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Is Motion Preservation With Three-Level Hybrid Cervical Surgery Achieved Without Compromising Clinical Outcomes? A Systematic Review and Meta-Analysis

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Abstract

Study design: Systematic review and meta-analysis.

Objective: To compare the clinical, radiographic, fusion and complication outcomes between three-level anterior cervical discectomy and fusion (ACDF) and hybrid constructs combining ACDF and cervical disc arthroplasty (CDA).

Methods: Systematic search of PubMed, Embase, Scopus, and Web of Science was performed in accordance with PRISMA guidelines. Comparative studies evaluating three-level ACDF and three-level hybrid surgery were included. Primary outcomes included neck disability index(NDI), visual analogue scale(VAS) scores, Japanese Orthopaedic Association (JOA) scores, C2-C7 Cobb angle, C2-7 range of motion (ROM), fusion rates, and complications. Random-effects meta-analyses were performed. Heterogeneity and publication bias were assessed using standard statistical methods.

Results: Twelve studies comprising 1008 patients (553 hybrid and 455 ACDF) met the inclusion criteria. Both surgical strategies demonstrated significant improvements in NDI ($P = 0.62$), VAS [neck ($P = 0.40$), arm($P = 0.70$)], and JOA ($P = 0.97$) scores, with no significant between-group differences across clinical outcomes. Hybrid constructs maintained ROM ($P = 0.06$), and cervical lordosis ($P = 0.93$) comparable to ACDF. Fusion rates at intended arthrodesis levels were high and similar in both cohorts. There were no significant differences in total, early or late complication rates, although heterogeneity was moderate to high across several outcomes.

Conclusion: In three-level cervical degenerative disease, hybrid surgery and ACDF provide equivalent improvements in pain, disability, neurological recovery, alignment, fusion success, and complication profiles. Hybrid constructs demonstrated a trend towards greater preservation cervical range of motion without compromising clinical efficacy or safety. These findings support hybrid surgery as a selective, motion-preserving alternative to three-level ACDF in appropriately chosen patients.

Level of evidence: II.

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Keywords
hybrid cervical surgery, three-level ACDF, cervical disc arthroplasty, range of motion, systematic review, meta-analysis

Introduction

Anterior cervical discectomy and fusion (ACDF) is the most commonly performed surgical procedure for the treatment of cervical degenerative disorders, with well-established efficacy in achieving neural decompression, pain mitigation and neurological recovery.[1-3] However, increasing the number of fused levels has been associated with reduced cervical mobility, altered segmental biomechanics and a higher risk of adjacent segment degeneration (ASD), implant-related complications, and construct rigidity.[4-6] These concerns are particularly relevant in 3-level ACDF, where cumulative loss of motion and stress transfer to adjacent segments may be most pronounced.

Cervical disc arthroplasty (CDA) was developed to preserve segmental motion while maintaining adequate decompression and sagittal alignment.[7-9] Hybrid cervical surgery, combining ACDF at selected levels with CDA at others, has subsequently emerged as a strategy to balance stability and motion preservation in multilevel disease. Biomechanical studies suggest that hybrid constructs may better preserve global cervical range of motion, reduce compensatory hypermobility and maintain sagittal alignment, as compared with multilevel fusion alone.[10-14] While ROM preservation is biomechanically beneficial, its translation into long-term clinical outcomes remains incompletely defined. Clinically, hybrid surgery has gained increasing acceptance for 2- or 3-level pathology.

Despite this growing adoption, the comparative effectiveness of 3-level hybrid constructs vs 3-level ACDF remains incompletely defined. Available clinical studies report heterogeneous findings with respect to functional outcomes, pain relief, neurological recovery, cervical mobility, alignment, and complication rates.[10,15-26] Several prior systematic reviews have evaluated hybrid surgery; however, most have pooled 2- and 3-level constructs, combined heterogeneous surgical configurations, or emphasised radiographic outcomes without comprehensive clinical correlation.[27-33] Importantly, outcomes specific to proper three-level procedures (such as biomechanical demands and complication profiles) have not been systematically synthesised in isolation. As a result, uncertainty persists regarding whether 3-level hybrid constructs provide clinically meaningful advantages over conventional 3-level ACDF, or whether potential benefits in motion preservation are offset by concerns related to complications, fusion success and durability. Clarifying these issues is essential for informed surgical decision-making and patient counselling in complex, multilevel cervical disease.

We hypothesised that, in comparison with three-level ACDF, 3-level hybrid cervical constructs would a. achieve comparable improvements in pain, disability and neurological function, b. preserve greater global cervical range of motion without compromising sagittal alignment, c. demonstrate similar complication and fusion rates at intended arthrodesis levels. To test these hypotheses, we performed a systematic review and meta-analysis comparing clinical, radiographic and complication-related outcomes between 3-level ACDF and 3-level hybrid cervical constructs.

Methods

Study Design and Protocol

This systematic review was conducted in accordance with PRISMA guidelines[34] to compare clinical outcomes between three-level ACDF and three-level hybrid constructs combining ACDF with CDA. The review protocol was prospectively developed to include both quantitative meta-analysis and qualitative synthesis of outcomes across multiple domains, including disability, pain, neurologic function, cervical mobility, and alignment.

Eligibility Criteria

Studies were eligible if they met the following criteria: (1) comparative design including both ACDF and hybrid groups; (2) three-level cervical procedures performed; (3) reporting of at least one clinical outcome measures; (4) minimum follow-up of 6 months; and (5) published in English. Exclusion criteria included single-arm studies, non-clinical database analyses, predictive modelling without outcome data, and studies involving lumbar spine procedures.

Data Sources and Search Strategy

A comprehensive literature search was performed using PubMed, Embase, Scopus, and Web of Science databases. The keywords included *"3-level ACDF," "hybrid cervical surgery," "cervical disc arthroplasty," "NDI," "VAS," "JOA," "ROM,"* and *"Cobb angle*". The reference lists of included studies were manually screened to identify additional eligible articles. The screening was done in duplicate by two reviewers, and any discrepancies were resolved through discussion with a third author.

Data Extraction and Outcomes

Data were extracted into a structured spreadsheet capturing study characteristics, sample sizes, demographic variables, surgical configurations, and outcome measures. Primary outcomes included Neck Disability Index (NDI), Visual Analogue Scale (VAS) scores for neck and arm pain, Japanese Orthopaedic Association (JOA) scores, C2–C7 range of

Table 1. Characteristics of the Included studies and key Complication Outcomes Comparing 3-Level ACDF With hybrid Constructs

First author, year	Study design	Sample size (hybrid/ ACDF)	Mean age (HS/ ACDF)	Sex distribution (HS/ACDF)	Operated levels	Follow-up (months)	Implant configuration	Key devices/ Constructs	Risk of bias
Brotzki et al (2020)	PCS	HS: 32; ACDF: 56	1R2F: 54.3 ± 10.7 y; 2R1F: 49.4 ± 5.7 y; ACDF: 55.6 ± 11.4 y	1R2F: 14 M/ 3F; 2R1F: 9 M/6F; ACDF: 23 M/33F	C3–C4–C5: 7; C4–C5–C6: 27; C5–C6–C7:40	Mean: 19.5 (range: 2-83)	3-level ACDF (BENGAL titanium mesh cage); hybrid (DCI – Paradigm spine/TDR – OrthoKinematica Cerkinetic)	ProDisc-C + cage vs plated ACDF	Low (ROB2)
Hung et al (2018)	RCS	HS: 22; ACDF: 20	HS: 55.5 ± 9.1 y; ACDF: 61.6 ± 7.9 y	HS: 10 M/ 12F; ACDF: 12 M/8F	C3–C4–C5; C4–C5–C6; C5–C6–C7	Mean: 28 (range 21-35)	3-level ACDF; 1 + 2& 2 + 1hybrid (Prestige-LP, Bryan, Prodisc-C)	Bryan + cage vs ACDF	Low (NOS)
Ding et al (2014)	RCS	HS: 13; ACDF: 15	HS: 50.6 ± 8.1 y; ACDF: 52.5 ± 7.6 y	HS: 8 M/5F; ACDF: 10 M/5F	C3–C4–C5; C4–C5–C6	Minimum 24	3-level ACDF (titanium mesh cage + Iliac Allograft/Cage + anterior cervical plate); 1 + 2hybrid (Mobi-C, titanium mesh cage, Syncage cage)	Mixed CDA + ACDF	Moderate (NOS)
Meng et al (2021)	RCS	HS: 41; ACDF: 32	NR	NR	C3–C4–C5; C4–C5–C6	Mean HS: 90.3 ± 25.5; mean ACDF: 86.3 ± 28.9	3-level ACDF (MC + PEEK cage); 2 + 1& 1 + 2hybrid (Prodisc-C, MC + PEEK cage)	Active-C/ Baguera C + ACDF	Low (NOS)
Wang et al (2020)	RCS	HS: 64; ACDF: 37	HS: 52.7 ± 7.4 y; ACDF: 65.4 ± 11.0 y	HS: 31 M/ 33F; ACDF: 17 M/20F	C3–C4–C5; C4–C5–C6	Mean HS: 47.48 ± 20.05; mean ACDF: 49.03 ± 14.73	3-level ACDF (Zero-P cage); hybrid (Prestige-LP, Zero-P cage)	Mixed CDA + cage	Low (NOS)
Huang et al (2022)	RCS	HS: 84; ACDF: 24	1R2F: 51.8 ± 6.9; 2R1F: 49.0 ± 9.0; ACDF: 56.7 ± 7.9	1R2F: 26 M/ 24F; 2R1F: 17 M/17F; ACDF: 13 M/11F	C3–C4–C5; C4–C5–C6	Mean HS-Type I: 29.13±14.40; mean HS-type II: 34.03±19.74; mean ACDF: 29.13±14.19	3-level ACDF (Zero-P cage); 1 + 2& 2 + 1hybrid (Prestige-LP, Zero-P cage)	Mixed CDA + Zero-P	Low (NOS)
Kan et al (2014)	RCS	HS: 31; ACDF: 32	HS 47.9 ± 7.3; ACDF: 46.4 ± 7.1	HS: 18 M/ 13F; ACDF: 17 M/15F	Noncontiguous 3-level (2 contiguous +1 skip level)	Median: 36 (range 6-66)	3-level ACDF (titanium mesh cage + anterior cervical plate + Stand-alone cage); hybrid (Discover artificial cervical disc)	Hybrid subtypes	Moderate (NOS)

