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Review Article

The Effectiveness of Three-Dimensional Planning and Augmented Reality Navigation-Assisted Total Hip Arthroplasty: A Systematic Review and Meta-Analysis

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Abstract: *Background:* Three-Dimensional (3D) Planning and Augmented reality (AR) navigation technology for various types of surgery has become common practice in the operating room. This study set out to examine the accuracy and safety of AR navigation assisted technology in Total Hip Arthroplasty (THA) compared to conventional technique. *Methods:* Our search was performed in the following online databases: PubMed, Embase, the Cochrane Library, Web of Science and CNKI (published between Jan 1, 2010, and Jan 1, 2023; no language restrictions). The study quality was independently evaluated by the consensus of two independent reviewers, and all statistical analysis was performed using STATA 16.0 (Stata Corp LLC, College Station, Texas, USA). The primary outcomes extracted from articles that met the selection criteria were expressed as odds ratios for dichotomous outcomes with a 95% confidence interval. Data regarding the first author, publication year, country, patient numbers, age, sex, and BMI of patients, study type, and other outcomes of interest were reported. *Results:* Seven randomized controlled trials (RCTs) and one retrospective comparative study (RCS) involving 422 patients were included in this meta-analysis. The meta-analysis showed that THA using 3D navigation assisted technology had shorter surgical time, higher accuracy of surgery, lower intraoperative blood loss, and fewer complications compared to conventional techniques. *Conclusion:* Considering the overall results of our meta-analysis, we can corroborates the accuracy and safety of AR navigation technology assisted THA.

Keywords: Augmented Reality, Meta-Analysis, Total Hip Arthroplasty, Three-Dimensional, Surgery Navigation

1. Introduction

Total hip arthroplasty (THA) is a widely adopted orthopedic procedure designed to alleviate pain and improve mobility in patients suffering from hip joint injuries or degeneration [1]. With the continuous advancements in medical technology, the frequency of THA surgeries is increasing. In 2018, worldwide more than 1.5 million primary total hip replacements (arthroplasties) were implanted [2]. In Germany, over 240,000 THAs were performed in 2019, with a predicted 27% increase by 2040 [3]. Although THA is a common procedure with a high success rate, it can lead to complications such as infections, fractures, and hip dislocations, necessitating revision surgery [4-6]. Recent technological advancements, including medical imaging, navigation, and robotics, have paved the way for the development and application of augmented reality (AR) technology in orthopedic surgery. Compared to traditional approaches, AR navigation can be used to prevent problems such as prosthetic malpositioning, dislocation, excessive surface wear, and the need for revision surgery [7].

AR is a technology that overlays virtual information onto a real-world environment, providing surgeons with real-time three-dimensional (3D) visual guidance and feedback during surgery [8, 9]. While AR has proved useful in spine, maxillofacial, and neurosurgery [10, 11], it has also shown promising results in enhancing surgical precision, reducing complications, and improving patient outcomes in THA [12]. However, the effectiveness and safety of AR technology in THA remain fragmented and unclear.

Several studies have compared the use of AR-assisted and conventional approaches for THA [13-20], but no systematic comparison or meta-analysis has been conducted yet. This meta-analysis aims to synthesize and evaluate the existing evidence on the use of AR in THA, assess the potential benefits and limitations of the technology, and shed light on its effectiveness and safety compared to traditional procedures. The results of this meta-analysis will have significant implications for the future adoption, implementation, and optimization of AR in clinical practice and research.

2. Methods

This study was registered with the International Prospective Register of Systematic Reviews (PROSPERO) number CRD42023401930.

2.1. Search Strategies

The Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) guidelines [21] were followed. Two reviewers (HYK and SYW) systematically searched the PubMed, Embase, Cochrane Library, Web of Science, and CNK1 electronic databases for articles published between January 1, 2010, and January 1, 2023. The following MeSH terms were used (using the Boolean operators "and" and "or"): 'THA'; 'augmented reality'; 'three-dimensional'; 'computer assisted'; 'assisted navigation'; 'reconstruction'; 'surgery planning'. There was no language restriction on the included articles.

