JSES Reviews, Reports, and Techniques 6 (2026) 100687

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The role of intraoperative navigation in reverse total shoulder arthroplasty and its impact on clinical outcomes: a systematic review and meta-analysis

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A B S T R A C T

Background: Reverse total shoulder arthroplasty (rTSA) has evolved since its introduction, with intraoperative navigation emerging to enhance implant positioning accuracy. While navigation improves glenoid component placement, its impact on functional and patient-reported outcomes remains unclear. This systematic review and meta-analysis evaluates the role of intraoperative navigation in rTSA and its effect on range of motion (ROM) and patient-reported outcome measures (PROMs).

Methods: Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, we searched MEDLINE, Embase, CINAHL, CENTRAL, Scopus, and Web of Science for studies from inception to April 2025. Eligible studies included randomized controlled trials, nonrandomized trials, or observational studies reporting ROM and/or PROMs in patients undergoing primary rTSA with intraoperative navigation, with or without comparison to conventional techniques, and a minimum 6-month follow-up. Two reviewers independently screened studies, extracted data, and assessed risk of bias using the Methodological Items for Nonrandomized Studies tool. Meta-analysis used random-effects models to calculate mean differences (MDs) or standardized mean differences for ROM and PROMs, with heterogeneity assessed via I^2 and Cochrane χ^2 tests.

Results: Five cohort studies involving 1,987 patients (751 navigated, 1,236 non-navigated) were included. Meta-analysis showed navigated rTSA significantly improved active external rotation (MD: 4.32°, 95% confidence interval [CI]: 2.64-6.00, $I^2 = 0.00\%$), Simple Shoulder Test (MD: 0.33, 95% CI: 0.09-0.58, $I^2 = 0.00\%$), and Shoulder Activity Scale (MD: 1.77, 95% CI: 0.65-2.89, $I^2 = 0.00\%$). No significant differences were found for active abduction, forward elevation, internal rotation, or other PROMs. Narrative synthesis of a single-arm retrospective cohort study showed statistically and clinically significant improvements in ROM and PROMs with navigation, while comparative

Ethics approval was not required for this study as it involved analysis of previously published data.

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https://doi.org/10.1016/j.xrrt.2026.100687
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studies found no significant differences between navigated and conventional techniques. Heterogeneity was substantial for some outcomes, and the risk of bias was moderate.

Conclusion: Our analysis shows primary rTSA with intraoperative navigation to be at least comparable, if not better in certain domains investigated, compared to conventional techniques. Emerging evidence suggests that the greatest utility of intraoperative navigation in rTSA may lie in its application to anatomically complex cases.

Level of evidence: Level IV; Systematic Review and Meta-Analysis

Keywords: Reverse total shoulder arthroplasty; Intraoperative navigation; Range of motion; Patient-reported outcome measures; Systematic review; Meta-analysis

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In 1985, Paul Grammont revolutionized shoulder arthroplasty by developing a reverse shoulder prosthesis that was significantly different from earlier designs.[5] The system included an uncemented, convex glenoid component fixed with peripheral screws and a press-fit peg, paired with a concave humeral component featuring a nonanatomic inclination. Crucially, the design shifted the center of rotation from the humeral head to the glenosphere, medializing and distalizing it relative to traditional anatomy.

These modifications confer several biomechanical advantages by enabling the deltoid to compensate for rotator cuff deficiency, the original primary indication for this procedure.[3] Advances in biomechanical understanding and awareness of related complications have since driven refinements in implant design and component positioning, aiming to improve the range of motion (ROM), preserve the deltoid lever arm, and minimize joint reactive forces.[15] Consequently, indications for reverse total shoulder arthroplasty (rTSA) have expanded to include proximal humerus fractures, glenoid bone loss, oncologic resection, and revision cases.

While addressing the underlying pathology is fundamental, clinical outcomes play a critical role in determining the overall success of a surgical procedure.[2] One emerging technology designed to enhance these outcomes is intraoperative navigation, also called computer-assisted navigation.[4] This technology combines comprehensive three-dimensional pre-operative planning with real-time intraoperative guidance to enhance implant positioning's precision, accuracy, and safety.

The importance of accurate implant positioning is supported by studies such as Gregory et al,[7] who demonstrated a significant association between glenoid malposition and reduced post-operative ROM at 1 year following anatomic total shoulder arthroplasty. Although procedural differences exist, it is reasonable to hypothesize that improved accuracy and precision of glenoid component placement in rTSA similarly influence functional outcomes and, by extension, patient-reported outcomes. Current literature substantiates the benefits of intraoperative navigation in rTSA, showing improved baseplate screw configuration as well as enhanced accuracy and precision of glenoid baseplate positioning compared to conventional techniques.[18,19] However, the overall effect of navigation on functional and patient-reported outcomes remains unclear.

Despite previous reviews addressing intraoperative navigation in shoulder arthroplasty, there remains a lack of consensus regarding its impact on functional and patient-reported outcomes in rTSA. Therefore, this systematic review and meta-analysis aims to synthesize current evidence to evaluate the role of intraoperative navigation in rTSA and its effect on ROM and patient-reported outcome measures (PROMs).

Methods

Eligibility criteria

Eligible studies for inclusion met the following criteria: (1) investigated patients undergoing primary rTSA using intraoperative computer-assisted navigation, with or without comparison to conventional techniques; (2) reported at least one of the following outcomes with mean ± standard deviation (SD) before and/or after the procedure: ROM measures (eg, active abduction) and/or PROMs (eg, Constant score); and (3) were randomized control trials, nonrandomized trials, or observational studies (prospective or retrospective cohort studies and comparative studies) conducted in human clinical settings with a minimum follow-up of 6 months and published in English from inception to April 2025. Due to the paucity of information, studies reporting any ROM and/or PROMs were included. Exclusion criteria included: (1) studies primarily evaluating alternative surgical treatments for shoulder conditions, such as revision rTSA, anatomic total shoulder arthroplasty, or nonsurgical treatments; and (2) animal studies, case reports, reviews, or studies not measuring ROM/PROMs.

Data sources and search strategy

A systematic review of the scientific literature was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses checklist.[13] Relevant studies were identified by searching 6 databases (MEDLINE-Ovid, EMBASE-Ovid, CINAHL-EBSCOhost, CENTRAL, Scopus, and Web of Science). Search strategies consisted of medical keywords and subject headings related to rTSA and computer-assisted navigation, with limits to the English language. All search strategies are presented in Table I. Search strategies were documented, and reference lists of identified systematic

Table I – Search strategy for identifying studies on rTSA with intraoperative navigation across selected databases.

