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AUGMENTED REALITY–ASSISTED TOTAL KNEE ARTHROPLASTY VERSUS CONVENTIONAL INSTRUMENTATION: A SYSTEMATIC REVIEW AND META-ANALYSIS OF OPERATIVE EFFICIENCY, ALIGNMENT ACCURACY, AND SAFETY

Januardi S Thene*, Su Djie To Rante, Tiara Rambu Renesia Tarapanjang
Department of Orthopaedics and Traumatology, Faculty of Medicine, Universitas Nusa Cendana, Jl. Adisucipto, Penfui, Kupang, Nusa Tenggara Timur 85001, Indonesia
*ardythene1234@gmail.com

ABSTRACT

Augmented reality–assisted navigation may improve component positioning during total knee arthroplasty while avoiding the infrastructure and imaging requirements of robotic platforms. However, its effects on operative efficiency, alignment, safety, and clinical outcomes remain uncertain. To compare augmented reality–assisted navigation with conventional instrumentation in adults undergoing primary total knee arthroplasty. PubMed, the Cochrane Library, and ScienceDirect were searched from database inception to July 2026 without a publication-year lower limit. The five included comparative studies were published between 2021 and 2026. Of 173 identified records, 166 were excluded during title and abstract screening; one duplicate and one ineligible full-text article were subsequently excluded. Five observational studies underwent qualitative synthesis, and four were pooled for operative time using a random-effects mean-difference model. Alignment, safety, and patient-reported outcomes were narratively synthesized because of heterogeneous reporting. Five observational studies involving 1,124 patients were included. Four studies comprising 879 procedures contributed to the operative-time meta-analysis. Augmented reality assistance significantly increased operative duration by 3.63 minutes compared with conventional instrumentation (95% CI 1.40–5.86; p=0.001; I^2=51%). AR guidance improved selected alignment parameters, including femoral coronal accuracy and tibial rotational alignment, but findings were inconsistent across components and planes. No clear differences were observed in patient-reported outcomes. No navigation-related complications were reported in two studies, while 30-day readmission did not differ significantly in the largest cohort. AR navigation provided selective technical improvements with only a modest operative-time penalty. However, improved alignment did not consistently translate into better clinical outcomes, and safety evidence remained limited. AR-assisted total knee arthroplasty is feasible and may improve selected alignment outcomes, but currently lacks evidence of meaningful clinical superiority over conventional instrumentation.

Keywords: augmented reality; component alignment; navigation; operative time; total knee arthroplasty

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INTRODUCTION

Knee osteoarthritis is a major and progressively increasing cause of pain, disability, and impaired mobility worldwide. In 2020, approximately 595 million individuals were living with osteoarthritis, and the global burden is projected to increase by nearly 75% by 2050 because of population ageing, population growth, and increasing obesity prevalence (GBD 2021 Osteoarthritis Collaborators, 2023). For patients with end-stage knee osteoarthritis who remain symptomatic despite appropriate nonoperative treatment, total knee arthroplasty (TKA) is an established intervention for reducing pain and restoring joint function. The demand for TKA is expected to rise substantially, with Medicare-based projections estimating increases of 139% by 2040 and 469% by 2060 compared with 2019 volumes (Shichman et al., 2023). Consequently, improving the accuracy, efficiency, and safety of TKA has become increasingly important for both patients and healthcare systems.

Successful TKA requires accurate bone resection and component positioning while maintaining appropriate limb alignment and soft-tissue balance. Conventional instrumentation relies on

intramedullary or extramedullary alignment guides and the intraoperative identification of anatomical landmarks, leaving component positioning partly dependent on surgeon experience and anatomical variability. Computer-assisted navigation and robotic platforms were introduced to improve the reproducibility of bone preparation and implant alignment. Evidence from randomized studies indicates that robotic-assisted TKA can reduce radiographic alignment deviations and outliers compared with conventional techniques. However, these improvements have not consistently translated into superior patient-reported outcomes and may be accompanied by longer operative times, substantial capital and consumable costs, additional equipment, preoperative imaging requirements, and workflow disruption (Ruangsomboon et al., 2023).

Augmented reality (AR) has emerged as a potentially more accessible alternative for technology-assisted TKA. AR systems integrate computer-generated navigation information with the real surgical environment, enabling surgeons to visualize mechanical axes, planned resection angles, and component orientation in real time. Current platforms may use smart glasses, head-mounted cameras, smartphones, or external displays with optical or QR-coded markers. Unlike many robotic platforms, imageless AR navigation can provide intraoperative guidance without a large robotic console, preoperative computed tomography, or extensive additional operating-room infrastructure. Early pilot investigations demonstrated that AR guidance could reproduce planned femoral and tibial resections with relatively small coronal and sagittal errors (Iacono et al., 2021). Nevertheless, previous reviews identified substantial heterogeneity in AR systems, surgical protocols, outcome definitions, and study designs, with limited evidence regarding patient-reported outcomes, safety, and long-term clinical effectiveness (Cacciola et al., 2025).