(continued)

Table 1. (continued)

First author, year	Study design	Sample size (hybrid/ ACDF)	Mean age (HS/ ACDF)	Sex distribution (HS/ACDF)	Operated levels	Follow-up (months)	Implant configuration	Key devices/ Constructs	Risk of bias
Kang et al (2013)	RCT	HS: 12; ACDF: 12	HS: 53.6 ± 6.1; ACDF: 55.3 ± 6.7	HS: 8 M/4F; ACDF: 7 M/5F	C3–C4–C5; C4–C5–C6	Mean HS: 32.8 ± 7.5; mean ACDF: 33.2 ± 7.7	3-level ACDF (Autogenous Iliac Crest graft + synthes plate); 1 + 2& 2 + 1hybrid (Prodisc-C, ZERO-P cage)	DCI + cage	Low (NOS)
Chen et al (2023)	RCS	HS: 73; ACDF: 33	1R2F: 50.9 ± 8.2; 2R1F: 47.1 ± 7.4; ACDF: 56.7 ± 12.6	1R2F: 20 M/ 27F; 2R1F: 13 M/13F; ACDF: 17 M/16F	C3–C4–C5; C4–C5–C6	Mean HS-Type I: 22.15 ± 13.61; mean HS-type II: 21.50±12.44; mean ACDF: 29.13±9.3	3-level ACDF (Zero-P cage); 1 + 2& 2 + 1hybrid (Prestige-LP, Zero-P cage)	ProDisc-C + stand-alone cages	Low (NOS)
Jang et al (2017)	RCS	HS: 19; ACDF: 30	HS: 53.5 ± 12.9; ACDF: 60.2 ± 14.4	HS: 13 M/ 6F; ACDF: 21 M/9F	C3–C4–C5; C4–C5–C6; C5–C6–C7-T1;	Mean HS: 30.5±18.6; mean ACDF: 32.2±13.1	3-level ACDF (Zephir plate + interbody graft); 1 + 2& 2 + 1hybrid (Active-C disc, Baguera-C, interbody cage)	Mixed CDA + cage	Moderate (NOS)
Xu et al (2020)	RCS	HS 61; ACDF 32	1R2F: 55.5 ± 7.5; 2R1F: 55.2 ± 12.6; ACDF: 57.2 ± 8.3	1R2F: 17 M/ 19F; 2R1F: 14 M/11F; ACDF: 17 M/15F	C3–C4–C5; C4–C5–C6	Mean: 76.4 ± 9.0	3-level ACDF (MC + PEEK cage); 1 + 2& 2 + 1hybrid (Prodisc-C, MC + PEEK cage)	Prestige-LP/ ProDisc-C	Low (NOS)
Qiu et al (2025)	RCS	HS: 26; ACDF: 20	HS: 51.8 ± 7.0; ACDF: 56.0 ± 8.5	HS: 12 M/ 14F; ACDF: 8 M/12F	C3–C4–C5; C4–C5–C6	Mean 141.85 ± 17.20	3-level ACDF (MC + or ROI-C cage); 1 + 2hybrid (Bryan disc, MC+/ROI-C cage)	Bryan + stand-alone cage	Low (NOS)

1R2F – 1CDA+2ACDF; 2R1F – 2CDA+1ACDF; ACDF – Anterior Cervical Discectomy and Fusion; CDA – Cervical Disc Arthroplasty; DCI – Dynamic Cervical Implant; HS – Hybrid Surgery; MC+ – Metal-on-Ceramic Plus; NOS – Newcastle–Ottawa Scale; NR – Not Reported; PCS – Prospective Cohort Study; PEEK – Polyetheretherketone; RCS – Retrospective Cohort Study; RCT – Randomized Controlled Trial; ROB2 – Cochrane Risk of Bias 2 tool; TDR – Total Disc Replacement.

motion (ROM), and C2–C7 Cobb angle. Where available, mean and standard deviation (SD) values were extracted for both preoperative and final follow-up time points. The data extraction was done in duplicate by two reviewers, and any discrepancy was resolved by discussion with a third author.

Risk of Bias and Quality Assessment

Two reviewers independently assessed the methodological quality. RCTs were evaluated using the Cochrane Risk of Bias 2.0 tool, addressing random sequence generation, allocation concealment, blinding, incomplete outcome data, and selective reporting. Observational studies were using the Newcastle-Ottawa Scale (NOS)[35] covering cohort selection, comparability and outcome ascertainment. Each study was categorised as low, moderate, or high risk of bias based on cumulative domain scores. Sensitivity analyses were planned to assess the robustness of pooled results following the exclusion of high-risk studies.

Statistical Analysis

Meta-analyses were performed using a random-effects model with restricted maximum likelihood (REML) estimation. Pooled mean differences were calculated for each outcome

domain, with 95% confidence intervals (CI). Heterogeneity was assessed using τ^2, I^2, and Cochran's Q statistics. Between-group differences were tested using subgroup Qβ statistics. Publication bias was assessed using the funnel plot, Galbraith plot asymmetry and Egger's regression test.[36] All analyses were performed using Stata version 17.0 (StataCorp LLC, College Station, TX, USA).

Results

Study Characteristics

Twelve studies met the inclusion criteria, comprising a total of 1008 patients: 553 in hybrid groups and 455 in ACDF groups (Table 1). The selection of studies included in the analysis is given in the PRISMA flow diagram Figure 1. Hybrid constructs included both 1R2F (1CDA+2ACDF) and 2R1F (2CDA+1ACDF) configurations, with CDA devices such as Prestige-LP, Prodisc-C, Bryan, and Active-C. ACDF constructs utilised Zero-P cages, titanium mesh cages, and anterior cervical plates. Follow-up durations ranged between 6 and 83 months, with most studies reporting outcomes at 12-36 months. Most studies were retrospective cohorts with moderate-to-high NOS scores (≥6) as shown in Table 1. One randomised controlled trial (RCT; Kang et al,[22] 2013) was included (low-risk across domains). No studies were excluded based on quality assessment.

NDI

NDI was reported in 10 of 12 studies, with extractable mean ± SD values in six. Meta-analysis showed substantial improvement in both groups. The pooled mean difference for hybrid surgery was 21.24 points (95% 16.78-25.69), while ACDF showed a pooled improvement of 19.71 points (95% 15.60-23.82). Between-group difference was not statistically significant (Qβ = 0.24, P = 0.62), as shown in Figure 2. Heterogeneity was high (I^2 = 82.6%), reflecting variability in baseline disability and device configurations. Clinically, both strategies exceeded the minimal clinically significant difference (MCID) for NDI, indicating meaningful improvement.