	Concept 1	Concept 2
Keywords	"reverse* shoulder" or "reverse* total shoulder"	Navigation*
Database	**Subject headings**	
Medline	Arthroplasty, replacement, shoulder/	Surgery, computer-assisted/
Embase	Reverse shoulder arthroplasty/	Computer-assisted surgery/
CINAHL	MH = "Arthroplasty, Replacement, Shoulder" OR "Arthroplasty, Reverse Total, Shoulder"	MH = "Surgery, Computer-Assisted"
Cochrane	(CENTRAL)	Arthroplasty, replacement, shoulder
Surgery,	Computer-Assisted	
Scopus	*Keywords only*	
Web of Science	*Keywords only*	

MH, medical subject heading; *rTSA*, reverse total shoulder arthroplasty.

reviews and included studies were hand searched to identify additional relevant records. Records were finally transferred to reference management software (EndNote 21).

Selection process

The search results were managed in Covidence, where duplicate papers were automatically identified and removed. Two independent authors (AB, RMS) removed duplicates manually and conducted the initial screening of titles and abstracts, followed by a full-text review. Discrepancies were resolved through discussion between the two authors.

Data collection and items

Two authors (AB, RMS) independently extracted data into a predesigned Excel table. For each study, the following information was collected and cross-checked: first author, year of publication, study design, sample size, navigation system used, age (mean ± SD), female sex %, indications for rTSA, ROM/PROMs assessed, and follow-up period (mean ± SD). Where data were missing or unclear, attempts were made to contact study authors. If data remained unavailable (eg, unreported SDs), they were excluded from quantitative synthesis and summarized narratively where appropriate.

Outcomes

This review examined both functional and patient-reported outcomes as indicators of clinical effectiveness following rTSA. The two primary outcome domains were:

1. ROM was assessed by measuring active abduction, forward elevation, and external rotation in degrees, and internal rotation using a 7-point scoring system based on the highest vertebral level reached by the thumb. Higher scores reflected greater ROM.
2. PROMs, including:
   - *Visual analog scale (VAS) for pain*: 0-10, lower scores indicate less pain
   - *'Pain on a daily basis'*: 0-10, lower scores indicate less pain
   - *Simple Shoulder Test (SST): 0-12, higher scores = better*
   - *Shoulder Pain and Disability Index (SPADI)*: 0-100, with lower scores indicating less pain and disability
   - *Constant score*: 0-100, with higher scores indicating better shoulder function
   - *American Shoulder and Elbow Surgeons (ASES) score*: 0-100, with higher scores indicating better shoulder function.
   - *University of California-Los Angeles (UCLA) shoulder score*: 0-35, with higher scores representing better shoulder performance.
   - *Shoulder Activity Scale (SAS):* 0-20, with higher scores indicating greater activity levels
   - *Oxford Shoulder Score (OSS):* 0-48, with higher scores reflecting better shoulder function.
   - Quick *Disabilities of the Arm, Shoulder and Hand (Quick-DASH):* 0-100, with lower scores indicating less pain and disability

The primary objective was to compare post-operative ROM and PROMs between navigated and non-navigated rTSA groups, with results pooled for meta-analysis. Secondary outcomes included evaluation of less commonly reported measures, such as pre-operative to post-operative improvements within groups and clinical outcomes reported in single-arm studies evaluating navigated rTSA at various follow-up intervals.

Risk of bias assessment

Given that all eligible studies were observational studies, risk of bias was assessed using the Methodological Items for Nonrandomized Studies (MINORS) tool.[16] MINORS evaluates internal validity and methodological quality through a structured set of 12 items. The first 8 items relate to internal validity (eg, clearly stated aim, inclusion of consecutive patients, prospective data collection), while the additional 4 items relate to aspects relevant to comparative studies, such as baseline group comparability. Each item is scored as 0 (not reported), 1 (reported by inadequate), or 2 (reported and adequate), yielding a maximum score of 16 for non-comparative studies or 24 for comparative studies. Overall risk of bias is stratified through total scores, with higher scores indicating lower risk.

Data synthesis

For meta-analysis, a subset of included studies was selected based on additional criteria:

1. The study reports post-operative means and SDs for ROM and PROM outcomes.
2. The study includes a comparison between navigated and conventional rTSA.

Post-operative outcomes reported by at least two studies were included in quantitative synthesis. Studies that did not meet these criteria were included in a narrative synthesis to describe and explore the potential impact of navigation on clinical outcomes.

We calculated the pooled mean difference (MD) or standardized mean difference (SMD), together with their 95% confidence intervals (95% CIs), for the following outcomes: Active abduction, forward elevation, external rotation and internal rotation; ASES score, Constant score, pain (VAS and pain on daily basis), SAS score, SPADI score, SST score, and UCLA score. Forest plots were generated using random-effects models. Overlap of the CIs was interpreted as indicating similar intervention effects, whereas minimal overlap or the presence of outliers suggested statistical heterogeneity.[9]

To quantify heterogeneity, we calculated the I^2 statistic and Cochrane χ^2 test. An I^2 value > 50% and a Cochrane's χ^2 test P value <.10 indicated substantial heterogeneity. Potential publication bias was assessed visually by funnel plots and statistically by Egger test. A P value <.05 in Egger test was considered suggestive of small-study effects and potential publication bias.[8] All statistical analyses were performed using STATA version 18.0.

Results

Study selection and characteristics

Through systematic literature retrieval, 421 studies were finally obtained from MEDLINE (n = 112), Embase (n = 111), Scopus (n = 93), Web of Science (n = 67), CINAHL (n = 36), and CENTRAL (n = 2). Covidence automatically removed 235 studies, and 11 were manually removed by the reviewing authors. Titles and abstracts of the remaining 175 studies were screened for relevance, resulting in 9 studies being subject to full-text assessment for eligibility. Finally, a total of 5 articles met the inclusion criteria.[1,6,10,12,20] Figure 1 illustrates the findings of the literature search, screening, and selection process. Four retrospective cohort studies[1,10,12,20] and one prospective cohort study[6] met the inclusion criteria. Four of the 5 studies[6,10,12,20] compared outcomes between navigated and non-navigated rTSA patients, while one study[1] only reported outcomes for navigated rTSA patients. The navigation system employed in all 5 included studies was the ExactechGPS (Exactech Inc.).[1,6,10,12,20] This system employs pre-operative computed tomography–based three-dimensional planning followed by intraoperative optical navigation, which uses a stereotactic tracker fixed to the coracoid process. Table II details the characteristics of the included studies and the results of their risk of bias assessments (MINORS). ROM outcomes measured included active abduction (n = 4), active forward elevation (n = 4), active internal rotation (n = 2), and active external rotation (n = 3). PROMs reported included VAS/pain on a daily basis (n = 2), SST (n = 2), SPADI score (n = 2), Constant score (n = 3), ASES score (n = 3), UCLA score (n = 2), and SAS score (n = 2). One study did not report SD for PROMs but did for ROM.[6]

Demographic information

A total of 1,987 rTSA procedures were included for pooled analysis, comprising 751 navigated and 1,236 non-navigated. Table III presents an overview of patient demographic data across the included studies.

