14-21].

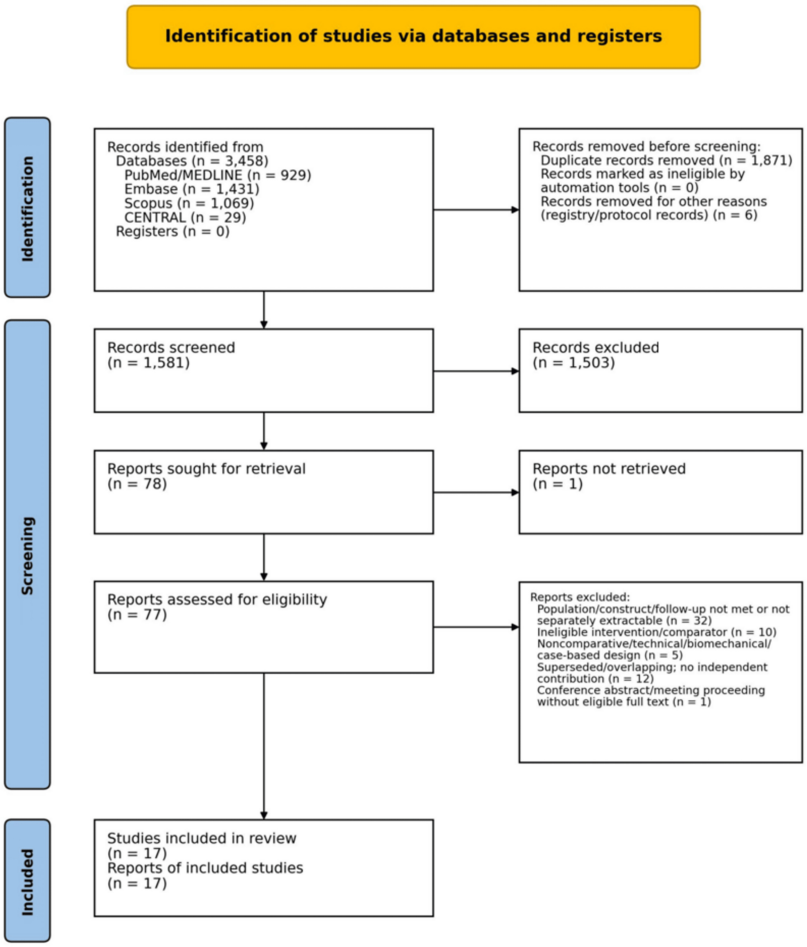


FIGURE 1: PRISMA flow diagram of study selection

The diagram summarizes study identification, screening, eligibility assessment, and inclusion. Database searches identified 3,458 records, with 17 studies included in the review.

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses; CENTRAL: Cochrane Central Register of Controlled Trials

Study Characteristics

The 17 studies included in this analysis consisted of one randomized trial and 16 observational studies. The studies assessed interventions such as multicomponent junctional/alignment strategies, ligament or tether augmentation, proximal hooks or alternative anchors, modified proximal screw constructs, and osteoporosis medications [22-37]. Cement augmentation was explored both comparatively, referencing the three-arm cohort by Cho et al., and descriptively, using the single-arm cohort from Tani et al. [27,38]. A review of the study designs, constructs, interventions, follow-up periods, and endpoints is presented in Tables *1*-*2*.

Study (first author)	Design and construct	Strategy	Follow-up and endpoint
Passias [22]	Retrospective; n=261 ≥5 levels; T1-T4 or T8-T12 UIV; pelvis	Multicomponent good summit/base vs other strategy	2 years; author-defined PJF; PJK; exploratory
Tsutsui [26]	Retrospective; n=53 Pelvis to T9/T10	TPH vs pedicle screw	≥1 y; PJK secondary
Yagi [23]	Propensity matched; n=64 Lower thoracic T9–T11 to pelvis	UIV+1 sublaminar tether vs control	2 y; Revision-PJF primary; PJK secondary
Cho [27]	Retrospective; n=139 T9/T10 to pelvis	Vertebroplasty vs hook vs no prophylaxis	≥2 y; Revision-PJF primary; PJK secondary
Park (hybrid) [31]	Retrospective; n=167 T10 UIV; routine iliac fixation	Hybrid pedicle+laminar screw vs bilateral pedicle screws	1 y; Revision-PJF primary; PJK secondary
Wilson [35]	Retrospective; n=83 >5 levels; pelvic fixation	Preop teriparatide vs no teriparatide	2 y; Critical RoB; exploratory only
Park (RCT) [34]	Randomized; mITT n=56 Long thoracolumbar fusion; T10 UIV; iliac fixation standard	Teriparatide vs denosumab	1 y; Trial-defined PJF indicating need for revision; PJK. Not confirmed performed-revision endpoint.
Ohba [36]	Retrospective; n=189 Thoracic UIV; bilateral S1 + iliac fixation	Osteoporosis therapy/timing comparisons	2 y; Subtype/reoperation exploratory
Liu [32]	Retrospective; n=115 >5 levels; thoracic UIV; S2AI	Tri-cortical proximal screw vs standard screw	≥2 y; Revision-PJF primary; PJK secondary
Tanaka [33]	Retrospective; n=54 T10 to pelvis/SAI	Triangular fixation vs conventional fixation	12-43 mo; PJK; inferred revision-PJF sensitivity
Bourghli [28]	Retrospective database; n=254 T12 or above to pelvis	Proximal hooks vs screws	≥2 y; PJK secondary
Maruo [37]	Retrospective; n=57 >5 levels; thoracic to pelvis	Perioperative teriparatide vs non-teriparatide	≥12 mo; Critical RoB; structural PJF sensitivity
Safaee [24]	Retrospective; n=319 overall; PSM 80 All pelvic; thoracic UIV	Ligament augmentation vs historical control	≥12 mo; Revision-PJF primary
Alluri [25]	Retrospective; n=83 Thoracic to pelvis; exact pelvic device unspecified	Semitendinosus allograft PLC augmentation vs control	≥6 mo; Revision-PJF primary; PJK secondary
Matsumura [29]	Retrospective; n=39 T9/T10; iliac or SAI	TPH vs pedicle screw; common sublaminar tape	≥2 y; PJK/structural secondary
Tani [38]	Single arm; n=29 T9/T10 to pelvis; S2AI	UIV/UIV+1 PMMA augmentation	≥3 y; Descriptive only; revision-PJF/harms
Rostami [30]	Retrospective; n=132 T7-T11 UIV to pelvis; S2AI; 3CO	TPH vs pedicle screw	≥2 y; PJK secondary; structural PJF supportive

TABLE 1: Characteristics of included studies

The table summarizes study design, sample size, fusion construct, preventive strategy, follow-up, and outcomes across the 17 included studies. The outcome column identifies each study's contribution to the primary, secondary, or descriptive analyses.

UIV: upper instrumented vertebra; PJF: proximal junctional failure; PJK: proximal junctional kyphosis; TPH: transverse process hook; PSM: propensity score matching; RCT: randomized controlled trial; mITT: modified intention-to-treat; RoB: risk of bias; PLC: posterior ligamentous complex; PMMA: polymethylmethacrylate; SAI: sacral alar-iliac; S2AI: S2 alar-iliac; 3CO: three-column osteotomy

Study	Available information	Limitations relevant to interpretation
Yagi (2022), propensity-matched cohort [23]	T-score -1.4±0.7 vs -1.3±0.6; age 67.2±7.0 vs 65.9±8.1 years; mFI-11 0.10±0.12 vs 0.09±0.11. Teriparatide 24/32 vs 21/32. Alignment measured and matching included bone density.	Residual era and selection confounding remain. Index revision cases 4/32 vs 4/32 are baseline surgery history, not PJF outcomes.
Safaee (2021), propensity-matched cohort [24]	Age 65 vs 65; prior fusion 19/40 in each arm. Hooks and vertebroplasty included as cointerventions. Matching included changes in SVA and PI-LL.	Table 4 of Safaee (2021) does not provide matched BMD/HU, frailty or muscle measurements. Postoperative alignment change is not a baseline confounder. Mean follow-up 21 vs 30 months.
Alluri 2021 [25]	Age 64±10 vs 62±9 years; index revision surgery 65% in each arm; osteotomy 90% vs 88%. Baseline and postoperative spinopelvic parameters reported.	No controlled bone-density assessment for the comparison; surgeon/era selection and unmeasured frailty remain. Table 1 of Alluri 2021 mean follow-up values 18.2±9.4 vs 23.4±14.1 have no printed unit label.
Park RCT 2025 [34]	Osteoporotic postmenopausal women aged 50-85; hip DXA and alignment measured. T10 UIV; iliac fixation routine. Teriparatide versus denosumab; subsequent bisphosphonate therapy.	Restricted population, active comparator and need-for-revision endpoint. Frailty, paraspinal muscle and GAP fields not synthesized as measured effect modifiers.
Passias [22]; Tsutsui [26]; Cho [27]; Park hybrid [31]; Wilson [35]; Ohba [36]; Liu [32]; Tanaka [33]; Bourghli [28]; Maruo [37]; Matsumura [29]; Tani [38]; Rostami [30]	Individual baseline-variable values are not tabulated in this review.	Variables not tabulated in this review should not be assumed to have been unreported in the original studies. Rostami's 3CO population and Matsumura's shared tape cointervention remain explicit design distinctions.

TABLE 2: Baseline characteristics and co-interventions

The table summarizes selected patient characteristics, matching variables, and additional treatments that may influence comparisons between study groups, together with relevant limitations. Paired values are presented as intervention versus comparator; propensity matching was performed by the original study investigators.

BMD: bone mineral density; DXA: dual-energy X-ray absorptiometry; HU: Hounsfield units; mFI-11: 11-item modified frailty index; SVA: sagittal vertical axis; PI-LL: pelvic incidence-lumbar lordosis mismatch; GAP: Global Alignment and Proportion; UIV: upper instrumented vertebra; PJF: proximal junctional failure; RCT: randomized controlled trial; 3CO: three-column osteotomy

Revision-requiring PJF was directly extracted from studies conducted by Yagi et al., Cho et al., Park et al. (hybrid screw), Liu et al., Safaee et al., and Alluri et al. [23-25,27,31,32]. The remainder of the included studies utilized a different approach. For example, Passias et al. identified the index event using a radiographic Lafage-type PJF definition rather than revision [22], whereas Bourghli et al. and Matsumura et al. primarily reported PJK/structural endpoints [28,29]. The cohort described by Rostami et al. included patients who presented with both radiographic PJK and structural PJF based on their respective definitions. All revision operations were grouped into this category of PJK/PJF reoperation, and therefore excluded from primary revision-PJF analysis [30]. The teriparatide trial reported a need-for-revision PJF endpoint without separately confirming that every operation occurred and was therefore retained as trial-defined PJF rather than pooled with confirmed reoperations [34].

