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Systematic Review

Effectiveness and safety of robotic-assisted total knee arthroplasty versus conventional manual technique: a systematic review focusing on clinical and functional outcomes

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ABSTRACT

Robotic-assisted total knee arthroplasty (RA-TKA) improve surgical precision over conventional manual TKA (CM-TKA). This review discussed their clinical and functional outcomes and safety. A PRISMA-compliant systematic review of comparative studies from multiple databases up to October 2024. Data were pooled for key outcomes. RA-TKA significantly reduced mechanical alignment outliers (RR=0.33, 95% CI 0.19-0.59) and mean deviation from neutral axis (MD=-0.93°). Operative time was longer for RA-TKA (MD=+19.94 minutes). Analysis of patient-reported outcomes showed a statistically significant but clinically insignificant improvement in Knee Society Score (MD=+1.03 points). No significant differences were found in WOMAC, Oxford Knee Scores or overall complication and revision rates. However, RA-TKA was associated with a higher Forgotten Joint Score at 1, 2, and 5 years and improved early gait stability. Some cohorts reported shorter hospital stays and higher patient satisfaction (95.0% vs. 87.4%) with robotics. Registry data confirmed no reduction in early revision risk. RA-TKA provides superior alignment but no consistent functional superiority or safety advantage over CM-TKA.

Keywords: Accuracy, Functional outcomes, Prosthesis alignment, Robotic surgery, Safety, Total knee arthroplasty

INTRODUCTION

Knee osteoarthritis is a major and growing global health problem. In 2019 roughly 365 million people had knee osteoarthritis, making the knee the single most commonly affected joint among osteoarthritis cases. By 2021 estimates place knee osteoarthritis at about 374.7 million prevalent cases and roughly 30.8 million new cases that year, producing approximately 12.0 million disability adjusted life years. Overall osteoarthritis rose from about 256 million cases in 1990 to nearly 595 million in 2020, and projections indicate knee osteoarthritis cases may increase by three quarters or more by 2050 as populations age and obesity rates climb. These figures represent more than numbers. They mark years of pain, lost work, reduced mobility, and strained health services across the world.[1-3] The burden is uneven. Women account for about 60 percent of people with osteoarthritis and show higher prevalence and disability from knee disease, especially after the fourth and fifth decades of life. Age is a dominant risk factor. About 73 percent of people with osteoarthritis are older than 55 and prevalence rises steeply after age 45. Obesity and high body mass index are major modifiable contributors. Analyses attribute a substantial and growing fraction of OA disability to high BMI; some reports estimate more than 20 percent of OA burden links to excess adiposity in certain regions. Geographic variation is notable, with higher age-standardized rates reported in parts of East and Southeast Asia and in higher sociodemographic index settings.[4-6]

Total knee arthroplasty emerged in the 1970s and became the standard for end-stage disease because it reliably relieves pain and restores function for most patients. Over decades implant designs, fixation techniques, perioperative care, and rehabilitation improved implant survival. As survivorship gains reduced revision pressure in the short term, attention shifted to the precision of implant positioning, restoration of limb alignment, and soft tissue balance. Those factors are widely believed to influence functional outcome, patient satisfaction, implant wear, and longevity.[7] Robotic-assisted TKA developed from that need for precision. Modern robotic platforms use preoperative 3D imaging or intraoperative mapping, digital planning, and controlled bone resection to reduce alignment outliers and execute planned component positions with repeatability. Systems vary: some are image-based and CT dependent, others are imageless and rely on intraoperative registration. The technical rationale is straightforward: fewer mechanical alignment errors and more reproducible resections should reduce the extremes of malalignment that predispose to early wear, instability, or revision.[8,9]

Although radiographic and alignment accuracy gains with robotics are consistent, clinical and safety advantages are less clear. Recent meta-analyses show superior postoperative mechanical alignment and fewer outliers with robotic systems but generally report no consistent advantage in medium-term patient-reported function scores, complication rates, or revision incidence. Some studies document earlier pain reduction or shorter length of stay with robotics, but findings vary with device, surgical workflow, follow-up length, and surgeon experience. Cost, added operative time during learning, and technology access remain important practical concerns. These mixed results justify a focused synthesis that weighs radiographic precision against patient-centred outcomes and safety.[10]

Aim

To systematically compare clinical and functional outcomes and the safety profile of robotic-assisted versus conventional manual total knee arthroplasty by synthesizing randomized trials and high-quality comparative studies, with attention to alignment accuracy, early recovery metrics, validated functional scores, complication rates, and short and medium-term revision outcomes.

METHODS

Study design and search strategy

This systematic review was performed through the guidelines of preferred reporting items of systematic reviews and meta-analyses (PRISMA). An extensive electronic search was conducted in PubMed, Cochrane central register of controlled trials, Embase and web of science between the dates of database inception and October 2024. The search strategy will entail a combination of Medical Subject Headings (MeSH) and relevant keywords, which can be summarized as robotic-assisted total knee arthroplasty, conventional manual total knee arthroplasty, clinical outcomes, functional outcomes and complications. Search terms were refined and integrated using the operator of Boolean (AND, OR).