Risk of bias

Risk of bias was assessed using the MINORS tool. The included comparative studies scored between 16 and 19, with a mean score of 17, while the single noncomparative study scored 11. The detailed assessment is presented in Table IV.

Results of syntheses

Narrative synthesis

Three retrospective cohort studies evaluated PROMs and/or ROM following navigated rTSA, with some outcomes not eligible for meta-analysis.[1,10,12] Two of these studies included comparative data against conventional rTSA.[10,12] Outcomes were assessed at various follow-up intervals, with ROM measured in degrees, except internal rotation (numerical assessment methods) and PROMs using standardized scales.

Andriollo et al[1] performed a retrospective cohort study assessing clinical outcomes in 56 patients who underwent navigated rTSA at a mean follow-up of 30.7 ± 13.5 months. The authors found that these patients significantly improved ROM and PROMs at final follow-up. Improved movement domains included active abduction (89° ± 21.5° to 146° ± 27°) and active external rotation (24.7° ± 8.3° to 35° ± 5°). Improved PROMs included QuickDASH (76 ± 23 to 19 ± 16), Constant score (37 ± 21 to 77 ± 18), and VAS (6.8 ± 2.7 to 0 ± 0.7). All findings were deemed statistically significant (all $P < .001$). The study noted that changes in all PROMs exceeded established minimally important differences (MIDs: QuickDASH >10-point reduction, Constant >10–15-point increase, VAS > 2-point reduction), indicating clinically meaningful improvements. No MIDs for ROM were reported.

Two studies evaluated pre-operative to post-operative improvements in ROM and PROMs at a minimum 2-year follow-up between navigated and non-navigated groups. Kim et al[12] (n = 33 navigated, n = 40 non-navigated) and Holzgrefe et al[10] (n = 113 navigated, n = 113 non-navigated) both reported improvements in ROM and PROMs across navigated and non-navigated groups, without statistically significant between-group differences. For example, Kim et al reported similar gains in abduction (navigated: +27.6° ± 47.7°, non-navigated: +26.4° ± 43.3°; $P = .117$) and Constant scores (navigated: +16.2 ± 16.4, non-navigated: +12.5 ± 15.9; $P = .386$). Holzgrefe et al similarly observed modest, nonsignificant differences in forward elevation (navigated: +44° ± 32°, non-navigated: +51° ± 34°; $P = .121$) and ASES scores (navigated: +39.9 ± 20.7, non-navigated: +43.2 ± 22.1; $P = .266$), with the direction of effect slightly favoring the non-navigated group for several outcomes, including forward elevation, ASES, and SPADI scores. CIs or standard errors for these comparisons were not reported in either study. Neither study commented on whether these differences exceed established MIDs.

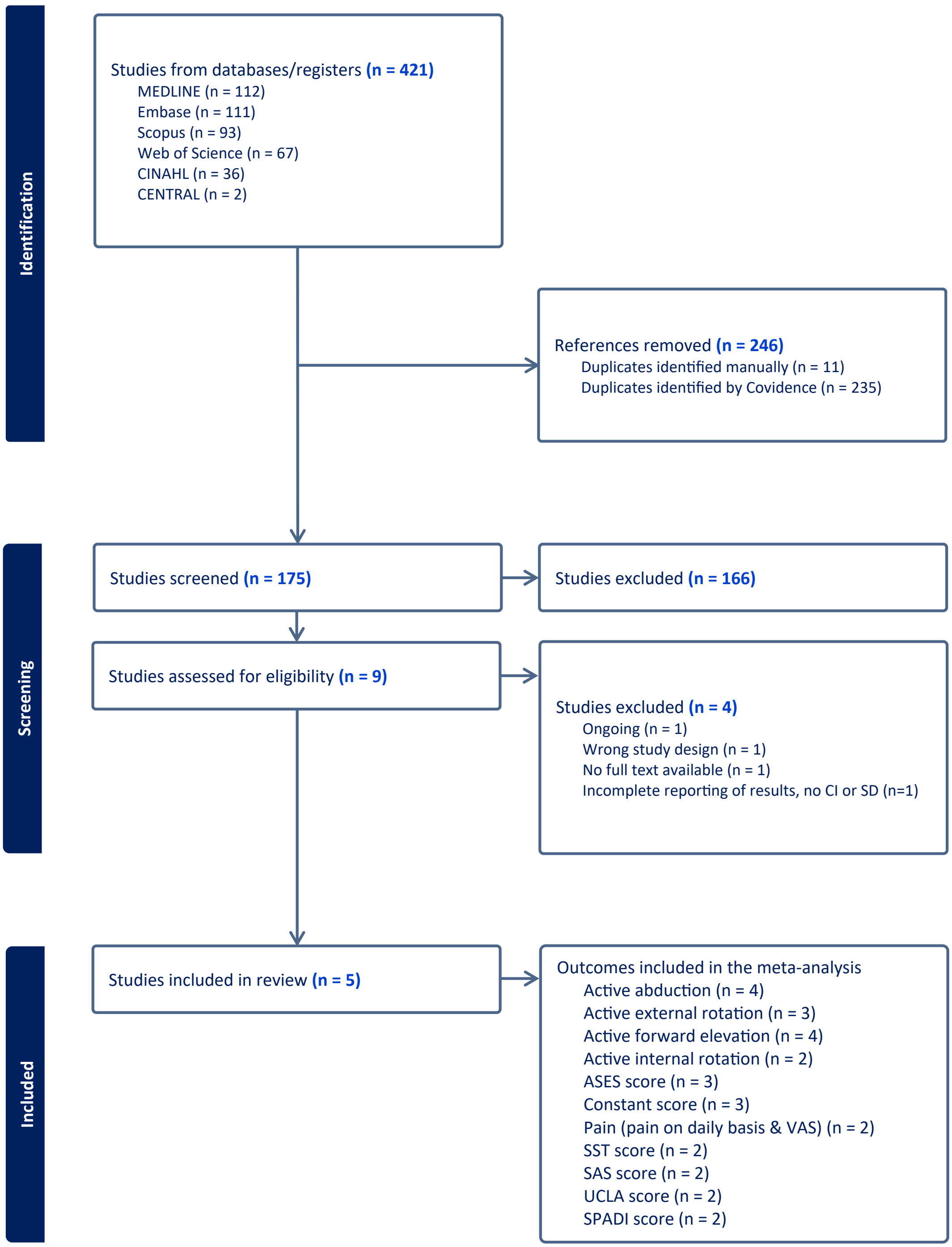

Figure 1 — PRISMA 2020 flow diagram illustrating the study selection process of the systematic review and meta-analysis. *PRISMA*, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; *ASES*, American Shoulder and Elbow Surgeons; *VAS*, visual analog scale; *SST*, Simple Shoulder Test; *SAS*, Shoulder Activity Scale; *UCLA*, University of California-Los Angeles; *SPADI*, Shoulder Pain and Disability Index.

