Complications Of Robotic Assisted Total Knee Arthroplasty Vs Manual Total Knee Arthroplasty: A Systematic Review and Meta-Analysis

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ABSTRACT

Introduction: Robot-assisted total knee arthroplasty (rTKA) is rapidly emerging as a superior technique in orthopaedic surgery, and its popularity continues to grow. The variations between robotic-assisted and manual TKA can significantly affect the likelihood of various complications. **Goals**: This study aims to compare the complications associated with robotic-assisted total knee arthroplasty (rTKA) and manual total knee arthroplasty (mTKA). **Methods:** A systematic review and meta- analysis were conducted and searches of PubMed, MEDLINE, and ScienceDirect were performed in October 2024. The review included observational studies only. There were 911 articles identified, following full text screening, 8 studies satisfied the inclusion criteria. Postoperative complications such as periprostetic joint infection, periprostetic fractures, arthrofibrosis, operative times, and blood loss were analyzed. **Result:** The meta-analysis demonstrated a lower risk of postoperative knee stiffness in the rTKA group compared to the mTKA group (RR = 0.57, 95% CI [0.48–0.68], $p < 0.00001$). Other complications such as aseptic loosening (RR = 0.98, 95% CI [0.52, 1.84], p = 0.95), periprosthetic fractures (RR = 0.73, 95% CI [0.25, 2.13], p = 0.57), and periprosthetic joint infection (RR = 0.76, 95% CI [0.56, 1.02], p = 0.07) showed no statistically significant differences between each group. **Conclusion**: The findings of this study indicate that rTKA is associated with a reduced risk of knee stiffness compared to mTKA. Additionally, the incidence of complications following rTKA and mTKA is comparable, with both procedures exhibiting a low complication rate.

Introduction

Total Knee Arthroplasty (TKA) has changed significantly since it was first performed in the mid-1900s. It began in the 1960s to help people with poor knee problems such as osteoarthritis by reducing pain and improving movement. Initially, surgeries depended on manual tools and skilled surgeons, which often caused differences in the placement of implants and led to worse long-term results due to technical issues (Mart and Goh, 2021; Nogalo et al., 2022). In the 1980s, technology improved, and computer-assisted systems started a new phase in orthopedic surgery. The first robotic system, ACROBOT, was developed in the late 1980s and has shown improved accuracy in implant placement (Gordon et al., 2021; Moon et al., 2012). Over time, robotic techniques have been improved to address problems associated with older methods. New robotic systems now provide real-time feedback during surgery and better navigation without requiring pre-surgery images such as CT scans (Held et al., 2021; Mart and Goh, 2021). Recent research shows that robotic-assisted total knee arthroplasty (rTKA) not only makes bone preparation and implant placement more precise but also leads to better patient outcomes, such as less pain after surgery and quicker recovery (Bhimani et al., 2020; Vanlommel et al., 2021). Today, rTKA uses advanced technology for careful planning and surgery, thereby improving precision and safety (Maman et al., 2024; Ong et al., 2022). As robotic methods become more common in hospitals, they promise to improve surgeries, leading to happier patients and better long-term joint function.

The comparison between rTKA and manual Total Knee Arthroplasty (mTKA) shows key differences that help in choosing the correct surgical method. Robotic-assisted TKA often leads to better early recovery and shorter hospital stay than manual methods. However, some studies have reported that the time taken for surgery is similar for both (Kayani et al., 2018). Complications such as stiffness or infection occur at similar rates with both methods, indicating that robotic assistance does not increase these risks (Batailler et al., 2020). Robotic systems can make more precise bone cuts and place implants better, reducing the risk of alignment problems common in mTKA due to differences in surgeon techniques (Marchand et al., 2017; Steelman et al., 2021). Despite these benefits, rTKA can have specific issues, especially when surgeons are new to this technology. Problems, such as minor infections, patellar dislocations, and mechanical issues, have been reported during the early use of robotic techniques (Batailler et al., 2020). Robotic surgeries require tracking pins, which can cause infections or fractures at pin sites (Desai et al., 2023). In contrast, mTKA risks mainly depend on the surgeon's skill, which can lead to alignment issues or improper placements, affecting the long-term outcomes (Nogalo et al., 2022).

