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MAKO robotic-assisted compared to conventional total hip arthroplasty for hip osteoarthritis: a systematic review and meta-analysis

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Abstract

Background Total Hip Arthroplasty (THA) is the gold standard for treating end-stage hip osteoarthritis. Robotic-assisted systems, particularly the MAKO system, have been introduced to enhance reproducibility and safety. However, meta-analyses comparing MAKO-assisted THAs (MAKO-THA) to conventional methods are lacking, and previous reviews often aggregate various indications, introducing heterogeneity.

Methods A random-effects meta-analysis was conducted on comparative studies between MAKO robotic-arm-assisted and conventional THAs in patients undergoing THA for solely hip osteoarthritis. Clinical outcomes (Harris Hip Scores [HHS], Forgotten Joint Scores [FJS], and Oxford Hip Scores [OHS]), radiographic parameters (implant positioning accuracy), leg-length-discrepancy, surgical duration, and complications were evaluated.

Results 20 comparative studies were included. MAKO-assisted THAs resulted in higher postoperative HHS (MAKO-THA: 89.1, 95%CI: 86.4–91.7; C-THA: 87.0, 95%CI: 83.8–90.1), FJS (MAKO-THA: 84.7, 95%CI: 79.9–89.6; C-THA: 74.9, 95%CI: 64.0–95.7), and OHS (MAKO-THA: 89.1, 95%CI: 86.4–91.7; C-THA: 87.0, 95%CI: 83.8–90.1). FJS and OHS improvements were significantly greater compared to conventional THA (HHS WMD 2.2 [95%CI: -0.3–4.7, $p=0.09$; FJS WMD: 8.7 [95%CI: 2.7–14.8], $p=0.005$; OHS WMD: 1.5 [95% CI: 0.1–2.8], $p=0.03$). MAKO-THA resulted in 94.7% and 90.3% of implants positioned within Lewinnek-and-Callanan zones, respectively, compared to 65.8% and 57.1% in conventional THA. MAKO-THA had longer mean surgical durations and lower postoperative leg-length discrepancy, but not significantly (Surgical Duration WMD: 3.5 [95%CI: -2.5–9.5], $p=0.3$; Leg Length Discrepancy WMD: -0.2 [95%CI: -0.7–0.4], $p=0.6$). Complication rates were low and non-significant (MAKO-THA: 3.0% [95%CI: 1.2–7.4]; C-THA: 3.5% [95% CI: 1.2–10.1), $p=0.3$).

Conclusion MAKO robotic-arm-assisted THA significantly improves Forgotten Joint Scores, Oxford Hip Scores and reproducibility in implant positioning without compromising on surgical duration and complication rates.

Protocol registration CRD42024542794.

Keywords Total hip arthroplasty, Hip osteoarthritis, Arthroplasty, Orthopaedic surgery, Meta-analysis

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Introduction

Hip osteoarthritis (OA) is the second most common form of OA resulting in debilitating joint pain on weightbearing and movement, stiffness, crepitus and limited range of motion [10]. It is estimated that 10–25% of those above 55 years-old suffer from hip OA [50]. Management comprises both conservative and surgical - with patient education, weight loss, physiotherapy and analgesia being the first-line [32]. Where conservative management is ineffective, surgical management is considered in the form of a Total Hip Arthroplasty (THA). The significance of this procedure is growing– with a forecast study of Medicare patients in the USA projecting a 176% increase in THA procedures by 2040 and 659% by 2060 [52].

Primary THA is the standard-of-care for end-stage hip OA [43]. In recent years, efforts to increase the reproducibility, safety and reduction in complications have yielded the introduction of robotic THA systems. Active robot systems tended to show relatively high intra-operative complication rates or intra-operative conversion to conventional THA [20]. Semi-active systems were developed thereforth. The MAKO Robotic-arm-assisted system is presently the most widely adopted robotic hip arthroplasty system worldwide, although others have developed semi-active systems like the ROSA, VELYS and CORI systems [8].

Multiple previous reviews suggest functional outcomes are similar between robotic and conventional THAs, but implant positioning accuracy and complication rates are improved [10, 48]. These reviews combined the 1st generation active robotic systems and the more recent semi-active systems– it has been suggested before that each robotic system has its own nuances and should not be grouped together as one entity. Also, they included all indications for THA - be it OA, dysplastic hip, avascular necrosis (AVN), rheumatoid arthritis (RA) or ankylosing spondylitis (AS). This introduces inherent challenges in interpreting results, as anatomical variations associated with non-standard cases can influence surgical complexity and thus the comparative efficacy of both techniques. On these grounds, there is need for pathology-specific and system-specific evaluations to better inform clinical decision-making. We aim to summarize current evidence to assess whether MAKO-assisted THA could improve clinical, functional, and radiological outcomes compared to conventional THA in standard hip osteoarthritis cases. A secondary aim is to assess any differences in associated complications and surgical duration in this group. We hypothesise that MAKO-assisted THAs result in improved clinical outcomes, implant positioning accuracy, with reduced complications and surgical duration.

Methods

Data sources and search strategy

This study was conducted in adherence with the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-analyses Statement) guidelines (Fig. 1) [41]. The protocol for this systematic review and meta-analysis was registered with the PROSPERO (ID: CRD42024542794) International prospective register of systematic reviews. We searched electronic databases MEDLINE, Embase, Cochrane Library and SCOPUS from inception, on May 25, 2024, for relevant studies using keywords and terms synonymous with THAs in patients with Hip OA. We did not limit our search to only articles written in the English language. Our search strategy can be found in the Supplementary Material. This study is exempt from IRB approval.