Risk of Bias

One of the 15 nonrandomized comparative studies was judged to have moderate overall ROBINS-I risk, 12 were judged at serious risk, and two at critical risk. The most common basis for a serious judgment was residual confounding from nonrandom treatment allocation, particularly treatment era, surgeon preference, indication, and baseline bone health, with incomplete adjustment for these factors. For example, Wilson et al. directly compared teriparatide-treated patients with poor bone quality to untreated patients with normal bone density, whereas Maruo et al. used an indication-driven teriparatide group compared with a heterogeneous group of non-teriparatide comparators [35,37]. The study by Rostami et al. was judged to be at serious risk of bias because proximal fixation was surgeon-selected and transverse-process hooks were preferentially used for patients perceived to have a higher junctional-failure risk [30]. The randomized teriparatide trial was judged to have some concerns because eight of 64 randomized participants were excluded from the modified intention-to-treat analysis after surgical cancellation [34]. Three teriparatide and five denosumab randomized participants were excluded after surgery was cancelled, leaving modified

intention-to-treat denominators of 29 and 27, respectively. Assessors and analysts were blinded, and while excluding these participants is reasonable, this does not necessarily indicate a high risk of bias. Risk-of-bias judgments for each domain and overall are presented in Figure 2, with supporting assessments for the tether cohorts (Appendix B), randomized trial (Appendix C), and other included studies (Appendix D).

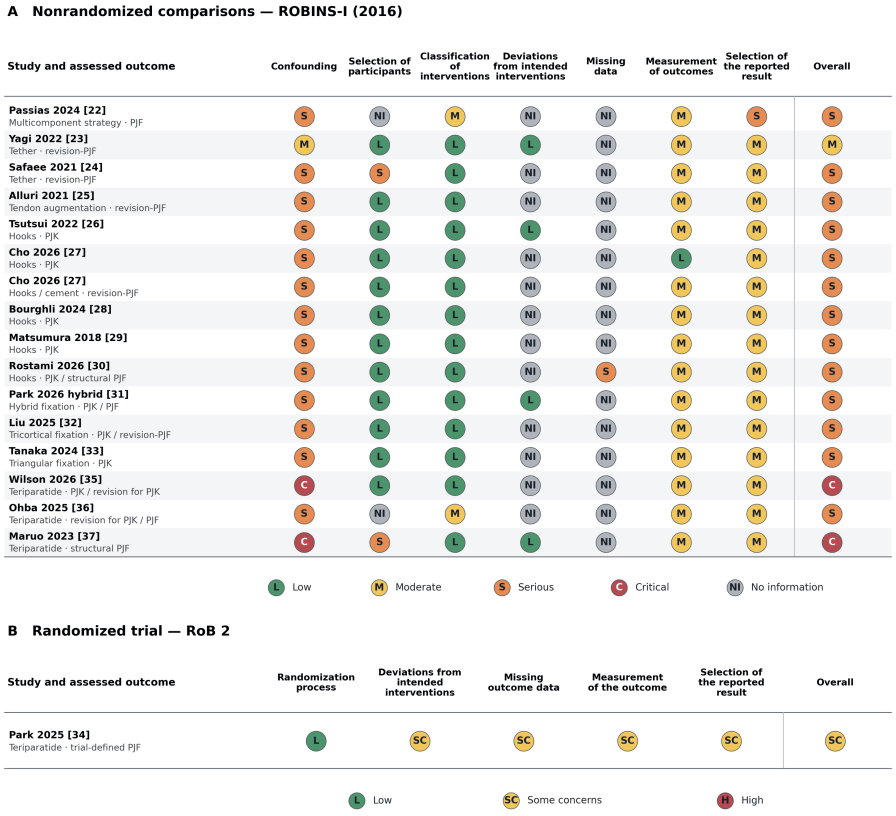


FIGURE 2: Risk of bias assessments

Domain-level and overall risk of bias are shown for the nonrandomized comparisons using ROBINS-I (panel A) and for the randomized trial using RoB 2 (panel B). Outcome-specific judgments and supporting reasons are provided in Appendix B; no information denotes insufficient reporting, not low risk.

Studies included [22-37]

ROBINS-I: Risk Of Bias In Non-randomized Studies of Interventions; RoB 2: revised Cochrane risk-of-bias tool for randomized trials; PJK: proximal junctional kyphosis; PJF: proximal junctional failure

Reporting Bias

Descriptive funnel plots for the tether and hook meta-analyses are presented in Figure 3. With only three and five studies, respectively, these plots do not permit reliable conclusions about publication bias.

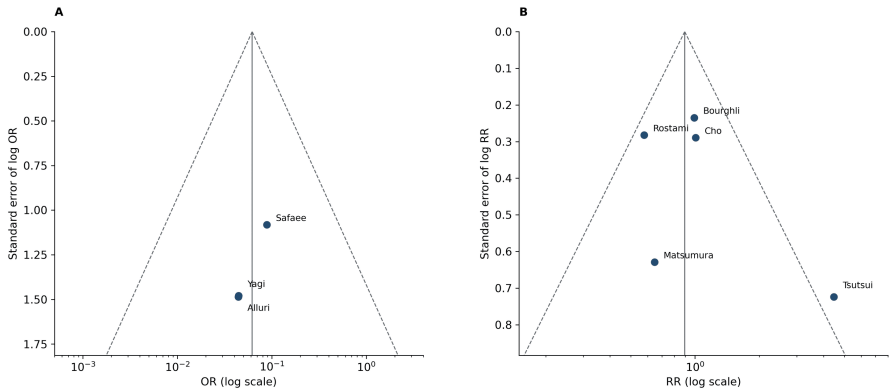


FIGURE 3: Descriptive funnel plots

Study effects are plotted against their standard errors for tether augmentation and revision-requiring PJF (A; three cohorts) and proximal hooks and radiographic PJK (B; five cohorts), with fixed-effect inverse-variance center lines and approximate 95% limits. Panel A adds 0.5 to all four cells of zero-cell studies; the primary binomial analysis uses no correction. The small study counts preclude reliable assessment of publication bias, and no funnel-asymmetry test was performed.

PJF: proximal junctional failure; PJK: proximal junctional kyphosis; OR: odds ratio; RR: risk ratio

Primary Outcome Revision Requiring PJF

Overall, there were three cohorts reporting on ligament/tether augmentation included in the primary meta-analysis. Yagi et al. observed zero revision-PJF events among the 32 tethered patients in their propensity-matched cohort, compared with eight revision-PJF events in 32 controls [23]. Safaee et al. reported a single revision-PJF event among the 40 patients receiving ligament augmentation in comparison to nine events among the 40 propensity-matched controls [24]. No PJF revisions were required among the 49 patients who received semitendinosus allografts compared with six revisions among 34 controls in the cohort study by Alluri et al. [25]. Yagi et al. reported one PJF event among 32 patients receiving tether augmentation, with no revisions performed for PJF. In Safaee et al.'s matched cohort, revision for PJF occurred in one of 40 patients receiving ligament augmentation and nine of 40 controls.

The binomial model estimated an association between ligament/tether augmentation and fewer revision-requiring PJF events (pooled OR 0.0309, 95% CI 0.00171-0.15142; likelihood-ratio P<0.001; Figure *4*). Observed revision events were 1/121 (0.8%) versus 23/106 (21.7%). The no-correction Mantel-Haenszel estimate was OR 0.0325 (95% CI 0.00436-0.24177). For Safaee et al., the propensity-matched 40-versus-40 comparison was used in the primary analysis; matching also included postoperative alignment changes and did not establish control of all baseline confounders [24]. In a sensitivity analysis using the full cohort (8/242 vs. 12/77), the association was attenuated but remained in the same direction and statistically significant (OR, 0.115; 95% CI, 0.047-0.256) [24]. GRADE certainty remained very low because of serious risk of bias, sparse events, imprecision, and possible small-study or publication bias. Excluding Alluri resulted in OR 0.0456 (95% CI 0.00249-0.23252), whereas excluding Safaee resulted in no treated events and a boundary OR of zero. This boundary value does not constitute evidence of stability. The continuity-corrected fixed-effect sensitivity analysis yielded an OR of 0.062 (95% CI 0.014-0.271). The random-effects sensitivity estimate was also 0.062, with a wider modified Hartung-Knapp interval of 0.0024-1.579 that included no effect (Figure *4*). Estimated heterogeneity in these corrected analyses was low (Q=0.210, df=2, P=0.900; I^2=0%; τ^2=0), although the sparse events and small study count limit interpretation. Additional sensitivity analyses are presented in Appendix H, and model diagnostics are provided in Appendix I.

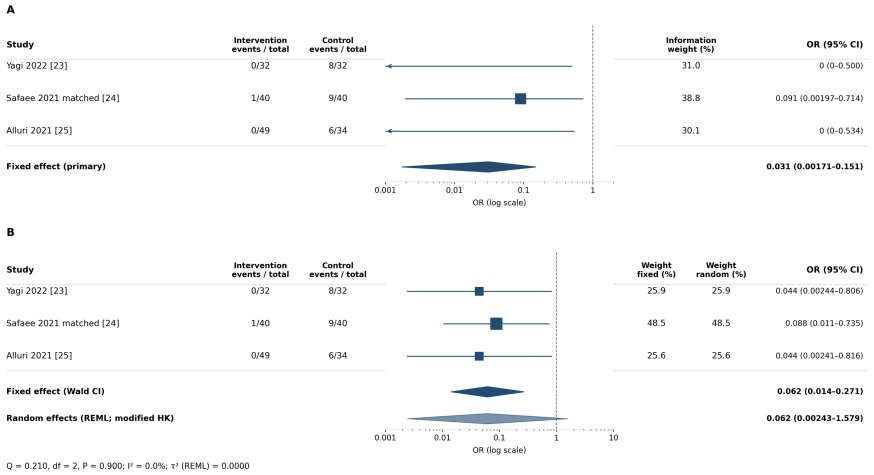


FIGURE 4: Ligament/tether augmentation and revision-requiring PJF

Panel A shows exact conditional study estimates and the primary fixed-effect binomial estimate with profile-likelihood confidence intervals and information weights, without continuity correction or estimation of between-study variance. Panel B shows inverse-variance fixed- and random-effects sensitivity analyses, adding 0.5 to all four cells of zero-cell studies and using modified Hartung-Knapp random-effects intervals with a variance scale of at least 1. Odds ratios below 1 favor augmentation; zero estimates cannot be plotted on the logarithmic axis, and arrows indicate confidence limits below the plotted range.

Studies included [23-25]

PJF: proximal junctional failure; OR: odds ratio; CI: confidence interval; REML: restricted maximum likelihood; HK: Hartung-Knapp

The heterogeneity of the remaining revision-PJF cohorts precluded pooling of analyses. Cho et al. observed two PJF revisions in 47 patients treated with hook fixation compared with two of 21 treated with vertebroplasty and 15 of 71 controls who received no prophylaxis [27]. A comparison by Park et al. of hybrid pedicle-laminar screw fixation with conventional bilateral pedicle screw fixation at the UIV showed four revisions in 89 patients as opposed to nine of 78 patients at the one-year mark [31]. Liu et al. reported one revision in 67 patients treated with tri-cortical augmentation at the UIV compared with three revisions in 48 patients treated with standard proximal screw constructs [32]. Data from these articles were analyzed as separate strategies rather than pooling the data to create an overall prophylaxis estimate.