Although rTKA may offer benefits in terms of accuracy and consistency, its safety, particularly concerning complications, continues to be a topic of discussion. Current research on complications such as knee stiffness, periprosthetic joint infection, periprosthetic fractures, and aseptic loosening often suffers from limitations like small sample sizes, single-center studies, or varied outcome measures. A comprehensive review of the existing evidence is necessary to determine if rTKA decreases complication rates compared to traditional manual methods or if it presents distinct risks.

Recent research highlights the importance of systematically exploring the complications associated with both robotic and manual total knee arthroplasty surgeries. This study aimed to compare knee complications associated with rTKA and mTKA by performing meta-analyses on knee stiffness, periprosthetic joint infection, periprosthetic fractures, and aseptic loosening.

Methods

Study Design and Registration

This systematic review and meta-analysis was conducted in adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guideline.

Search Strategy

Literature search was conducted using three electronic databases: PubMed, MEDLINE, and ScienceDirect, to identify relevant studies comparing postoperative complications between rTKA and mTKA. The search strategy employed a combination of Medical Subject Headings (MeSH) and free-text keywords, including: “Complications”, “Total Knee Arthroplasty”, and “Robotic Assisted”. The search was restricted to full-text articles published in English. Duplicates were removed, and titles and abstracts were screened for eligibility. Reference lists of selected studies were also reviewed to identify additional relevant publications.

Study Eligibility

PICO framework (patient/problem, intervention/exposure, comparison/control, outcome) was utilised to determine the inclusion criteria. The inclusion criteria included (a) having comparative observational studies (prospective/retrospective cohort, propensity-matched studies) as the study designs; (b) study population: Adults (typically ≥18 years) with end-stage knee osteoarthritis, rheumatoid arthritis, or other non-infectious indications for primary TKA.; (c) intervention: Robotic-assisted total knee arthroplasty using any platform; (d) comparator/control: manual/conventional total knee arthroplasty performed without robotic assistance; (e) outcomes: knee stiffness, periprosthetic joint infection, periprosthetic fractures, and aseptic loosening. Studies excluded: (a) Review article, commentaries, editorials, and conference abstracts are excluded (b) population excluded: Revision TKA, unicompartmental knee arthroplasty (UKA), or TKA for septic/tumor cases, Pediatric patients or non-primary arthroplasty

Study selection

The review process for each article was conducted independently, following the PRISMA flow diagram. Mendeley Desktop 1.19.8 software was used to remove duplicates. Two independent reviewers, IS and FIW, initially screened the titles and abstracts of the studies based on accessibility criteria. Following this, the same reviewers carried out a comprehensive full-text review of the selected studies to ensure they met the eligibility criteria. Any differences in opinion were addressed through discussion until a consensus was reached.

Data Extraction and Quality Assessment

Information from the studies included in the analysis was gathered using a predefined outcome sheet formatted as a table in Microsoft Excel. This sheet contained key informations such as the author and publication year, study characteristics, location, study population, intervention, follow-up, type of prosthesis, robot system employed, and study outcomes, specifically focusing on periprosthetic joint infection, periprosthetic fracture, knee stiffness, and aseptic loosening. The data collection was conducted by one review author (IS) and subsequently verified for accuracy by another review author (FIW).

To evaluate the quality of each study included, the Risk Of Bias In Non-randomised Studies - of Interventions (ROBINS-I) tool was utilized. This assessment involved examining seven specific domains as defined by ROBINS-I: confounding bias, participant selection bias, intervention classification bias, bias from deviations from the intended intervention, bias due to missing data, bias in outcome measurement, and bias in the selection of reported results. The evaluation was performed by two independent reviewers, IS and FIW, who resolved any differences through consultation.

Quantitative Data Analysis

A meta-analysis was performed using Review Manager (RevMan) version 5.4 (The Cochrane Collaboration, Copenhagen, Denmark). The primary effect measure for all dichotomous outcomes was the risk ratio (RR) with corresponding 95% confidence intervals (CI). The Mantel–Haenszel method was used to calculate pooled estimates across studies.