Study selection

We included studies that compared MAKO-assisted THAs and conventional THAs, where the indication for THA was primary Hip OA. Studies were selected based on a priori based on the study population, intervention, outcomes measured and study design (Table 1).

Patients having had prior procedures performed before the THA was not seen as a criterion for exclusion so long as the patient was undergoing Primary THA for Hip OA.

The inclusion of an article was evaluated by three independent blinded authors (R.L., Y.K, and Y.H.), with any disagreements being resolved by obtaining the consensus of the senior author (B.T.).

Data extraction and outcomes

Data was extracted from the included studies by the same three researchers independently, and any discrepancies were resolved by the senior author subsequently.

Data extraction was performed to extract basic study characteristics (first author, year of publication, study design, average age of patients, sample size, follow-up duration, proportion by gender, surgical duration). Primary outcomes considered for this study were clinical outcomes– Harris Hip Scores (HHS), Oxford Hip Scores (OHS) and Forgotten Joint Scores (FJS) and implant position accuracy (Proportion of implants positioned within the Lewinnek and Callanan Safe Zones). As secondary outcomes, complications and surgical duration were noted.

Means and standard deviations were extracted for pooling of continuous outcome data. When means and standard deviations were unavailable and instead data were presented as medians with ranges, we derived the means and standard deviations in accordance with Wan and colleagues [60]. Binary outcome data were extracted in the form of the number of events that occurred per sample size.

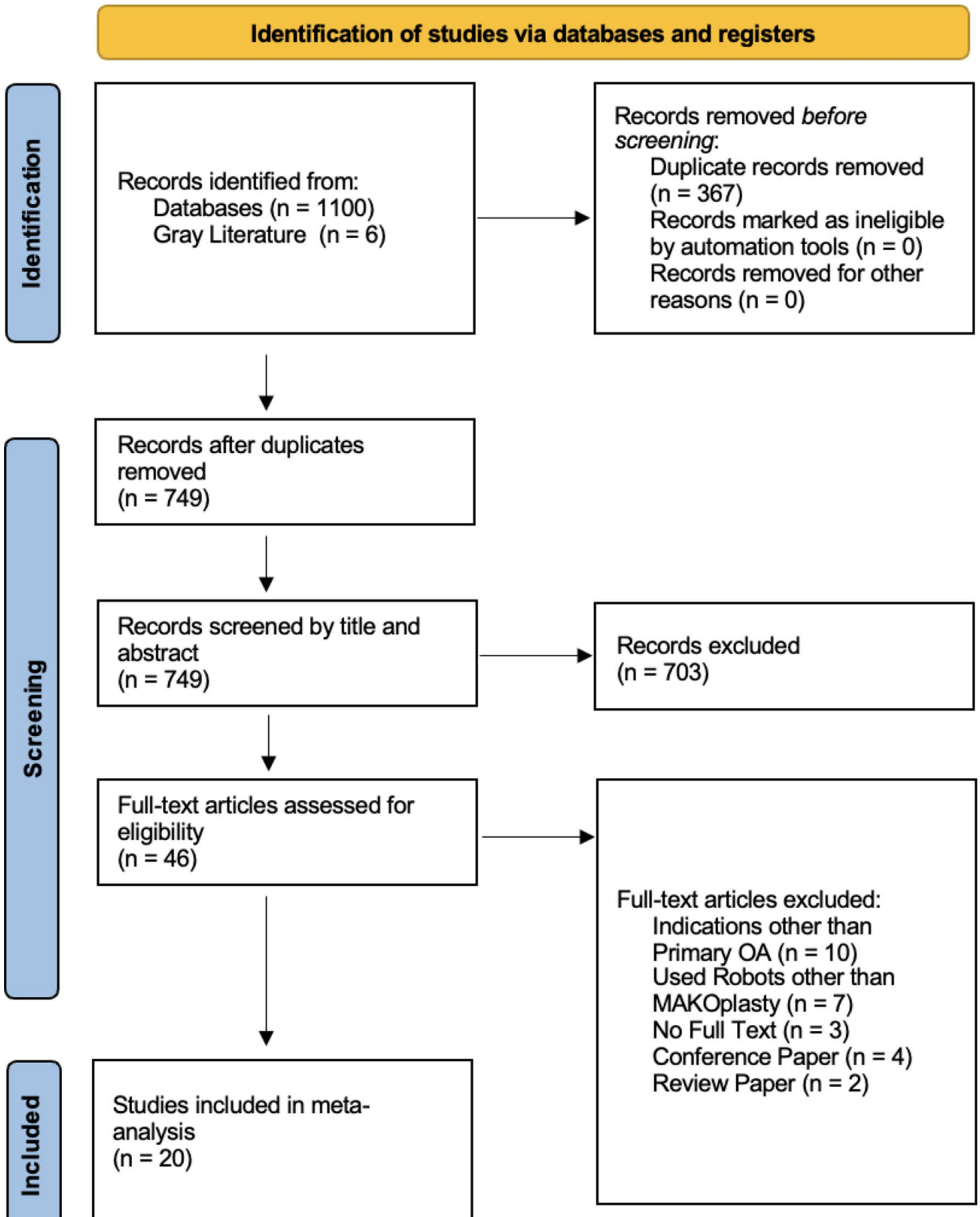

Fig. 1 PRISMA Schema

Data analysis

Statistical analyses were performed using RStudio (Version 2022.12.0 + 353). We performed a random-effects (Dersimonian-and-Laird) meta-analysis to synthesize continuous and binary outcomes using the respective *metamean* and *metaprop* functions of the R meta package.