VAS – Neck Pain

VAS scores for neck pain were reported in eight studies. The pooled mean difference across all studies was 4.24 points (95% 3.87-4.60), with hybrid surgery showing slightly greater improvement (4.33 points) than ACDF (4.20 points), though the difference was not statistically significant (Qβ = 0.76, P = 0.40), as shown in Figure 3A. Heterogeneity was moderate (I^2 = 62.78%). Individual studies such as Kang et al[22] (2013) and Huang et al[14,21] (2022) reported significant reductions in neck pain, with final scores below 2.0 in both groups.

VAS – Arm Pain

VAS arm pain scores were available in six studies. The pooled mean difference was 4.03 points (95% 3.71-4.36), with no significant difference between hybrid and ACDF groups (Qβ = 0.40, P = 0.70), as shown in Figure 3B. Heterogeneity was moderate (I^2 = 59.54%). Brotzki et al[16] (2020) and Qiu et al[26] (2025) reported the most significant reductions, with final arm pain scores below 1.0 in both groups. These findings suggest that both surgical strategies are equally effective in alleviating radicular symptoms.

JOA Scores

JOA scores were reported in seven studies, with extractable data in four. The pooled mean difference indicated significant neurologic recovery in both groups. Hybrid surgery showed a mean improvement of 5.25 points (range: 2.62 to 6.20), while ACDF showed similar gains (range: 5.26 to 6.20). Between-group differences were not significant (Qβ = 0.97, P = 0.97), as shown in Figure 4A. Heterogeneity was high (I^2 = 98.06%), likely due to differences in baseline scores and device types. Despite this, final JOA scores consistently exceeded 15 across studies, indicating substantial recovery.

Cervical ROM (Range of Motion; C2–C7)

Six studies provided extractable ROM data. Hybrid constructs preserved significantly more motion than ACDF. The pooled mean difference for hybrid was 15.75° (95% 12.14-19.35), compared to 10.39° (95% 6.03- 14.75) for ACDF. The overall pooled mean difference was 13.14° (95% 10.09-16.19), although it did not reach statistical significance in group comparison (Qβ = 3.44, P = 0.06), as shown in Figure 4B. Heterogeneity was high (I^2 = 73.83%). Studies such as Wang et al[18,19] (2020) and Jang et al[24] (2017) demonstrated clear preservation of motion in hybrid groups, supporting the biomechanical rationale for CDA inclusion.

Cervical Alignment (C2–C7 Cobb Angle)

Cobb angle data were available in five studies. Meta-analysis showed a pooled mean increase of 3.40° (95% 2.23- 4.58) in cervical lordosis across both groups. Hybrid and ACDF constructs showed similar improvements, with no significant between-group difference (Qβ = 0.93, P = 0.93), as shown in Figure 5A. Heterogeneity was modest (I^2 = 30.87%). Studies such as Xu et al[25] (2020) and Qiu et al[26] (2025) reported final Cobb angles between 10° and 13°, indicating restoration of sagittal alignment.

Fusion Rates

Comparable fusion rates were reported in 3 studies. Hybrid and ACDF constructs showed similar fusion rates, with no

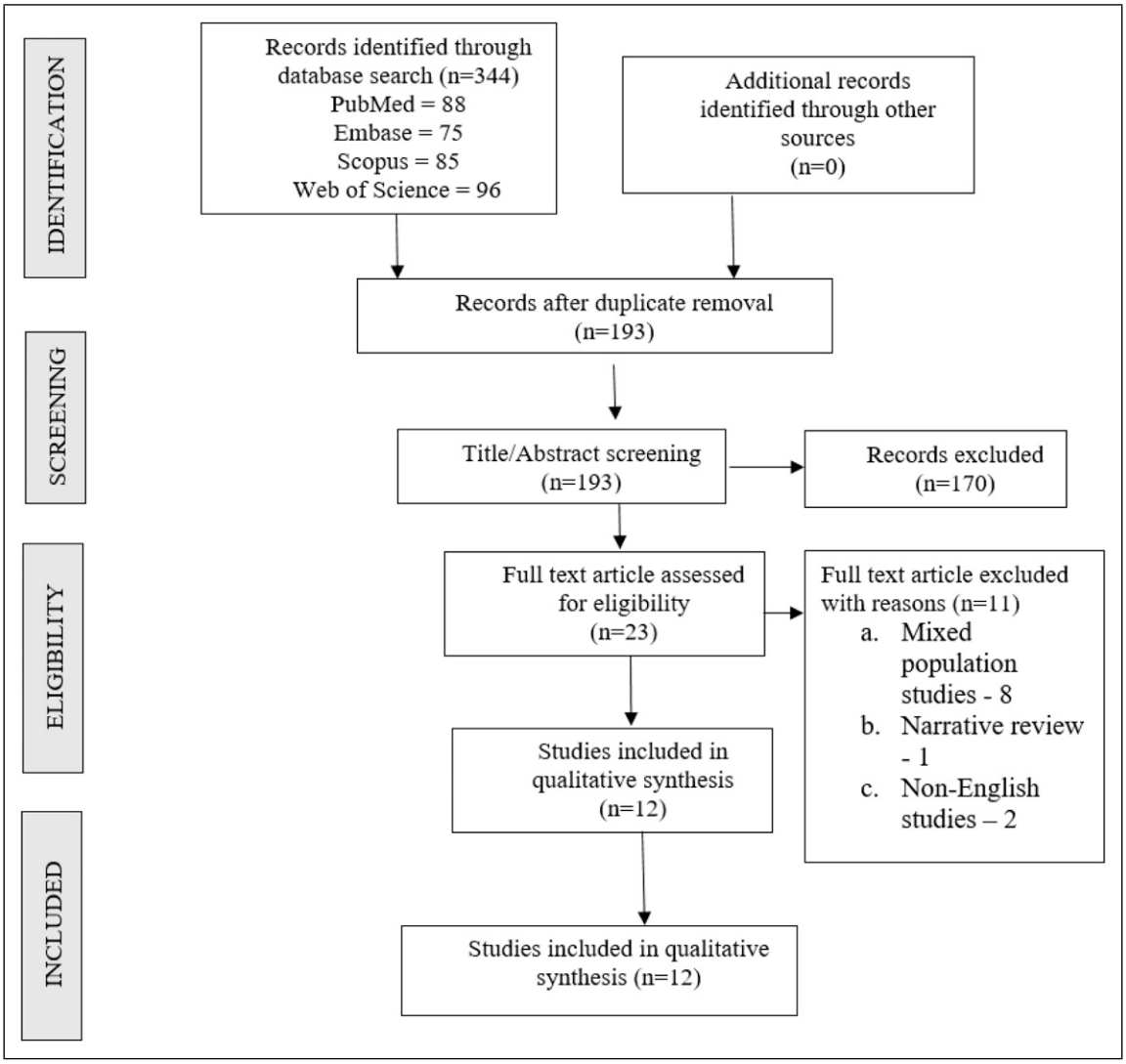


Figure 1. PRISMA Flow diagram of inclusion of studies in the review

significant between-group difference (Qi = 3.81, $P = 0.15$), as shown in Figure 5B. Fusion rates for ACDF and hybrid constructs were reported in 9 and 7 studies, respectively. Fusion rates in ACDF ranged from 88% to 100%, while fusion in hybrid constructs ranged between 84% and 95%. No significant differences were observed in the achievement of fusion at the intended arthrodesis levels between the groups. Fusion assessment methods varied considerably across studies, with most relying on surgeon-reported criteria rather than standardised approaches. According to CSRS guidelines, fusion should be defined by CT evidence of extra-graft or extra-cage bridging bone, or by flexion/extension radiographs demonstrating ≥4 mm motion at an adjacent unoperated level and <1 mm interspinous motion at the fused level, assessed by at least two independent observers.[37] The lack of uniform adoption of these validated criteria likely explains the wide variance in reported fusion rates.

Complication Rates

Across nine studies comparing total complication rates between hybrid and ACDF groups in three-level cervical surgeries, the pooled odds ratio (OR) was 1.43 (95% 0.46- 4.43), indicating no statistically significant difference in overall risk. The between-study heterogeneity was substantial ($\tau^2 = 1.79$, $I^2 = 70.32\%$, $H^2 = 3.37$), and the test for heterogeneity was significant (Q(8) = 23.98, $P = 0.00$). The test for overall effect was non-significant (z = 0.63, $P = 0.53$), suggesting no definitive advantage of either technique in terms of total complications, as shown in Figure 6A.