Meta-analysis

Range of motion

From the 5 studies that reported at least one post-operative shoulder ROM outcome, only those comparing navigated vs. non-navigated rTSA were eligible for pooled analysis.[6,10,12,20] One study was excluded from the internal rotation analysis because its scoring system assigned higher scores to a worse ROM, opposite to the other studies.[12] Meta-analysis of post-operative ROM outcomes demonstrated mixed findings across different movement domains. Results are displayed through Fig. 2 (active abduction,

Table II – Characteristics of included studies.

References	Design	Navigation system	Implant design	Follow-up (mean, mo)		MINORS
				NAV	CON	
Youderian et al[20]	Retrospective cohort study	ExactechGPS (Exactech Inc.)	Equinoxe Shoulder System (Exactech Inc.)	30.6 ± 8.9	32.2 ± 8.4	16
Kim et al[12]	Retrospective cohort study	ExactechGPS (Exactech Inc.)	Equinoxe Shoulder System (Exactech Inc.)	29.6 ± 7.3	30.4 ± 5.5	17
Holzgrefe et al[10]	Retrospective cohort study	ExactechGPS (Exactech Inc.)	Equinoxe Shoulder System (Exactech Inc.)	30.7 ± 7.7	34.9 ± 9.5	17
Gaj et al[6]	Prospective cohort study	ExactechGPS (Exactech Inc.)	Equinoxe Shoulder System (Exactech Inc.)	16	16	19
Andriollo et al[1]	Retrospective cohort study	ExactechGPS (Exactech Inc.)	Equinoxe Shoulder System (Exactech Inc.)	30.7 ± 13.5	NR	11

NAV, navigated reverse total shoulder arthroplasty; *CON*, conventional reverse total shoulder arthroplasty; *NR*, not reported.

external rotation, and forward elevation) and Fig. 3 (active internal rotation).

Active abduction was reported in 4 studies (n = 2032 patients).[6,10,12,20] The pooled MD between navigated and non-navigated rTSA was −0.40° (95% CI: −3.75 to 2.97), with low heterogeneity ($\tau^2 = 2.15$, $I^2 = 14.05\%$, $H^2 = 1.16$), indicating no statistically significant difference between the groups.

Active external rotation was assessed in 3 studies (n = 1898 patients).[10,12,20] The pooled MD 4.32° (95% CI: 2.64-6.00), with no observed heterogeneity ($\tau^2 = 0.00$, $I^2 = 0.00\%$, $H^2 = 1.00$), suggesting a statistically significant improvement favoring navigated rTSA.

Active forward elevation was reported in 4 studies (n = 2032 patients).[6,10,12,20] The pooled MD was −2.20° (95% CI: −8.77 to 4.36), with substantial heterogeneity ($\tau^2 = 30.24$, $I^2 = 76.64\%$, $H^2 = 4.28$), indicating no significant difference between groups.

A separate pooled analysis combined active abduction, external rotation, and forward elevation from relevant studies (n = 2032 patients).[6,10,12,20] The pooled MD was 0.78° (95% CI: −2.24 to 3.80), with high heterogeneity ($\tau^2 = 14.01$, $I^2 = 75.05\%$, $H^2 = 4.01$), showing no significant difference between navigated and non-navigated rTSA.

Active internal rotation was reported in two studies (n = 1825 patients).[10,20] A separate meta-analysis showed no statistically significant difference between groups (MD: 0.10, 95% CI: −0.38 to 0.58), with moderate heterogeneity ($\tau^2 = 0.09$, $I^2 = 73.55\%$, $H^2 = 3.78$).

Patient-reported outcome measures

From the 5 studies that reported at least one PROM at final follow-up, only those comparing navigated vs. non-navigated RTSA were eligible for pooled analysis.[10,12,20] Positive MDs indicate better outcomes with navigated rTSA, except for pain assessed through ‘pain on a daily basis’ and VAS, and SPADI scores, where negative MDs indicate reduced pain or disability. Given the paucity of evidence, PROMs recorded in at least two studies were considered for analysis.

Three studies (n = 1,898) eligible for analysis reported ASES scores.[10,12,20] The pooled MD was 1.11 (95% CI: −1.41 to 3.63), with low heterogeneity ($\tau^2 = 1.65$, $I^2 = 27.20\%$, $H^2 = 1.37$), indicating no significant difference or advantage between navigated and non-navigated rTSA (Fig. 4).

Three studies (n = 1,898) eligible for analysis reported Constant scores.[10,12,20] The pooled MD was 2.36 (95% CI: −1.62 to 6.24), with high heterogeneity ($\tau^2 = 9.04$, $I^2 = 78.84\%$, $H^2 = 4.73$), indicating no significant difference between navigated and non-navigated rTSA (Fig. 5).

One study (n = 1,599) reporting ‘pain on a daily basis’ and another (n = 73) reporting pain VAS scores were pooled for analysis given similarity in range and purpose.[12,20] The SMD was calculated to account for scale differences. The pooled SMD was 0.10 (95% CI: −0.00 to 0.20), with no heterogeneity ($\tau^2 = 0.00$, $I^2 = 0.00\%$, $H^2 = 1.00$), suggesting no significant difference between groups (Fig. 6).

Two studies (n = 1,825) reporting SST scores were eligible for analysis.[10,20] The pooled MD was 0.33 (95% CI: 0.09-0.58), with no heterogeneity ($\tau^2 = 0.00$, $I^2 = 0.00\%$, $H^2 = 1.00$), indicating a statistically significant improvement with navigated rTSA (Fig. 7).

Two studies (n = 1,825) reporting SAS scores were eligible for analysis.[10,20] The pooled MD was 1.77 (95% CI: 0.65-2.89), with no heterogeneity ($\tau^2 = 0.00$, $I^2 = 0.00\%$, $H^2 = 1.00$), suggesting a statistically significant improvement with navigated rTSA (Fig. 8).

Two studies (n = 1,825) reporting UCLA scores were eligible for analysis.[10,20] The pooled MD was 0.56 (95% CI: −0.11 to 1.24), with heterogeneity was low ($\tau^2 = 0.84$, $I^2 = 19.49\%$, $H^2 = 1.24$), indicating no significant difference between navigated and non-navigated rTSA (Fig. 9).

Two studies (n = 1,825) reporting SPADI scores were eligible for analysis.[10,20] The pooled MD was −2.62 (95% CI: −8.17 to 2.93), with moderate heterogeneity ($\tau^2 = 10.91$, $I^2 = 62.70\%$, $H^2 = 2.68$), indicating no significant difference between groups (Fig. 10).

Publication bias

Publication bias was assessed only for the pooled analyses of active abduction, external rotation, and forward elevation due to the limited number of studies evaluating other outcomes and variability in their measurement methods. Funnel plot

Table III – Patient demographics and indications for rTSA in the included studies.