A fixed-effect model was applied under the assumption that the true treatment effect was the same across all included studies, and observed variations were due to chance. This model was selected due to the limited number of studies available for each outcome and the desire to provide more conservative pooled estimates. However, statistical heterogeneity was assessed using the Chi^2 test (with $p < 0.10$ considered significant) and quantified using the I^2 statistic, where I^2 values >50% were interpreted as substantial heterogeneity.

Forest plots were generated for each outcome, including knee stiffness, periprosthetic joint infection, periprosthetic fracture, and aseptic loosening. Each comparison evaluated the relative risk of complications in robotic-assisted TKA (rTKA) versus manual TKA (mTKA).

Result

Search results

A total of 911 records were initially identified through database searching: PubMed (n = 493), ScienceDirect (n = 343), and Google Scholar (n = 75). After removing 86 duplicate records, 825 unique records remained for screening. During the title and abstract screening phase, 747 records were excluded due to being review articles, case reports, book chapters, or using different surgical methods.

The full texts of 78 articles were sought for retrieval, but 67 could not be obtained due to lack of full-text access. Thus, 11 full-text articles were assessed for eligibility. Among these, 3 randomized controlled trials (RCTs) were excluded, as only observational studies were included in the analysis. Ultimately, 8 studies met the inclusion criteria and were included in the systematic review and meta-analysis.

Critical Appraisal

Risk of bias was assessed using the ROBINS-I tool by two independent reviewers. Any discrepancies in the assessment were resolved through discussion until a consensus was reached. Overall, the included studies demonstrated low risk of bias across most domains, including confounding, selection of participants, classification of interventions, deviations from intended interventions, measurement of outcomes, and selection of the reported result.

Only one study, conducted by Fary et al. (2023), exhibited a high risk of bias due to missing data. This domain-specific concern may affect the internal validity of its reported outcomes. Nevertheless, the general consistency in low risk across the other studies supports the methodological robustness and credibility of the synthesized evidence in this meta-analysis.

Characteristic of Included Study

A total of eight studies were included in this meta-analysis, comprising five retrospective cohort studies and three prospective cohort studies. The studies originated from various countries, including the USA (n=5), Australia (n=1), Belgium (n=1), and South Korea (n=1). The sample sizes varied significantly, with the number of knees analyzed ranging from 113 to over 755,000. The follow-up period also differed between studies, ranging from 1.5 months to 60 months.

Across these studies, data were collected on postoperative complications such as periprosthetic joint infection, periprosthetic fracture, knee stiffness, and aseptic loosening in both robotic-assisted total knee arthroplasty (rTKA) and manual total knee arthroplasty (mTKA) groups. The number of events reported for each complication varied by study and procedure. For instance, knee stiffness was frequently reported, while aseptic loosening and periprosthetic fracture were relatively rare.

Several types of robotic systems were employed, including the Stryker Mako system, ROSA® Knee System, NAVIO, Mako Robotic Arm–Assisted Surgery Platform, and ROBODOC Surgical Assistant. Likewise, a variety of prostheses were used, such as the Stryker Implants, Persona/Vanguard/Nextgen Knee System, Cemented CR Triathlon (Stryker), and the NexGen cruciate-retaining prosthesis. These technological and implant variations reflect the diversity in surgical approaches and institutional practices among the included studies.