2.2. Inclusion and Exclusion Criteria

The PICOS (population; intervention; comparison; outcome; study) framework was used to classify the criteria used for study selection.

The inclusion criteria were:

1. Population: adults, including elderly patients, requiring THA;
2. Intervention: THA;
3. Comparison: AR-assisted vs conventional approach;
4. Outcomes: duration of surgery; accuracy of surgery; postoperative complications; intraoperative blood loss;
5. Study: Randomized controlled trials (RCTs) or randomized controlled studies (RCSs).

The exclusion criteria were:

1. Studies lacking primary data;
2. Duplicate publications by the same author or institution;
3. Cohort studies, reviews, conference abstracts, case series, and editorials.

2.3. Data Extraction and Outcome Measures

A structured template based on the Cochrane Consumers and Communication Group was used for data extraction. The analysis was conducted in accordance with the guidelines of the Cochrane Consumers and Communication Group reviews: Meta-analysis [22]. The full-text versions of the identified studies were independently analyzed by two of the authors to decide the final studies for inclusion. Disagreements were settled by discussion or by consultation with a third author. Information on the first author, publication year, country, patient numbers, age, sex, and BMI of patients, study type, and other outcomes of interest was recorded.

Regarding missing data such as standard deviation, we were able to calculate them through the use of formulas established by the Cochrane handbook for systematic reviews of interventions or from the data presented in relevant figures within the corresponding articles.

2.4. Evidence Quality Assessment

The methodological quality of the RCTs was analyzed by two authors using the Cochrane risk of bias tool from the Cochrane Collaboration. The Newcastle–Ottawa scale (NOS), as proposed by Stang [23] for the scoring of case-control studies was used to analyze the quality of RCSs.

2.5. Statistical Analyses

To conduct statistical analysis, the present review employed forest plots as a concise and informative means of presenting the synthesized results. Data were analyzed with Stata 16.0 (Stata Corp LLC, College Station, Texas, USA). The mean difference (MD) was used in the analysis of continuous data, while the Odds Ratio (OR) was used in the analysis of dichotomous data. The results are expressed as mean differences or odds ratios with a 95% confidence interval (CI).

Heterogeneity was examined using the I^2 statistic. I^2 ranges between 0 and 100 and gauges the amount of inconsistency in the study results, as follows:

1. $I^2 \leq 25\%$: low heterogeneity;
2. $25\% < I^2 \leq 50\%$: moderate heterogeneity;
3. $I^2 > 50\%$: high heterogeneity.

The random effects model was used to determine the pooled OR and 95% CI to produce more conservative results. Significance was set at $P < 0.05$.

3. Results

3.1. Study Selection

Initially, a search was conducted resulting in the identification of 701 relevant articles, including 190 from PubMed, 83 from Embase, 235 from Web of Science, 37 from the Cochrane Library, and 156 from CNK1, that were assessed in terms of the PRISMA guidelines (Figure 1). Screening the abstracts indicated that 295 of the articles were not relevant to THA. Twenty-five articles were found to be eligible according to the inclusion criteria, of which 17 were then excluded due to lack of control groups or for other reasons. Thus, 8 articles were finally included, of which 7 were RCTs and 1 was an RCS.