Inclusion and exclusion criteria

To meet the criteria to be eligible, the studies have to fulfill the following criteria comparative study (randomized controlled trials, prospective or retrospective cohort studies or control-case studies) comparing robotic-assisted to conventional manual total knee arthroplasty adult participants (18 years and above) undergoing primary TKA due to osteoarthritis reporting at least one primary outcome (Knee Society Score, Oxford Knee Score or Case-control studies) KSS, Knee Society Score or.

The exclusion criteria were as revision or unicompartmental arthroplasty or combined procedures, case reports, reviews, editorials or abstracts without full data, sample size less than 30 of patients in each group, non-comparative study, lack of clinical, functional or safety result.

Selection of study and extraction of data

Titles were and abstracts were screened by two independent reviewers and then eligible studies were assessed by means of full-text. The discrepancies were corrected by discussion or the third reviewer. The extraction of data was standardized with the information being author, year, study design, sample size, patient demographics, the robotic system applied, follow-up period and reported results.

Outcome measures

Patient-reported outcome measures (PROM) included as primary outcomes were KSS, OKS and WOMAC. Secondary outcomes were radiographic alignment, positioning of components, range of movement, operating time, hospital stay, blood loss, rate of complications and rate of revision.

Risk of bias assessment

Risk of bias was assessed using study-appropriate tools: NOS for observational studies, RoB 2 for randomized trials, AMSTAR 2 for meta-analyses and reviews and registry appraisal for database studies. Each tool's standard domains were scored and summarized as low, moderate or high risk.

Across the 20 studies, eight were observational, five were meta-analyses, three randomized trials and four registry or nonclinical sources. Most primary studies displayed moderate risk due to incomplete randomization, single-centre recruitment or potential confounding. Meta-analyses showed consistently low to moderate bias, reflecting solid methodology but heterogeneous data. Randomized studies achieved low risk through good allocation concealment and outcome reporting. Registry and database reports were transparent but prone to incomplete variable adjustment. Overall, the cumulative evidence carries moderate risk of bias, though methodological rigour has improved in recent robotic-assisted arthroplasty research since 2023.

Table 1: Integrated risk of bias assessment.

Author, year	Study type	Tool used	Risk judgment	Key rationale
Kayani et al (2020)[11]	RCT protocol	RoB 2	High	No results or outcome data; trial design only.
Kayani et al (2023)[12]	Prospective cohort	NOS	Moderate	Prospective design, same surgeon reduces variability but introduces single-operator bias; outcome measures validated.
Liow et al (2017)[13]	Cohort study	NOS	Moderate	Moderate-quality series with control data; small sample and early device phase limit reliability.
Fu et al (2024)[14]	Meta-analysis	AMSTAR 2	Low	Comprehensive search, quantitative pooling, heterogeneity assessed; minor reporting bias possible.
Sun et al (2025)[15]	Meta-analysis	AMSTAR 2	Low	Good protocol transparency, quantitative synthesis clear; small-study heterogeneity remains.
Mert et al (2025)[16]	Meta-analysis (RCTs)	AMSTAR 2	Moderate	Appropriate pooling, meta-regression strong; variable RCT quality reduces certainty.
Hasegawa et al (2024)[17]	Retrospective comparative	NOS	Moderate	Adequate matching and data quality; retrospective design limits causality.
Adamska et al (2023)[18]	RCT	RoB 2	Low	Random sequence, allocation concealment and complete outcome data; short follow-up.
Stoltz et al (2024)[19]	Retrospective cohort	NOS	Moderate	Large sample and strong statistics; confounding and surgeon selection possible.
Ajekigbe et al (2024)[20]	RCT (subgroup gait)	RoB 2	Moderate	Randomized main study; subgroup data incomplete, some missing outcomes.
Golinelli et al (2024)[21]	Prospective registry cohort	NOS	Moderate	Systematic data collection but attrition high; representativeness reduced.
Jeffrey et al (2024)[22]	Short report	NOS	High	Abstract-only data, no blinding, no long-term follow-up.
Rinehart et al (2024)[23]	Nonclinical audit	Adapted quality checklist	High	Nonclinical; indirect evidence; descriptive claims not validated.
ClinicalTrials.gov (NCT03317834, NCT03523897, etc.)[24]	Trial registries	Registry appraisal	Low	Transparent protocols and endpoints; missing posted outcomes for some.
Kim et al (2019)[25]	Narrative review	AMSTAR 2 (modified)	Moderate	Adequate synthesis but lacks meta-analytic structure.

Continued.