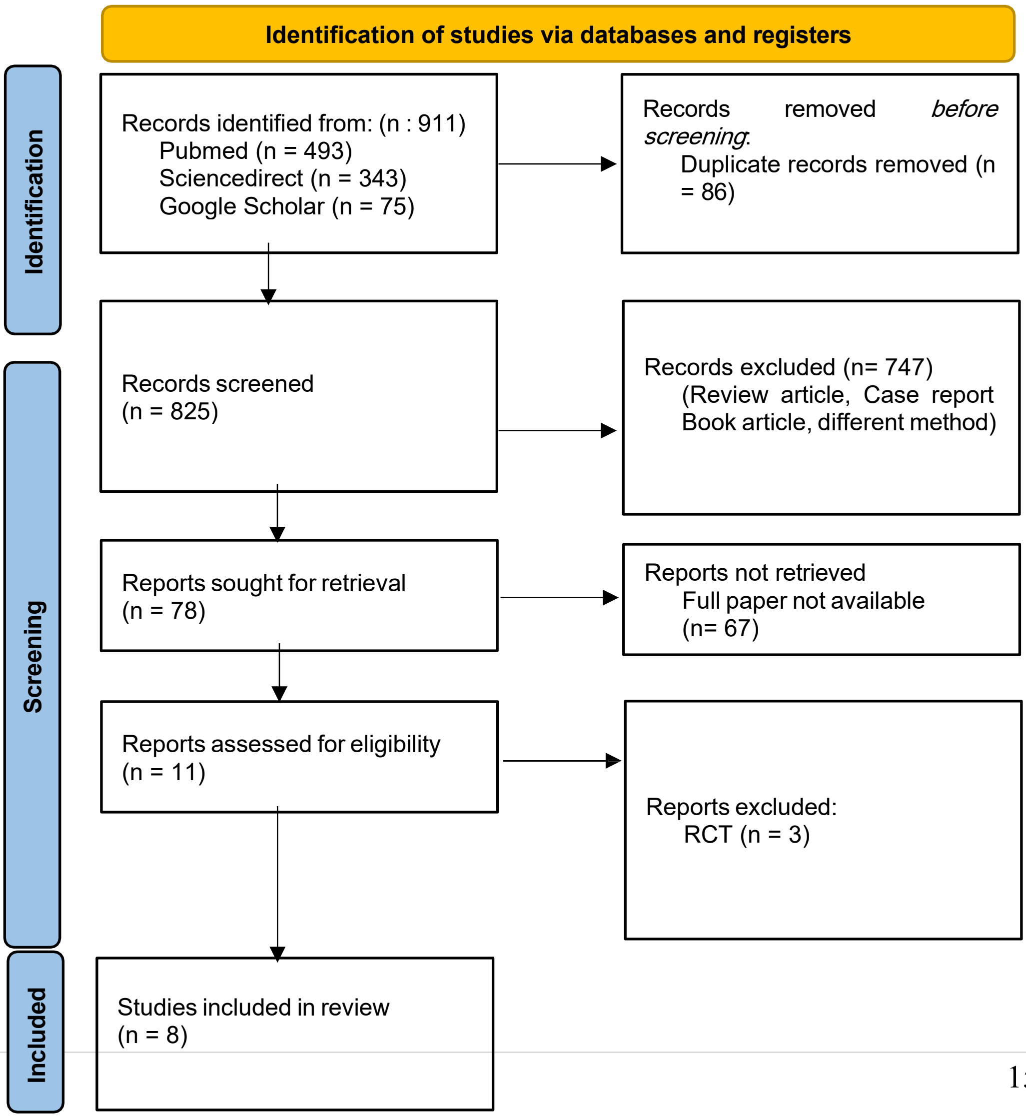

Figure 1. PRISMA Flow chart

Study outcomes

A total of eight studies were included in the meta-analysis comparing postoperative complications between robotic-assisted total knee arthroplasty (rTKA) and manual total knee arthroplasty (mTKA). The primary outcomes evaluated were knee stiffness, periprosthetic fracture, aseptic loosening, and periprosthetic joint infection. The results of this meta-analysis evaluating postoperative complications between robotic-assisted total knee arthroplasty (rTKA) and manual total knee arthroplasty (mTKA) are presented as follows:

Knee stiffness was reported in six studies involving a total of 6,651 knees in the rTKA group and 75,123 knees in the mTKA group. The meta-analysis revealed a statistically significant lower risk of postoperative knee stiffness in the rTKA group compared to mTKA (RR = 0.57, 95% CI [0.48, 0.68], $p < 0.00001$). However, there was substantial heterogeneity among studies ($I^2 = 86\%$), indicating variation in effect sizes across studies.

Aseptic loosening was analyzed from two studies. The combined analysis, which included 5,299 rTKA and 750,164 mTKA cases, showed no statistically significant difference between groups (RR = 0.98, 95% CI [0.52, 1.84], p = 0.95), with low heterogeneity ($I^2 = 3\%$). This suggests that both rTKA and mTKA groups had comparable risks of developing aseptic loosening postoperatively.

Periprosthetic fracture data were obtained from two studies. Although the point estimate slightly favored rTKA (RR = 0.73, 95% CI [0.25, 2.13]), the result was not statistically significant (p = 0.57), and there was high heterogeneity ($I^2 = 87\%$), suggesting substantial variability between the included studies.