Continuous outcomes were pooled using weighted mean approach with random effects, and the Dersimonian-and-Laird (DL) estimator applied for between-study variance. Meta-analyses of proportions were conducted for binary outcomes, using random effects modelling. The lower and upper confidence limits for the 95% confidence intervals were estimated using the

Table 1 Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Comparative studies between MAKO-assisted and Conventional THA Patients undergoing THA for Primary Osteoarthritis	Patients undergoing Robotic THA with systems other than the MAKO system Patients undergoing THA for conditions other than Primary OA, such as Hip Dysplasia, Avascular Necrosis, Rheumatoid Arthritis or Trauma
Prospective/Retrospective Clinical Studies and Randomized Controlled Trials	Nonclinical or in-vitro or biomechanical studies
Clinical Outcomes, Implant-Accuracy, Survivorship, Complications and Surgical Duration	Case Reports, Review Articles, Editorials, Technical Notes, Commentaries
Studies published between 2010 and 2024	Animal or Cadaveric Studies.

Clopper-Pearson method and the DL estimator applied for between-study variance. *P*-value was calculated directly based on the estimated proportions and their standard errors using the *Z*-test.

We assessed statistical heterogeneity among studies by visual inspection of forest plots, as well as I^2 and τ^2. I^2 values of 25%, 50% and 75% were thresholds for low, moderate or high heterogeneity, respectively.

We performed prespecified subgroup analyses for each study design (prospective or retrospective) and risks of bias (low, moderate or serious). Sensitivity analysis was performed on studies deemed 'serious' risk-of-bias to assess for its suitability for inclusion in this study.

Further subgrouping was done on type of approach. Publication bias was assessed by the visual inspection of the funnel plots, and Egger's test.

Risk of Bias and quality assessment

The same three researchers independently assessed the risk of bias of included studies. Similarly, any disagreements were resolved by obtaining the consensus of the same senior author.

Quality assessment of non-randomized articles was performed using the ROBINS-I tool, which grades each article on seven domains [54]. For studies found to have moderate or serious risk of bias, sensitivity analyses were performed to ascertain the robustness of the extracted data. Studies with critical risk of bias would not be included. For Randomized Controlled Trials (RCTs), the Cochrane Risk of Bias tool was used.

A summary of the risk of bias and quality assessment of included studies can be found within the Supplementary Material.

Patient characteristics

3,161 patients underwent MAKO-THA and 3,275 patients underwent Conventional THA. The weighted mean age was 63.0 years (95% CI: 61.3–64.7) in the Robotic group, and 63.2 (95% CI: 61.1–65.3) in the conventional group. Men constituted 45.0% of the MAKO cohort, and 44.8% of the Conventional group. Weighted mean follow-up duration was 25.4 months (95% CI: -2.6–53.3) in the Robotic group, and 26.2 (95% CI: 0.4–52.0) in the Conventional group. Weighted mean BMI was 27.7 kg m^{-2} (95% CI: 26.7–28.1) in the Robotic group, and 28.1 kg m^{-2} (95% CI: 27.5–28.8) in the Conventional group.

Results

Summary of included articles

A systematic search of the literature using our search strategy yielded 1110 articles, with 6 further studies included from gray search of existing literature. 367 duplicate records were removed which left 749 records for screening. A total of 703 studies were excluded based on study title and abstract, leaving 46 full-text articles for full-text review. 28 were excluded for the following reasons: Conference Papers ($n=4$), Review Article ($n=2$), Indications other than Primary OA ($n=10$), Used Robots other than MAKO-THA ($n=7$), and Unable to Find Full Text Article ($n=3$). 20 articles fit the inclusion criteria and were thus considered for review.

13 had a retrospective study design and 7 had a prospective study design. All were classified as low risk-of-bias except one.

Publication bias was assessed via funnel plot of overall complication rates, since most studies reported on them, and Egger's Test. The symmetrical funnel plot (Fig. 2) and Egger's Test ($P=0.63$) suggest no publication bias is present.

The included articles utilised Direct Anterior or Posterior approaches. Some articles had a mix of patients where some underwent MAKO-THA or C-THA with Direct Anterior and others with Posterior approaches. To account for heterogeneity with differing approaches, we performed subgrouping of the articles into "Direct Anterior", "Posterior" or "Mixed", where we found no significant differences between subgroups.

A summary of included studies can be found in Table 2, while the respective risk-of-bias, quality assessment and subgroup/sensitivity analyses can be found in the Supplementary Material.

Clinical scores

Harris Hip Scores (HHS). MAKO-assisted THAs resulted in higher postoperative Harris Hip Scores (MAKO-THA Mean: 88.6, 95%CI: 86.1–91.0; C-THA Mean: 86.7, 95%CI: 84.0-89.5), but this was not significant (HHS Weighted Mean Difference (WMD) 1.87 [95% CI: -0.26–4.01], $p=0.09$) (Figures 3, 4 and 5).