Results	Sample size		Age ± SD		Female sex, % (n)		Indications for rTSA
	NAV	CON	NAV	CON	NAV	CON	
Youderian et al[20]	533	1,066	71.6 ± 7.3	71.6 ± 7.8	55.7 (297)	55.7 (594)	GOA, RCT, and/or RCTA
Kim et al[12]	33	40	74.0 ± 7.2	73.8 ± 4.8	78.8 (26)	77.5 (31)	Irreparable RCT, RCTA, or GOA
Holzgrefe et al[10]	113	113	70.7 ± 7.8	70.6 ± 8.1	51.3 (58)	50.4 (57)	GOA, massive RCT, or RCTA
Gaj et al[6]	16	17	73 ± NR	74 ± NR	81.3 (13)	70.6 (12)	RCTA
Andriollo et al[1]	56	0	72.8 ± 6.6	NR	60.7 (34)	NR	GOA, RSD, and CPHF

SD, standard deviation; *n*, number of patients; *NAV*, navigated rTSA; *CON*, conventional rTSA; *rTSA*, reverse total shoulder arthroplasty; *GOA*, glenohumeral osteoarthritis; *RCT*, rotator cuff tear; *RCTA*, rotator cuff tear arthropathy; *RSD*, recurrent shoulder dislocations; *CPHF*, complex proximal humeral fracture.

Table IV – Risk of bias assessment of included studies using the MINORS tool.

MINORS	Youderian et al[20]	Kim et al[12]	Holzgrefe et al[10]	Gaj et al[6]	Andriollo et al[1]
A clearly stated aim	2	2	2	2	2
Inclusion of consecutive patients	2	2	2	2	2
Prospective collection of data	1	1	1	2	1
Endpoints appropriate to the aim of the study	1	2	2	2	2
Unbiased assessment of the study endpoint	0	0	0	0	0
Follow-up period appropriate to the aim	2	2	2	2	2
Loss to follow-up less than 5%	1	1	2	2	2
Prospective calculation of the study size	0	0	0	0	0
An adequate control group	2	2	2	2	NA
Contemporary groups	2	1	0	2	NA
Baseline equivalence of groups	1	2	2	1	NA
Adequate statistical analyses	2	2	2	2	NA
Total score	16	17	17	19	11

MINORS, Methodological Items for Nonrandomized Studies.

and Egger test were used to evaluate publication bias. The funnel plots for these outcomes showed no indication of publication bias, and Egger test did not reveal statistically significant evidence of small-study effects ($P = .4615$). However, Egger test has low power given the small number of studies analyzed. Results are displayed in Fig. 11.

Discussion

This systematic review and meta-analysis assessed whether intraoperative navigation in rTSA improves clinical outcomes compared to conventional methods. A total of 5 cohort studies involving 1,987 rTSA procedures were included, 4 of which directly compared navigated and non-navigated techniques. Meta-analysis of post-operative ROM and PROMs demonstrated marginal yet statistically significant improvements in active external rotation, SST, and SAS scores with navigation. Most other outcomes, including active abduction, active forward elevation, active internal rotation, pain (measured through VAS and 'pain on a daily basis'), ASES, Constant, UCLA, and SPADI scores, demonstrated no statistically significant differences.

The narrative synthesis of included studies revealed that literature supports the positive outcomes of rTSA with navigation; however, benefits cannot be statistically attributed to the role of navigation when compared to conventional techniques. These findings suggest that its overall impact on global post-operative clinical outcomes is unknown and potentially limited. This nuanced outcome profile reflects the paucity of research in this field, the complexity of rTSA rehabilitation, and the multifactorial nature of surgical success.

While some outcomes showed statistically significant differences, it is important to consider their clinical relevance. Simovitch et al[17] conducted a retrospective, international, multicenter cohort study assessing 8,581 primary total shoulder arthroplasty procedures (62% rTSA) to determine the minimal clinically important difference for ROM and PROMs. One of their conclusions was that the minimal clinically important difference for active external rotation is 4°. This review found that navigation significantly improves external rotation in rTSA procedures (MD: 4.32°, 95% CI: 2.64-6.00), indicating that this difference is not only statistically significant but also clinically meaningful, a finding potentially explained by enhanced glenoid position accuracy. Velasquez et al[19] explore this through a systematic review and meta-analysis, concluding that navigation reduces the error range for glenoid component inclination, as well as non-significant improvements in version accuracy in clinical settings.

Emerging evidence suggests that the greatest utility of intraoperative navigation in rTSA may lie in its application to anatomically complex cases. Karuna Pathirannehelage et al[11] conducted a retrospective case series of 14 patients undergoing guided personalized surgery–navigated rTSA focused on patients with distorted glenoid anatomy, such as retroversion and significant bone loss. The study found statistically