Clinical comparative evidence has expanded in recent years. Smartphone-based AR guidance has been associated with a lower absolute error in distal femoral coronal alignment than conventional intramedullary instrumentation (Tsukada et al., 2021). A prospective matched observational study subsequently evaluated clinical recovery after smart-glasses-assisted TKA and suggested that early patient-reported outcomes may be affected by a surgeon learning curve (Van Overschelde et al., 2022). More recent evidence indicates that AR guidance may also improve tibial rotational positioning, although its effects on coronal and sagittal tibial alignment remain less consistent (Tsukada et al., 2025). Larger comparative cohorts have examined operative efficiency and clinical outcomes, reporting modest increases in operative time without significant differences in short-term readmission or functional improvement (Farner et al., 2026). Another comparative study reported improved femoral alignment reproducibility and reduced postoperative haemoglobin decline, but found no significant differences in operative duration or patient-reported outcome measures (Panchal et al., 2026). These findings suggest that AR may improve selected technical outcomes, but the magnitude and clinical relevance of its benefits remain uncertain.

Existing reviews have primarily mapped technical, preclinical, and early clinical applications of AR rather than quantitatively synthesizing direct comparisons between AR-assisted navigation and conventional manual instrumentation (Cacciola et al., 2025; Iacono et al., 2021). Moreover, several larger comparative studies were published after the searches of previous reviews, leaving uncertainty regarding whether improved intraoperative visualization is achieved without an unacceptable increase in operative burden or safety risk. Therefore, this systematic review and meta-analysis aimed to compare AR-assisted navigation with conventional instrumentation in adults undergoing primary TKA, focusing on operative efficiency, component alignment accuracy, safety outcomes, and patient-reported outcomes.

METHOD

Study Design and Reporting Framework

This systematic review and meta-analysis compared augmented reality assisted navigation with conventional manual instrumentation in adults undergoing primary total knee arthroplasty. The

review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 guidelines.

Search Strategy

A systematic literature search was conducted in PubMed, the Cochrane Library, and ScienceDirect from each database's inception through July 2026, without an initial publication-year restriction. The eligible comparative clinical publications ultimately spanned 2021–2026; this is the publication period of the included studies, not a prespecified search-year limit. The search strategy combined terms related to augmented reality, total knee arthroplasty, navigation, bone resection, component alignment, and clinical outcomes. PubMed field tags were not applied. The exact search strategy used in PubMed was: ("augmented reality" AND ("total knee arthroplasty" OR TKA)) AND (navigation OR "bone resection" OR "component alignment" OR "clinical outcome"). The exact search strategy used in the Cochrane Library was: ("augmented reality" AND ("total knee arthroplasty" OR TKA)) AND (navigation OR "bone resection" OR "component alignment" OR "clinical outcome"). The exact search strategy used in ScienceDirect was: "augmented reality" AND ("total knee arthroplasty" OR TKA) AND (navigation OR "bone resection" OR "component alignment" OR "clinical outcome"). The reference lists of eligible studies and relevant reviews were manually screened to identify additional reports. Conference proceedings were also assessed to capture potentially eligible studies that were not indexed in the three electronic databases.

Eligibility Criteria

Studies were eligible if they included adults undergoing primary total knee arthroplasty, evaluated an augmented reality assisted navigation or guidance system, included a comparator group undergoing total knee arthroplasty using conventional or manual instrumentation, and reported at least one relevant clinical, perioperative, or radiographic outcome. Outcomes of interest included operative time, component alignment accuracy, perioperative or postoperative complications, readmission, and patient-reported outcome measures. Randomized controlled trials and nonrandomized comparative studies, including prospective and retrospective cohort studies, were eligible. Studies involving revision total knee arthroplasty, unicompartmental knee arthroplasty, robotic assisted surgery without a separately identifiable augmented reality intervention, conventional computer navigation without augmented reality, cadaveric studies, Sawbones-only experiments, case reports, noncomparative case series, reviews, editorials, and technical reports without comparative clinical data were excluded. When a publication contained both experimental and clinical components, only the clinical comparative cohort was included.

Study Selection

All retrieved records underwent title and abstract screening based on the predefined eligibility criteria. Records retained after the initial screening were assessed for duplication, and duplicate reports were removed before full-text assessment. The full texts of potentially eligible studies were subsequently reviewed to determine final inclusion. Studies that did not fulfill the eligibility criteria were excluded, and the reasons for full-text exclusion were documented. Any uncertainty regarding study eligibility was resolved through reassessment of the complete publication and consensus within the review team.

Data Extraction

Data were extracted using a standardized data collection table. Extracted study characteristics included the first author, publication year, country, study design, sample size, demographic characteristics, clinical indication, augmented reality platform, surgical technique, conventional comparator, implant system, and follow-up duration. Extracted outcomes included operative duration, femoral and tibial component alignment, coronal, sagittal, and rotational alignment errors, alignment outliers, perioperative and postoperative complications, readmission, blood loss, range of motion, opioid utilization, and patient-reported outcome measures. For continuous outcomes, the

group sample size, mean, and standard deviation were extracted. For dichotomous outcomes, the number of events and total number of participants in each group were recorded. When a study reported more than one definition of operative time, the measurement representing the complete duration from incision to the end of the procedure was selected to improve comparability and prevent double counting of the same population. Final scores and change scores for patient-reported outcomes were recorded separately.