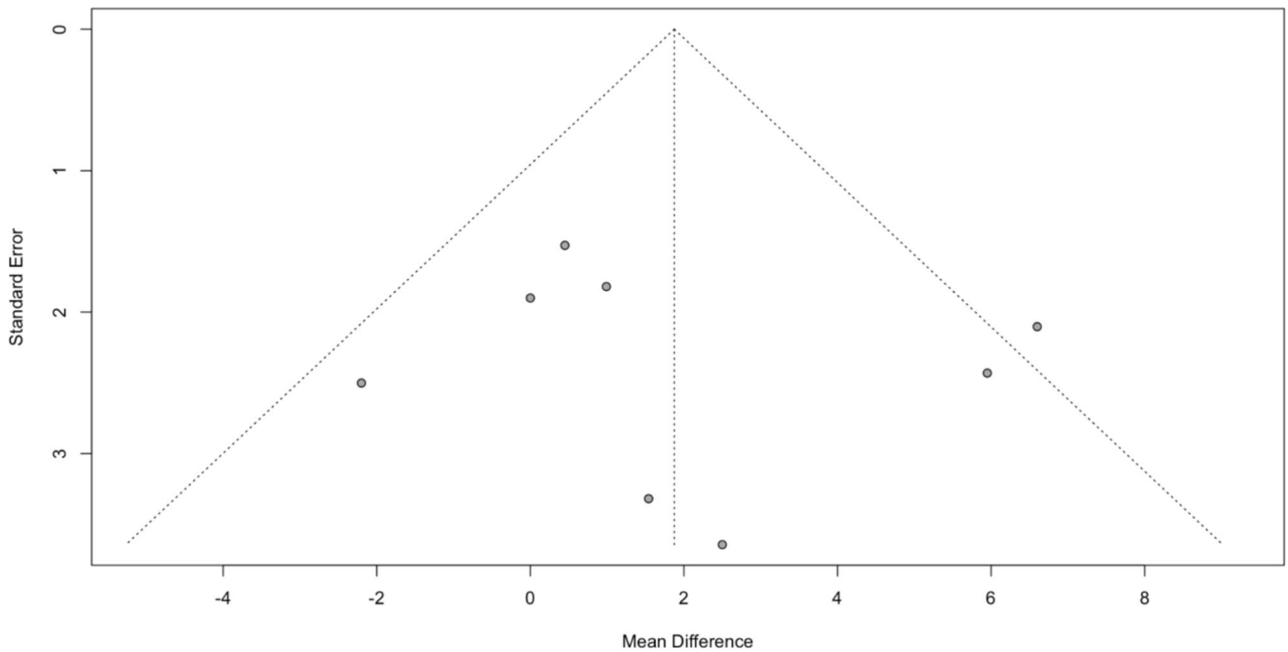

Fig. 2 Forest Plot of Harris Hip Scores

Radiographic outcomes

Implant Positioning. Accuracy in implant positioning was also significantly greater ($p<0.001$) in the MAKO-THA group compared to conventional THA, with a mean of 94.7% (95%CI: 89.1–97.5) and 90.3% (95%CI: 84.3–94.2) of implants positioned within the Lewinnek-and-Callanan zones respectively. This is contrasted to a mean of 65.8% (95%CI: 57.2–73.4) and 57.1% (95%CI: 50.9–64.2) respectively in the conventional THA group (Fig. 6a and 6b).

Secondary outcomes

Surgical Duration. Mean surgical duration was longer in the MAKO-THA group (MAKO-THA Mean: 86.7 min [95%CI: 72.5-100.9]; C-THA Mean: 82.3 min [95%CI: 67.5–97.2]), but this was not significant (WMD: 3.45 [95%CI: -2.59–9.49], $p=0.26$) (Fig. 7).

Discussion

The most important finding of this systematic review and meta-analysis is that MAKO Robotic Total Hip Arthroplasty provides significantly improved Forgotten Joint Scores and Oxford Hip Scores, along with a higher likelihood of component placement with safe zones, without compromising surgical duration and complication rates. It also affirms that MAKO-THA can reduce postoperative leg-length discrepancy, albeit not to a significant degree.

Presently, MAKO-THA is the most prevalently used RTHA system worldwide, but no meta-analysis has been performed to assess its performance with respect to conventional THA. Clinically, we found significantly greater OHS and FJS in the MAKO-THA group, while HHS were greater although not significant in this group too. The OHS wholly assesses patients' pain levels and function [22], while Forgotten Joint Score is an indirect measure of patients' quality-of-life postoperatively [53]. Significantly greater OHS and FJS in MAKO-THA may suggest it is able to reduce pain and improve postoperative functionality compared to conventional THA. Previous meta-analyses had not assessed these outcomes [9, 20, 31], however, its proven clinical importance lends support to the necessity of reporting this data [6, 40]. Whilst prior meta-analyses had not discussed OHS and FJS, a registry study and systematic review have shown that OHS and FJS were not significantly different [53, 59]. This seems to reflect the sentiment as reported by Kort et al.'s review of meta-analyses where clinical outcomes were not affected by robot assistance [36].

Our findings regarding OHS and FJS are thus an interesting and welcome development. We believe this difference is possibly contributed by previous studies including other active robotic systems, such as the ROBODOC system, which, according to Honl et al.'s randomized trial, found higher dislocation and revision rates attributable to intraoperative muscle damage [25], amongst other technical complications [57]. Other factors including variations in surgical approach and development of technical tricks to improve safety over time are also contributory.