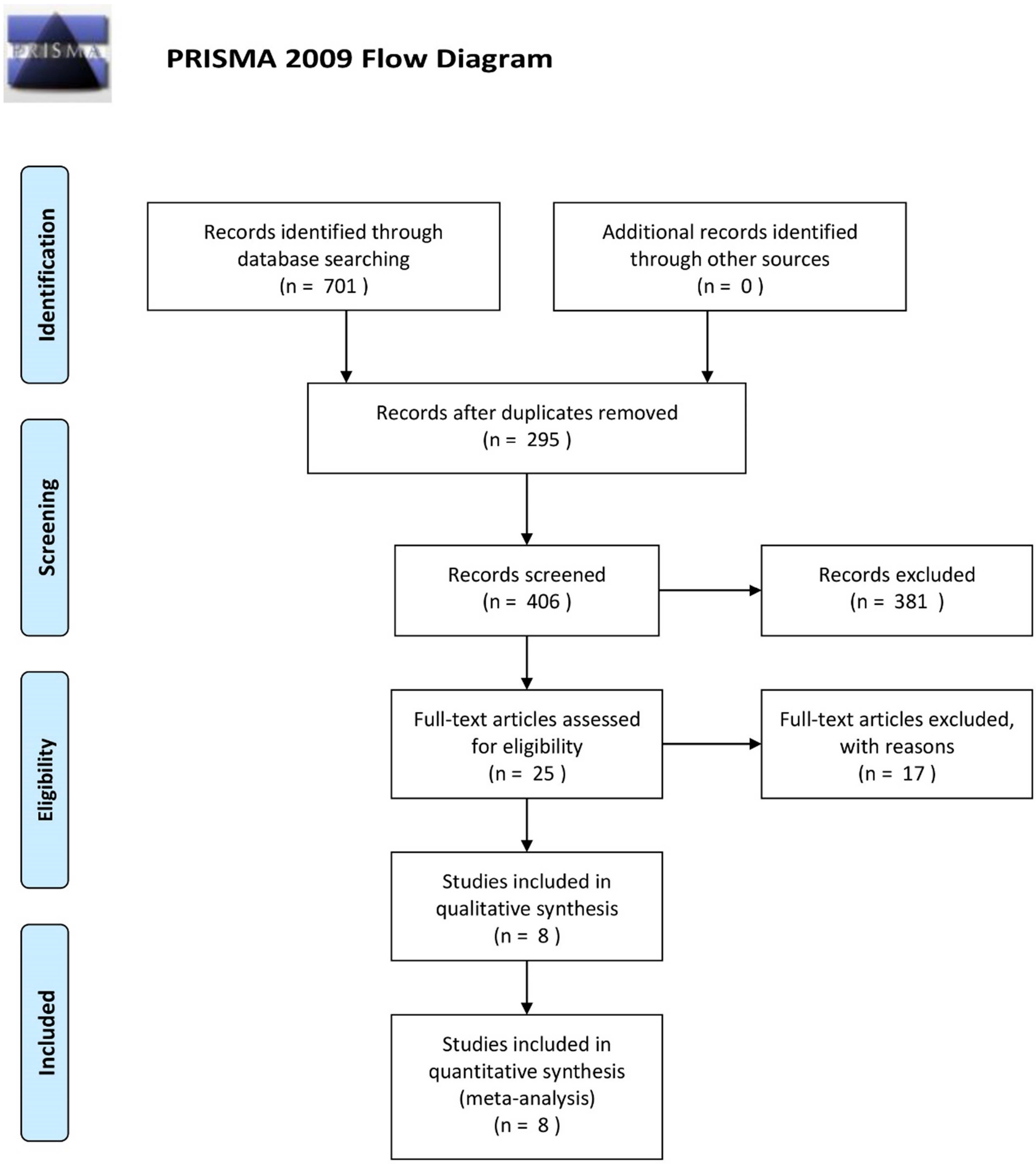

Figure 1. *Flow chart of the selection process.*

3.2. Study Characteristics

The eight studies analyzed an overall number of 422 patients, with 211 (50%) in the intervention group and 211 (50%) in the control group. Table 1 shows the baseline characteristics of the patients. All the studies were single-center, with four undertaken in Germany, two in China, two in Japan, and one each in Brazil and France. Assessment of the RCS showed that the modified NOS score (ranging from 0 to 9) was 8, indicating high quality.