Risk-of-Bias Assessment

Risk of bias was summarized using domain-based judgements, as presented in Figure 2. For Tsukada et al. (2021), the assessment reported seven domains: confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selection of the reported result. The other four studies were assessed across three reported domains: selection, performance, and detection/reporting. The original domain judgements and overall ratings were retained without modification. Because the studies were displayed using different assessment structures, cross-study comparisons of risk-of-bias ratings require caution.

Data Synthesis and Statistical Analysis

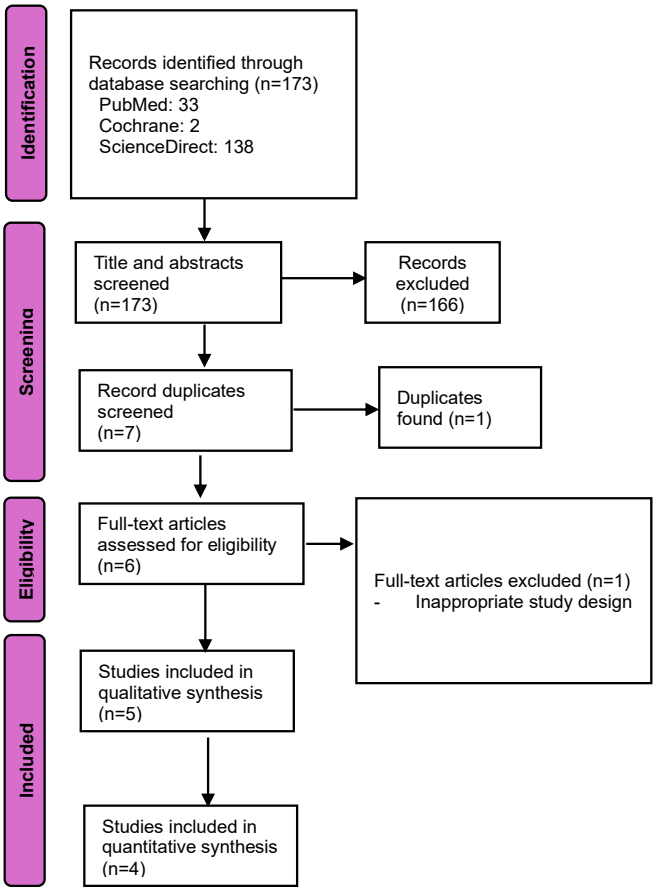

Figure 1. PRISMA flow diagram of study selection.

Quantitative synthesis was performed when at least two studies reported sufficiently comparable outcomes using compatible definitions and data formats. Operative time was pooled as a continuous outcome using the mean difference with corresponding 95% confidence intervals because all eligible studies reported operative duration in minutes. A random-effects model was applied because clinical and methodological heterogeneity was anticipated across studies, including

differences in augmented reality platforms, surgical workflows, surgeon experience, operative-time definitions, and institutional settings. The direction of effect was defined so that a lower operative duration favored augmented reality assisted total knee arthroplasty. Statistical heterogeneity was assessed using Cochran's chi-square test and the I^2 statistic. I^2 values of approximately 25%, 50%, and 75% were interpreted as low, moderate, and high heterogeneity, respectively. A two-sided p value below 0.05 was considered statistically significant for the pooled effect estimate. Alignment accuracy was synthesized narratively because the included studies evaluated different anatomical components, alignment planes, target angles, imaging modalities, and outcome definitions. Patient-reported outcomes were also synthesized narratively because different instruments, follow-up periods, and reporting formats were used. Safety outcomes were not pooled because complication definitions were inconsistent, several studies reported no events in either group, and the only estimable dichotomous safety outcome was reported by a single study. The meta-analysis and forest plot were generated using Review Manager software.