Interestingly, Kawakami et al. found perceived LLD significantly worsens postoperative FJS [33]. Our study found that MAKO-THA reduces postoperative LLD,

Table 2 Summary of included studies

Author	Year of Study	Title	Study Design - Prospective or Retrospective or RCT	Study Location
LaValva et al. [38]	2024	Robotics and Navigation do not affect the risk of periprosthetic joint infection following primary total hip arthroplasty	Retrospective	USA
Rogers et al. [47]	2024	Lower 90-day inpatient readmission and 1-year reoperation in patients undergoing robotic versus manual total hip arthroplasty through an anterior approach	Prospective	USA
Karlin et al. [30]	2024	Patient Outcomes of Conventional Versus Robot Assisted Total Hip Arthroplasty	Retrospectively	USA
Fontalis et al. [19]	2024	A Prospective Randomized Controlled Trial Comparing CT-based Planning with Conventional Total Hip Arthroplasty versus Robotic Arm-assisted Total Hip Arthroplasty	Prospective RCT	UK
Alessia-Mazzola et al. [2]	2024	Direct anterior approach with conventional instruments versus robotic posterolateral approach in elective total hip replacement for primary osteoarthritis: a case–control study	Retrospective	Italy
Fontalis et al. [18]	2023	Patient-Reported Outcome Measures in Conventional Total HipArthroplasty Versus Robotic-Arm Assisted Arthroplasty: A Prospective Cohort Study With Minimum 3 Years' Follow-Up	Prospective	UK
Foissey et al. [17]	2022	Image-based robotic-assisted total hip arthroplasty through direct anterior approach allows a better orientation of the acetabular cup and a better restitution of the centre of rotation than a conventional procedure	Retrospective	France
Coulomb et al. [12]	2023	Does acetabular robotic-assisted total hip arthroplasty with femoral navigation improve clinical outcomes at 1-year post-operative? A case-matched propensity score study comparing 98 robotic-assisted versus 98 manual implantation hip arthroplasties	Retrospective	France
Domb et al. [14]	2020	Minimum 5-Year Outcomes of Robotic-assisted Primary Total Hip Arthroplasty With a Nested Comparison Against Manual Primary Total Hip Arthroplasty: A Propensity Score–Matched Study	Retrospective	USA
Peng et al. [44]	2019	In vivo kinematic analysis of patients with robotic-assisted total hip arthroplasty during gait at 1-year follow-up	Retrospective	USA
Kayani et al. [34]	2019	The learning curve of robotic-arm assisted acetabular cup positioning during total hip arthroplasty	Prospective	UK
Kayani et al. (2) [52]	2019	Assuring the Long-Term Total Joint Arthroplasty: A Triad of Variables	Prospective	UK
Heng et al. [23]	2018	Conventional vs. Robotic Arm Assisted Total Hip Arthroplasty Surgical Time, Transfusion Rates, Length of Stay, Complications and Learning Curve	Retrospective	Australia
Suarez Ahedo et al [55]	2017	Robotic-Arm Assisted Total Hip Arthroplasty Results in Smaller Acetabular Cup Size in Relation to the Femoral Head Size: A matched-pair controlled study	Retrospective	USA
Tsai et al. [54]	2016	Does haptic robot-assisted total hip arthroplasty better restore native acetabular and femoral anatomy?	Retrospective	USA
El Bitar et al. [16]	2015	Leg-Length Discrepancy After Total Hip Arthroplasty: Comparison of Robot-Assisted, Posterior, Fluoroscopy-Guided Anterior, and Conventional Posterior Approaches	Retrospective	USA
Perets et al. [45]	2021	Short-term Clinical Outcomes of Robotic Arm Assisted Total Hip Arthroplasty: A Pair Matched Controlled Study	Prospective	USA
Incesoy et al [27]	2023	CT-based, Robotic Arm Assisted Total Hip Arthroplasty (MAKO) through anterior approach provides improved cup placement accuracy but no difference in clinical outcomes when compared to conventional technique	Retrospective	Turkey
Nicholas D Clement et al. [11]	2021	Robotic arm-assisted versus manual total hip arthroplasty	Prospective	Scotland
Banchetti et al. [3]	2018	Comparison of conventional versus robotic-assisted total hip arthroplasty using the Mako system: An Italian retrospective study	Retrospective	Italy

Table 3 Patient characteristics

	Sample Size, *n*	Age, y	Follow-up, m	Men, %	BMI, kg m^{-2}
Robotic THA	3,161	63.0 (61.3–64.7)	25.4 (-2.6–53.3)	45.0	27.7 (26.7–28.1)
Conventional THA	3,275	63.2 (61.1–65.3)	26.2 (0.4–52.0)	44.8	28.1 (27.5–28.8)

albeit not to a significant degree, but nonetheless reiterates the link between mechanical outcomes and final patient satisfaction. Indeed, the Minimally Clinically Important Difference (MCID) for FJS was reported to be 8.1 [46], and our study found a difference of 9.8 between MAKO-THA and conventional THA.