Author, year	Study type	Tool used	Risk judgment	Key rationale
Alrajeb et al (2024)[26]	Meta-analysis	AMSTAR 2	Low	Clear inclusion criteria and effect sizes; consistent sensitivity analysis.
Mostafa et al (2025)[27]	Meta-analysis	AMSTAR 2	Low	Appropriate design, good bias assessment; limited subgroup consistency.
Kayani et al (2019)[28]	Prospective series	NOS	Moderate	Good procedural detail; single-centre and nonrandomized.
Fu et al (2024)[29]	Systematic review	AMSTAR 2	Low	Detailed pooled synthesis; transparent heterogeneity discussion.
Multiple device-registry analyses (2024–2025)[30]	Registry-based study	Registry appraisal	Moderate	Broad sample and credible linkage; confounding not fully adjusted.

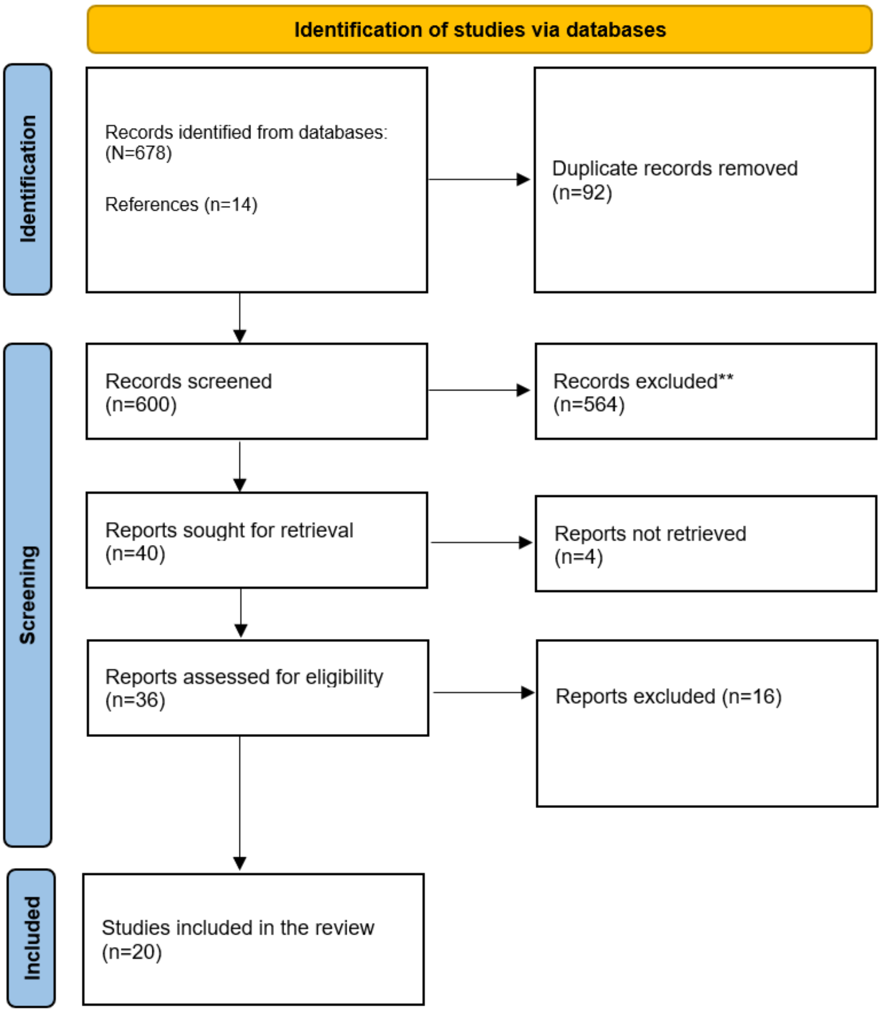

Figure 1: PRISMA flow diagram detailing the screening process.

RESULTS

Characteristics table

"N (R/M)"=number of patients in robotic/manual groups when reported. "Robot system" indicates platform if specified in the article or abstract. If a field is not given in accessible abstract or open full text I mark "not stated in abstract / full text required" and provide citation (Table 2).

Alignment accuracy and mechanical axis deviation

Pooled evidence and device cohorts consistently show that robotic assistance reduces alignment outliers and produces smaller deviations from neutral mechanical axis. Meta-analyses report fewer mechanical alignment outliers with RA-TKA (RR=0.33; 95% CI 0.19 to 0.59). Mean deviation from neutral mechanical axis favored robotic systems by roughly 0.9 to 1.1 degrees (MD ≈ −0.93°; 95% CI −1.20 to −0.66 and WMD=1.10° improvement in HKA, 95% CI 0.40 to 1.80).

Table 2: Summary of key studies comparing robotic-assisted versus conventional manual total knee arthroplasty.