Based on seven studies that reported early postoperative complications (includes dysphagia, CSF leak, haematoma, early implant failure and graft dislodgement within 90 days of the post-operative period), the pooled OR was 1.16 (95% CI: 0.65-2.08), indicating no significant difference between the hybrid and ACDF groups. The heterogeneity was negligible

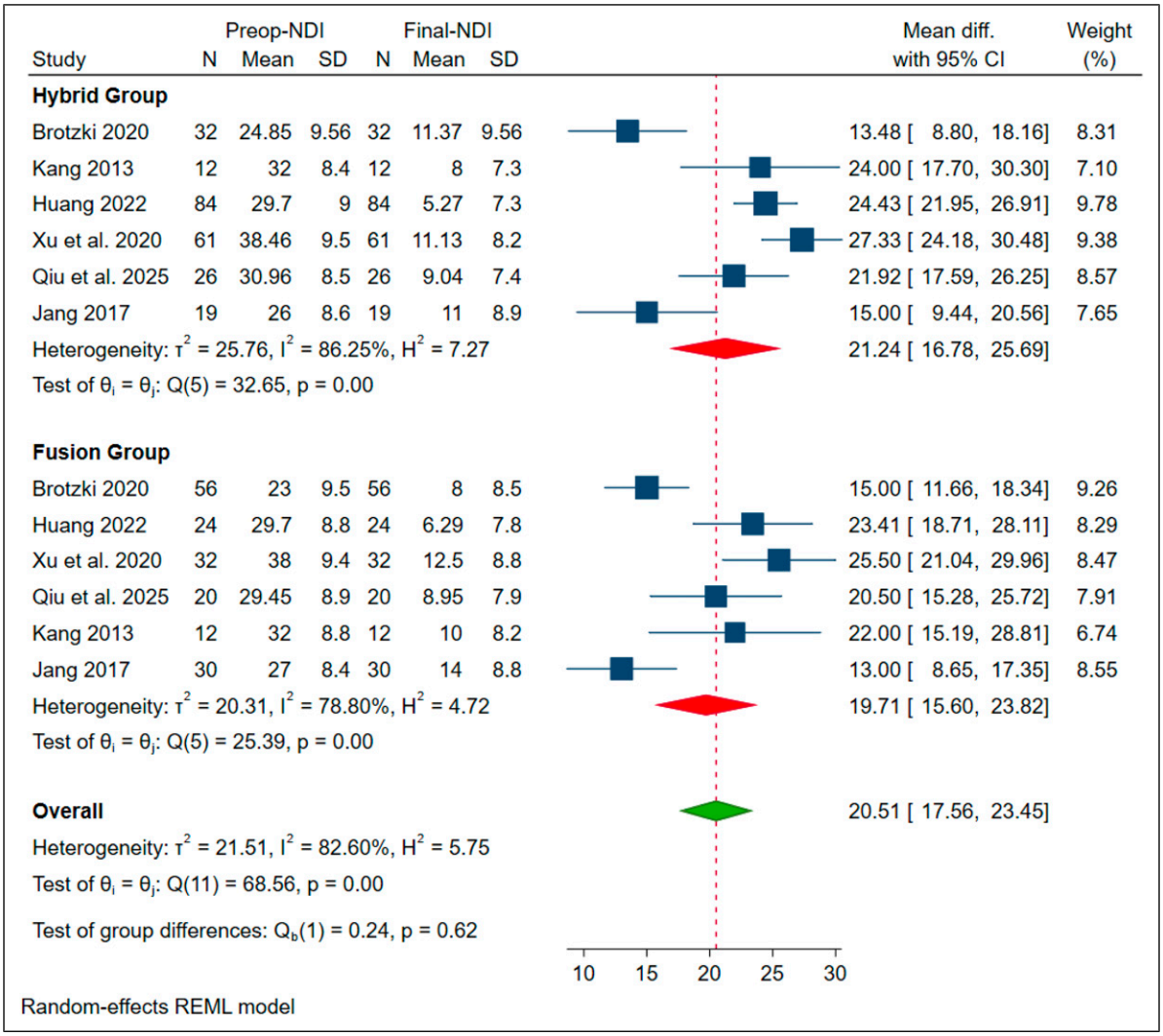


Figure 2. Forest plot of analysis of neck disability index between the ACDF group and hybrid group among the included studies

(τ^2 = 0.00, I^2 = 0.00%, H^2 = 1.00), and the test for heterogeneity was non-significant [Q(6) = 6.00, P = 0.42], as shown in Figure 6B.

Based on six studies that contributed data on late complications (includes heterotopic ossification, implant subsidence, locked prosthesis and ASD after 1-year post surgery), the pooled OR was 0.86 (95% CI: 0.34-2.18; no significant difference between groups). Moderate heterogeneity was observed (τ^2 = 3.79, I^2 = 49.72%, H^2 = 1.99), with a borderline non-significant test for heterogeneity (Q(5) = 10.30, P = 0.07). The test for subgroup differences between early and late complications was also non-significant ($Q_\beta(1)$ = 0.80, P = 0.37), indicating no temporal shift in complication risk attributable to the surgical technique, as shown in Figure 6B.

Sensitivity Analysis

We performed a sensitivity analysis to explore the heterogeneity noted among the reported outcomes. The results of the leave-one-out sensitivity analysis confirmed the robustness of pooled estimates, with no individual study altering the overall significance. Subgroup analysis restricted to RCTs was not feasible due to the inclusion of only one RCT. Meta-regression did not yield meaningful associations, reflecting limited statistical power. Most studies did not stratify outcomes by CDA location (1R2F vs 2R1F). As such, subgroup analysis by construct orientation was not feasible.

Publication Bias

Funnel plot analysis revealed a symmetrical distribution of studies with no significant asymmetry, suggesting minimal risk of publication bias. The regression line remained centred within the pseudo 95% confidence limits, and trim-and-fill imputation identified only one potentially missing study, as shown in Figure 7A, indicating robust and unbiased pooled estimates across included trials. Similar results were noted in the Galbraith plot, demonstrating the pooling of studies with the 95% confidence limits as indicated in Figure 7B.

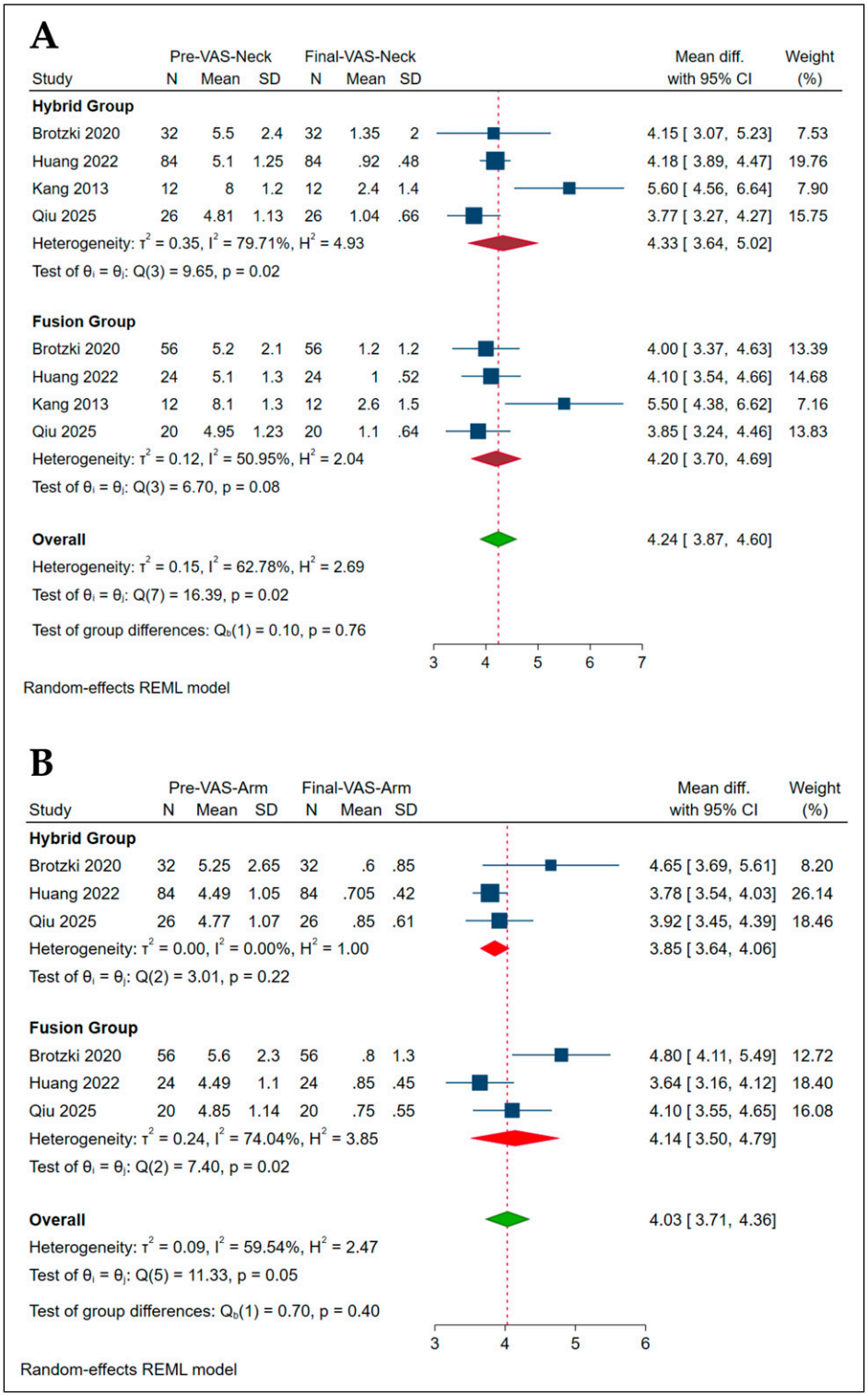


Figure 3. Forest plot of analysis of visual analog score for A, neck pain and B, arm pain between the ACDF group and hybrid group among the included studies