However, for OHS, the Minimal Important Difference (MID) was 5 points, suggesting that it may not be clinically significant [5]. Another study however suggested

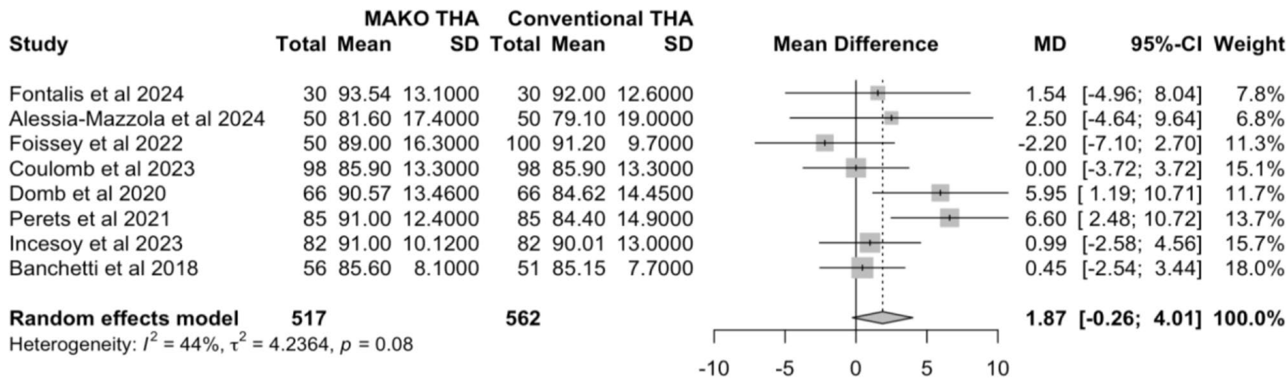

Fig. 3 Harris hip scores. *Oxford Hip Scores (OHS).* MAKO-assisted THAs resulted in significantly improved postoperative Oxford Hip Scores (MAKO-THA Mean: 89.1, 95%CI: 86.4–91.7; C-THA Mean: 87.0, 95%CI: 83.8–90.1; OHS WMD: 1.45 [95% CI: 0.11–2.78], $p=0.03$)

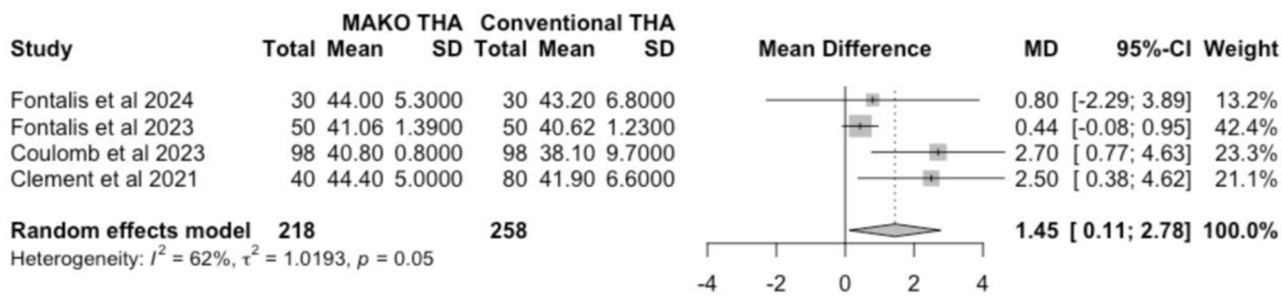

Fig. 4 Oxford hip scores. *Forgotten Joint Scores (FJS).* MAKO-assisted THAs resulted in significantly improved postoperative Forgotten Joint Scores (MAKO-THA Mean: 84.7, 95% CI: 79.9–89.6; C-THA Mean: 74.9, 95%CI: 64.0-95.7; FJS WMD: 8.72 [95% CI: 2.68–14.77], $p=0.005$)

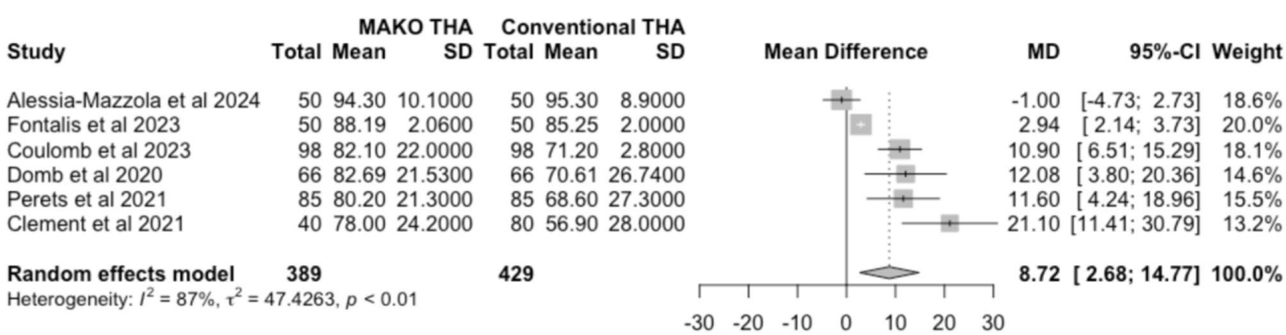

Fig. 5 Forgotten joint scores

that the MID in OHS is as low as two to three points, which would support our study [40]. Regardless, we advise surgeons to consider the validity of OHS, which has been recently critiqued as lacking important items for present-day patients [24], highlighting the importance of holistic assessment of clinical and functional outcomes postoperatively.

HHS yielded greater, but non-significant differences in MAKO-THA compared to conventional THA, and this is corroborated by previous meta-analyses - Bargar et al. found that their robot group exhibited small, but crucial, improvement in these clinical outcomes [4]. Taken together, we agree with Han et al. that robotic-assisted THA simplifies the operative procedure, but still has a certain learning curve [22]. With adequate expertise, the benefit of RTHA may be leveraged to improve outcomes.