Secondary Outcome: Radiographic PJK

Five studies examining radiographic PJK and hook versus standard fixation met criteria for the primary synthesis. Tsutsui et al. reported increased rates of PJK when utilizing transverse-process hooks as compared to pedicle screws (10/28 (35.7%) vs 2/25 (8.0%) [26]. Cho et al., Bourghli et al., and Matsumura et al. reported imprecise study-specific results [27-29]. Rostami et al. reported on PJK in 15/70 (21.4%) patients treated with transverse-process hooks compared with 23/62 (37.1%) treated with pedicle screws [30]. The pooled relative risk of 0.91 (95% CI 0.47-1.78; P=0.729; τ^2=0.05760; I^2=49.7%; Figure *5*) provides no clear evidence of a reduction in PJK with hooks compared with pedicle screws; the interval permits both benefit and harm. The fixed-effect sensitivity estimate was similar (RR 0.895, 95% CI 0.672-1.191). Heterogeneity was Q=7.948 (df=4, P=0.093), I^2=49.7%, and τ^2=0.0576 (Figure *5*). Excluding Tsutsui et al. yielded RR 0.83 (95% CI 0.52-1.32), with I^2 estimated as 0% and τ^2=0.01200; this does not establish the absence of heterogeneity [26]. The findings from Rostami et al. included an adjusted OR of 0.329 (95% CI 0.129-0.840; P=0.020) [30]. However, since their model included postoperative alignment variables, the adjusted estimate was considered supportive evidence and was not pooled with the crude RRs. The assessment of certainty was very low, stemming from substantial bias, directional discrepancies, and imprecise measurements. Sensitivities excluding Rostami's three-column-osteotomy cohort, Matsumura's common-tape cohort, and both cohorts gave RRs of 1.05 (95% CI 0.53-2.06), 0.98 (0.36-2.66), and 1.09 (0.37-3.21), respectively.

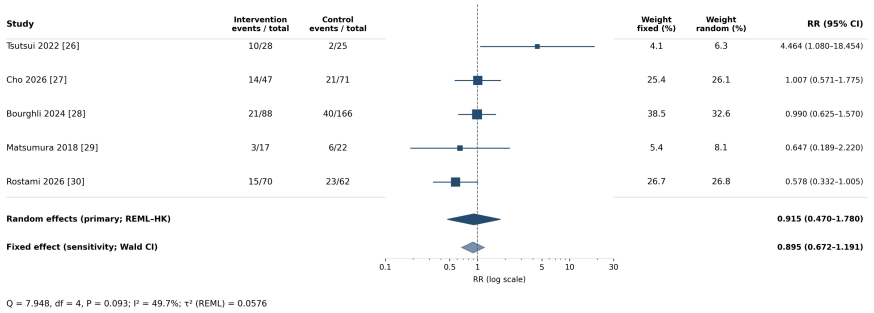


FIGURE 5: Proximal hooks and radiographic PJK

The forest plot compares proximal hooks with pedicle screws across five cohorts using a primary REML random-effects model with unmodified Hartung-Knapp confidence intervals and a fixed-effect sensitivity model with Wald intervals. Both models use inverse-variance weights; square areas represent random-effects weights, and heterogeneity statistics appear below the plot. Risk ratios below 1 favor hooks.

Studies included [26-30]

PJK: proximal junctional kyphosis; RR: risk ratio; CI: confidence interval; REML: restricted maximum likelihood; HK: Hartung-Knapp

Modified Proximal Fixation

Hybrid pedicle-laminar screws, proximal tri-cortical screws, and triangular fixation techniques were pooled separately since they are biomechanically unique constructs. PJK occurred in 15/89 versus 27/78 patients treated with hybrid fixation; 2/67 versus 13/48 with tri-cortical fixation and 4/14 versus 19/40 with triangular fixation (corresponding RRs: 0.49 (95% CI 0.28-0.85), 0.11 (0.03-0.47) and 0.60 (0.25-1.46) respectively) [31-33].

Bone Health Strategies

The randomized study by Park et al. evaluated perioperative teriparatide versus denosumab in osteoporotic postmenopausal women [34]. Trial-defined PJF indicating a need for revision at one year was observed in 1/29 (3.4%) patients treated with teriparatide versus 6/27 (22.2%) treated with denosumab (trial-reported Pearson chi-square P=0.034); radiographic PJK occurred in 5/29 (17.2%) patients and 9/27 (33.3%) patients, respectively [34]. The relative risk for PJF between groups was independently calculated at 0.16 (95% CI 0.02-1.21; Wald P=0.075). A two-sided Fisher's exact test gave P=0.0476. These are different inferential procedures, and the trial did not separately confirm that all seven events resulted in surgery. Similar to previous trends, due to the sparse number of events, there is little confidence in this estimate. Observational studies examining teriparatide could not be pooled with randomized data given significant heterogeneity in indication and treatment for bone health [35-37]. For the broad adult population and confirmed-revision outcome, certainty was very low due to risk-of-bias limitations, imprecision, and indirectness; for the trial's restricted population and need-for-revision outcome, certainty was low without applying the indirectness downgrade (Table *3*).

Comparison and endpoint	Observed events and relative estimate	GRADE assessment and interpretation
Tether augmentation Confirmed PJF revision 3 cohorts, n=227 Yagi [23]; Safaee [24]; Alluri [25]	1/121 (0.8%) vs 23/106 (21.7%). Binomial OR 0.0309 (95% CI 0.00171-0.15142). Crude difference -20.9 percentage points.	Very low. Observational starting level low; risk of bias -1 for residual confounding; imprecision -1 for one treated event and unstable sparse information. Inconsistency/indirectness: no further formal downgrade; common-effect analysis does not prove homogeneity. Publication bias cannot be reliably assessed. Crude difference is not study-adjusted or causal.
Hooks Radiographic PJK 5 cohorts, n=596 Tsutsui [26]; Cho [27]; Bourghli [28]; Matsumura [29]; Rostami [30]	63/250 (25.2%) vs 92/346 (26.6%). RR 0.915 (95% CI 0.470-1.780). τ^2=0.05760; I^2=49.7%.	Very low. Observational starting level low; risk of bias -1, imprecision -1. Clinical inconsistency also concerning; no claim of homogeneity. At observed control risk 26.6%, RR implies approximately 24.3% (12.5%-47.3%); illustrative, not an adjusted absolute causal effect.
Teriparatide vs denosumab Trial-defined PJF indicating need for revision 1 RCT, mITT n=56 Park [34]	1/29 (3.4%) vs 6/27 (22.2%). RR 0.155 (95% CI 0.020-1.207); Wald P=0.075. Source Pearson P=0.034; Fisher check P=0.0476.	Very low for broad all-adult confirmed-revision question: RCT starts high; risk of bias -1 (post-randomization exclusions and incomplete outcome/process certainty), imprecision -1 (seven events, wide interval), indirectness -1 (restricted population and endpoint). For osteoporotic postmenopausal women with the trial-defined endpoint, low certainty without the indirectness downgrade. No inconsistency assessment possible in one trial.
Distinct fixation modifications Radiographic PJK Park hybrid [31]; Liu [32]; Tanaka [33]	Hybrid: 15/89 vs 27/78; RR 0.49 (0.28-0.85). Tri-cortical: 2/67 vs 13/48; RR 0.11 (0.03-0.47). Triangular: 4/14 vs 19/40; RR 0.60 (0.25-1.46).	No combined estimate. Each observational comparison has serious bias concerns and limited events; very low certainty.
Cement augmentation Revision-PJF endpoint Cho [27]; Tani [38]	Cho: 2/21 vs 15/71; RR 0.45 (95% CI 0.11-1.81).	Very low certainty: observational starting level low, risk of bias -1, imprecision -1. Single-arm Tani contributes descriptive evidence only.

TABLE 3: Quantitative findings and certainty of evidence

The table summarizes observed events, effect estimates, and GRADE certainty ratings for each preventive strategy. Revision-requiring PJF, trial-defined PJF, and radiographic PJK are presented separately; events are reported as n/N and effect estimates with 95% confidence intervals.

GRADE: Grading of Recommendations Assessment, Development and Evaluation; PJF: proximal junctional failure; PJK: proximal junctional kyphosis; OR: odds ratio; RR: risk ratio; CI: confidence interval; RCT: randomized controlled trial; mITT: modified intention-to-treat; n/N: events/participants; τ^2: between-study variance; I^2: percentage of variability attributable to between-study heterogeneity

Cement Augmentation

A single study directly compared revision-PJF for construct eligibility with cement augmentation, while a separate study presented only descriptive statistics [27,38]. The estimate for comparative vertebroplasty was also imprecise (RR 0.45, 95% CI 0.11-1.81; very low certainty).

Multicomponent Strategies

Passias et al. reported author-defined PJF after using a multicomponent "good summit" protocol, which included prophylaxis, proximal contouring, and correction of UIV inclination. Results were reported descriptively, as this combined intervention and author-defined endpoint could not be directly compared with studies reporting results of individual preventive strategies or revision requiring PJF [22].

Descriptive funnel plots for tether augmentation and proximal hooks are shown in Figure *4*.

Discussion

Principal Findings

Revision-requiring PJF was the clinically prioritized outcome in this review. Ligament/tether augmentation was associated with fewer revision-PJF events, but the evidence was derived from a small, nonrandomized dataset. Proximal hooks did not show a pooled reduction in radiographic PJK across five strict-construct cohorts, and the effect of modified proximal fixation remained uncertain. The randomized teriparatide trial showed a favorable signal for trial-defined PJF in osteoporotic postmenopausal women, although the estimate was imprecise and population-specific. Overall, the evidence is strategy-specific and remains insufficient to support routine adoption of any single prophylactic approach.

Ligament/tether augmentation was associated with fewer revision-PJF events, but this finding warrants substantial caution. All three studies contributing to the primary tether meta-analysis were retrospective single-center cohorts, and only one of 121 tether-treated patients (0.8%) experienced revision-PJF [23-25]. Such an unusually low event rate is vulnerable to residual confounding from treatment era, surgeon selection, cointerventions, and selective publication; the pooled OR should therefore be interpreted as a signal rather than a precise causal effect.

Our narrower eligibility criteria required pelvic fixation, a thoracic UIV, fusion of at least five levels, adjudication of overlapping cohorts, and revision-requiring PJF as the primary endpoint. The replacement binomial model retained zero-event treatment arms without an arbitrary continuity correction. The pooled OR of 0.0309 is an observational association and should not be interpreted as a causal risk reduction. Table *3* provides the crude absolute difference as descriptive context rather than a study-adjusted pooled risk difference.

Comparison With Previous Reviews

Hsu et al. reported reduced odds of PJF (OR 0.36, 95% CI 0.19-0.69) and PJK (OR 0.44, 95% CI 0.27-0.71) in a broader collection of tether studies [5].

The Hsu et al. analysis included broader spinal-fusion populations than the present review and applied a 0.5 continuity correction to zero-event cells. Funnel-plot asymmetry was present, and trim-and-fill adjustment moved the PJF estimate toward the null [5]. Texakalidis et al. likewise reported lower odds of PJK and PJF with posterior ligamentous augmentation, but included broader patient populations. Their review also described revision-defined PJF, so the distinction concerns construct eligibility and extraction rather than an exclusive focus on clinical endpoints [9].

Babar et al. reported a reduction in PJF with proximal hooks (RR 0.32) but not PJK (RR 0.76), while Jin et al. reported a similar PJF signal in their review of operative strategies [6,7]. Rostami et al. reported lower PJK with transverse-process hooks than with pedicle screws (15/70 (21.4%) vs 23/62 (37.1%); adjusted OR 0.329, 95% CI 0.129-0.840; P=0.020) [30]. Because fixation strategy was surgeon-selected and the adjusted model included postoperative alignment variables, the crude study-level effect was used in the pooled analysis. Incorporating that estimate yielded a pooled RR of 0.91 with a wide confidence interval and no statistically supported reduction in PJK.