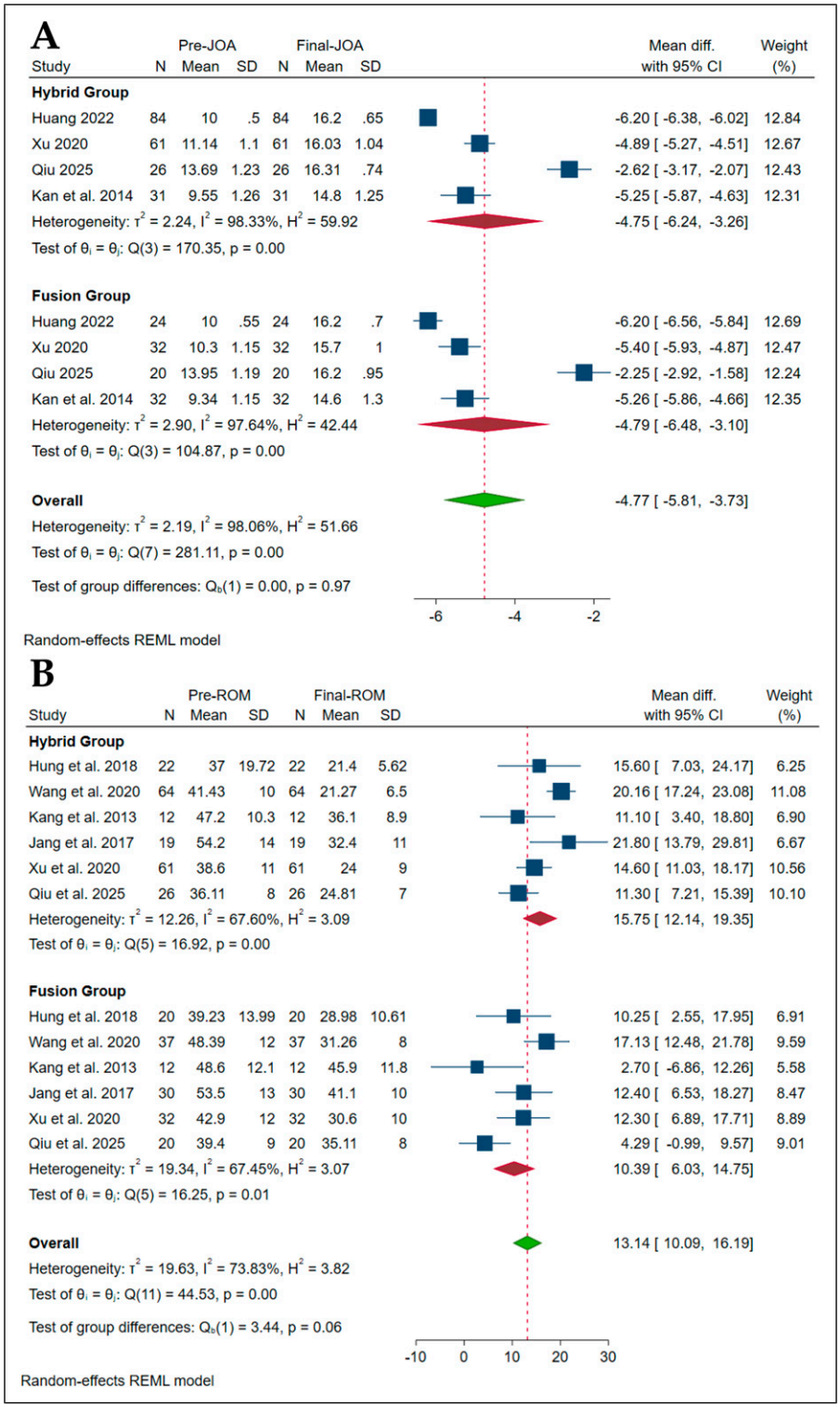


Figure 4. Forest plot of analysis of A, JOA scores and B, cervical range of movements (C2-C7) between the ACDF group and hybrid group among the included studies

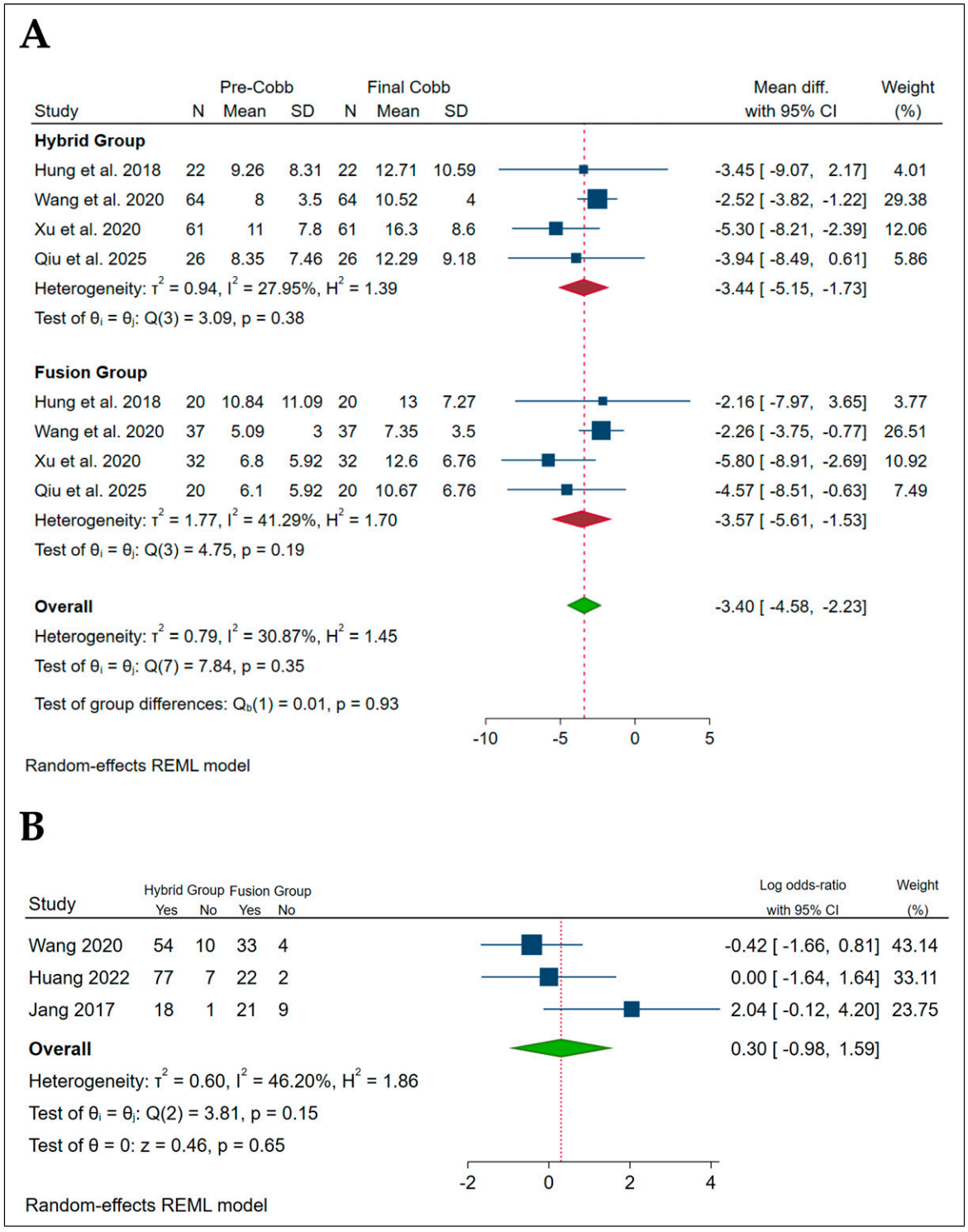


Figure 5. Forest plot of analysis of A, Cervical Alignment (C2–C7 Cobb Angle) and B, fusion rates between the ACDF group and hybrid group among the included studies