Periprosthetic joint infection rates were reported in four studies with a total of 5,745 rTKA and 750,869 mTKA knees. The pooled analysis showed no statistically significant difference between rTKA and mTKA groups (RR = 0.76, 95% CI [0.56, 1.02], p = 0.07), with no evidence of heterogeneity ($I^2 = 0\%$).

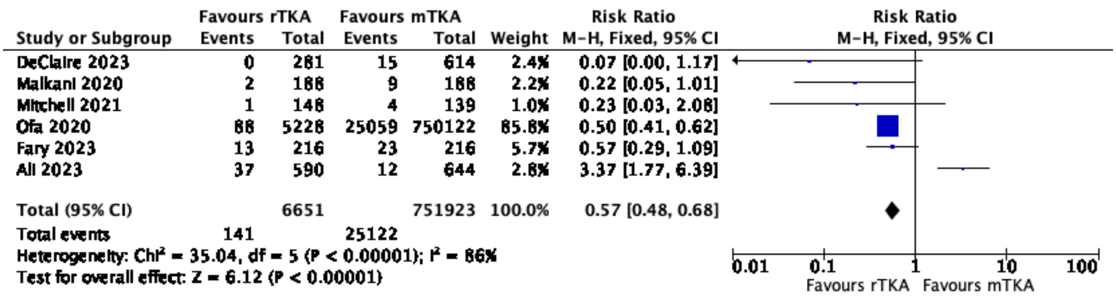

Figure 2. Forrest plot of knee stiffness complication after robotic assisted total knee arthroplasty vs conventional total knee arthroplasty

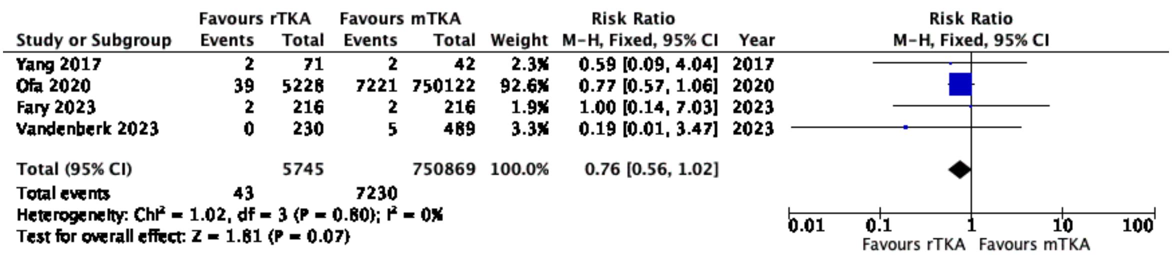

Figure 3. Forrest plot of periprosthetic joint infection complication after robotic assisted total knee arthroplasty vs conventional total knee arthroplasty

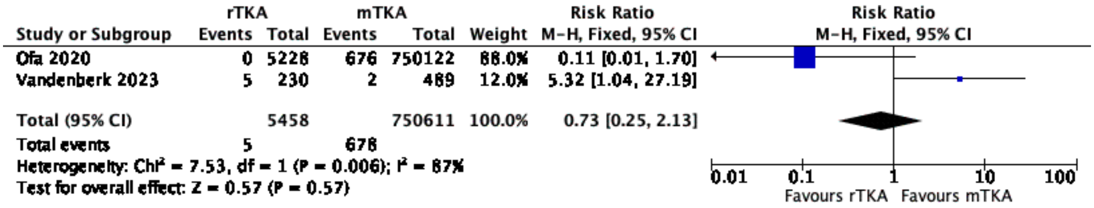

Figure 4. Forrest plot of periprosthetic fractures complication after robotic assisted total knee arthroplasty vs conventional total knee arthroplasty

Figure 5. Forrest plot of aseptic loosening complication after robotic assisted total knee arthroplasty vs conventional total knee arthroplasty

Discussion

Several comprehensive meta-analyses have previously compared robotic-assisted total knee arthroplasty (rTKA) with manual total knee arthroplasty (mTKA), focusing primarily on outcomes such as alignment accuracy, functional recovery, and implant positioning. However, to the best of our knowledge, this is the first meta-analysis specifically designed to evaluate and compare postoperative complications between rTKA and mTKA.