Table 1. *Characteristics of the included studies.*

Author	**Year**	**Country**	**Numbers (N/C)**	**Sex (male/female)**	**Age (years) mean ± SD**	**BMI (kg/m^2) mean ± SD**	**Type of study**	**Nos.**
Tsukada et al.	2021	Japan	N: 45 C: 42	N: 38/7 C: 34/8	66±9 62±11	24.7±3.9 25.0±4.2	RCS	8
Brenneis et al.	2020	Germany	N: 23 C: 28	N: 13/10 C: 12/16	60.2±10.7 63.5±10.0	27.8±4.6 27.7±4.0	RCT	
Yan et al.	2020	China	N: 12 C: 13	N: 2/10 C: 2/11	59.8±11.1 65.5±10.8		RCT	
Ogawa et al.	2019	Japan	N: 22 C: 19	N: 19/3 C: 17/2	65±11 67±12	22.9±3.8 22.6±4.4	RCT	
Yamada et al.	2017	Japan	N: 40 C: 40	N: 11/29 C: 4/36	60.8±14.7 63.4±13.5	24.4±6.9 23.7±4.1	RCT	
Sariali et al.	2016	France	N: 28 C: 28	N: 18/10 C: 20/8	60.8±13.4 59.4±10.9	26.6±4.0 26.7±4.3	RCT	
Sariali et al.	2011	France	N: 30 C: 30	N: 21/9 C: 23/7	60±15 57.2±13	27.1±3.7 25.8±6.7	RCT	
Zhang et al.	2011	China	N: 11 C: 11	N: 7/4 C: 5/6	48.6±6.8 49.3±4.9		RCT	

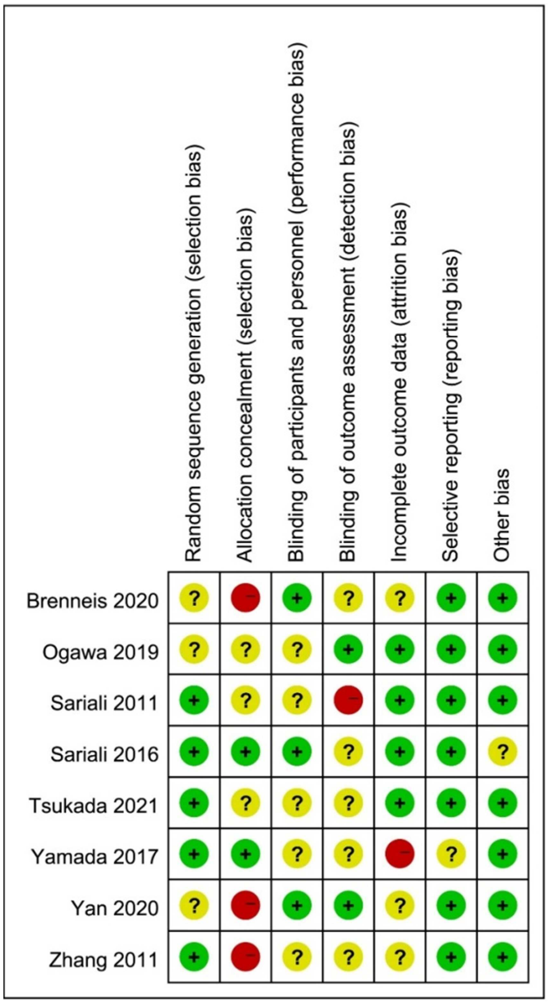

Figure 2. *Bias risk evaluation of the RCTs.*

3.3. Quality Assessment

This study presented a thorough evaluation of potential biases, including selection, attrition, and reporting. The risks associated with these biases are deemed low. However, the risk of detection bias and performance bias were considered moderate. Overall, this study exhibited a high methodological quality. Independent reviewers assessed bias levels of studies included in this work through the Cochrane Collaboration's Risk of Bias technique, whose results are displayed in Figure 2.

3.4. Accuracy of Surgery

Our study reported on the outcomes of a pooled analysis of data from five randomized controlled trials involving 286 patients. The study investigated the impact of augmented reality (AR) navigation on acetabular cup anteversion and inclination angle deviations in total hip arthroplasty (THA). The results revealed that the acetabular cup anteversion angle deviation in the AR navigation group was 0.64° lower than that of the THA performed using conventional techniques (MD, -0.64; 95% CI, -0.92 to -0.36; I^2 = 21.57%; p = 0.00; Figure 3 (A)). Moreover, the deviation in the acetabular cup inclination angle in THA performed using AR navigation was 2.29° lower than that of the conventional technique (MD, -2.29; 95% CI, -3.10 to -1.49; I^2 = 35.73%; p = 0.00; Figure 3 (B)). These results suggest that the use of AR navigation during THA may lead to improved precision in acetabular cup placement.