Table 1.
Characteristics and results of the included studies

Study	Country and Study Design	Sample Size, AR / Conventional	Patient Characteristics	AR System and Technique	Conventional Comparator	Follow-up	Outcomes Reported	Summary of Findings
Van Overschelde et al., 2022	Belgium, prospective observational matched cohort	122 / 122	Groups matched by age and sex; indication for TKA and numerical baseline characteristics not reported; two surgeons; Evolution medial-pivot implant	Pixee Knee+ smart-glasses system providing real-time femoral and tibial axis, resection-angle, and slope guidance	Conventional manual TKA	6 weeks and 3 months	KOOS, Oxford Knee Score, Forgotten Joint Score; learning curve	The AR group initially had worse KOOS symptoms at 6 weeks and worse KOOS quality of life, Oxford Knee Score, and Forgotten Joint Score at 3 months. Outcomes improved with increasing surgeon experience. No extractable operative-time, alignment-accuracy, or safety outcome was reported.
Tsukada et al., 2021	Japan, single-surgeon nonrandomized comparative clinical study with an additional Sawbones validation study	31 / 41	Age 73 ± 9 vs 74 ± 7 years; BMI 27.1 ± 3.8 vs 27.7 ± 4.3 kg/m²; OA/RA 29/2 vs 40/1	Smartphone-based AR-KNEE imageless navigation for distal femoral resection; femoral mechanical axis and cutting angle superimposed on the operative field	Conventional intramedullary femoral guide	Postoperative standing long-leg radiograph after flexion contracture was <5°; exact timing NR	Operative duration, absolute femoral coronal alignment error, complications	AR significantly reduced absolute femoral coronal alignment error but increased operative duration by approximately 9 minutes. No complications were observed in either group.
Tsukada et al., 2025	Japan, single-surgeon nonrandomized comparative cohort	58 / 64	Age 76 ± 8 vs 75 ± 7 years; BMI 27.5 ± 4.3 vs 27.4 ± 4.0 kg/m²; OA/RA 56/2 vs 63/1	Smartphone-based AR-KNEE with QR-coded markers; AR guidance for tibial coronal and sagittal resection and replication of Akagi's anteroposterior axis after resection	Manual determination of tibial rotational alignment	Postoperative CT; exact timing NR	Operative duration, tibial rotational, coronal, and sagittal alignment errors, rotational outliers, soft-tissue balance, navigation-related complications	AR reduced tibial rotational alignment error and the proportion of rotational outliers. Coronal and sagittal tibial errors and operative duration were not significantly different. No navigation-related complications

Study	Country and Study Design	Sample Size, AR / Conventional	Patient Characteristics	AR System and Technique	Conventional Comparator	Follow-up	Outcomes Reported	Summary of Findings
								occurred.
Farner et al., 2026	United States, retrospective consecutive single-surgeon cohort	309 / 261	Age 70.38 ± 8.45 vs 69.67 ± 8.25 years; BMI 32.32 ± 6.47 vs 33.04 ± 6.94 kg/m²; women 63.4% vs 62.1%; indication for TKA not explicitly reported	Pixee Knee+ AR-assisted navigation using a camera-equipped headset and QR-coded markers; Vanguard cruciate-retaining implant	Conventional manual instrumentation	30-day readmission, 90-day opioid use, and 1-year KOOS-JR	Incision-to-closure time, total operative time, 30-day readmission, opioid utilization, KOOS-JR	AR increased total operative time by approximately 3.5 minutes. Thirty-day readmission and KOOS-JR improvement were not significantly different. No radiographic alignment outcomes were reported.
Panchal et al., 2026	United Kingdom, retrospective comparative analysis of prospectively collected single-surgeon data	39 / 77	Age 68.8 years, range 52–81, vs 69.3 years, range 54–82; men/women 18/21 vs 35/42; indication for TKA not explicitly reported	Pixee Knee+ used for femoral component positioning; tibial preparation remained conventionally jigged in both groups; MicroPort Evolution medial-pivot implant	Conventional jig-based TKA	Radiographs at 6 weeks and 1 year; ROM and PROMs at 1 year	Component alignment, hemoglobin reduction, operative duration, ROM, FJS, HAAS, and OKS	AR produced a femoral coronal angle closer to the 90° target and lower alignment variability. Hemoglobin reduction was smaller and ROM was greater with AR, while operative duration and PROMs were comparable. No complication counts were reported.