This meta-analysis revealed that robotic-assisted total knee arthroplasty (rTKA) was associated with a significantly lower risk of postoperative knee stiffness compared to mTKA, with a pooled risk ratio of 0.57 (95% CI: 0.48–0.68, $p < 0.00001$). This suggests a potential advantage of robotic systems in achieving optimal soft tissue balancing and implant positioning, which may contribute to improved early range of motion and reduced need for postoperative interventions such as manipulation under anesthesia. However, substantial heterogeneity ($I^2 = 86\%$) was observed, which may be attributed to differences in study design, patient population, and follow-up duration.

Knee stiffness during traditional total knee arthroplasty (TKA) can arise from various intraoperative factors that affect the surgical outcome (Bong and Di Cesare, 2004). Incorrect placement of the femoral or tibial components can result in abnormal joint mechanics, as well Using components that are too large can restrict motion as contributing to stiffness (Zaffagnini et al., 2021). Higher intraoperative tibial forces compared to the native knee can lead to stiffness, as evidenced by loss of extension and flexion (Shelton et al., 2018). Robotic systems allows for more accurate restoration of the knee's natural alignment, which can minimize the risk of stiffness, rTKA also tends to favor better anatomical restoration, potentially leading to reduced stiffness (Alrajeb et al., 2024). Robotic assisted TKA is associated with fewer outliers in mechanical alignment, which is crucial for optimal joint function and may contribute to reduced stiffness (Riantho et al., 2023).

For other complications, including periprosthetic joint infection (RR = 0.76, 95% CI: 0.56–1.02, p = 0.07), periprosthetic fracture (RR = 0.73, 95% CI: 0.25–2.13, p = 0.57), and aseptic loosening (RR = 0.98, 95% CI: 0.52–1.84, p = 0.95), no statistically significant differences were found between rTKA and mTKA. A study using propensity scorematching found no significant difference in PJI rates between RA-TKA (0.3%) and conventional TKA (0.5%) within 90 days post-surgery, suggesting that robotic assistance does not increase infection risk (LaValva et al., 2024). Meta-analyses report low surgical site infection rates in rTKA, with overall infection rates at 0.568% and deep infections at 0.154%, indicating a low incidence of PJI in robotic procedures (Raj et al., 2023). The avoidance of intramedullary violation in computer-assisted TKA, which shares some technological aspects with rTKA, has been associated with a lower incidence of PJI compared to mTKA (Chen et al., 2022).

Periprosthetic fractures following total knee replacement (TKR) is a significant concern in orthopedic surgery, with reported rates varying based on the type of arthroplasty and patient demographics. The incidence of these fractures is generally estimated to be between 0.3% and 2.5% after primary TKR, with a higher incidence observed following revision procedures (Steele and Klatt, 2011). The occurance can be as high as 28% following revision TKA, indicating a significantly higher risk compared to primary procedures (Zazirnyi, 2024). These fractures can occur in the femur, tibia, or patella and are influenced by various risk factors and surgical techniques. Anterior cortical notching, a common surgical error, significantly increases the risk of femoral fractures, with an odds ratio of 17 (Zainul-Abidin et al., 2019). Forced flexion during trialing, especially with under-resected bone, can lead to patella, tibial plateau, or tubercle fractures (Siddiqi et al., 2023).

The comparison of aseptic loosening rates between robotic-assisted total knee arthroplasty (TKA) and mTKA reveals no significant differences in long-term outcomes. In a study analyzing revision surgeries due to periprosthetic joint infection (PJI), 22% of patients experienced aseptic loosening within 7.3 years post-reimplantation (Kienzle et al., 2020). Randomized controlled trial found that the aseptic loosening rate was 2% in both robotic-assisted and conventional TKA groups, with no significant difference in the Kaplan-Meier survivorship of the components at 15 years (98% in both groups) (Kim et al., 2020). Another study reported similar findings, with no significant differences in revision rates due to aseptic loosening between robotic-assisted and conventional TKA over a mean follow-up of 10 years (Song et al., 2018). Robotic-assisted TKA has been shown to achieve more accurate alignment of the prosthesis, with fewer mechanical axis alignment outliers compared to conventional TKA (Alrajeb et al., 2024). Despite these improvements in alignment, the clinical outcomes, including aseptic loosening rates, do not differ significantly between the two methods (Kim et al., 2020).