The importance of the present study in segregating the different indications for THA is underscored as a previous study showed that in a cohort of only developmental dysplasia of the hip (DDH), there was no significant improvement in HHS, but a separate report on a patient that underwent robotic-assisted THA in one hip and conventional THA in the other for osteonecrosis of the femoral head showed a greater HHS in the side that had underwent robotic THA [26, 60]. Literature regarding outcomes of THA for specific pathologies like AVN or DDH is scarce, and from our study, we propose the utility and efficacy of robotic-assistance in THA may be

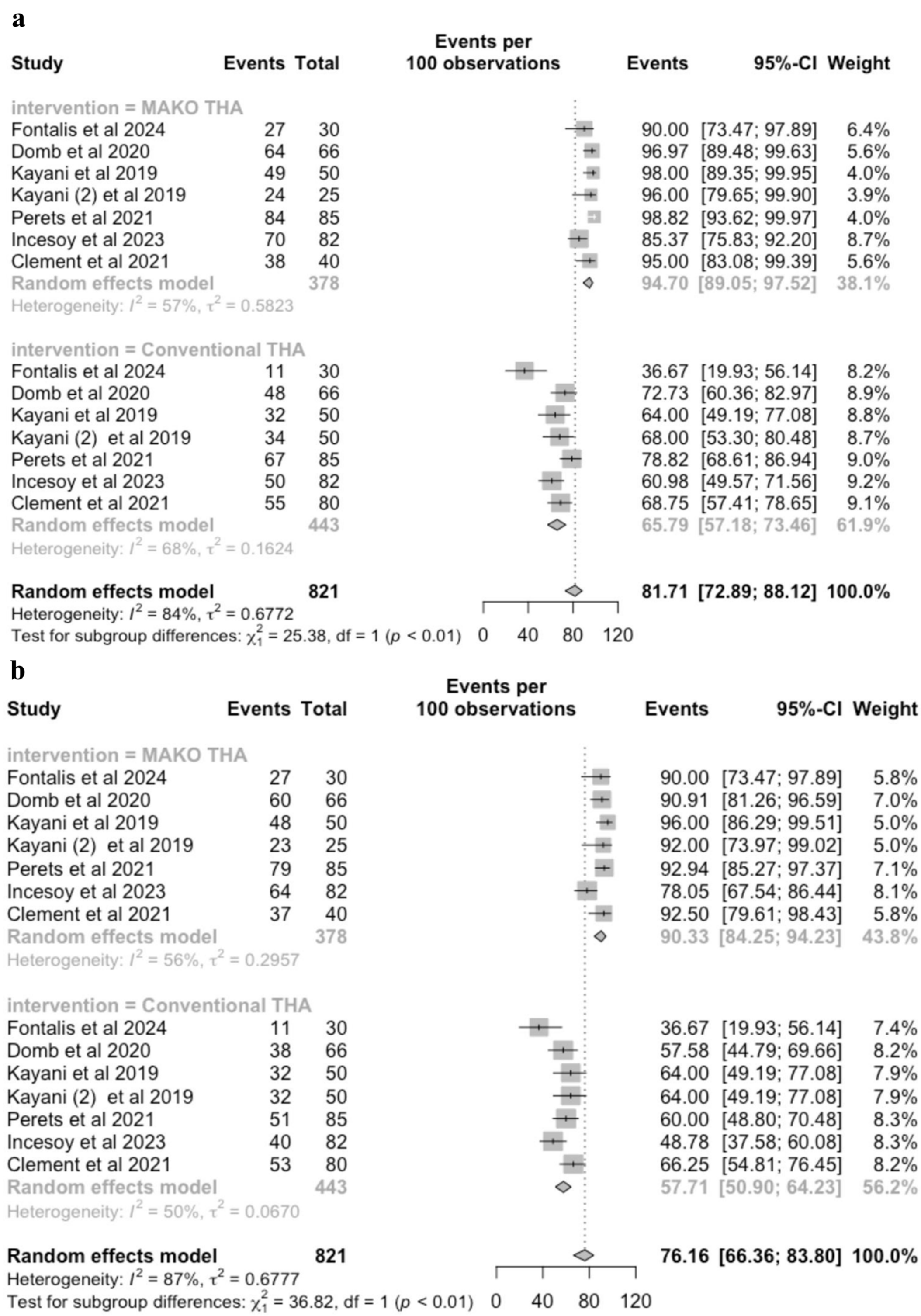

Fig. 6 (**a**) Implant Positioning within Lewinnek "Safe Zones". (**b**) Implant Positioning within Callanan "Safe Zone"

dependent on patients' pathology and should be explored in future studies.