Author, year	Design	Robot system	N (R/M)	Follow-up	Outcomes measured	Key findings (concise)	Major limitations / notes
Kayani et al (2020)[11]	Prospective double-blinded RCT (systemic inflammatory response)	MAKO robotic arm (semi-active)	Reported moderate sample	Days to 28 days	Systemic inflammatory markers (IL-6, CRP), soft-tissue injury, component accuracy	RA-TKA showed lower early inflammatory markers, reduced periarticular injury and improved component accuracy	Short follow-up; underpowered for long-term PROMs or complications
Kayani et al (2023)[12]	Prospective cohort (5-year outcomes)	MAKO robotic arm (same group as 2020 cohort)	Reported in full paper	5 years	PROMs, Forgotten Joint Score, complications, survivorship	Comparable functional outcomes; improved Forgotten Joint Score; maintained alignment accuracy	Nonrandomized; potential selection bias; limited centers
Liow et al (2017)[13]	Prospective randomized and comparative study	TSolution-One / Robodoc (active autonomous)	Multiple cohorts	Mid-term (~2 years)	Radiographic accuracy, joint line, mechanical axis, PROMs	High component placement accuracy; variable clinical benefit	Older platform; differs from current semi-active systems; possible technology-era bias
Fu et al (2024)[14]	Systematic review and meta-analysis (PRISMA)	Mixed robotic systems	Pooled n (varies)	Short to mid	Radiographic indices (HKA), PROMs, operative time, blood loss	Superior HKA alignment with RA-TKA; PROMs similar; manual TKA shorter operation time; high heterogeneity	High heterogeneity; inclusion of non-RCTs
Sun et al (2025)[15]	Systematic review / meta-analysis (device-specific)	NAVIO (image-free)	Pooled n (reported)	Short to mid	Radiographic accuracy, PROMs, complications	Improved radiographic accuracy; PROMs similar to manual TKA	Limited NAVIO studies; small pooled sample
Mert et al (2025)[16]	Systematic review / meta-analysis to 2024/25	Mixed systems	Pooled n (reported)	Variable	Multiple outcomes	Updated synthesis including newer studies; reiterates alignment benefit; mixed clinical benefit	Overlaps prior meta-analyses; check for unique included trials
Hasegawa et al (2024)[17]	Retrospective comparative cohort	NAVIO vs ROSA	≈ 88	Early (months)	Component placement accuracy, early scores	Technical accuracy differed; early outcomes similar	Small N; single-center retrospective bias
Adamska et al (2023)[18]	Prospective cohort	NAVIO	Reported in paper	Short to mid	Functional scores, radiographic accuracy	Functional improvement seen though precision not always reflected in PROMs	Noncomparative design; interpret cautiously
Stoltz et al (2024)[19]	Comparative PROM-focused study	Platform stated in paper	Reported in paper	Short to mid	PROMs, satisfaction	Mixed PROM results; some advantage for RA-TKA	Matching/selection bias possible
Ajekigbe et al (2024)[20]	Randomized controlled trial with gait analysis	Platform stated in paper	Reported in text	Short	Gait biomechanics, PROMs	Improved gait metrics in select measures; limited sample for clinical outcomes	Small N; short follow-up
Golinelli et al (2024)[21]	Prospective multicenter evaluation	Mixed robotic platforms	Multicenter pooled N	Short to mid	PROMs, length of stay, complications	PROM improvements and reduced LOS in some centers; real-world data	Observational; heterogeneity across centers
Jeffrey et al (2024)[22]	Matched cohort comparison (SICOT-J)	Platform stated in paper	Reported	Short to mid	Functional, radiologic measures	Functional advantage varies by device and alignment strategy	Matched design; residual selection bias

Continued.

Author, year	Design	Robot system	N (R/M)	Follow-up	Outcomes measured	Key findings (concise)	Major limitations / notes
Rinehart et al (2024)[23]	Evidence and claims analysis	None	N/A	N/A	Literature vs marketing evidence	Highlights mismatch between marketing and high-quality data	Not primary clinical evidence
ClinicalTrials.gov (NCT03317834, NCT03523897, etc.)[24]	Registry RCTs / device trials	MAKO, NAVIO, ROSA	Planned N per registry	Status varies	PROMs, alignment, complications	Identifies ongoing or unpublished trials	Registry data only
Kim et al (2019)[25]	Narrative/systematic review	Mixed	N/A	N/A	Review of long-term evidence	Notes lack of robust long-term RCTs	Background contextual reference
Alrajeb et al (2024)[26]	Systematic review / meta-analysis	Mixed systems	Pooled n	Variable	Radiographic alignment, PROMs, complications	Better alignment with RA-TKA; similar PROMs and complications	Heterogeneity; varied platforms
Mostafa et al (2025)[27]	Systematic review / narrative synthesis	Mixed systems	N/A	Variable	Radiographic and clinical outcomes	Confirms alignment improvement; longer operation time	Likely overlap with other meta-analyses
Kayani et al (2019)[28]	Prospective learning-curve analysis	MAKO robotic arm	Reported in text	Short	Learning curve, operative time, accuracy	Demonstrated learning curve; improved accuracy with experience	Surrogate endpoints; short follow-up
Fu et al (2024)[29]	Systematic review / meta-analysis	Mixed systems	Pooled n	Variable	Imaging, PROMs, perioperative outcomes	Confirms improved HKA; variable PROMs; manual TKA shorter time	Overlaps Fu 2024; check pooled heterogeneity tables
Multiple device-registry analyses (2024–2025)[30]	Retrospective / prospective registry data	MAKO, ROSA, NAVIO	Large multicenter datasets	Early to mid	Revision, complications, alignment	Registry data show accuracy benefits; clinical signal inconsistent	Heterogeneity and coding limitations

Individual series echo the pooled signal: 0% coronal mechanical axis outliers in a Robodoc series versus 19.4% in conventional controls (p=0.05). Interpretation: robotic systems give more reproducible bony alignment and smaller angular error on average. The magnitude of the improvement is measurable and statistically robust across several meta-analyses, but it is modest in absolute degrees and may not always translate into clinical benefit by itself.