3.5. Intraoperative Blood Loss and Complications

Information regarding blood loss during surgical procedures was presented in four studies. The meta-analysis demonstrated that the AR approach reduced blood loss by 26.95 mL.. Additionally, no clear heterogeneity was found among the studies (MD, -26.95; 95% CI, -54.77 to 0.88; I^2 = 43.79%; p = 0.06; Figure 4).

In addition, four of the included studies reported complications arising in patients undergoing total hip arthroplasty (THA) using the AR approach and conventional methods. These complications included fractures, surgical site infections, postoperative hip dislocation, and leg length discrepancy. Upon analysis, no significant differences were detected between the two groups (OR, -0.67; 95% CI, -1.50 to 0.16; I^2 = 2.09%; p = 0.12; Figure 4 (B)).

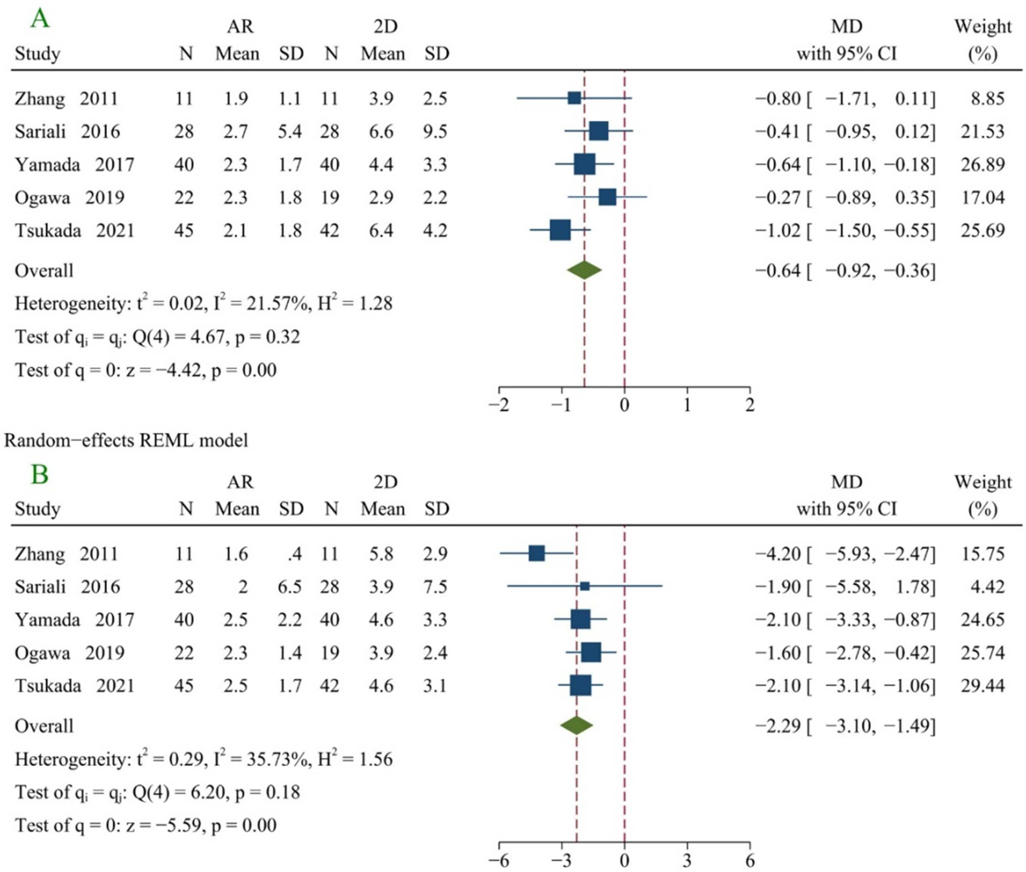

Figure 3. *Pooled analysis of surgical accuracy. (A) Deviation of the inclination angle; (B) Deviation of the anteversion angle.*