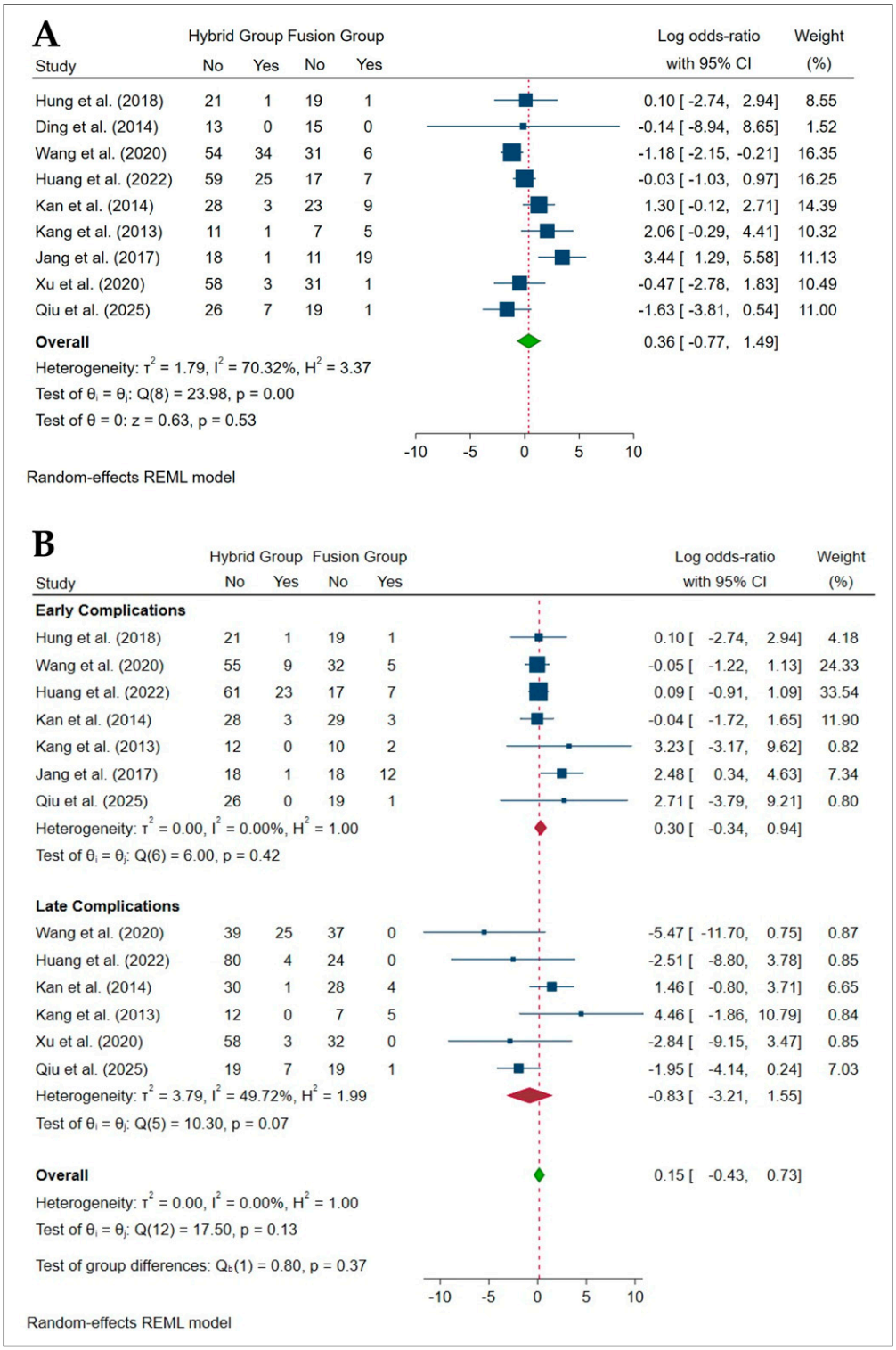


Figure 6. Forest plot of analysis of A, total complications and B, subgroup analysis between early and late complications between the ACDF group and hybrid group among the included studies

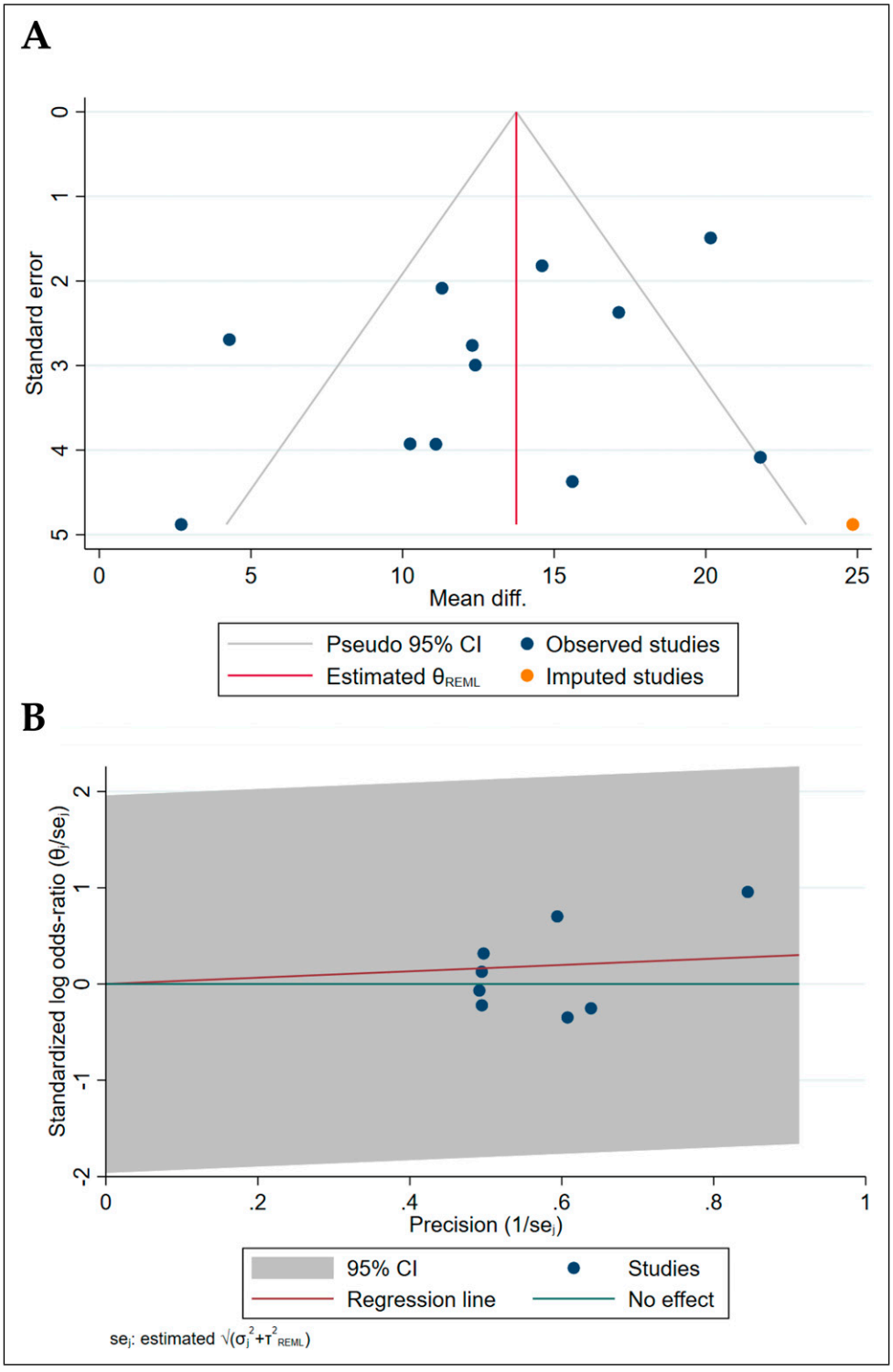


Figure 7. A, Funnel plot; B, Galbraith plot for analysis of publication bias among the included studies

Discussion

Several systematic reviews have previously compared hybrid surgery with ACDF for multilevel cervical degenerative disease.[27-33] While these studies consistently demonstrated that hybrid constructs better preserve ROM without apparent differences in pain relief, disability and complication rates, crucial methodological limitations have constrained their clinical interpretability. Most prior reviews pooled 2- or 3-level procedures, combined heterogeneous hybrid configurations, or included non-uniform definitions of hybrid surgery (occasionally incorporating corpectomy), thereby obscuring construct-specific biomechanical and clinical effects. In addition, many analyses emphasised radiographic endpoints, with limited synthesis of neurological recovery, fusion outcomes and temporal patterns of complications. Critically, outcomes specific to valid three-level anterior cervical constructs, where biomechanical demands, fusion biology and complication profiles differ substantially from shorter constructs, have not been systematically synthesised in isolation. Furthermore, earlier meta-analyses were often constrained by small sample sizes, early generation implants, limited heterogeneity assessment and absence of subgroup or sensitivity analyses, reducing confidence in their conclusions (Table 2). The present review addresses these gaps by restricting inclusion to comparative three-level hybrid vs three-level ACDF studies, applying contemporary meta-analytic methods and integrating clinical, radiographic, fusion and complication outcomes to provide focused, clinically-actionable evidence.