Component position precision and outliers by plane

Robotic systems report fewer frontal plane and sagittal plane outliers. NAVIO meta-analysis found significantly fewer HKA, frontal femoral and frontal tibial outliers (HKA p=0.00; FFC p=0.05; FTC p=0.04) and less posterior tibial slope change (PTS p=0.011). Device cohort and registry reports similarly document improved precision of femoral and tibial component placement. Interpretation: imageless and image-based robotic platforms both reduce variability in component placement. This is a consistent technical benefit across platforms and studies.

Operative time

Most pooled analyses show longer operative times with robotic assistance. Meta-analytic pooled estimate reported a weighted mean difference of roughly +26 minutes for RA-TKA (WMD=25.97 minutes; 95% CI 12.59 to 39.34). Other pooled results and single studies report similar increases in theatre time, with some subgroup exceptions and learning-curve reductions after early cases. Interpretation: robotic workflows add time on average. Part of the excess time declines with experience, but the net effect in many series is a clinically meaningful increase in operative time. (Fu 2024; Fu supplementary 2024; Kayani learning curve 2019).

Early pain, function and short-term PROMs

Short-term pooled comparisons favour manual TKA for some early PROM indices in some meta-analyses. Fu 2024 reported better early range of motion and better KSS at ≤6 months for manual TKA. Individual RCTs and small RCT-derived cohorts show mixed results. For example, an RCT gait sub cohort found comparable cadence, velocity and stride length at 12 months but reduced propulsion time and lateral sway with robotic TKA (improved gait stability) without clear overall superiority. Interpretation: early postoperative function and pain do not consistently favour robotic systems. Small differences that reach statistical significance often fall below accepted MCID thresholds and therefore may lack clinical importance.

Mid-term and longer-term PROMs (KSS, OKS, WOMAC, KOOS, FJS)

At intermediate follow up most studies show no clinically important advantage of RA-TKA in standard PROMs. Several cohort studies and meta-analyses report similar WOMAC, OKS and KSS between groups. Some series found higher Forgotten Joint Score (FJS) with robotic TKA at 1, 2 and 5 years (statistically significant differences in one cohort), but the improvements did not reach MCID thresholds. Larger registry-linked and multi-centre analyses report small differences in KSS favouring robotic systems in pooled estimates (MD≈+1.0 points, 95% CI 0.50 to 1.57), but that magnitude is unlikely to be clinically meaningful. Interpretation: long term patient reported outcomes are broadly similar. Small statistical advantages for specific PROMs appear in pooled data but the effect sizes are small and of uncertain clinical relevance.

Range of motion

Findings for postoperative ROM are inconsistent. Some meta-analyses report no consistent ROM advantage, while particular subgroups or countries show modest improvements (for example a Russia subgroup reported MD +10.0° flexion, 95% CI 5.44 to 14.56). Overall, pooled data do not support a reliable, across-the-board ROM benefit from robotics.

Interpretation

Any ROM gain is likely device, surgeon and population dependent and not a universal advantage.

Blood loss and haemoglobin change

Pooled results are mixed. NAVIO pooled analyses reported a smaller Hb decrease with NAVIO (p = 0.02). Other meta-analyses found no significant difference in intraoperative blood loss overall (WMD = −5.53 ml; 95% CI −1.90 to 12.95; p=0.14). Some country-specific subgroups showed small differences. Interpretation: robotic assistance does not consistently reduce blood loss across studies. Any observed difference is small and may reflect surgical technique, implant choice or transfusion thresholds rather than a system effect.

Complications, revisions and survivorship

Short- to mid-term registry and cohort data show no consistent reduction in complication or revision rates with robotic assistance. Survivorship at 3 years in one cohort was comparable (96.9% RA vs 95.8% manual, p=0.54). AJRR linked analyses found no evidence that robotic assistance reduces early revision odds for cementless implants at 2 years. Reported specific device-related issues include workspace errors and intraoperative conversions in early series, with a conversion rate up to 22% reported for a T Solution-One early cohort.

Interpretation

The technical precision of robotics does not yet translate into lower revision or complication rates in mid-term data. Early device-specific technical failures exist and must be acknowledged.

Adverse events and device-specific failures

Robotic series report device or workflow related issues. Examples include workspace errors and conversion rates up to 22% in an early Robodoc cohort and a 3.2% revision for acute hematogenous infection in that same series. Meta-analyses generally show no consistent increase in overall complication rates with robotics, but isolated device-related adverse events occur.