Overall, robotic assistance in TKA demonstrates a favorable profile in certain outcomes, but further high-quality studies are needed to confirm its impact on long-term complication rates.

Research Limitation

This study has several limitations that should be acknowledged. First, a high level of heterogeneity was observed in some outcomes, particularly in the analysis of postoperative knee stiffness ($I^2 = 86\%$). This heterogeneity may be attributed to variability in surgical techniques, types of robotic systems used, differences in patient demographics, perioperative protocols, and duration of follow-up across the included studies. Although a fixed-effect model was used in most analyses, such variability could have influenced the pooled effect estimates and reduced the overall comparability between studies.

Second, most of the included studies were observational in nature, which inherently carry risks of selection bias and confounding, even though the risk of bias was assessed using the ROBINS-I tool. Furthermore, not all studies reported every outcome of interest, resulting in limited data for certain complications such as periprosthetic fractures and aseptic loosening. Lastly, despite efforts to include the most up-to-date and relevant literature, publication bias cannot be entirely ruled out, especially considering the growing enthusiasm and positive reporting trends associated with robotic surgical technologies.

Future Research Direction

Future studies should focus on conducting high-quality randomized controlled trials (RCTs) comparing rTKA and mTKA, with standardized reporting of postoperative complications and long-term follow-up. Given the heterogeneity observed in current evidence, future research should also aim to stratify patients based on relevant variables such as age, BMI, comorbidities, and implant type to identify subgroups that may benefit most from robotic assistance. Additionally, comparative cost-effectiveness analyses that incorporate complication rates, functional outcomes, and implant survivorship would provide valuable insights for both clinicians and healthcare policymakers when evaluating the broader impact of rTKA in clinical practice.

Conclusion

This meta-analysis demonstrates that rTKA is associated with a significantly lower risk of postoperative knee stiffness compared to mTKA, suggesting potential benefits in early functional recovery. However, no significant differences were found between the two techniques in terms of other major complications, including infection, periprosthetic fracture, and aseptic loosening. Further robust research is warranted to confirm these findings and to determine the long-term impact of robotic assistance on surgical safety and patient outcomes.

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Table 1. Tabulation of study characteristic

Author	Ali 2023	Malkani 2020	DeClaire 2024	Fary 2023	Vandenberk 2023	Mitchell 2021	Ofa 2020	Yang 2017
Design	Retrospective Cohort	Prospective Cohort	Retrospective Cohort	Prospective Cohort	Prospective cohort	Retrospective cohort study	Retrospective Cohort	Retrospective Cohort
Country	USA	USA	USA	Australia	Belgium	USA	USA	Korea
Number of knees	1234	376	895	432	719	287	755350	113

rTKA		590	188	281	216	230	148	5228	71
mTKA		644	188	614	216	489	139	750122	42
Followup (months)		12	24	1,5	12	12	12	12	60
Periprosthetic Joint Infection	rTKA	0	0	0	2	0	0	39	2
	mTKA	0	0	0	2	5	0	7221	2
Periprosthetic fracture	rTKA	0	0	0	0	5	0	0	0
	mTKA	0	0	0	0	2	0	676	0
Knee Stiffness	rTKA	37	2	0	13	0	1	88	0
	mTKA	12	9	15	23	0	4	25059	0
Aseptic Loosening	rTKA	0	0	0	0	0	0	9	0
	mTKA	0	0	0	0	0	0	1212	1
Prostesis		Stryker Implants	-	-	Persona/ Vanguard/ Nextgen Knee System	-	Cemented CR Triathlon (Stryker)	Stryker Implants	The NexGen cruciate-retaining (CR) prosthesis
Robot System		Stryker Mako system (Stryker Orthopaedics)	-	-	ROSA® Knee System	NAVIO	Mako Robotic Arm–Assisted Surgery platform (Stryker)	Stryker Mako Robotic-arm Assist	ROBODOC Surgical Assistant