Principal Findings of Our study

This systematic review and meta-analysis demonstrates that, in three-level cervical surgery, hybrid constructs combining ACDF and CDA achieve clinical outcomes comparable to three-level ACDF, while offering marginal advantage in preserving global cervical ROM, without increasing complication rates or compromising fusion at intended arthrodesis levels. Improvements in disability (NDI), pain (VAS neck and arm), and neurological function (JOA) were substantial in both groups and exceeded established MCID thresholds, with no statistically significant between-group differences. In contrast, motion preservation emerged as the most reproducible differentiator, favouring hybrid constructs.

Clinical Outcomes: Disability, Pain and Neurological Recovery

Our pooled analyses demonstrate equivalent improvements in NDI, VAS, and JOA scores between hybrid surgery and ACDF. This aligns closely with individual 3-level comparative cohorts, including Kang et al[22] (2013) and Jang et al[24] (2017), which reported similar functional and pain outcomes, despite differing biomechanical profiles.[25]

Similarly, Wang et al[18,19] (2020) found no significant differences in NDI, JOA and VAS between 3-level ACDF and hybrid surgery at short- and mid-term follow-up, reinforcing the conclusion that motion preservation does not come at the cost of symptomatic relief. Collectively, these data suggest that the primary value proposition of hybrid constructs lies not in superior early clinical outcomes, but in biomechanical preservation.

Cervical ROM and Biomechanical Considerations

The most consistent advantage of hybrid constructs in this meta-analysis was preservation of C2-C7 ROM, with a trend towards statistical significance. This finding is concordant with multiple 3-level studies demonstrating reduced loss of global motion and attenuated compensatory hypermobility at adjacent segments following hybrid surgery.[16,24,25] From a biomechanical perspective, hybrid constructs reduce the number of rigidly fused segments, thereby limiting stress concentration at adjacent levels. Finite-element and radiographic studies have shown that preserved motion at arthroplasty levels may normalise segmental kinematics and reduce excessive adjacent-level ROM, a known precursor to adjoining segment degeneration (ASD). Although our analysis did not demonstrate a definitive reduction in ASD rates, likely due to limited long-term follow-up, Xu et al[25] reported more stable upper and lower adjacent segment ROM over 5 years in hybrid cohorts, as compared with ACDF.

Cervical Alignment and Sagittal Balance

Both surgical strategies achieved comparable restoration of cervical lordosis, with no significant differences in C2-C7 Cobb angle. These findings mirror those of Hung et al[17] (2018) and Xu et al[25] (2020), who demonstrated that hybrid surgery can restore and maintain cervical sagittal alignment to a degree similar to ACDF, provided appropriate level selection and implant positioning are employed.

Importantly, alignment preservation appears to be construct-dependent rather than technique-dependent, with studies showing that hybrid configurations incorporating a greater number of fusion levels may achieve superior lordotic correction at the expense of motion. In contrast, constructs with more arthroplasty levels favour ROM preservation but require careful sagittal planning.[14,20,21]

Complications and Fusion Outcomes

Our pooled analyses found no significant differences in total, early or late complication rates between hybrid surgery and ACDF, despite substantial heterogeneity across studies. This finding is clinically reassuring and consistent with prior reports demonstrating comparable safety profiles for 3-level hybrid constructs.[14,18,19,21,24]

Table 2. Comparative Analysis of Current Review With Previous Reviews [on Hybrid Cervical Surgery vs Anterior cervical Discectomy and fusion (ACDF)]

First author, year (journal)	Levels included	Key outcomes assessed	Principal conclusions of prior review	Key limitations of prior review	What the current review adds
Tian 2015 (Sci Rep)	Mixed multilevel (mostly 2-level)	VAS, NDI, C2–C7 ROM, adjacent ROM, complications	Hybrid surgery preserved global and adjacent-segment ROM better than ACDF; clinical outcomes and complications were similar	Small sample size (n = 160); early-era implants; no level-specific analysis; short follow-up	Restricts analysis to true three-level constructs, incorporates modern implants, and evaluates clinical + radiographic + complication domains simultaneously
Hollyer 2019 (Acta Neurochir)	Multilevel (2-3 levels pooled)	ROM, adjacent ROM, return to work, complications	Hybrid surgery preserved ROM and reduced adjacent ROM; no difference in complications	Very low GRADE certainty; heterogeneous hybrid definitions (some including corpectomy); limited clinical outcome depth	Uses strict hybrid definition (ACDF + CDA only) and provides granular clinical outcomes (NDI, VAS, JOA) specific to three levels
Zhang 2020 (Medicine)	Multilevel (2-3 levels pooled)	NDI, VAS, ROM, adjacent ROM	Hybrid surgery showed better NDI recovery and ROM preservation at 2 years	Pooled 2- and 3-level surgeries; no separation of hybrid configurations; limited heterogeneity analysis	Isolates three-level surgery, applies REML random-effects modeling, and formally tests between-group differences
Bhatt 2024 (J spine Surg)	2- And 3-level (radiographic study)	Global ROM, adjacent ROM, alignment	Hybrid constructs reduced superior adjacent-segment burden and preserved global ROM	Not a systematic review; limited clinical outcome reporting	Synthesizes clinical, radiographic, and complication outcomes across multiple comparative cohorts
Ragab 2025 (world Neurosurg)	Multilevel (2-3 levels pooled)	VAS, NDI, ROM, adjacent ROM, ASD, HO	Hybrid surgery preserved ROM and reduced adjacent ROM; no superiority in clinical outcomes or complications	Did not isolate three-level constructs; ASD and HO underpowered; mixed pathology	Demonstrates that even in three-level disease, clinical outcomes and complications remain comparable, while ROM benefit persists
Yang 2025 (global spine J)	Two-level only	ROM, NDI, JOA, VAS, complications	Hybrid surgery improved radiographic outcomes with equivalent clinical results	Limited to two-level disease; findings not generalizable to longer constructs	Extends evidence to three-level surgery, where biomechanical and complication profiles differ substantially

ACDF – Anterior Cervical Discectomy and Fusion; ASD – Adjacent Segment Disease; CDA – Cervical Disc Arthroplasty; C2–C7 ROM – Cervical spine range of motion from vertebrae C2 to C7; GRADE – Grading of Recommendations Assessment, Development and Evaluation; HO – Heterotopic Ossification; JOA – Japanese Orthopaedic Association score; NDI – Neck Disability Index; ROM – Range of Motion; VAS – Visual Analog Scale.

Fusion rates at the intended levels of arthrodesis were similarly high in both groups, supporting the concept that adjacent arthroplasty does not impair fusion biology; however, subgroup analyses from Wang et al[18,19] (2021) highlight that patient-specific factors, particularly smoking, may adversely affect fusion within hybrid constructs, underscoring the importance of meticulous patient selection. Fusion outcomes may be influenced by patient-specific factors (e.g., smoking, bone quality, implant type). These variables were inconsistently controlled across studies, limiting the interpretability of the pooled fusion rates. Future studies should adopt a standardised reporting of these variables.