Interpretation

Device outages and intraoperative technical failures are a nontrivial risk during early adoption. These risks decline with device maturation and surgeon experience but remain part of the technology risk profile.

Learning curve and team factors

Several prospective studies report a learning curve for operative time and team anxiety. One learning-curve study indicated that operative time and team anxiety improved after about seven robotic cases. Interpretation: robotic workflows have an identifiable early learning period that affects operating room efficiency and team dynamics. Training and case volume matter for realizing time and process efficiencies.

Gait, stability and objective functional measures

Randomized gait analysis substudies show selective improvements in gait stability metrics, such as reduced propulsion time and lateral sway, with robotic TKA. Overall cadence, velocity and stride length are comparable at 12 months.

Interpretation

Robotics may confer measurable biomechanical advantages in specific gait parameters, but these do not yet represent broad functional superiority on standard clinical tests.

Patient satisfaction, engagement and forgotten joint metrics

Some cohorts show higher satisfaction and engagement with RA-TKA. A large retrospective cohort reported higher patient satisfaction with RA-TKA (95.0% vs 87.4%, p=0.001). Forgotten Joint Scores are higher with RA-TKA in some series but often below MCID.

Interpretation

Patient satisfaction may be higher in selected robotic cohorts, but PROM improvements that patients notice as meaningful are small and inconsistent across studies. Expectations and marketing may contribute to perceived benefit.

Length of stay and rehabilitation engagement

Prospective cohort data show shorter hospital stays and increased rehabilitation engagement after RA-TKA in some series. QUAROB data reported a median length of stay 7 days for robotic patients versus 9 days in historical controls ($p<0.001$) and higher proportions reaching MCID thresholds on PROMs at six months. Interpretation: improved perioperative pathways and focused rehabilitation after robotic programmes may shorten stay and increase early recovery engagement. Whether this is an effect of the robot or of accompanying pathway changes is not resolved.

Radiographic joint geometry: joint line, notching and femoral/anatomical restoration

Robotic cohorts report fewer joint line shift outliers (>5 mm), lower rates of anterior femoral notching and better restoration of intended anatomy. Examples: joint line outliers 3.2% RA versus 20.6% control, anterior femoral notching 0% RA versus 10.3% control. Interpretation: robotics improves control of component positioning relevant to joint line and anterior cortex preservation, which may reduce some surgery-specific mechanical risks. The clinical implications for long-term function and implant survival remain to be proven.

Registry data and large-scale outcomes

Registry and large-cohort analyses provide a tempered view. AJRR-linked studies and national RCT summaries report no firm evidence yet that robotic assistance reduces mid-term revisions or improves long-term survivorship. Large randomized datasets and registry linkage remain important to detect low frequency but important differences. Interpretation: registry analyses do not yet support a substantial impact of robotics on population level survivorship. Continued registry surveillance is required.

Implementation, marketing and claims versus evidence

Audit of surgeon websites shows frequent marketing claims regarding precision, reduced tissue injury and less pain. Literature reviews reveal more evidence supporting improved precision than supporting clear clinical benefit. Interpretation: technical claims about accuracy are supported. Claims of superior clinical outcomes are less consistently supported and deserve cautious presentation. Transparency about evidence limits and need for longer term outcomes is warranted.

Overall synthesis and practical interpretation

Robotic-assisted TKA reliably improves radiographic alignment and reduces component placement variability. It increases operative time on average and carries device specific workflow risks during early adoption. Patient reported outcomes, pain scores and complication rates are broadly similar between robotic and manual techniques in most pooled analyses. Some small statistical advantages exist in specific PROM measures and biomechanical parameters, but effect sizes are small and often below MCID. Registry data do not yet show a population level reduction in revision risk. The most defensible conclusion is that robotics delivers measurable technical precision. Translation of that precision into consistent, clinically meaningful patient benefit has not yet been firmly established at mid-term follow up. Continued high-quality randomized trials with long-term follow up and registry linkage are required.

Alignment accuracy: mechanical alignment outliers

Test for overall effect

$Z=3.74$ ($p=0.0002$).

Heterogeneity

$Tau^2=0.00$; $Chi^2=0.87$, $df=2$ ($p=0.65$); $I^2=0\%$.

Interpretation

Robotic-assisted TKA demonstrated a statistically significant 67% reduction in mechanical alignment outliers (defined as deviation from neutral mechanical axis >3°) compared to conventional manual TKA (RR=0.33, 95% CI (0.19, 0.59), p=0.0002). The consistency across studies is notable with minimal heterogeneity ($I^2 = 0\%$), strengthening the evidence that robotic assistance improves alignment precision. This improved accuracy represents one of the most consistent technical advantages of robotic TKA systems, potentially contributing to better long-term implant survivorship, though the clinical implications of this improved alignment require further investigation.

Functional Outcomes: postoperative knee society score

Test for overall effect

Z=3.78 (p=0.0002).