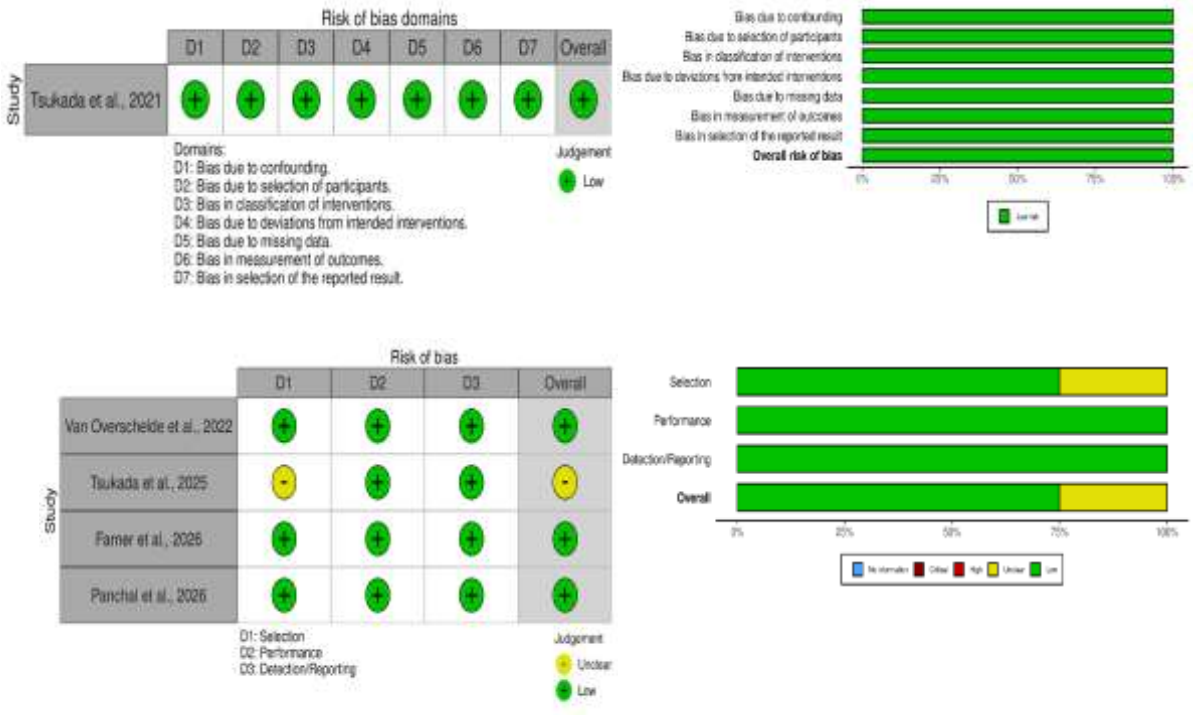

Figure 2. Risk of bias assessment results of the included studies

RESULT

Study Selection

The database search identified 173 records, comprising 33 records from PubMed, two from the Cochrane Library, and 138 from ScienceDirect. All 173 records underwent title and abstract screening, after which 166 records were excluded because they did not meet the predefined eligibility criteria. Seven potentially relevant records remained for duplicate assessment. One duplicate was identified and removed, leaving six full-text articles for eligibility assessment. One full-text article was excluded because of an inappropriate study design. Consequently, five studies were included in the qualitative synthesis, of which four provided sufficiently comparable operative-time data for quantitative meta-analysis, as illustrated in Figure 1.

Characteristics of the Included Studies

The five included studies were published between 2021 and 2026 and involved 1,124 patients undergoing primary total knee arthroplasty, including 559 procedures performed with augmented reality assistance and 565 procedures performed using conventional instrumentation. The studies were conducted in Belgium, Japan, the United States, and the United Kingdom. All were comparative observational studies, with no randomized controlled trial identified. Study designs included one prospective matched observational cohort, two nonrandomized comparative studies, and two retrospective single-surgeon cohorts.

Three studies evaluated the Pixee Knee+ platform, which uses camera-equipped smart glasses or a head-mounted display with QR-coded markers to provide real-time visualization of mechanical axes and bone-resection angles. The remaining two studies evaluated the smartphone-based AR-KNEE imageless navigation system. The extent of AR assistance differed among studies. Some systems guided both femoral and tibial resections, whereas the AR intervention in one study was limited to femoral component positioning, with conventional tibial instrumentation used in both groups.

The individual study sample sizes ranged from 72 to 570 participants. The largest study included 309 AR-assisted and 261 conventional procedures, whereas the smallest included 31 AR-assisted and 41 conventional procedures. Participants were generally older adults, with reported mean ages ranging from approximately 69 to 76 years. Where available, baseline age, sex distribution, and body mass index were comparable between treatment groups. Two Japanese studies predominantly included patients with osteoarthritis but also included a small number of patients with rheumatoid arthritis. Follow-up varied according to the outcomes assessed, ranging from immediate postoperative imaging to clinical and patient-reported assessments at one year.

Operative Efficiency

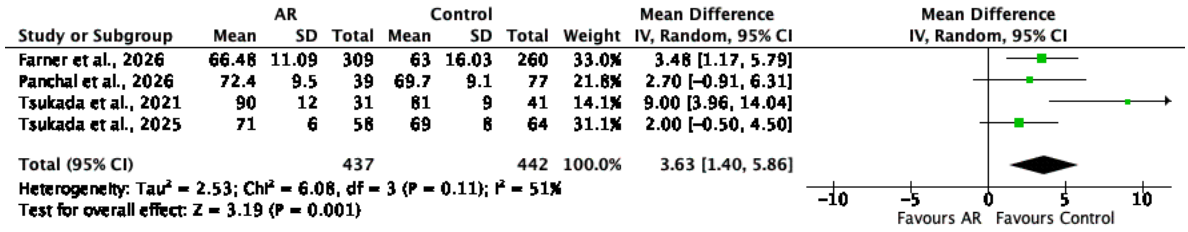

Figure 3. Pooled result for operative time

Operative duration was reported by four of the five included studies. In the 2021 Japanese study, AR-assisted surgery required 90 ± 12 minutes compared with 81 ± 9 minutes for conventional surgery, representing an unadjusted difference of nine minutes. The 2025 Japanese study reported a smaller difference, with operative durations of 71 ± 6 minutes in the AR group and 69 ± 8 minutes

in the conventional group. In the largest cohort, total operative duration from incision to case completion was 66.48 ± 11.09 minutes among 309 AR-assisted procedures and 63.00 ± 16.03 minutes among 260 conventional procedures. The same study also reported a shorter incision-to-closure interval, but total operative duration was selected for meta-analysis to maintain comparability with the other studies. The United Kingdom study reported operative durations of 72.4 ± 9.5 minutes in the AR group and 69.7 ± 9.1 minutes in the conventional group, with no statistically significant between-group difference. The Belgian study did not provide extractable operative-time data. Overall, the individual studies consistently showed numerically longer operative times with AR assistance, although the magnitude of the difference ranged from approximately two to nine minutes and was not statistically significant in two of the four studies.