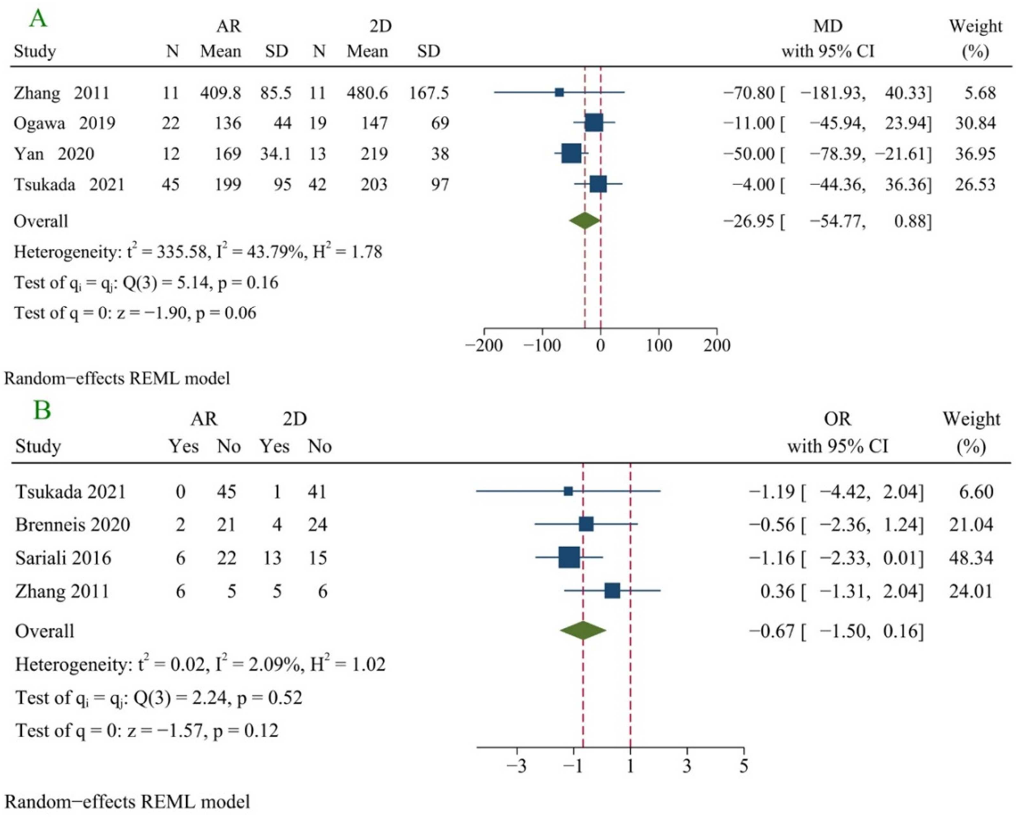

Figure 4. *Pooled analysis of intraoperative blood loss and complications.*

3.6. Surgical Time

Seven studies provided information on surgical time. Analysis showed that the surgical time was shorter with AR than with the conventional approach. There was no significant difference between the two groups (MD, -2.98; 95% CI, -5.34 to -0.61; I^2 = 26.73%; p = 0.01; Figure 5).