Similarly, the growing evidence for cement augmentation demonstrates the impact of construct heterogeneity on pooled estimates. Matsoukas et al. showed decreased rates of PJF revision with vertebral cement augmentation (6.8% vs 13.3%; OR 0.43), but did not observe a statistically significant decrease in PJK [8]. The pooled population included heterogeneity in pelvic fixation, lumbar UIVs, and shorter constructs of five levels or less. Because most cohorts failed to match the construct parameters of this review, only one strict comparative estimate and the descriptive Tani et al. cohort were included [38].

Clinical Interpretation and Safety

A biomechanical explanation may account for the lack of a consistent hook effect. Proximal hooks can reduce facet violation and alter local anchor stiffness at the UIV, but PJF is often driven by vertebral fracture, posterior ligamentous disruption, sagittal overcorrection, and poor bone quality - mechanisms that changing the terminal anchor alone may not address. Hooks may therefore soften the local screw-to-hook transition without sufficiently reducing the global stiffness gradient of a long thoracic-to-pelvis construct [1]. These considerations may explain why some individual studies reported favorable hook effects while the pooled PJK analysis remained inconclusive. The available hook evidence does not establish a reduction in revision surgery for PJF.

Biomechanical data support distinct mechanisms for different prophylactic strategies. Tethers and semirigid constructs aim to reduce the abrupt stiffness transition and distribute motion across adjacent levels, whereas cement augmentation increases vertebral resistance to compressive failure. A systematic review of biomechanical studies found changes in proximal range of motion or intradiscal pressure with tether, tape, and hook configurations and fewer fractures with two-level vertebroplasty under experimental loading [1]. These findings establish biomechanical plausibility but not clinical efficacy. The choice of preventive strategy may reasonably be guided by the suspected predominant failure mechanism while acknowledging the low certainty of comparative clinical evidence. Preoperative bone-health assessment should consider

osteoporosis risk and prior vertebral fractures, including dual-energy X-ray absorptiometry (DXA) when indicated and opportunistic CT Hounsfield-unit assessment when suitable CT images are available. CT attenuation provides complementary risk information rather than an interchangeable osteoporosis diagnosis. Treatment should be individualized, and future trials should stratify by baseline bone quality [39,40].

Park et al. provided the only randomized trial in this review and noted a possible decrease in trial-defined PJF, indicating a need for revision comparing perioperative teriparatide to denosumab [34]. The observational studies examining teriparatide were nearly all affected by indication. In many cases, patients who received anabolic therapy possessed significantly worse baseline bone quality compared to untreated controls. Both Wilson et al. and Maruo et al. similarly attained critical ROBINS-I risk for this reason, and pooling these studies with the randomized trial would have resulted in a more precise but less credible estimate [35,37]. These findings highlight the importance of prospective comparative trials with prespecified treatment algorithms and appropriate adjustment for baseline fracture risk. Broader reviews of perioperative anabolic treatment provide context but should not be equated with confirmed PJF reoperations in the present construct-defined population [19,20]. Viswanathan et al. reported three procedure-related adverse events in two patients undergoing sublaminar band placement. This excluded efficacy cohort informs procedural safety [18].

Limitations and Research Priorities

Several design choices were used to improve clinical comparability. Quantitative syntheses were restricted to thoracic UIVs, pelvic distal fixation, and the stated minimum fusion length. Revision-requiring PJF was assessed separately from radiographic PJK and author-defined structural failure. Overlapping multicenter and institutional cohorts were adjudicated to avoid duplicate patients, and studies at critical ROBINS-I risk were excluded from the primary quantitative synthesis. The rare-event model retained intervention groups with zero events without a continuity correction, and certainty ratings were assigned irrespective of statistical significance. These choices were consistent with recommendations for standardized PJF definitions, clinical outcome reporting, and improved between-study comparability [4].

Most comparisons were retrospective and nonrandomized, and 12 of the 15 observational studies were judged at serious ROBINS-I risk. Residual confounding from treatment allocation by surgeon preference, calendar era, indication, bone quality, or perceived risk was common. The tether meta-analysis included only three retrospective single-center cohorts with 24 total revision-PJF events and only one event among 121 treated patients (0.8%), producing a very low GRADE rating and substantial susceptibility to selection bias. The small number of tether studies also precluded a reliable formal assessment of publication bias. Included variables in Safaee's matching consisted of changes in alignment after surgery. Totals of each arm could not maintain matched-pair correlation. The common-effect model assumes no between-study treatment effect heterogeneity. A tight range of numbers cannot overcome unmeasured confounding.

The hook analysis was also imprecise, with moderate heterogeneity across five studies and inclusion of the high-risk three-column-osteotomy cohort reported by Rostami et al. [30]. Follow-up ranged from six months to at least three years across the included studies. Because consistent hazard ratios, individual time-to-event data, and extractable Kaplan-Meier estimates were unavailable, event-based syntheses relied on the reported follow-up windows; studies with longer follow-up therefore had more opportunity to accrue late failures, which may bias comparisons of cumulative risk. PJF definitions and follow-up schedules were also heterogeneous, and the strict pelvic-fixation criteria may limit generalizability. The absence of patient-level data further prevented robust evaluation of effect modification. Future prevention studies should use clinically consequential, revision-defined PJF as a primary endpoint rather than radiographic PJK alone. Shorter follow-up may miss late revisions for PJF, and differences in follow-up duration remain even after excluding the tether cohort with the shortest follow-up. The trial also defined PJF by the need for revision, without confirming that all affected patients underwent surgery.

Future studies should report whether each proximal junctional event involved fracture, fixation failure, neurologic deficit, hospitalization, invasive treatment, or revision surgery, together with the thoracic UIV level, distal pelvic fixation technique, number of fused levels, bone-health status and treatment, planned sagittal alignment target, and proximal cointerventions. Multicenter randomized trials or well-designed prospective target-trial emulations would be particularly valuable for tether and hook strategies. Future comparative work should prioritize clinically meaningful failure rather than isolated changes in proximal junctional angle.

Conclusions

Among adults undergoing long thoracic-to-pelvis ASD reconstruction, ligament/tether augmentation was associated with fewer revision-requiring PJF events, but certainty is very low because the evidence is based on three retrospective single-center cohorts with sparse events and substantial risk of confounding. Proximal hooks did not show a pooled reduction in radiographic PJK. Evidence for modified proximal fixation and cement augmentation remains insufficient to support routine use, while perioperative teriparatide showed a possible benefit for trial-defined PJF in one small randomized trial of osteoporotic

postmenopausal women; this finding requires replication. These findings support revision-defined PJF, rather than radiographic PJK alone, as the clinically meaningful endpoint for future comparative trials.

Appendices

Appendix A

Search Execution

PubMed/MEDLINE, Embase, Scopus, and the Cochrane Central Register of Controlled Trials were searched on August 8, 2026, without database filters. The searches identified 929, 1,431, 1,069, and 29 records, respectively. English-language eligibility was applied during study selection. The Embase interface was not recorded.

Registration

The review began on June 15, 2026, and was registered in PROSPERO on August 16, 2026 (CRD420261479414). Searching and screening were complete at registration; data extraction, risk-of-bias assessment, and synthesis had not started. The registration specified September 22, 2026 as the anticipated completion date. The protocol and search strategy are available in the public registration record.

Study Selection and Extraction

Microsoft Excel (Microsoft Corp., Redmond, WA, USA) was used to remove 1,871 duplicate records. Six registry or protocol records were removed before screening; no records were excluded using an automated eligibility tool. Of 1,581 screened records, 1,503 were excluded. Seventy-eight reports were sought, one was not retrieved, and 77 were assessed; 60 were excluded, and 17 studies represented by 17 reports were included. The unretrieved report was not identified in the retained records. Two registry entries are included among the 60 exclusions in Appendix G.

Review Procedures

Two reviewers independently performed screening, data extraction, and risk-of-bias assessment, with disagreements resolved by a third reviewer. RoB 2 was used for the randomized trial and ROBINS-I for nonrandomized comparative studies. Outcome-specific GRADE assessments are presented in main-text Table *3*.

Additional Searching

Reference lists were checked. Targeted examination of selected reports on October 26, 2026 supplemented source identification and endpoint interpretation but did not constitute an updated database search. No systematic registry search, additional forward-citation search, author contact, or controlled-vocabulary sensitivity search was performed. The database search cutoff remained August 8, 2026.

PubMed MEDLINE (PubMed Interface)

(("adult spinal deformity"[tiab] OR "adult spinal deformities"[tiab] OR "adult scoliosis"[tiab] OR "degenerative scoliosis"[tiab] OR "spinal deformity"[tiab]) AND ("proximal junctional"[tiab] OR "proximal junctional kyphosis"[tiab] OR "proximal junctional failure"[tiab] OR "proximal junctional fracture"[tiab] OR PJK[tiab] OR PJF[tiab]))

Embase

('adult spinal deformity':ti,ab,kw OR 'adult spinal deformities':ti,ab,kw OR 'adult scoliosis':ti,ab,kw OR 'degenerative scoliosis':ti,ab,kw OR 'spinal deformity':ti,ab,kw) AND ('proximal junctional':ti,ab,kw OR 'proximal junctional kyphosis':ti,ab,kw OR 'proximal junctional failure':ti,ab,kw OR 'proximal junctional fracture':ti,ab,kw OR pjk:ti,ab,kw OR pjf:ti,ab,kw)

Scopus

TITLE-ABS-KEY("adult spinal deformity" OR "adult spinal deformities" OR "adult scoliosis" OR "degenerative scoliosis" OR "spinal deformity") AND TITLE-ABS-KEY("proximal junctional" OR "proximal junctional kyphosis" OR "proximal junctional failure" OR "proximal junctional fracture" OR PJK OR PJF)

Cochrane CENTRAL

("adult spinal deformity" OR "adult spinal deformities" OR "adult scoliosis" OR "degenerative scoliosis" OR

"spinal deformity"):ti,ab,kw AND ("proximal junctional" OR "proximal junctional kyphosis" OR "proximal junctional failure" OR "proximal junctional fracture" OR PJK OR PJF):ti,ab,kw

Appendix B

ROBINS-I domain	Yagi tether [23]	Safaee tether [24]	Alluri tendon [25]
Confounding	Moderate concern: matching includes BMD and alignment; residual era and unmeasured confounding possible.	Serious concern: historical treatment, residual bone/frailty differences, postoperative matching variables and cointerventions.	Serious concern: surgeon/era selection and inadequate bone-health control.
Selection into study	NI regarding the complete selection/attrition mechanism; matched sample selected from larger cohort.	NI for complete selection mechanism; matched historical subset and unequal follow-up.	NI for complete follow-up selection mechanism; retrospective cohort.
Intervention classification	Low concern: operative tether exposure described.	Low concern: operative augmentation exposure described.	Low concern: operative allograft exposure described.
Deviations from interventions	NI for target-trial adherence/deviation effect; concomitant bone treatment common.	NI; hooks/vertebroplasty and other care vary.	NI; operative cointerventions and postoperative care not causally isolated.
Missing data	NI for outcome-specific missing-data consequences after eligibility selection.	NI; unequal observation duration explicitly documented.	NI; minimum follow-up eligibility and incomplete loss-to-follow-up detail.
Outcome measurement	Revision status ascertainable; decision to operate can depend on unblinded clinical care.	Revision status ascertainable; thresholds for surgery may change by era.	Revision-based definition explicit; unblinded decisions may differ.
Selection of reported result	NI without a dated analysis plan for the source outcome.	NI without a dated plan for matched/full analyses.	NI without a dated source analysis plan.
Overall	Moderate	Serious	Serious

TABLE 4: Risk of bias assessment: tether cohorts assessed using ROBINS-I

The table presents domain-level and overall risk-of-bias judgments with the supporting reasons for each assessed comparison and outcome. Nonrandomized comparisons were assessed with ROBINS-I and the randomized trial with RoB 2; no information indicates insufficient reporting to judge a domain.