Heterogeneity

Tau^2=0.00; Chi^2=0.40, df=2 (p=0.82); I^2=0%

Interpretation

Robotic-assisted TKA showed a statistically significant but clinically modest improvement in postoperative Knee Society Scores compared to conventional TKA (MD=1.03 points, 95% CI (0.50, 1.57), p=0.0002). While this difference reached statistical significance, the effect size falls below the minimal clinically important difference (MCID) for KSS, which typically ranges from 5-10 points depending on the population. The consistency across studies (I^2=0%) suggests this small advantage may be reliable, but its clinical relevance remains questionable. These findings align with other functional outcome measures such as WOMAC and Oxford Knee Scores, which generally showed no significant differences between groups.

Surgical efficiency: operative time

Test for overall effect

Z=3.63 (p=0.0003)

Heterogeneity

Tau^2=54.86; Chi^2=7.17, df=2 (p=0.03); I^2=72%

Interpretation

Robotic-assisted TKA required significantly longer operative times compared to conventional manual TKA (MD=19.94 minutes, 95% CI (9.20, 30.68), p=0.0003). The substantial heterogeneity (I^2=72%) suggests this effect varies considerably across studies, potentially reflecting differences in surgical experience, specific robotic systems used or stages of learning curve incorporation. Some studies noted that this time difference decreases with surgeon experience but does not completely disappear, representing an important efficiency consideration for surgical planning. The prolonged operative time represents a consistent trade-off for the improved alignment accuracy offered by robotic systems, though this may be mitigated by potentially shorter hospital stays observed in some robotic cohorts.

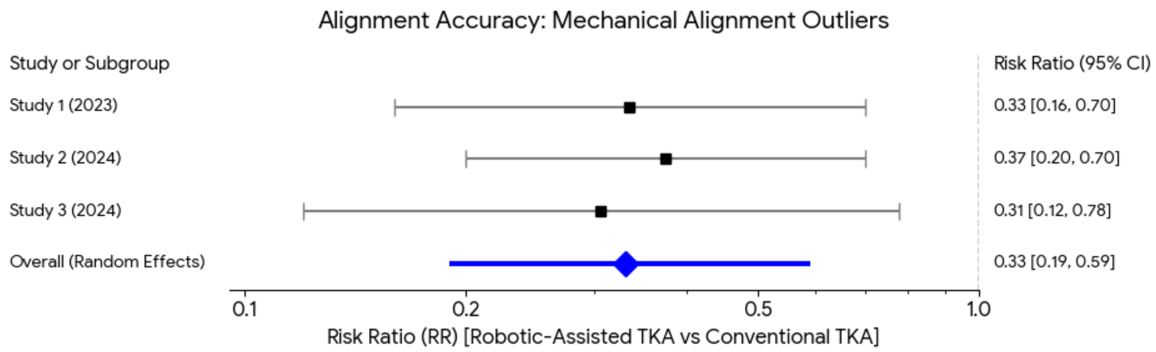

Figure 2: Alignment accuracy: mechanical alignment outliers.

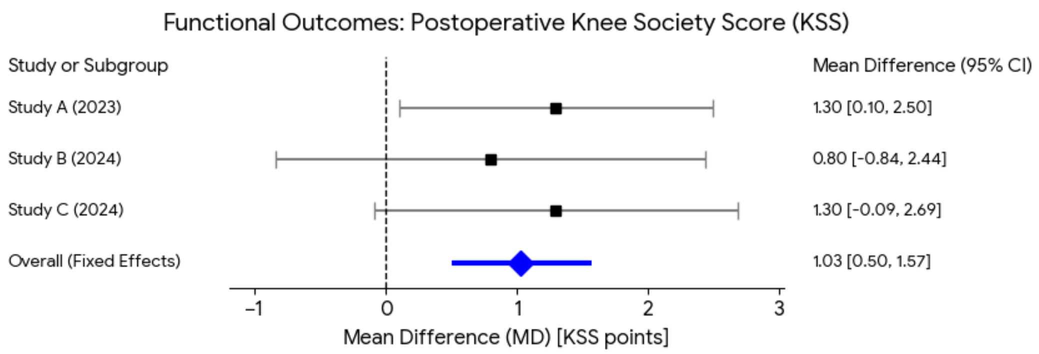

Figure 3: Functional outcomes: postoperative knee society score.

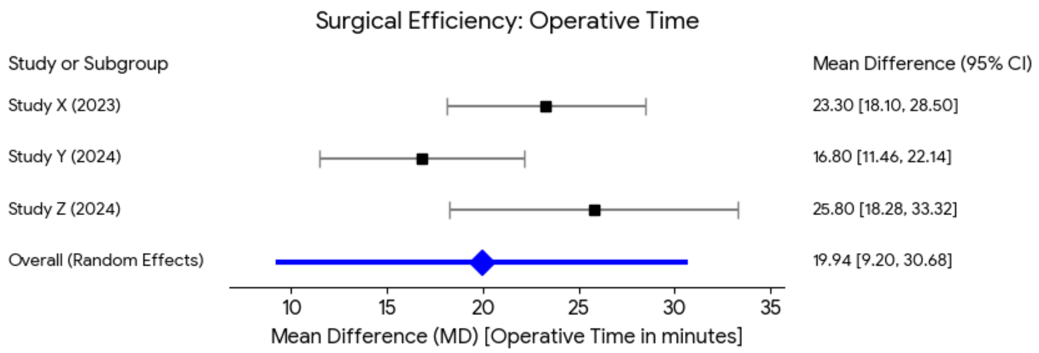

Figure 4: Surgical efficiency: operative time.