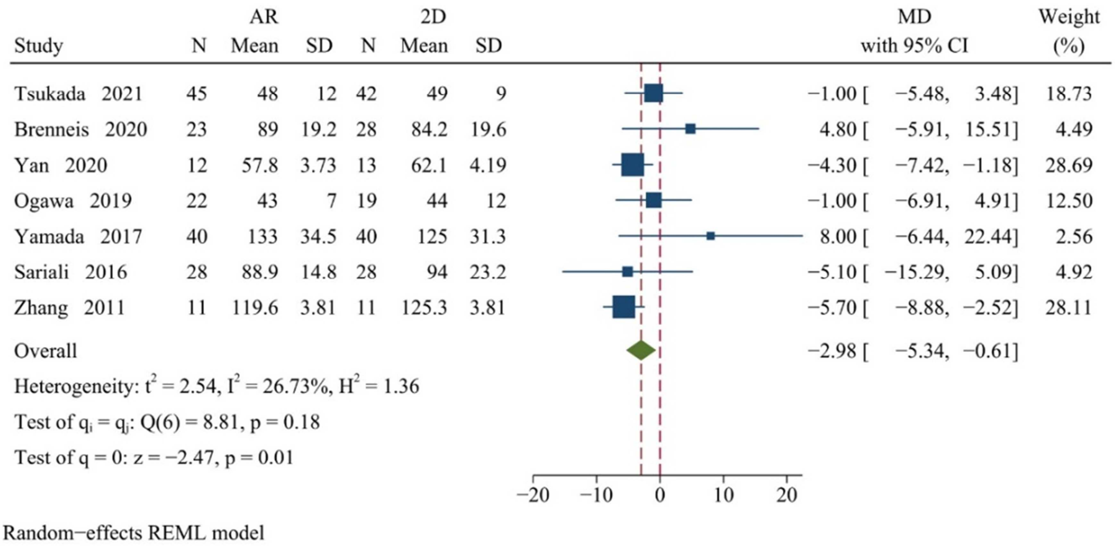

Figure 5. *Pooled analysis of surgical time.*

4. Discussion

Total hip arthroplasty (THA) is widely regarded as one of the most cost-effective and consistently successful procedures in orthopedics. Despite this, the issue of THA instability remains a persistent challenge [24]. In traditional total hip replacement surgery, the lack of complete understanding of the anatomy and the location of the lesions can have a negative impact on the final outcome of the surgery. As a result, some Augmented Reality (AR) systems have been integrated into the field of joint replacement surgery to assist orthopedic surgeons in accurately dissecting the location of the lesion during surgery. These AR systems have been successful in addressing these problems. However, as AR technology represents a new navigation technique, it is essential to evaluate its accuracy, safety, and effectiveness when used in total hip replacement surgery. Such evaluation is critical to the assessment of the advantages and limitations of AR technology, and it serves to guide the use of this technique by surgeons [25, 26].

This meta-analysis included seven RCTs and one RCS which, in total, comprised 422 patients. It is important to note that this is the first comprehensive meta-analysis that compares the accuracy and safety of AR-assisted THA to traditional techniques. While there have been reports in the past discussing the advantages of total hip replacement using AR technology, these claims had not previously been substantiated by evidence-based medicine. To draw objective and rigorous conclusions, a systematic review and meta-analysis was conducted.

The present meta-analysis revealed that there was a reduced deviation in acetabular cup anteversion angles and inclination angles, with ranges between 1.9° to 2.7° and 1.6°to 2.5°, respectively, during total hip arthroplasty when AR navigation assistance technology was employed. In contrast, conventional hip arthroplasty exhibited higher deviation ranges in anteversion angle (2.9°~6.6°) and inclination angle (3.9°~5.8°). The findings suggest that the use of AR-assisted navigation technology enhances surgical precision and stability. Notably, the AR navigation system enables the reconstruction of real superimposed three-dimensional images and three-dimensional measurements of the acetabular cup's inclination and anteversion angles, which significantly improves measurement accuracy, reduces experimental error, and enhances the present meta-analysis's reliability.

Our meta-analysis revealed that AR-navigated total hip arthroplasty (THA) resulted in 27.0 mL less intraoperative blood loss compared to conventional THA. The average blood loss during AR navigation ranged from 136 to 409.8 mL, whereas the average blood loss during conventional surgery ranged from 147 to 480.6 mL. AR technology provides surgeons with a clear visualization of the three-dimensional structure within the hip joint, which may reduce the amount of intraoperative bleeding. However, the extent of tissue damage cannot be solely determined by intraoperative blood loss. Other outcome parameters such as total blood loss and laboratory parameters are also important to consider, including CRP, IL-6, IL-10, IL-1a, ESR, and CK levels [27].