BMD: bone mineral density; BMI: body mass index; DXA: dual-energy X-ray absorptiometry; HU: Hounsfield units; NI: no information; PJF: proximal junctional failure; PJK: proximal junctional kyphosis; RoB 2: revised Cochrane risk-of-bias tool for randomized trials; ROBINS-I: Risk Of Bias In Non-randomized Studies of Interventions; UIV: upper instrumented vertebra

Appendix C

RoB 2 domain	Assessment and supporting evidence
Randomization process	Low risk: independent random-number generation and concealed allocation were described.
Deviations from intended interventions	Some concerns: participants and surgeons were unblinded; three teriparatide and five denosumab participants were excluded after surgery cancellation.
Missing outcome data	Some concerns: imputation was reported, with limited outcome-specific information on the extent and consequences of missing data. Preoperative cancellations were distinguished from postoperative loss to follow-up.
Measurement of the outcome	Some concerns: assessors and analysts were blinded, but the clinically determined need-for-revision endpoint could be influenced by unblinded treatment.
Selection of reported result	Some concerns regarding selection of the reported PJF endpoint and analysis population.
Overall	Some concerns: The modified intention-to-treat analysis included 29 teriparatide and 27 denosumab participants. The per-protocol analysis additionally excluded two teriparatide participants with adverse events.

TABLE 5: Risk of bias assessment: Park randomized trial[34] assessed with RoB-2

Risk of bias is summarized by domain for the tether cohorts and randomized trial and by overall judgment for the remaining studies. Two reviewers assessed risk independently, with disagreements resolved by a third reviewer. NI denotes insufficient reported information and does not indicate low risk.

BMD: bone mineral density; NI: no information; PJF: proximal junctional failure; RCT: randomized controlled trial; RoB 2: revised Cochrane risk-of-bias tool for randomized trials; ROBINS-I: Risk Of Bias In Non-randomized Studies of Interventions; TPH: transverse process hook

Appendix D

Study	Overall risk of bias	Risk of bias rationale
Passias et al. [22]	Serious	Composite/data-derived strategy; residual confounding and selective-analysis concerns.
Tsutsui et al. [26]	Serious	Sequential treatment eras; no robust adjustment.
Cho et al. [27]	Serious	Era/preference-based intervention selection; mediator-adjusted models.
Park et al. (hybrid) [31]	Serious	Sequential historical comparison.
Wilson et al. [35]	Critical	Treated poor-bone cohort vs untreated normal-BMD controls.
Ohba et al. [36]	Serious	Treatment/timing confounded by bone health; adherence/duration uncertain.
Liu et al. [32]	Serious	Historical control; evolving cointervention during rollout.
Tanaka et al. [33]	Serious	Technique changed after prior failures; no adjustment; reporting inconsistencies.
Bourghli et al. [28]	Serious	Baseline/center differences and incomplete causal adjustment.
Maruo et al. [37]	Critical	Indication-driven treatment and heterogeneous comparator.
Matsumura et al. [29]	Serious	Sequential treatment eras; small cohort.
Tani et al. [38]	Not assessed	No comparative treatment effect.
Rostami et al. [30]	Serious	Retrospective single-surgeon study; surgeon-selected fixation evolved over time and TPH was preferentially used in perceived high-risk patients.

TABLE 6: Other included studies

Risk of bias is summarized by domain for the tether cohorts and randomized trial and by overall judgment for the remaining studies. Two reviewers assessed risk independently, with disagreements resolved by a third reviewer. NI denotes insufficient reported information and does not indicate low risk.

BMD: bone mineral density; NI: no information; PJF: proximal junctional failure; RCT: randomized controlled trial; RoB 2: revised Cochrane risk-of-bias tool for randomized trials; ROBINS-I: Risk Of Bias In Non-randomized Studies of Interventions; TPH: transverse process hook

Appendix E

Cohort family	Treatment in the synthesis	Overlap considerations
Yagi Keio [23]	Separate institutional family from Safaee UCSF and Alluri USC. Matched 32/32 comparison only.	No combined cross-strategy pool is used. The primary tether analysis includes one Yagi comparison.
Safaee UCSF [24]	The matched 40/40 and full 242/77 cohorts are overlapping representations. The matched cohort was used in the primary analysis and the full cohort in a separate sensitivity analysis.	Earlier Safaee reports were not counted as independent cohorts. Matched and full-cohort observations were never combined within the same analysis.
Alluri USC [25]	One 49/34 comparison used.	Related USC technique reports are not added as independent comparisons in the primary analysis.
Park South Korea [31,34]	RCT and hybrid-fixation reports answer different intervention questions; no combined intervention pool.	These reports were evaluated within separate intervention-specific analyses.
Other cohort families	Passias [22]/Line ISSG; Bourghli [28] ESSG; UVA tether; Johns Hopkins cement; Rostami [30] institutional 3CO cohorts were considered when assessing potential overlap.	These cohort families were evaluated within their respective intervention comparisons and were not combined into a single cross-intervention estimate.

TABLE 7: Cohort overlap and included in the analyses

The table identifies related cohorts and explains their use in the primary and sensitivity analyses. Matched and full-cohort data from the same study were evaluated separately to avoid counting participants twice.

3CO: three-column osteotomy; ESSG: European Spine Study Group; ISSG: International Spine Study Group; RCT: randomized controlled trial; UCSF: University of California San Francisco; USC: University of Southern California; UVA: University of Virginia

Appendix F

Study and comparison	Endpoint and counts	Source and follow-up
Yagi 2022 matched [23]	Confirmed revision-PJF: 0/32 vs 8/32. Broader PJF: 1/32 vs 8/32.	Results and Discussion: Table 4 of Yagi 2022 concerns broader PJF. At least two years. Thoracic T9-T11 to pelvis.
Safaee 2021 matched [24]	Confirmed PJF reoperation: 1/40 vs 9/40.	Table 4 of Safaee 2021, Results. Minimum 12 months; matched mean 21 vs 30 months. All thoracic UIV and pelvic fixation.
Safaee full cohort [24]	Confirmed PJF reoperation: 8/242 vs 12/77.	Main Results and full-cohort comparison. Used in a separate sensitivity analysis in place of the matched cohort.
Alluri 2021 [25]	Revision-defined PJF: 0/49 vs 6/34. All-cause reoperations 15/49 vs 17/34 are not substituted.	Results, Figure 2 of Alluri 2021. Minimum six months; thoracic-to-pelvis with unspecified pelvic-device subtype.
Park 2025 RCT [34]	Trial-defined PJF indicating need for revision: 1/29 vs 6/27. PJK: 5/29 vs 9/27.	Figure 3 of Park 2025; one year. Modified intention-to-treat population after cancellations. Not confirmed performed revision for every event.

TABLE 8: Endpoint definitions and source locations

The table links outcome definitions and source locations to the event counts used in the analyses. Counts are shown as events/participants, with the intervention group first. Confirmed revision surgery, trial-defined need for revision, radiographic PJK, and structural PJF were treated as distinct outcomes.

PJF: proximal junctional failure; PJK: proximal junctional kyphosis; RCT: randomized controlled trial; UIV: upper instrumented vertebra

The Cho hook and cement comparisons share a control group and were analyzed separately.

Appendix G

No.	Citation and year	DOI or registry identifier	Code	Specific exclusion reason
1	Fields et al. - Can patient-specific precontoured rod instrumentation reduce the rate of proximal junctional kyphosis for adult spinal deformity? A propensity score-matched analysis (2026).	10.3171/2026.1.spine251110	P	Only ~80% of patients were fused to the sacrum/pelvis, and the reported subgroup combined sacral and pelvic distal fixation; pelvic-only outcomes were not separately extractable.
2	Oh et al. - Impact of Preoperative Teriparatide Use on Proximal Junctional Kyphosis Prevention in Osteopenic/Osteoporotic Patients Undergoing Adult Spinal Deformity Surgery: A Propensity Score-Matched Study (2026).	10.3390/jcm15145682	P	The matched cohort included nonpelvic distal fixation and UIVs extending into the lumbar spine (including L2/T11-L1). No jointly eligible thoracic-UIV, pelvic-fixation subgroup was separately extractable.
3	Hyun et al. - Proximal junction uninstrumented bone fusion for proximal junctional kyphosis/failure prevention: a retrospective matched cohort study in Korea (2026).	10.31616/asj.2025.0768	P	The report did not provide a separately extractable subgroup meeting all strict construct criteria simultaneously (thoracic UIV, fusion of at least 5 levels, and distal pelvic fixation).
4	Sargut et al. - Standardized translaminar spinal tethering to prevent proximal junctional kyphosis in adult spinal deformity correction surgery (2026).	10.1007/s00586-025-09267-0	P	Pelvic fixation was not universal (24/25 vs 33/34), minimum follow-up could be as short as 3 months, and no jointly eligible thoracic-UIV/pelvic-fixation/≥6-month subgroup was separately extractable.
5	Schimmel et al. - Brace yourself: routine postoperative bracing after adult spinal deformity surgery offers no clinical benefit and may increase harm (2025).	10.21037/jss-25-121	I	Postoperative bracing was not an eligible prevention component for the primary strategy-specific synthesis.
6	Sawada et al. - Effect of romosozumab administration on proximal junctional kyphosis in corrective spinal fusion surgery (2025).	10.1016/j.spinee.2024.12.021	P	Pelvic fixation was present only in a subset of the cohort; outcomes for the strict thoracic-to-pelvis subgroup were not separately extractable.
7	Park et al. - Effects of Transverse Process Hook Fixation for Preventing Proximal Junctional Kyphosis/Failure in Adult Spinal Deformity Surgery: A Multiple Regression Analysis Adjusting for Confounding Factors (2025).	10.1177/21925682251319758	P	Fusion was reported to the sacrum and pelvic fixation was routine but not universal; an all-pelvic-fixation subgroup was not separately extractable.
8	Park et al. - Hook Fixation at Uppermost Instrumented Vertebra +1 Reduced Proximal Junctional Failure in Adult Patients With Spinal Deformity Having Achieved Optimal Deformity Correction by Sagittal Age-Adjusted Score (2025).	10.1227/neu.0000000000003075	P	Pelvic fixation was not universal in the analyzed cohort; outcomes for a strict thoracic-to-pelvis subgroup were not separately extractable.