Classification of Three-Level Hybrid Constructs and Their Clinical Relevance

An important consideration when interpreting outcomes of 3-level hybrid surgery is the heterogeneity of construct configurations, which has only recently been systematically addressed in the literature. Based on the number and location of arthroplasty and fusion levels, 3-level hybrid constructs are most commonly classified into 1R2F (1CDA+2ACDF) and 2R1F (2CDA+1ACDF) configurations. Huang et al[14,21] proposed a formal classification system and demonstrated that these constructs exhibit distinct biomechanical and radiographic behaviours. While 2R1F constructs provide superior preservation of global cervical range of motion and

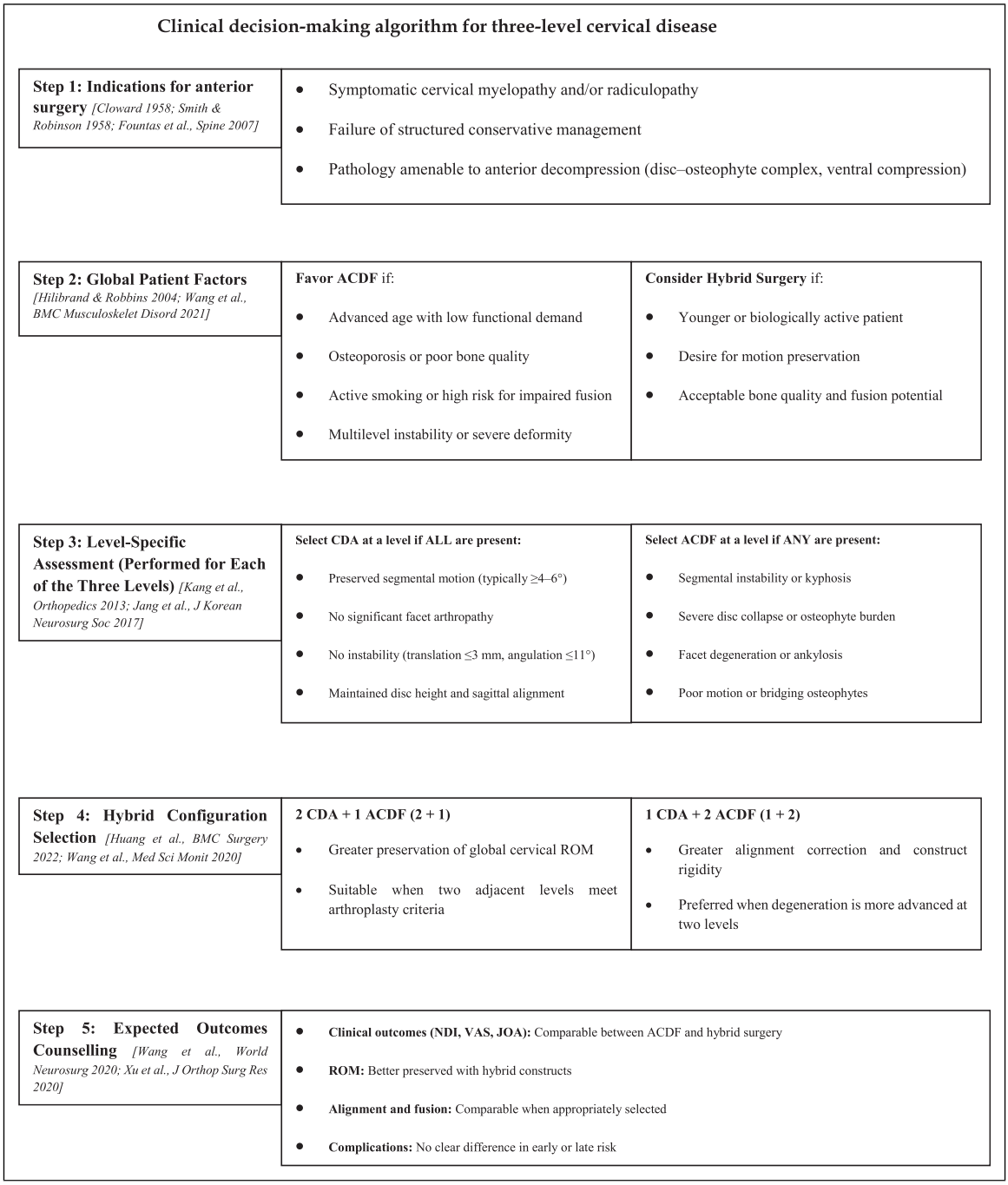


Figure 8. Clinical decision-making algorithm for three-level cervical disease

smaller increases in adjacent segment motion, 1R2F constructs achieved greater lordotic correction and segmental stability.[20] Similar findings were reported by Wang et al, who observed construct-dependent differences in ROM preservation, heterotopic ossification (HO) and lordosis correction between 1R2F and 2R1F techniques, underscoring that hybrid surgery is not a single entity, but rather a spectrum of motion-stability trade-offs.[18,19] Although construct configuration (1R2F vs 2R1F) may influence biomechanics and motion preservation, the included studies did not provide sufficient subgroup data to allow meaningful comparison. Future investigations should stratify outcomes by CDA location to clarify whether construct orientation impacts clinical or radiographic outcomes.

Importantly, most comparative studies, including those pooled in the present meta-analysis, aggregate different hybrid configurations, which likely contribute to the substantial heterogeneity observed in ROM and alignment outcomes. This construct-level variability highlights the need for future

studies and meta-analyses to stratify hybrid surgery by configuration, as pooling all hybrid constructs may obscure meaningful differences in biomechanical performance, alignment behaviour and long-term adjacent-segment mechanics. Clinically, these data reinforce the concept that optimal outcomes in 3-level disease depend not only on choosing hybrid surgery over ACDF, but on tailoring the specific hybrid configuration to level-specific degeneration and global sagittal goals.

Clinical Decision-Making Algorithm for 3-Level Cervical Disease

Taken together, 3-level hybrid surgery must be viewed as a selective, level-tailored, motion-preserving alternative to a clinically superior replacement for ACDF. For appropriately-selected patients, particularly younger individuals with preserved facet joints and segmental mobility, hybrid constructs offer long-term biomechanical advantages, without sacrificing safety of symptomatic improvement. Conversely, 3-level ACDF remains a reliable option for patients with advanced degeneration, instability or contraindications to arthroplasty. Based on the findings of this meta-analysis and contemporary literature, the following pragmatic decision-making framework may guide construct selection in 3-level cervical pathology (Figure 8).

Strengths and Limitations of the Study

Our study has several strengths. Restricting the inclusion to 3-level cervical procedures avoids dilutional bias from mixed construct lengths and addresses an understudied population. A comprehensive outcome spectrum evaluation (involving clinical, neurologic, radiographic, fusion, and complications) allows integrated functional and biomechanical assessment. Robust methodology using REML random-effects modelling, multiple heterogeneity metrics, and validated risk-of-bias tools enhances reliability. Finally, the incorporation of construct-specific and level-based considerations provides clinically actionable insights for surgical decision-making in complex 3-level cervical disease.

The review is limited by the predominance of retrospective studies, with only one randomised trial, introducing potential selection and confounding bias. Substantial heterogeneity across outcomes reflects variability in patient characteristics, indications, hybrid configurations, implants, and follow-up duration, which could not be fully mitigated despite random-effects modelling. Hybrid surgery was analysed as a pooled intervention, precluding configuration-specific analyses. Follow-up was primarily short-term to mid-term, limiting assessment of long-term durability, ASD and reoperation risk. Radiographic methods and patient-reported outcomes were inconsistently reported, and publication bias and limited generalizability cannot be excluded. Fusion rate variability likely reflects differences in assessment methodology. Adoption of standardised criteria may improve consistency and reliability in the reported outcomes in the included studies. Fusion outcomes may be influenced by patient-specific factors (e.g., smoking, bone quality, implant type). These variables were inconsistently controlled across studies, limiting interpretability. Surgeon-related variability was not consistently reported. Most included studies were retrospective, multi-surgeon cohorts, and few specified whether the same surgeon performed both ACDF and hybrid procedures. Surgeon variability was therefore not consistently controlled and may represent an uncontrolled confounder. It is also necessary to note that industry sponsorship and the evolution of implant designs over time may confound pooled outcomes.

Future Directions

Future research should prioritise long-term, construct-specific outcomes of 3-level hybrid cervical surgery, particularly with respect to ASD, implant durability and late reoperation rates. Prospective comparative studies stratified by hybrid configuration (1R2F vs 2R1F), prosthesis type and sagittal alignment targets are needed to determine whether specific construct designs confer differential biomechanical or clinical advantages. Future studies should evaluate construct-specific outcomes, as CDA location may influence biomechanics and adjacent segment motion. Standardised reporting, incorporation of patient-specific risk factors, and integration of advanced imaging or biomechanical modelling (including finite element and motion analysis) may further refine patient selection and surgical planning.

Conclusion

In three-level cervical degenerative disease, hybrid and ACDF-based constructs yield equivalent improvements in pain, disability, neurological recovery, alignment and complication rates. Hybrid constructs demonstrated a trend towards preserving cervical range of motion, supporting its role as a selective, motion-preserving strategy rather than a universally superior technique.

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Data generated in the study will be made available upon reasonable request to the authors.

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