Alignment Accuracy

Three studies evaluated radiographic or computed tomography-based alignment accuracy, although the anatomical component, imaging modality, and alignment definition differed across studies. The 2021 Japanese study evaluated distal femoral coronal resection and found that the mean absolute deviation from the target alignment was significantly lower with AR assistance than with conventional intramedullary instrumentation, at 1.1 ± 1.0° versus 2.2 ± 1.6°, respectively.

The 2025 Japanese study focused primarily on tibial component positioning. The absolute tibial rotational alignment error was 3.7 ± 3.4° in the AR group compared with 5.1 ± 4.4° in the conventional group. Rotational outliers exceeding 5° occurred in 15 of 58 AR-assisted procedures and 29 of 64 conventional procedures. In contrast, no significant differences were observed in tibial coronal alignment error, which was 1.1 ± 0.9° versus 1.2 ± 1.0°, or tibial sagittal alignment error, which was 1.9 ± 1.3° versus 1.7 ± 1.4°.

The United Kingdom study found that the mean femoral coronal component angle was closer to the intended 90° target in the AR group than in the conventional group, at 90.28 ± 1.72° versus 91.05 ± 2.05°. Alignment variability was also lower with AR assistance. Femoral component flexion was more accurately achieved in the AR group, whereas tibial coronal alignment and posterior slope did not differ significantly. Interpretation of the tibial findings was limited because tibial preparation was performed using conventional instrumentation in both groups. The Belgian and United States studies did not report extractable radiographic alignment data. Because the available studies assessed different components, anatomical planes, target angles, and outcome definitions, alignment results were synthesized qualitatively rather than pooled quantitatively.

Safety and Perioperative Outcomes

Safety outcomes were inconsistently reported. The 2021 Japanese study reported no complications in either group, including no AR jig loosening, intraoperative fracture, or other device-related adverse event. Similarly, the 2025 Japanese study reported no navigation-related complications, periprosthetic fractures, or wound infections in either treatment group. The United States cohort reported four 30-day readmissions among 309 AR-assisted procedures and eight among 261 conventional procedures. This difference was not statistically significant. No conversion from AR-assisted navigation to conventional instrumentation was required. The Belgian study did not report operative or postoperative complications, while the United Kingdom study did not provide extractable complication counts. Additional perioperative findings were reported in the United Kingdom study. The postoperative hemoglobin reduction was smaller following AR-assisted surgery than following conventional surgery, at 13.44 versus 18.62 g/L. Postoperative range of motion at one year was also greater in the AR group, at 130.8° compared with 123.5°. However, these outcomes were reported by only one study and were therefore not suitable for quantitative pooling.

Patient-Reported Outcomes

Patient-reported outcomes were assessed in three studies using different instruments and follow-up intervals. The Belgian matched cohort reported that both groups experienced postoperative improvement, but AR-assisted patients had significantly poorer KOOS symptom scores at six weeks. At three months, the AR group also had lower KOOS quality-of-life scores, Forgotten Joint Scores, and Oxford Knee Scores. Analysis according to the chronological sequence of AR procedures demonstrated progressive improvement in KOOS change scores, suggesting the presence of an early learning-curve effect. The United States study found comparable KOOS-JR improvements between groups. At the early postoperative assessment, the mean improvement was 13.04 ± 16.46 points in the AR group and 13.69 ± 18.67 points in the conventional group. At 10–14 months, the corresponding improvements were 26.22 ± 19.40 and 26.78 ± 18.26 points. Initial postoperative opioid prescriptions were lower in the AR group, but cumulative opioid utilization at 90 days did not differ significantly.

At one year, the United Kingdom study reported a Forgotten Joint Score of 71.7 ± 16.6 in the AR group and 65.5 ± 19.4 in the conventional group. The High Activity Arthroplasty Score was 10.4 ± 1.7 versus 10.6 ± 3.2, while the Oxford Knee Score was 43.6 ± 1.9 versus 43.8 ± 3.1. None of these between-group differences was statistically significant. Patient-reported outcomes were not quantitatively pooled because the studies used different measurement instruments, follow-up periods, and outcome formats, including final scores and change scores.

Quantitative Synthesis of Operative Time

Four studies involving 879 procedures contributed to the meta-analysis of operative time, including 437 AR-assisted and 442 conventional procedures. Random-effects analysis demonstrated that AR-assisted total knee arthroplasty was associated with a significantly longer operative duration than conventional instrumentation, with a pooled mean difference of 3.63 minutes (95% CI 1.40 to 5.86; $Z = 3.19$; $p = 0.001$), as shown in Figure 3.

Moderate statistical heterogeneity was observed across the included studies, with $\tau^2 = 2.53$, $\chi^2 = 6.08$, three degrees of freedom, $p = 0.11$, and $I^2 = 51\%$. The largest individual effect was observed in the 2021 Japanese study, which reported a mean difference of 9.00 minutes (95% CI 3.96 to 14.04). The other studies demonstrated smaller differences of 2.00–3.48 minutes. Despite variation in operative-time definitions and AR systems, the direction of effect was consistent across all four studies, favoring conventional instrumentation for shorter operative duration.