9	Shahi et al. - Post-Operative Hyperextension Bracing Has the Potential to Reduce Proximal Junctional Kyphosis: A Propensity Matched Analysis of Braced versus Non-braced Cohorts (2025).	10.1177/21925682241260278	I	Postoperative hyperextension bracing was not an eligible prevention component for the primary strategy-specific synthesis.
10	Park et al. - Preventive Effects of Cement and Hook Augmentation on Proximal Junctional Kyphosis Development in Adult Spinal Deformity Surgery: Multiple Regression Analyses With Adjustment for Confounding Factors (2025).	10.1227/neu.0000000000003454	P	The cohort included sacral rather than uniformly pelvic distal fixation; an eligible pelvic-fixation subgroup was not separately extractable.
11	Passias et al. - Proximal Junctional Kyphosis and Failure Prophylaxis Improves Cost Efficacy, While Maintaining Optimal Alignment, in Adult Spinal Deformity Surgery (2025).	10.1227/neu.0000000000003427	I	Cost-effectiveness analysis without an independent eligible comparative prevention effect for the clinical synthesis.
12	Yoo et al. - Application of Transverse Process Hooks at Distal Thoracic Vertebrae in Uppermost Vertebral Instrumentation for Adult Spinal Deformity Surgery: Special Focus on Delayed-Onset Neurologic Deficits (2024).	10.14245/ns.2448804.402	P	The distal construct was reported to the sacrum rather than verified pelvic fixation for all patients; no strict pelvic subgroup was separately extractable.
13	Sargut et al. - Application of a translaminar spinal tethering system to prevent proximal junctional kyphosis in adult spinal deformity correction (2024).	10.1016/j.bas.2024.103962	O	Earlier/meeting report of the Sargut translaminar-tether cohort; superseded by the later full-text publication and contributed no independent outcome window.
14	Mohanty et al. - Impact of Teriparatide on Complications and Patient-Reported Outcomes of Patients Undergoing Long Spinal Fusion According to Bone Density (2024).	10.2106/jbjs.23.00272	P	Pelvic fixation was not universal; the eligible thoracic-to-pelvis treatment comparison could not be isolated.
15	Shen et al. - Osteoporosis Treatment and Outcomes in Patients Undergoing Adult Spinal Deformity Surgery (2024).	10.1016/j.wneu.2024.08.053	I	Broad osteoporosis-treatment/outcomes comparison without an isolated eligible preventive-treatment contrast matching the intervention question.
16	Bartolozzi et al. - Polymethyl methacrylate augmentation and proximal junctional kyphosis in adult spinal deformity patients (2024).	10.1007/s00586-023-07966-0	P	Distal fixation was mixed (sacrum or pelvis); pelvic-only outcomes were not separately extractable.
17	Lee et al. - Radiographic and Clinical Outcomes of Transverse Process Hook Placement at the Proximal Thoracic Upper Instrumented Vertebra in Adult Spinal Deformity Surgery (2024).	10.14245/ns.2347116.558	P	Pelvic fixation was not uniform across the cohort; outcomes for the strict thoracic-to-pelvis subgroup were unavailable.
18	Hospital for Special Surgery, New York. The use of a novel post-operative thoracolumosacral orthosis for prevention of proximal junctional kyphosis after adult	NCT06491030	I	Trial registration for postoperative thoracolumbosacral orthosis/bracing, an intervention outside the

	spinal deformity surgery [Internet]. ClinicalTrials.gov; 2024 [cited 2026 Oct 28]. Trial-registry entry.			strategy-specific synthesis; no eligible independent treatment-effect report.
19	Passias et al. - 11. The impact of lumbopelvic realignment vs prevention strategies at the upper-instrumented vertebra on rates of junctional failure following adult spinal deformity surgery (2023).	10.1016/j.spinee.2023.06.063	O	Conference/meeting report superseded by the subsequent Passias full publication; no independent data contribution.
20	Gibbs et al. - Delayed stenosis associated with sublaminar band placement in the thoracic spine for proximal junctional kyphosis (2023).	10.25259/sni_375_2022	D	Noncomparative complication/case-based report focused on delayed stenosis after sublaminar-band placement rather than an eligible comparative prevention effect.
21	Yoo et al. - P118: Effect of transverse process hook of UIV instruments on prevention of re-operation associated myelopathy following adult spinal deformity surgery (2023).	10.1177/21925682231166109	O	Conference/meeting report overlapping the Yoo transverse-process-hook cohort; superseded by the later full-text article and contributed no independent data.
22	Passias et al. - P131: The summit versus the base: Which aspect of the construct has more influence on the development of proximal junctional kyphosis following adult spinal deformity surgery? (2023).	10.1177/21925682231166109	I	Summit-versus-base/alignment analysis did not isolate an eligible prevention intervention/comparator contrast.
23	Gassie et al. - Percutaneous Vertebroplasty and Upper Instrumented Vertebra Cement Augmentation Reducing Early Proximal Junctional Kyphosis and Failure Rate in Adult Spinal Deformity: Case Series and Literature Review (2023).	10.1227/ons.0000000000000802	P	The cohort included L2 UIV cases and some patients with less than 6 months of follow-up; a jointly eligible subgroup was not separately extractable.
24	Lord et al. - The Impact of Global Alignment and Proportion Score and Bracing on Proximal Junctional Kyphosis in Adult Spinal Deformity (2023).	10.1177/21925682211001812	I	GAP/alignment and bracing analysis did not provide an isolated eligible prevention contrast under the strategy definitions.
25	Ye et al. - Use of multiple rods and proximal junctional kyphosis in adult spinal deformity surgery (2023).	10.3171/2023.4.spine23209	I	Multi-rod configuration was evaluated as a global construct strategy rather than an isolated eligible proximal-junction prevention intervention.
26	Passias et al. - 144. Prophylactic proximal junctional measures improves cost efficacy of adult spinal deformity surgery, with optimal cost utility seen in those with concurrent optimal realignment (2022).	10.1016/j.spinee.2022.06.162	O	Overlapping ISSG cost-utility/meeting analysis; no independent patient/outcome contribution beyond retained reports.
27	Oquendo et al. - 54. PMMA augmentation is not protective against proximal junctional kyphosis in adult spinal deformity correction bridging the thoracolumbar	10.1016/j.spinee.2022.06.068	O	Meeting abstract subsequently represented by the full Bartolozzi PMMA report; no

	junction (2022).			independent contribution.
28	Durand et al. - Low-Density Pedicle Screw Constructs Are Associated with Lower Incidence of Proximal Junctional Failure in Adult Spinal Deformity Surgery (2022).	10.1097/brs.0000000000004290	P	The reported sacropelvic construct definition included patients without confirmed pelvic fixation; pelvic-only outcomes were not separately extractable.
29	Kolz et al. - Postoperative and Intraoperative Cement Augmentation for Spinal Fusion (2022).	10.1016/j.wneu.2022.01.046	P	Mixed spinal-fusion indications and constructs; an eligible adult-ASD thoracic-to-pelvis subgroup was not separately extractable.
30	Rabinovich et al. - A Novel Weave Tether Technique for Proximal Junctional Kyphosis Prevention in 71 Adult Spinal Deformity Patients: A Preliminary Case Series Assessing Early Complications and Efficacy (2021).	10.1093/ons/opab305	P	Iliac fixation was not universal (approximately 93%); the strict pelvic-fixation subgroup was not separately extractable.
31	Rodnoi et al. - Ligament Augmentation With Mersilene Tape Reduces the Rates of Proximal Junctional Kyphosis and Failure in Adult Spinal Deformity (2021).	10.14245/ns.2142420.210	P	The treated cohort included UIV levels T9-L1; a thoracic-only treated denominator/outcome set was not separately extractable.
32	Cazzulino et al. - Soft Landing technique as a possible prevention strategy for proximal junctional failure following adult spinal deformity surgery (2021).	10.21037/jss-20-622	P	The series included nonpelvic distal constructs; outcomes for the strict thoracic-to-pelvis subgroup were not separately extractable.
33	Park et al. - The Hybrid Open Muscle-Sparing Approach in Adult Spinal Deformity Patients Undergoing Lower Thoracic Fusion to the Pelvis (2021).	10.14245/ns.2040334.167	D	Technical/noncomparative muscle-sparing approach report without an eligible comparative prevention effect.
34	Durand et al. - 84. Low density pedicle screw constructs are associated with lower incidence of proximal junctional failure in adult spinal deformity surgery (2020).	10.1016/j.spinee.2020.05.187	O	Conference abstract superseded by the later full Durand low-density-screw publication; no independent data contribution.
35	Seoul National University Bundang Hospital. Comparative study for incidence of proximal junctional kyphosis between parathyroid hormone and denosumab following adult spinal deformity surgery: a prospective, randomized controlled trial [Internet]. ClinicalTrials.gov; 2020 [cited 2026 Oct 28]. Trial-registry entry.	NCT04241211	O	Trial registration linked to the included Park et al. 2025 randomized trial (DOI: 10.1007/s00198-025-07449-6). It contributes protocol information but no independent study population or treatment-effect estimate.
36	Line et al. - Effective Prevention of Proximal Junctional Failure in Adult Spinal Deformity Surgery Requires a Combination of Surgical Implant Prophylaxis and Avoidance of Sagittal Alignment Overcorrection (2020).	10.1097/brs.0000000000003249	P	Pelvic fixation was not universal in the analyzed cohort; the strict thoracic-to-pelvis subgroup was not separately extractable.
				Conference report of

37	Crawford et al. - P86. Postoperative bracing does not improve the rate of proximal junctional kyphosis in adult spinal deformity (2020).	10.1016/j.spinee.2020.05.484	I	postoperative bracing, an intervention not eligible for the prevention synthesis.
38	Rodriguez-Fontan et al. - Strap stabilization for proximal junctional kyphosis prevention in instrumented posterior spinal fusion (2020).	10.1007/s00586-020-06291-0	P	Mixed lumbar/thoracic UIVs and mixed sacral/pelvic distal fixation; no jointly eligible thoracic-to-pelvis subgroup was separately extractable.
39	Han et al. - Effect of Vertebroplasty at the Upper Instrumented Vertebra and Upper Instrumented Vertebra +1 for Prevention of Proximal Junctional Failure in Adult Spinal Deformity Surgery: A Comparative Matched-Cohort Study (2019).	10.1016/j.wneu.2018.12.113	P	Distal fixation included sacral constructs and UIV level was mixed; the strict eligible subgroup could not be isolated.
40	Dafrawy et al. - P143. Efficacy of multi-rod constructs: comparison of two different 4-rod and 3-rod configurations in adult spinal deformity patients with long fusions to the sacrum (2019).	10.1016/j.spinee.2019.05.568	I	Multi-rod configuration comparison addressed rod/construct strategy rather than an isolated eligible proximal-junction prevention intervention.
41	Alluri et al. - P93. Semitendinosus ligament reinforcement for prevention of proximal junctional kyphosis and failure in adult spinal deformity (2019).	10.1016/j.spinee.2019.05.518	O	Earlier semitendinosus-reinforcement abstract superseded by the later Alluri full-text cohort; no independent contribution.
42	Lee et al. - Preliminary report on the flexible rod technique for prevention of proximal junctional kyphosis following long-segment fusion to the sacrum in adult spinal deformity (2019).	10.3171/2019.4.spine1915	P	Constructs extended from T10 to S1 rather than the pelvis; distal fixation criterion not met.
43	Daniels et al. - Proximal junctional failure prevention in adult spinal deformity surgery utilizing interlaminar fixation constructs (2019).	10.4081/or.2019.8068	D	Technical/noncomparative report of interlaminar fixation constructs without an eligible comparative clinical treatment effect.
44	Buell et al. - A pilot study on posterior polyester tethers as an anti-PJK device for multilevel spinal instrumentation for adult spinal deformity (2018).	10.1177/2192568218771030	O	Earlier tether meeting abstract from an overlapping cohort; no independent extractable contribution beyond later reports.
45	Cho et al. - Attenuation of proximal junctional kyphosis using sub-laminar polyester tension bands (2018).	10.1177/2192568218771072	O	Earlier sublaminar-tension-band meeting report from an overlapping tether cohort; no independent extractable contribution.
46	Safaee et al. - Ligament augmentation for prevention of proximal junctional kyphosis and proximal junctional failure in adult spinal deformity (2018).	10.3171/2017.9.spine1710	O	Earlier Safaee ligament-augmentation report from the same institutional cohort; superseded by Safaee 2021 and not pooled independently.
47	Viswanathan et al. - Prospective assessment of the safety and early outcomes of sublaminar band placement for the prevention of proximal junctional kyphosis (2018).	10.3171/2017.8.spine17672	P	Distal fixation was mixed (L5/S1/ilium) and minimum follow-up was only 3 months; a patient-level subgroup meeting both pelvic-fixation and