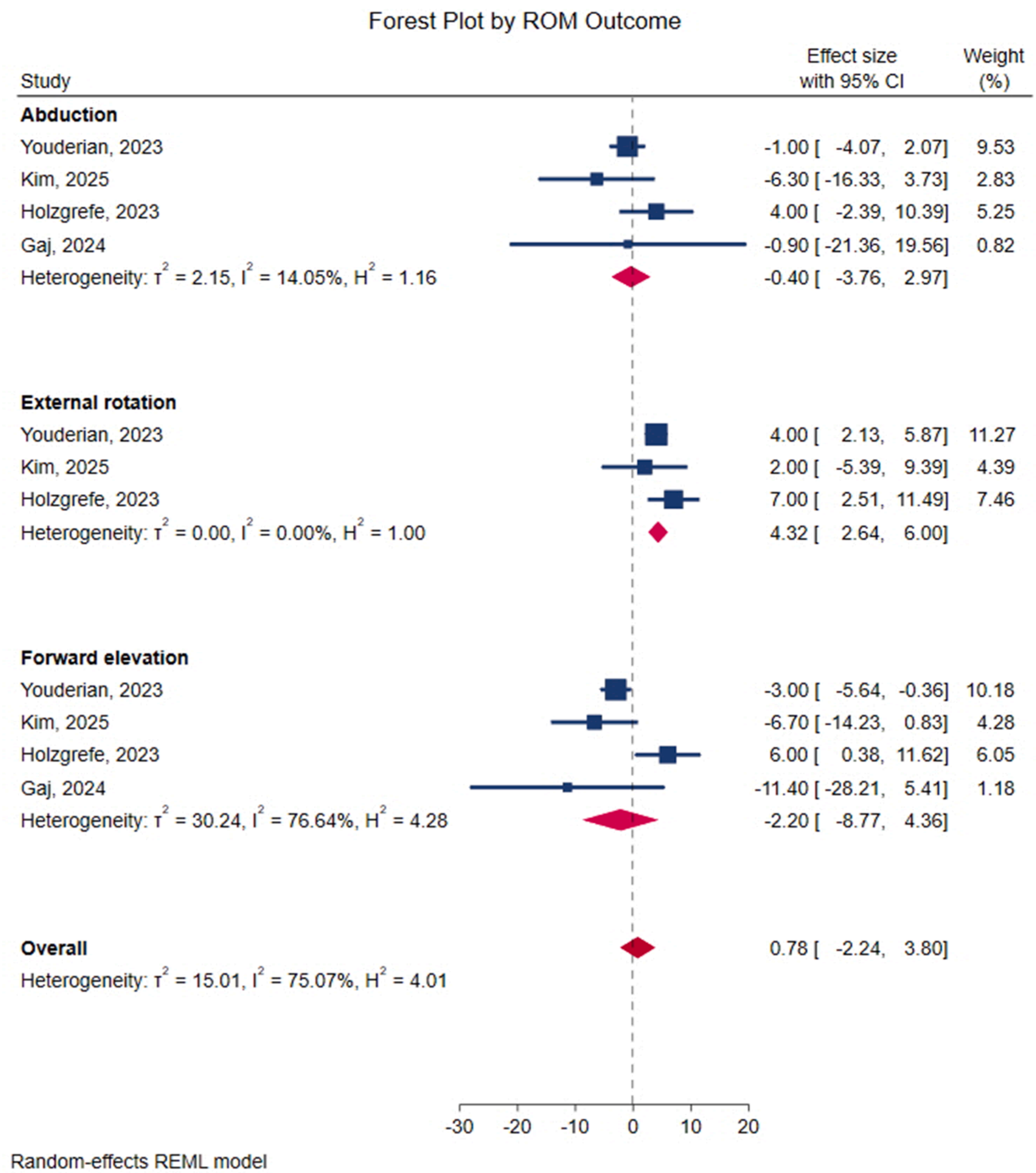

Figure 2 – Forest plot of shoulder range of motion outcomes—active abduction, active forward elevation, active external rotation, and combined—using a random-effects meta-analysis. *ROM*, range of motion; *CI*, confidence interval; *REML*, restricted maximum likelihood.

significant improvements in OSS, rising from a pre-operative mean of 17.21 ± 5.90 to 38.86 ± 4.22 at six months ($P < .05$), with progressive improvements up to three years (mean OSS, 47). In addition, 10 out of 14 patients required augmented glenoid baseplates, and no cases of glenoid loosening, dislocation, or scapular notching were reported, findings that suggest enhanced implant stability in anatomically challenging scenarios. These outcomes support this review's observation that navigation may offer targeted benefits, particularly in patients with complex glenoid morphology.

Youderian et al[20] further support this by demonstrating that in navigated rTSA cases with pre-operative to post-operative version correction exceeding 15°, patients exhibited significant improvements in forward elevation, internal rotation, and multiple PROMs, such as Constant, ASES, and SPADI scores, compared to those corrected by less than 15°. These results suggest that the advantages of navigation may be amplified in cases requiring substantial glenoid correction, potentially due to improved implant positioning and a higher rate of augmented glenoid usage (98.8% vs. 70.5%, $P < .001$). However, the high heterogeneity reported in related literature (e.g., $I^2 = 83\%$ in Velasquez Garcia et al[19]) and the small sample sizes within these subgroups (eg, only 80 cases with >15° correction[20]) limit the generalizability of these findings.

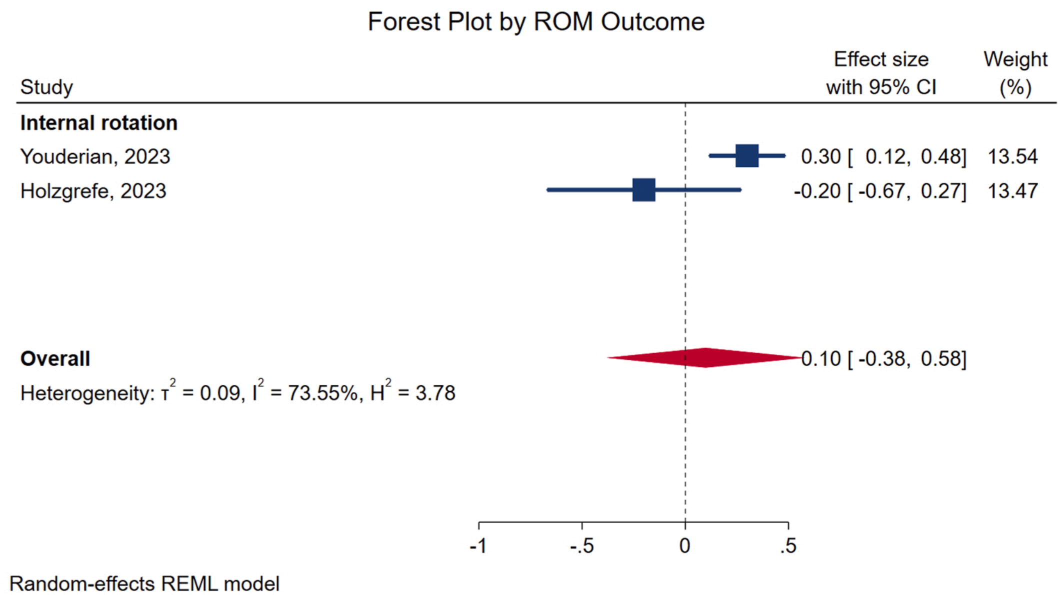

Figure 3 — Forest plot of shoulder range of motion for active internal rotation using a random-effects meta-analysis. *ROM*, range of motion; *CI*, confidence interval; *REML*, restricted maximum likelihood.

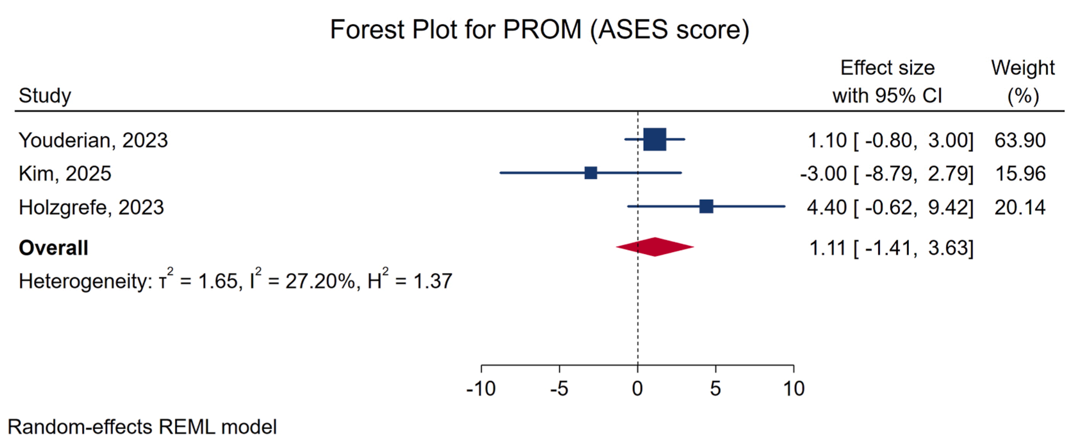

Figure 4 — Forest plot of ASES score using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *ASES*, American Shoulder and Elbow Surgeons; *CI*, confidence interval; *REML*, restricted maximum likelihood.