DISCUSSION

This systematic review and meta-analysis evaluated augmented reality assisted navigation compared with conventional manual instrumentation in primary total knee arthroplasty. The principal quantitative finding was that AR-assisted TKA required a significantly longer operative time, with a pooled mean increase of 3.63 minutes. Although the magnitude of this difference was modest, the direction of effect consistently favored conventional instrumentation across all four studies included in the meta-analysis. Moderate heterogeneity was present, which was likely related to differences in AR platforms, surgeon experience, operative workflows, and definitions of surgical duration. Beyond operative efficiency, AR assistance produced selective improvements in component alignment, particularly femoral coronal alignment and tibial rotational positioning. However, these technical improvements were not consistent across all anatomical planes and did not translate into clearly superior patient-reported outcomes. Safety findings were generally reassuring, but the available evidence was too limited to establish equivalence between the approaches (Farner et al., 2026; Panchal et al., 2026; Tsukada et al., 2021, 2025; Van Overschelde et al., 2022).

The modest increase in operative duration observed with AR assistance is biologically and operationally plausible. Although AR systems are designed to avoid the large consoles, extensive preoperative planning, and complex equipment associated with robotic platforms, they still require additional intraoperative steps for marker placement, landmark registration, axis calculation, cutting-guide adjustment, and verification of the planned resection. A hierarchical task analysis comparing conventional, robotic-assisted, and AR-navigated TKA similarly demonstrated that technology-assisted procedures involve additional workflow stages and more potential points of inefficiency or failure than conventional surgery (Koucheki et al., 2024). Nevertheless, an average increase of approximately four minutes is considerably smaller than the additional operative burden historically reported during the adoption of several robotic systems. The clinical importance of this increase will therefore depend on institutional surgical volume, operating-room turnover, staff familiarity, and whether the time difference decreases after completion of the learning curve.

The variation in operative time among the included studies also suggests an important effect of surgeon experience. The largest increase was observed in the smaller 2021 cohort, whereas later and larger cohorts reported differences of only approximately two to four minutes. One included study additionally demonstrated progressive improvement in early patient-reported outcomes as experience with the AR system accumulated, supporting the presence of an adoption-related learning curve (Van Overschelde et al., 2022). Evidence from robotic-assisted TKA indicates that the learning curve predominantly affects operative efficiency rather than component-positioning accuracy. A recent literature review estimated that approximately 16 cases were required to reach operative proficiency and a larger number of cases could be needed before operative time became comparable with manual TKA (Pujol et al., 2025). Although robotic and AR systems are not interchangeable, this pattern suggests that the pooled operative-time penalty may partly represent early implementation rather than a permanent disadvantage of AR guidance. Future studies should therefore report the chronological order of procedures and analyze outcomes according to learning and proficiency phases.

The available alignment findings support the technical capacity of AR navigation but also demonstrate that its effect is dependent on the component and plane being assessed. AR guidance reduced the absolute error of distal femoral coronal alignment and improved tibial rotational positioning, including a reduction in rotational outliers. In contrast, no meaningful improvements were identified for tibial coronal or sagittal alignment in the study that assessed all three tibial planes (Tsukada et al., 2021, 2025). Another study demonstrated improved femoral coronal accuracy and reproducibility but found no difference in tibial alignment (Panchal et al., 2026). However, tibial preparation in that cohort remained conventionally instrumented in both groups, meaning that the tibial findings should not be interpreted as evidence against AR guidance. These variations emphasize that AR-assisted TKA is not a uniform intervention. Some systems guide both femoral and tibial resections, whereas others are used only for selected surgical stages.

The observed alignment benefits are consistent with noncomparative validation research demonstrating that AR systems can reproduce planned resections with small coronal and sagittal deviations. An in vivo evaluation of the Knee+ platform found high agreement between intraoperative AR measurements and postoperative radiographic component positioning, with accuracy considered comparable to more resource-intensive technology-assisted approaches (Lambrechts et al., 2024). Nevertheless, technical accuracy under controlled conditions does not ensure that every clinically relevant alignment parameter will improve. Registration quality, landmark identification, marker stability, imaging methods, component design, and the surgeon's selected alignment target may all influence the final result. The use of raw component angles in some studies and absolute deviation from a target in others further prevented meaningful quantitative pooling of alignment accuracy.

An important finding of this review was the absence of a consistent relationship between improved alignment and superior patient-reported outcomes. Early outcomes were inferior in the AR group in one prospective cohort, although performance improved with increasing experience (Van Overschelde et al., 2022). In contrast, the larger contemporary studies found comparable KOOS-JR improvement, Oxford Knee Scores, Forgotten Joint Scores, and activity scores between AR-assisted and conventional TKA (Panchal et al., 2026). Several explanations are possible. First, the alignment improvements were relatively small and may not have been sufficient to produce perceptible differences in pain or function. Second, postoperative recovery is influenced by multiple factors beyond component angles, including soft-tissue balance, implant design, analgesia, rehabilitation, preoperative functional status, and patient expectations. Third, the included studies used different instruments, follow-up periods, and reporting formats, limiting the ability to identify a consistent clinical effect.