				≥6-month criteria was not separately extractable.
48	Wilkening et al. - Staggered instrumentation in adults undergoing posterior spinal fusion: A novel technique for soft tissue preservation at the upper instrumented vertebra (2018).	10.1177/2192568218771072	D	Technical description of staggered instrumentation without an eligible comparative clinical prevention effect.
49	Zygourakis CC, DiGiorgio AM, Crutcher CL 2nd, Safaee M, Nicholls FH, Dalle Ore C, et al. The safety and efficacy of CT-guided, fluoroscopy-free vertebroplasty in adult spinal deformity surgery. World Neurosurg. 2018;116:e944-e950.	10.1016/j.wneu.2018.05.139; PMID:29857213	P	Strict construct eligibility of the historical comparator could not be verified; an eligible thoracic-to-pelvis comparison was not separately extractable.
50	Ghobrial et al. - Prophylactic vertebral cement augmentation at the uppermost instrumented vertebra and rostral adjacent vertebra for the prevention of proximal junctional kyphosis and failure following long-segment fusion for adult spinal deformity (2017).	10.1016/j.spinee.2017.05.015	P	Although 81/85 patients were fused to the pelvis, five patients had an L1 UIV; the jointly eligible thoracic-UIV/pelvic subgroup was not separately reported.
51	Raman et al. - The effect of prophylactic vertebroplasty on the incidence of proximal junctional kyphosis and proximal junctional failure following posterior spinal fusion in adult spinal deformity: a 5-year follow-up study (2017).	10.1016/j.spinee.2017.05.017	P	Pelvic fixation was not universal; outcomes for the strict thoracic-to-pelvis subgroup were not separately extractable.
52	Berven SH. Clinical incidence of PJK/ASD in adult deformity surgery: a comparison of rigid fixation and semirigid fixation-rigid. Spine (Phila Pa 1976). 2016;41 Suppl 7:S35-S36.	10.1097/BRS.0000000000001439; PMID:27015073	D	Noncomparative/technical discussion of rigid versus semirigid fixation without an extractable eligible comparative clinical effect.
53	Line et al. - Failure patterns of prophylactic techniques utilized to prevent proximal junctional failure following adult spinal deformity surgery are predictable: A guideline for surgeons (2016).	10.1016/j.spinee.2016.07.355	O	Earlier overlapping ISSG prophylaxis report; no independent contribution after cohort-overlap adjudication.
54	Yagi et al. - Teriparatide improves volumetric bone mineral density and fine bone structure in the UIV+1 vertebra, and reduces bone failure type PJK after surgery for adult spinal deformity (2016).	10.1007/s00198-016-3676-6	P	Pelvic fixation was present only in a subset; outcomes for the strict thoracic-to-pelvis teriparatide subgroup were not separately extractable.
55	Sandquist et al. - Preventing proximal junctional failure in long segmental instrumented cases of adult degenerative scoliosis using a multilevel stabilization screw technique (2015).	10.4103/2152-7806.159383	P	Distal fixation was mixed and not uniformly pelvic; the eligible thoracic-to-pelvis subgroup was not separately extractable.
56	Theologis et al. - Prevention of Acute Proximal Junctional Fractures After Long Thoracolumbar Posterior Fusions for Adult Spinal Deformity Using 2-level Cement Augmentation at the Upper Instrumented Vertebra and the Vertebra 1 Level Proximal to the Upper Instrumented Vertebra (2015).	10.1097/brs.0000000000001043	P	Comparator groups included lumbar UIV cases; a thoracic-UIV comparison meeting the strict construct criteria was not separately extractable.
57	Martin et al. - Preliminary Results of the Effect of Prophylactic Vertebroplasty on the Incidence of Proximal Junctional Complications After Posterior	10.1016/j.jspd.2013.01.005	P	Pelvic fixation was not universal; the strict thoracic-to-pelvis subgroup was not

	Spinal Fusion to the Low Thoracic Spine (2013).			separately extractable.
58	Hassanzadeh et al. - Type of Anchor at the Proximal Fusion Level Has a Significant Effect on the Incidence of Proximal Junctional Kyphosis and Outcome in Adults After Long Posterior Spinal Fusion (2013).	10.1016/j.jspd.2013.05.008	P	Distal pelvic fixation was not established for all patients; no separately extractable strict pelvic-fixation subgroup.
59	Hassanzadeh et al. - Proximal junctional kyphosis in adults following long posterior spinal fusion: Comparison between two different construct at the upper end of the construct (2011).	10.1016/j.spinee.2011.08.078	P	Construct reporting did not establish universal pelvic fixation for the compared groups; an eligible thoracic-to-pelvis subgroup could not be verified/extracted.
60	Mullin et al. - The Use of Tethers and Hooks is Independently Associated With a Reduced Rate of Surgical Revisions for Proximal Junctional Kyphosis in Patients Undergoing Adult Spinal Deformity Surgery (2026).	10.1227/neu.0000000000003964_263	A	Conference abstract/meeting proceeding only; no eligible full-text article was available for inclusion as an independent study.

TABLE 9: Excluded reports with associated reasoning

The table lists the 60 excluded reports and assigns one primary reason to each. Exclusions comprised 32 population, construct, or follow-up mismatches; 10 intervention or comparator mismatches; five ineligible study designs; 12 overlapping or superseded reports; and one abstract-only report.

A: abstract-only report; ASD: adult spinal deformity; CT: computed tomography; D: ineligible study design; DOI: digital object identifier; GAP: Global Alignment and Proportion; I: ineligible intervention or comparator; ISSG: International Spine Study Group; O: overlapping or superseded report; P: ineligible population, construct, or follow-up; PJF: proximal junctional failure; PJK: proximal junctional kyphosis; PMMA: polymethylmethacrylate; PMID: PubMed identifier; UIV: upper instrumented vertebra

Appendix H

Tether analysis	OR	95% CI	Interpretation
Primary binomial model	0.03090	0.00171-0.15142	Three cohorts; confirmed revisions
Mantel-Haenszel	0.03248	0.00436-0.24177	No correction; RBG variance
Conditional profile	0.03192	0.00177-0.15565	Likelihood interval, not exact CI
Full Safaee cohort [24]	0.11543	0.04700-0.25596	Full cohort (8/242 vs 12/77) analyzed instead of matched cohort (1/40 vs 9/40)
Omit Yagi [23]	0.04613	0.00252-0.23780	Two cohorts
Omit Safaee [24]	0 (boundary)	0-0.10021	All treated events zero; no finite log OR
Omit Alluri [25]	0.04557	0.00249-0.23252	Restricts included cohorts to a minimum of 12 months of follow-up and excludes the cohort with unspecified pelvic-device subtype

TABLE 10: Sensitivity analyses

The table compares the primary pooled estimate for revision-requiring PJF with alternative models and cohort-exclusion analyses. Omitting Safaee leaves no events in the intervention groups, producing a boundary estimate of zero rather than evidence of a stable treatment effect.

CI: confidence interval; OR: odds ratio; PJF: proximal junctional failure; RBG: Robins-Breslow-Greenland