Limitations

This review is constrained by several significant limitations that affect its findings, potentially due to the emerging nature of navigation in upper limb orthopedics. A paucity of evidence resulted in an unintentional reliance on observational cohort studies, limiting the strength of causal inference with no randomized controlled trials identified. In addition, the small number of included studies, combined with the wide variety of PROMs measured, resulted in a limited number of studies per outcome (often 2-3), diminishing statistical power and rendering publication bias assessments, such as Egger test, unreliable due to low power. A key limitation is the inconsistent reporting of pre-operative to post-operative change scores across the included studies, resulting in our primary analysis focused on post-operative means, the only outcome consistently extractable from all sources. This may introduce confounding from baseline differences in indications or pre-operative function. Surgical indications also varied substantially between studies. This heterogeneity introduces potential confounding by case severity and prevents reliable subgroup analyses by indication, limiting attribution of observed outcomes solely to navigation. A major limitation is that all included studies exclusively evaluated a single navigation platform (ExactechGPS; Exactech, Inc.). This restricts generalizability to other navigation platforms, which differ in tracking technology, user interface, and workflow.

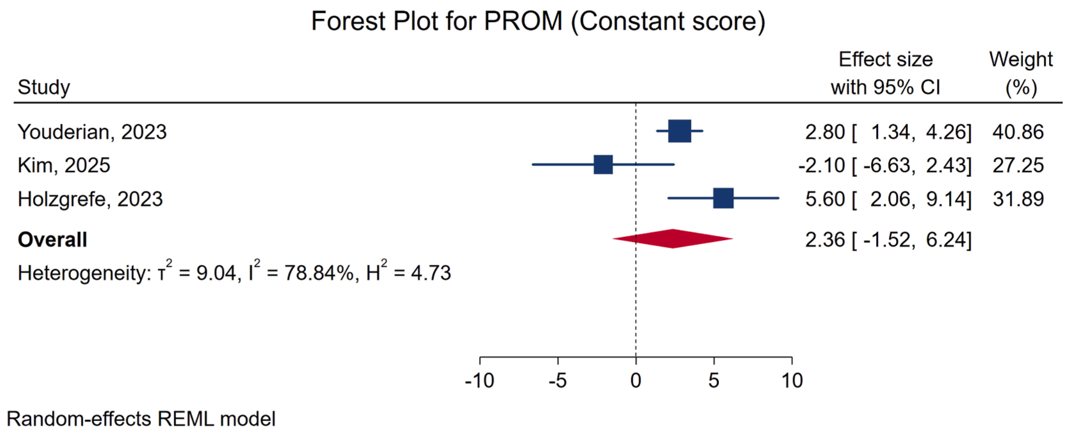

Figure 5 — Forest plot of Constant score using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *CI*, confidence interval; *REML*, restricted maximum likelihood.

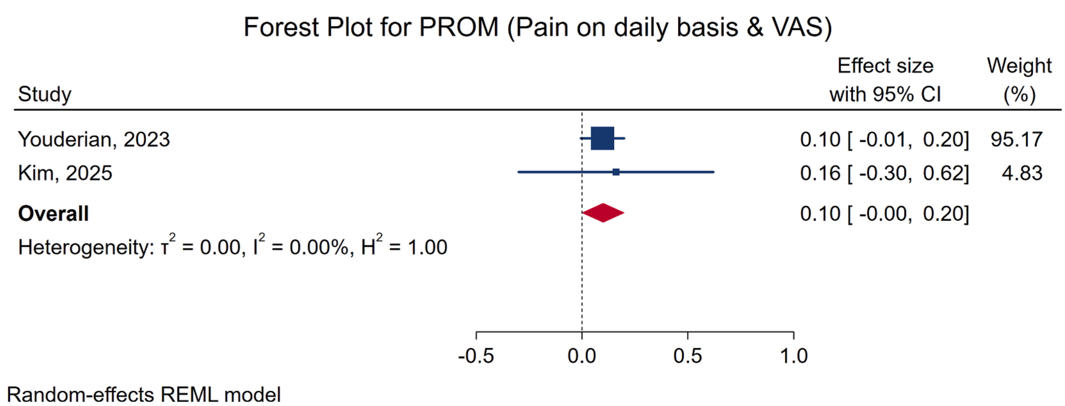

Figure 6 — Forest plot of pain using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *VAS*, visual analog scale; *CI*, confidence interval; *REML*, restricted maximum likelihood.

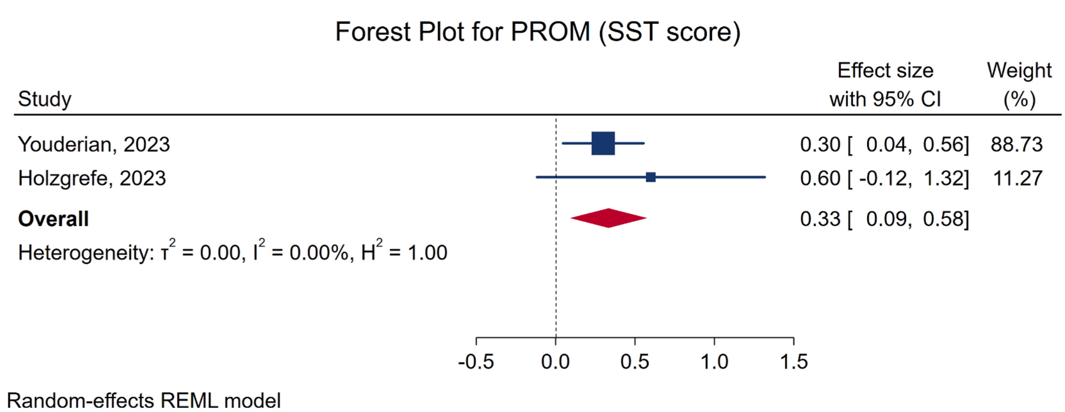

Figure 7 — Forest plot of SST score using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *SST*, Simple Shoulder Test; *CI*, confidence interval; *REML*, restricted maximum likelihood.