The uncertain clinical relevance of modest radiographic improvements is consistent with the broader TKA literature. A systematic review examining component placement after manually instrumented TKA found substantial inconsistency in the relationship between alignment parameters and patient-reported or functional outcomes (Narkbunnam et al., 2022). Similarly, meta-analytic evidence from randomized trials of robotic-assisted TKA has shown better anatomical and mechanical alignment than conventional TKA, while clinical outcomes and complication rates have generally remained comparable (Alrajeb et al., 2024). These findings do not imply that alignment accuracy is unimportant. Rather, they suggest that a single universal target may not adequately represent the complex relationship between implant positioning, native anatomy, joint-line orientation, ligament balance, and postoperative function. AR guidance may ultimately have greater clinical value when used to reproducibly execute an appropriate patient-specific alignment plan rather than simply to achieve neutral mechanical alignment in every patient.

Safety outcomes were insufficiently reported to support quantitative synthesis. No device-related complications, intraoperative fractures, or navigation-related wound infections were reported in the two Japanese studies, while the largest cohort found no significant difference in 30-day readmission (Farner et al., 2026; Tsukada et al., 2021, 2025). However, two studies reported no events in either group, one study reported only readmission, and the remaining studies did not provide extractable complication counts. Consequently, the absence of observed complications should not be interpreted as definitive evidence of equivalent safety. Rare adverse events require substantially larger samples and longer surveillance than those available in the included studies. Standardized reporting should include intraoperative conversion, marker or pin instability, fracture, neurovascular injury, infection, thromboembolism, stiffness, reoperation, readmission, and revision.

From a clinical perspective, AR navigation may occupy an intermediate position between conventional instrumentation and full robotic assistance. It offers real-time intraoperative guidance with a comparatively small equipment footprint and without mandatory preoperative computed tomography for the systems evaluated in this review. The current evidence indicates that these advantages can be achieved with only a modest increase in operative duration and without an evident increase in short-term complications. However, routine adoption cannot yet be justified on the assumption that greater technical precision will automatically improve patient experience or implant longevity. Decisions regarding implementation should also consider acquisition or per-case costs, staff training, system reliability, compatibility with different implants and alignment philosophies, and the volume required to overcome the learning curve.

This review has several strengths. It addressed a focused comparison between AR-assisted and conventional primary TKA, separated operative efficiency from radiographic and patient-reported outcomes, and avoided pooling clinically incompatible alignment measures. For operative time, all studies reported the outcome in minutes, permitting the use of an interpretable pooled mean

difference. Selection of the complete operative-duration measure from the study reporting two time intervals also prevented duplication of participants.

Several limitations should be considered. Only five studies were identified, and all were observational comparative studies. Most were conducted at a single center by one or two surgeons, limiting external validity. Sequential cohort designs were susceptible to temporal confounding because improvements in perioperative care, surgical experience, and patient selection may have occurred alongside adoption of AR technology. Two studies originated from the same Japanese institution, although they assessed different procedures and alignment outcomes. The extent of AR assistance, implant systems, alignment targets, imaging modalities, and follow-up periods varied substantially. Operative time was defined differently across studies, contributing to statistical heterogeneity. Patient-reported outcomes could not be pooled because of inconsistent instruments and the use of both final and change scores. Safety events were underreported, and no study provided sufficiently long follow-up to evaluate revision, implant survival, or late complications. Publication bias could not be meaningfully assessed because fewer than ten studies contributed to the meta-analysis.

Future research should prioritize adequately powered multicenter randomized trials with standardized operative-time definitions and clear separation of the learning and proficiency phases. Alignment outcomes should be reported as both absolute deviation from the intended target and the proportion of clinically defined outliers for each component and anatomical plane. Studies should document whether AR is used for femoral preparation, tibial preparation, soft-tissue assessment, or the entire procedure. Patient-reported outcomes should be collected using consistent instruments at predefined intervals and interpreted alongside clinically meaningful thresholds. Comprehensive complication reporting, cost-effectiveness analyses, operating-room workflow assessment, and long-term surveillance of revision and implant survival are also required. Such studies would determine whether the demonstrated technical precision of AR navigation provides sufficient clinical and economic value to support widespread implementation.

CONCLUSION

Augmented reality–assisted navigation in primary total knee arthroplasty was associated with a modest but statistically significant increase in operative time compared with conventional instrumentation. AR guidance demonstrated selective improvements in component alignment, particularly femoral coronal accuracy and tibial rotational positioning, without clear superiority in patient-reported outcomes. Available safety findings were reassuring, although complication reporting was limited and inconsistent. AR-assisted TKA appears feasible and technically accurate, but its clinical and long-term advantages over conventional instrumentation remain uncertain. Larger multicenter randomized studies with standardized alignment, safety, functional, and cost-effectiveness outcomes are required before routine implementation can be recommended.

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