Appendix I

```
"""Supplementary Appendix S2. Aggregate-data analysis of PJF prevention.
Primary analyses, sensitivity models, forest-plot weights and funnel-plot inputs."""
from operator import getitem
import json, sys
from pathlib import Path
import numpy as np
import scipy
from scipy.special import expit, logsumexp, gammaln
from scipy.optimize import minimize_scalar, brentq, minimize
from scipy.stats import chi2, norm, t, fisher_exact, chi2_contingency
from scipy.stats.contingency import odds_ratio
OUT = Path(file).parent
TETHER = list((list(('Yagi 2022', 0, 32, 8, 32)), list(('Safaee 2021 matched', 1, 40, 9, 40)), list(('Alluri 2021', 0, 49, 6, 34))))
HOOK = list((list(('Tsutsui', 10, 28, 2, 25)), list(('Cho', 14, 47, 21, 71)), list(('Bourghli', 21, 88, 40, 166)), list(('Matsumura', 3, 17, 6, 22)), list(('Rostami', 15, 70, 23, 62))))

def pll(beta, rows):
"""Profile binomial log likelihood, dropping constants independent of parameters."""
total = 0.0
for name, a, n1, c, n0 in rows:
m = a + c
alpha = brentq(lambda z: n0 * expit(z) + n1 * expit(z + beta) - m, -100, 100)
total += c * alpha - n0 * np.logaddexp(0, alpha) + a * (alpha + beta) - n1 * np.logaddexp(0, alpha + beta)
return total

def profile(rows, fun=pll):
a = sum((getitem(r, 1) for r in rows))
fit = minimize_scalar(lambda b: -fun(b, rows), bounds=(-40, 15), method='bounded', options={'xatol': 1e-11})
beta = float(fit.x)
ll = float(-fit.fun)
boundary = a == 0
if boundary:
beta = -np.inf
ll = fun(-40, rows)
target = chi2.ppf(0.95, 1)
f = lambda b: 2 * (ll - fun(b, rows)) - target
low = 0.0 if boundary else np.exp(brentq(f, -50, beta))
high = np.exp(brentq(f, -40 if boundary else beta, 20))
LR = 2 * (ll - fun(0, rows))
return {'OR': 0.0 if boundary else float(np.exp(beta)), 'lower': float(low), 'upper': float(high), 'LR': float(LR), 'P_LR': float(chi2.sf(LR, 1)), 'logLik_omitting_constants': ll, 'boundary_MLE': boundary, 'optimizer_success': bool(fit.success), 'score_numerical': None if boundary else float((fun(beta + 1e-05, rows) - fun(beta - 1e-05, rows)) / 2e-05)}

def mh(rows):
x = np.array(list((getitem(r, slice(1, None, None)) for r in rows)), float)
a, n1, c, n0 = x.T
b = n1 - a
d = n0 - c
N = n1 + n0
R = np.sum(a * d / N)
S = np.sum(b * c / N)
v = np.sum((a + d) * a * d / N ** 2) / (2 * R ** 2) + np.sum(((a + d) * b * c + (b + c) * a * d) / N ** 2) / (2 * R * S) + np.sum((b + c) * b * c / N ** 2) / (2 * S ** 2)
y = np.log(R / S)
se = np.sqrt(v)
return {'OR': float(np.exp(y)), 'lower': float(np.exp(y - 1.96 * se)), 'upper': float(np.exp(y + 1.96 * se)), 'P_Wald': float(2 * norm.sf(abs(y / se))), 'continuity_correction': False}

def conditional_ll(beta, rows):
ll = 0
for _, a, n1, c, n0 in rows:
m = a + c
k = np.arange(max(0, m - n0), min(n1, m) + 1)
lc = gammaln(n1 + 1) - gammaln(k + 1) - gammaln(n1 - k + 1) + gammaln(n0 + 1) - gammaln(m - k + 1) - gammaln(n0 - m + k + 1)
```

```
ll += a * beta - logsumexp(lc + k * beta)
return float(ll)

def rr(a, n1, c, n0):
y = np.log(a / n1 / (c / n0))
se = np.sqrt(1 / a - 1 / n1 + 1 / c - 1 / n0)
return {'RR': float(np.exp(y)), 'lower': float(np.exp(y - 1.96 * se)), 'upper': float(np.exp(y + 1.96 * se)),
'P_Wald': float(2 * norm.sf(abs(y / se)))}

def reml_hk(rows):
x = np.array(list((getitem(r, slice(1, None, None)) for r in rows)), float)
a, n1, c, n0 = x.T
y = np.log(a / n1 / (c / n0))
v = 1 / a - 1 / n1 + 1 / c - 1 / n0
k = len(rows)

def obj(tau): w = 1 / (v + tau) mu = np.dot(w, y) / sum(w) return 0.5 * (sum(np.log(v + tau)) + np.log(sum(w)) +
sum(w * (y - mu) ** 2)) opt = minimize_scalar(obj, bounds=(0, 5), method='bounded', options={'xatol': 1e-13})
tau = float(opt.x) if opt.fun < obj(0) else 0.0 w = 1 / (v + tau) mu = np.dot(w, y) / sum(w) q = sum(w * (y - mu)
** 2) / (k - 1) se = np.sqrt(q / sum(w)) crit = t.ppf(0.975, k - 1) w0 = 1 / v mu0 = np.dot(w0, y) / sum(w0) Q =
float(sum(w0 * (y - mu0) ** 2)) return {'studies': list((getitem(r, 0) for r in rows)), 'N': int(sum(n1 + n0)), 'RR':
float(np.exp(mu)), 'lower': float(np.exp(mu - crit * se)), 'upper': float(np.exp(mu + crit * se)), 'P': float(2 *
t.sf(abs(mu / se), k - 1)), 'tau2': tau, 'I2_Q': max(0.0, 100 * (Q - (k - 1)) / Q), 'HK_scale': float(q), 'HK_modified':
False}

def validate_joint_fit(rows):

def nll(x): beta = getitem(x, 0) al = getitem(x, slice(1, None, None)) ans = 0 for z, (_, a, n1, c, n0) in zip(al,
rows): ans += n0 * np.logaddexp(0, z) - c * z + n1 * np.logaddexp(0, z + beta) - a * (z + beta) return ans fits =
list() for b in list((-6, -3, 0)): fit = minimize(nll, list((b,)) + list((-1.5,)) * len(rows), method='BFGS', options=
{'gtol': 1e-07}) fits.append({'OR': float(np.exp(getitem(fit.x, 0))), 'logLik': float(-fit.fun), 'gradient_max':
float(max(abs(fit.jac)))}) return fits

full = list((getitem(TETHER, 0), list(('Safaee 2021 full', 8, 242, 12, 77)), getitem(TETHER, 2)))
res = {'date': '2026-10-26', 'software': {'python': getitem(sys.version.split(), 0), 'numpy': np.version, 'scipy':
scipy.version}, 'inputs_tether': TETHER, 'inputs_hook': HOOK, 'tether_primary_binomial': profile(TETHER),
'tether_joint_optimization_check': validate_joint_fit(TETHER), 'tether_MH': mh(TETHER),
'tether_conditional_profile': profile(TETHER, conditional_ll), 'tether_leave_one_out': list(({'omitted':
getitem(r, 0), **profile(getitem(TETHER, slice(None, i, None)) + getitem(TETHER, slice(i + 1, None, None)))}
for i, r in enumerate(TETHER))), 'tether_full_safaee': {'inputs': full, **profile(full)},
'tether_minimum_12_months': profile(getitem(TETHER, slice(None, 2, None))), 'tether_single_studies': list(),
'park_pjf': {'inputs': list((1, 29, 6, 27)), **rr(1, 29, 6, 27), 'Pearson_P': float(chi2_contingency(list((list((1, 28)),
list((6, 21)))), correction=False).pvalue), 'Fisher_P': float(fisher_exact(list((list((1, 28)), list((6,
21))))).pvalue)}, 'park_pjk': rr(5, 29, 9, 27), 'cement_cho': rr(2, 21, 15, 71), 'modified_fixation_individual':
list(({'study': getitem(r, 0), **rr(*getitem(r, slice(1, None, None)))} for r in list((list(('Park hybrid', 15, 89, 27,
78)), list(('Liu', 2, 67, 13, 48)), list(('Tanaka', 4, 14, 19, 40)))))), 'hook_primary': reml_hk(HOOK),
'hook_sensitivities': list(({'omitted': name, **reml_hk(list((r for r in HOOK if getitem(r, 0) not in names)))} for
name, names in list((('Tsutsui', list(('Tsutsui',))), ('Rostami', list(('Rostami',))), ('Matsumura',
list(('Matsumura',))), ('Rostami and Matsumura', list(('Rostami', 'Matsumura')))))))}
for name, a, n1, c, n0 in TETHER:
s = odds_ratio(list((list((a, n1 - a)), list((c, n0 - c)))), kind='conditional')
ci = s.confidence_interval()
getitem(res, 'tether_single_studies').append({'study': name, 'OR': float(s.statistic), 'lower': float(ci.low),
'upper': float(ci.high)})
assert max((abs(getitem(x, 'OR') - getitem(getitem(res, 'tether_primary_binomial'), 'OR')) for x in
getitem(res, 'tether_joint_optimization_check'))) < 1e-06

def inverse_variance(y, v, modified_hk=False):
y, v = (np.asarray(y), np.asarray(v))
k = len(y)
w0 = 1 / v
mu0 = float(np.dot(w0, y) / w0.sum())
se0 = float(1 / np.sqrt(w0.sum()))
Q = float(np.dot(w0, (y - mu0) ** 2))

def objective(tau2): w = 1 / (v + tau2) mu = np.dot(w, y) / w.sum() return 0.5 * (np.log(v + tau2).sum() +
np.log(w.sum()) + np.dot(w, (y - mu) ** 2)) opt = minimize_scalar(objective, bounds=(0, 5),
method='bounded', options={'xatol': 1e-13}) tau2 = float(opt.x) if opt.fun < objective(0) else 0.0 assert
```

```
opt.success and tau2 < 4.99 w = 1 / (v + tau2) mu = float(np.dot(w, y) / w.sum()) q = float(np.dot(w, (y - mu) **
2) / (k - 1)) scale = max(1.0, q) if modified_hk else q se = float(np.sqrt(scale / w.sum())) z = norm.ppf(0.975)
crit = t.ppf(0.975, k - 1) return dict(log_effects=y.tolist(), variances=v.tolist(),
fixed=dict(estimate=float(np.exp(mu0)), lower=float(np.exp(mu0 - z * se0)), upper=float(np.exp(mu0 + z *
se0)), weights=(100 * w0 / w0.sum()).tolist()), random=dict(estimate=float(np.exp(mu)),
lower=float(np.exp(mu - crit * se)), upper=float(np.exp(mu + crit * se)), weights=(100 * w / w.sum()).tolist(),
tau2=tau2, HK_scale=q, HK_scale_used=scale, HK_modified=modified_hk), Q=Q, df=k - 1,
P_Q=float(chi2.sf(Q, k - 1)), I2=max(0.0, 100 * (Q - (k - 1)) / Q))

def additional(primary):
tether = getitem(primary, 'inputs_tether')
hook = getitem(primary, 'inputs_hook')
beta = np.log(getitem(getitem(primary, 'tether_primary_binomial'), 'OR'))
infos = list()
for name, a, n1, c, n0 in tether:
alpha = brentq(lambda z: n0 * expit(z) + n1 * expit(z + beta) - a - c, -100, 100)
p1, p0 = (expit(alpha + beta), expit(alpha))
u1, u0 = (n1 * p1 * (1 - p1), n0 * p0 * (1 - p0))
infos.append(float(u1 * u0 / (u1 + u0)))
info_pct = 100 * np.array(infos) / sum(infos)
y, v, corrected = (list(), list(), list())
for name, a, n1, c, n0 in tether:
cells = np.array((a, n1 - a, c, n0 - c), float)
zero = bool(np.any(cells == 0))
if zero:
cells += 0.5
a, b, c, d = cells
y.append(np.log(a * d / (b * c)))
v.append(sum(1 / cells))
corrected.append(zero)
ts = inverse_variance(y, v, modified_hk=True)
ts.update({'correction_applied': corrected, 'correction_rule': '0.5 to all four cells only in studies with a zero
cell; secondary models and funnel display only'})
y, v = (list(), list())
for name, a, n1, c, n0 in hook:
y.append(np.log(a / n1 / (c / n0)))
v.append(1 / a - 1 / n1 + 1 / c - 1 / n0)
hs = inverse_variance(y, v, modified_hk=False)
for key, oldkey in list((('estimate', 'RR'), ('lower', 'lower'), ('upper', 'upper'), ('tau2', 'tau2'))):
assert np.isclose(getitem(getitem(hs, 'random'), key), getitem(getitem(primary, 'hook_primary'), oldkey),
rtol=1e-07, atol=1e-10)
assert np.isclose(sum(info_pct), 100)
return dict(tether_primary_information_percent=info_pct.tolist(),
tether_primary_efficient_information=infos, tether_inverse_variance_sensitivity=ts, hook_models=hs)
res.update({'figure_statistics_date': '2026-11-03', 'figure_statistics': additional(res)})
(OUT / 'reanalysis_results.json').write_text(json.dumps(res, indent=2))
print(json.dumps(res, indent=2))
```

For the primary tether model, each study's relative contribution was calculated from its efficient Fisher information for the common log odds ratio after profiling its intercept. With $u_{1i}=n_{1i}p_{1i}(1-p_{1i})$ and $u_{0i}=n_{0i}p_{0i}(1-p_{0i})$, the study information was $I_i=u_{1i}u_{0i}/(u_{1i}+u_{0i})$. The fitted probabilities were evaluated at the joint maximum-likelihood estimate, and each information value was divided by the sum across studies to obtain a percentage. These percentages describe information contributions; the common odds ratio was not calculated as a weighted mean of individual-study odds ratios.

Secondary tether analyses used log odds ratios with variance 1/a+1/b+1/c+1/d, adding 0.5 to all four cells only when a study contained a zero cell. Fixed-effect weights were $1/v_i$, and random-effects weights were $1/(v_i+\tau^2)$, normalized to sum to 100%. Between-study variance was estimated by restricted maximum likelihood. Fixed-effect confidence intervals used normal quantiles. The tethered random-effects interval used t quantiles with k-1 degrees of freedom and a modified Hartung-Knapp variance scale bounded below by 1. The hook random-effects analysis retained its original unmodified Hartung-Knapp procedure; its added fixed-effect analysis used the same study-level log risk ratios and variances.

Cochran's Q and I^2 were calculated from the fixed-effect inverse-variance fit, and τ^2 was obtained from the corresponding random-effects fit. The tethered Q, I^2, and τ^2 values describe the corrected sensitivity analysis rather than the primary binomial model. The funnel plots display log effect estimates against their standard errors, with a fixed-effect inverse-variance center and approximate limits of the center ±1.96 standard errors. Yagi and Alluri have nearly overlapping points in the tether funnel plot. No funnel-asymmetry test or publication-bias adjustment was performed.

The fixed- and random-effects display comparisons, information weights, and descriptive funnel plots were added during editorial revision. They were not prespecified analyses. The primary models, event counts, and original sensitivity estimates were retained.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Derek S. Sheinberg, Roberto A. Moya, Andrew R. Moya, Robert E. Carrier, Alyan Zafar

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Disclosures

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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