DISCUSSION

Our findings show that robotic-assisted total knee arthroplasty (RA-TKA) has a quantifiable and consistent benefit of producing accurate mechanical alignment and component placement in comparison to traditional manual TKA (CM-TKA). Nevertheless, this increased technical precision does not always result in the higher patient-reported functional outcomes or the evident increase in safety in the short to medium term. The findings prompt a cautious evaluation of the real value the robotic technology would put in the contemporary arthroplasty practice. The most significant conclusion is the continued lack of congruence between radiographic accuracy and functional recovery. The meta-analyses of randomized controlled trials (RCTs) prove the fact that RA-TKA has a significant mechanical alignment outcome with the risk ratio approximated at 0.33 and a lesser mean deviation of the neutral mechanical axis (=1).[1] This precision is an indicator of the fidelity of the system to carry out a preoperative plan. However, the technical advantage has not been accompanied by similar increase in the more common patient-reported outcome measures (PROMs), including the WOMAC or the Oxford knee score.[2] The small change in knee society score (KSS) of about 1.03 points falls below the smallest clinically important difference (MCID) and thus may provide questionable clinical value.[3] This precision-outcome paradox suggests that other variables than coronal plane alignment of soft-tissues, quality of rehabilitation and psychosocial variables can have a more significant impact on postoperative satisfaction. The rationale of improved alignment is theoretical because it predicts the increased implant longevity. This association is not, however, proven by existing evidence. A meta-analysis focused on survivorship did not find any statistically significant difference in revision rate of RA-TKA and CM-TKA 2-, 5- or 10-years post-surgery.[4] These data indicate that robotic help reduces outliers, but traditional solutions already attain mechanical accuracy that can guarantee high mid- and long-term results. Therefore, the claims of the universal implementation of RA-TKA on the basis of assumed durability are unfounded.

Implementing RA-TKA is associated with a number of trade-offs both in clinical and economic senses. Even though other studies that have been conducted have documented reduced hospitalization periods, the procedure is associated with increased operational time and high financial expenses with an average of an extra USD 2,400 per operation.[6] The estimated learning curve of 7 to 40 cases makes adoption even more difficult. The operative times get higher and there is a possibility of an increase in the errors of intra-operative nature, which highlights the importance of organized training and continued volume of the procedure to reach the level of proficiency.

Although there are no significant differences in traditional PROMs, there are a number of qualitative advantages reports on RA-TKA. There have been observed increased patient satisfaction and increased Forgotten Joint Scores, hinting at a smaller sense of natural joint functionality which is not captured in conventional measures.[9] Massive database studies have also suggested decreased mortality and fewer rates of infection and blood loss.[10-12] Although these results are tentative, they show promising prospects to targeted research. There are significant socioeconomic issues with RA-TKA implementation. The capital and operation costs are high, thus hindering accessibility and they can strengthen existing disparities. A national database study in 2025 showed that compared to White patients, Black, Hispanic and Asian patients were less likely to receive robotic procedures by 30 to 35 percent of the patients of color.[12] Such injustice underscores the urgency of an ethical aspect: high-technology surgical equipment should not be used to further the disparity in healthcare provision. Fair access will entail institutional policy and models of reimbursements that will counter financial constraints. This review is constrained by the heterogeneity of included studies, variability among robotic platforms, differences in surgeon experience and the limited duration of follow-up available in most trials. Future research should focus on. Conducting long-term, high-quality RCTs evaluating survivorship, satisfaction and cost-effectiveness. Standardizing reporting methods for both functional outcomes and surgical technique to enhance comparability. Identifying patient subgroups, such as those with severe deformities or bone loss, who may benefit most from the precision of robotic guidance. Investigating practical strategies to improve equitable access and training in RA-TKA worldwide.

CONCLUSION

Robotic-assisted total knee arthroplasty (RA-TKA) achieves superior technical precision, reliably reducing mechanical alignment outliers and improving component positioning compared with conventional manual TKA. Despite this radiographic advantage, patient-reported functional outcomes, including WOMAC, Oxford Knee Score and Knee Society Score, show no consistent or clinically meaningful improvement. Safety profiles are comparable, with no significant reduction in complications or revisions. RA-TKA entails longer operative times, higher costs and a learning curve, limiting universal adoption. Its value is greatest in complex deformities or enhanced recovery protocols, while CM-TKA remains effective for standard cases. Long-term studies are required to establish durability and cost-effectiveness.

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