Our analysis did not identify any significant difference in postoperative complications between AR-navigated and conventional THA, including fractures, surgical site infections, postoperative hip dislocations, and leg length discrepancies. Interestingly, the AR-assisted group had almost no complications related to leg length differences, which may contribute to the lower overall complication rate observed compared to the conventional group.

The present meta-analysis examines the effect of augmented reality (AR) navigation on total hip arthroplasty (THA) surgery time as compared to conventional methods. The analysis reveals a statistically significant reduction in surgery time by 3.0 minutes in AR-navigated THA surgery compared to the conventional THA procedure. The average operation time for AR navigation was 43.0–119.6 minutes, while the average operation time using the conventional method was 44–125.3 minutes, with no significant difference between the two methods. Surgery time is a complex parameter affected by several factors such as patient age, medical level, and physician experience, among others. Longer operating times usually occur during the surgeon's learning curve. However, it was not clear whether the total hip replacement via AR navigation was performed by learners, skilled surgeons, or specialists. By mastering surgical skills, AR navigation can significantly reduce the surgical time for total hip replacement. The dramatic change in the surgical time for total hip replacement via AR navigation from 43 minutes to 119.6 minutes supports the view that the surgeon's surgical experience and the level of hospital care play important roles, and indicates that it is possible to shorten the operation time. Furthermore, the differences in the medical level between Asia and Europe, with European countries such as Germany generally having higher medical standards, advanced medical equipment, and experienced surgeons, may contribute to the heterogeneity observed in the study. Therefore, it is essential to consider these factors when interpreting the results. In conclusion, this study suggests that AR navigation can be a useful tool to reduce surgery time in total hip replacement surgeries [28, 29].

The eight studies that were included in the analysis adhered strictly to the inclusion and exclusion criteria, and also demonstrated a high level of methodological quality. As a result, the findings can be regarded as both credible and reliable. However, there are a few limitations worth noting. Firstly, the analysis comprised a relatively small number of studies, with many reports lacking critical details pertaining to the underlying clinical conditions and surgical procedures. This can reduce the certainty of the effect sizes that were pooled in the analysis. Secondly, due to the incompleteness of raw data reported in the studies, some degree of bias may be present [30].

Despite the limitations of the study, the results suggest that augmented reality (AR) technology may have the potential to enhance the outcomes of total hip replacement surgery. Future research should aim to identify the optimal use of AR technology and establish standardized approaches to evaluate its effectiveness. Furthermore, there is a need to improve the accessibility and training of AR technology to promote its broader implementation in clinical practice. Therefore, the multicentered and large population- based designs of future research should be considered, and more long-term follow-up surveys should be focused and reported.

5. Conclusion

The utilization of augmented reality (AR) assistance in total hip arthroplasty (THA) has demonstrated a remarkable progression in intraoperative guidance, contributing to enhanced surgical precision, superior patient outcomes, and improved surgical efficiency. Through our research, we have determined that AR-assisted THA is significantly more effective than the conventional approach in enhancing accuracy, diminishing the incidence of complications, minimizing intraoperative blood loss, and reducing surgical time. Nonetheless, further comparison between these two techniques necessitates larger prospective studies with lengthier follow-ups.

Ethics Declarations

Declaration of Interest

No potential conflict of interest was reported by the author(s).

Ethical Approval

Although the present study involved human participants, ethical approval was not required because all data were based on previously published studies that were analysed anonymously without any potential harm to the participants.

Informed Consent

Informed consent from the participants was not required because all data were based on previously published studies that were analysed anonymously without any potential harm to the participants.

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IRB Statement

This meta-analysis article does not require IRB approval.

Abbreviations

Augmented Reality (AR); Total Hip Arthroplasty (THA); Mean Difference (MD); Odds Ratio (OR); Randomized Controlled Trial (RCT); Retrospective Comparative Study (RCS); Confidence Interval (CI).

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