Consequently, observed outcomes may reflect system-specific attributes rather than intraoperative navigation as a broader class of technology. Substantial heterogeneity and variability in outcome measures further hinder direct comparisons and meta-analytic reliability. The absence of gray literature, unpublished data, and nonindexed conference abstracts risks publication bias, despite underpowered yet nonsignificant Egger tests results. Moreover, MID thresholds were

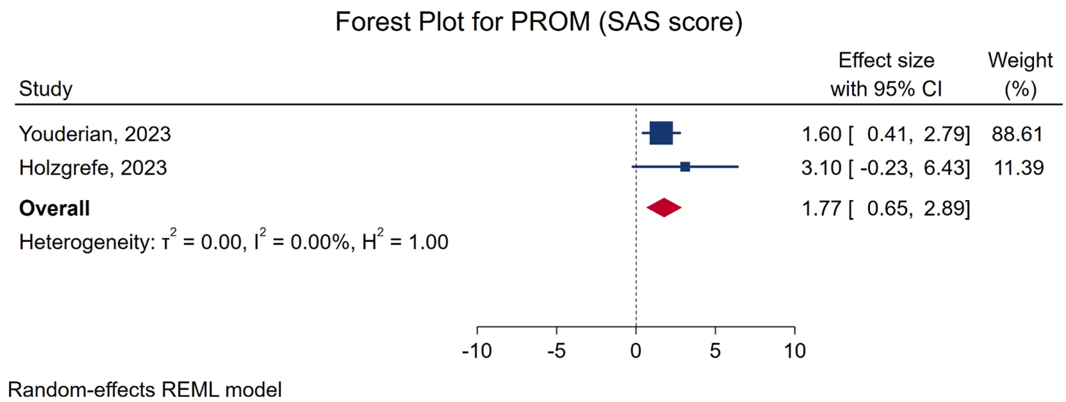

Figure 8 — Forest plot of SAS score using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *SAS*, Shoulder Activity Scale; *CI*, confidence interval; *REML*, restricted maximum likelihood.

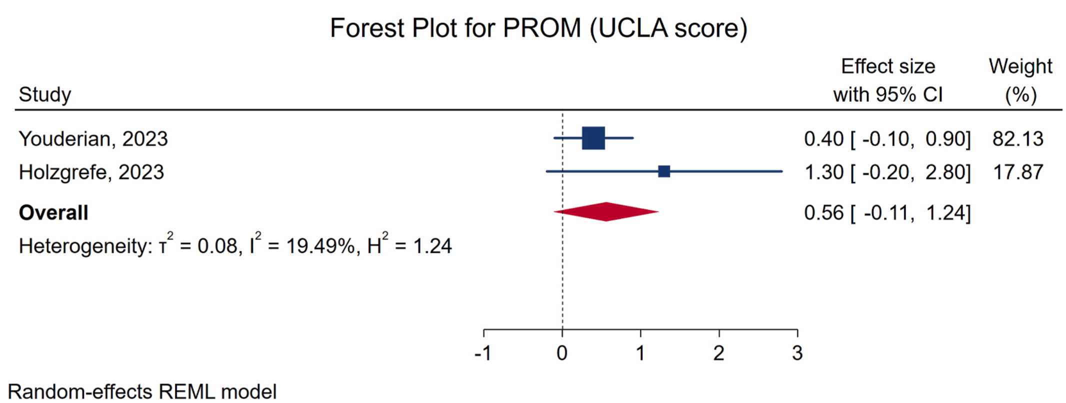

Figure 9 — Forest plot of UCLA score using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *UCLA*, University of California-Los Angeles; *CI*, confidence interval; *REML*, restricted maximum likelihood.

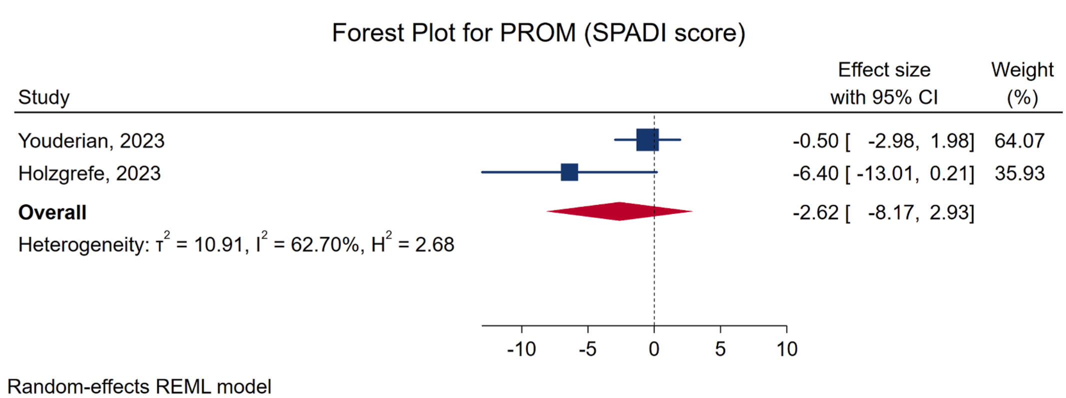

Figure 10 — Forest plot of SPADI score using a random-effects meta-analysis. *PROM*, patient-reported outcome measure; *SPADI*, Shoulder Pain and Disability Index; *CI*, confidence interval; *REML*, restricted maximum likelihood.

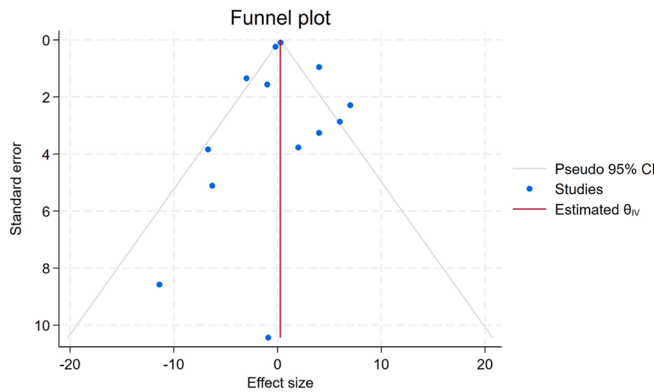

Figure 11 – Funnel plot of shoulder range of motion outcomes—active abduction, active forward elevation, and active external rotation—assessing publication bias. *CI*, confidence interval; θ_{IV}, pooled effect size.

inconsistently reported across PROMs, reducing the interpretability of clinical relevance.

Conclusion

This systematic review and meta-analysis suggest that intraoperative navigation in rTSA offers modest benefits in active external rotation, SST, and SAS scores, particularly in complex cases with glenoid deformity, but does not consistently improve other ROM or PROMs, alluding to limited justification for routine use in clinical practice or policy without further evidence. At the time of writing, a prospective, multicenter, randomized controlled trial evaluating ExactechGPS vs. conventional instrumentation in primary rTSA is in progress.[14] This study aims to assess patient-reported outcomes through the ASES score and ROM through active abduction and forward flexion. The study, started in 2024 with a target enrollment of 220 patients, may provide high-quality evidence to address this review's limitations by offering robust comparative data on navigation's impact in rTSA.

Disclaimers:

Funding: No funding was disclosed by the authors.

Conflicts of interest: The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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