While the MAKO system remains the most popular, other systems are present, and early literature suggest they may also yield similar efficacy to the MAKO system. The ROSA system was found to have greater Hip Dysfunction and Osteoarthritis Scores (HOOS) compared to conventional THA at one-year postoperatively,

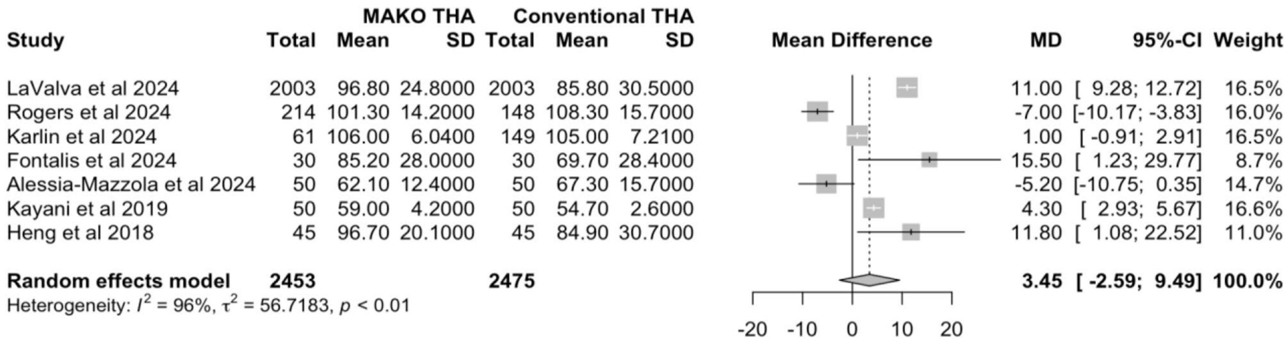

Fig. 7 Surgical duration. *Leg-Length Discrepancy(LLD).* MAKO-THA also had lower postoperative leg-length discrepancy (MAKO-THA Mean: 2.72, [95%CI: 1.48–3.96]; C-THA Mean: 3.0, [95%CI: 1.2–4.8]), but not to a significant degree (WMD: -0.16, 95%CI: -0.72–0.4, p = 0.57). (Fig. 8)

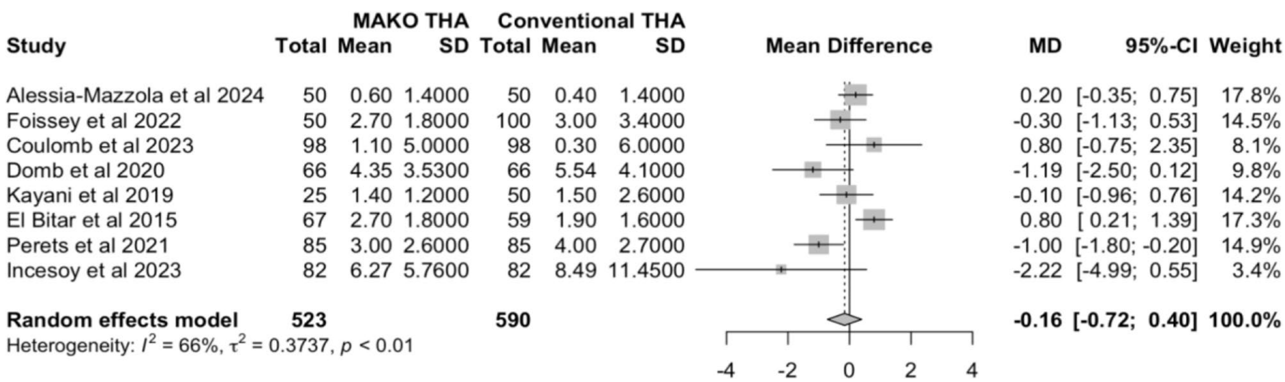

Fig. 8 Leg-length discrepancy. *Complication Rates.* Our study comprised both medical and surgical complications. Medical complications included superficial or deep infections, postoperative pneumonia, deep vein thrombosis or pulmonary embolism, anaemia and myocardial infarctions. Surgical complications included dislocations, prosthesis loosening, periprosthetic fractures or delayed wound healing. Complication rates were low (MAKO-THA Mean: 3.0% [95%CI: 1.18–7.37]; C-THA Mean: 3.5%, 1.2–10.1 and non-significant (p = 0.3) between both groups. Importantly, the rates of prosthetic dislocations were low and non-significant between both groups (MAKO-THA Mean: 1.3% [95% CI: 0.7–2.3%]; C-THA Mean: 0.7% [95%CI: 0.4–1.4%]; P-Value: 0.2). (Fig. 9)

in a recent study by Buchan et al. [7] The ROSA System currently solely enables performing THA via the direct anterior approach. Separately, an RCT showed a new "Jianjia" robot system by Hang Zhou Jianjia Robot Technology yielded a HHS of 89.9 ± 0.91 postoperatively [58], comparable to the findings of our study. There remain several other systems beyond what has been mentioned, but studies that explore the utility of individual systems remain lacking.

Lewinnek-and-Callanan "safe zones" are established radiological markers to prevent postoperative dislocation of acetabular components [8, 39]. The present study's findings of increased implant positioning within the Lewinnek-and-Callanan safe zones is corroborated by previous meta-analyses [9, 20, 31]. Nonetheless, these traditional safe zones have been challenged recently due to increased subluxations and dislocations in cups placed within them [1], and no difference in dislocation rates in implants positioned in and out of these "safe zones" [51]. Indeed, we found no difference in dislocations between both groups despite the wide discrepancy between cup positioning within the "safe zones".

Dorr et al. introduced a functional safe zone over the traditional Lewinnek-and-Callanan zones– a patient-specific safe zone to avoid instability or impingement which is dependent on various patient-specific factors [9, 15]. However, instability or impingement with regard to the Lewinnek safe zone was described only in patients with abnormal spinopelvic mobility [9, 13, 29], which may not be the case for all patients - although common in patients with hip osteoarthritis [28]. Regardless, amidst conflicting literature, we agree with Fontalis and Sathikumar et al. that patient-specific approaches enabled by developments in surgical technology are preferrable.[21.52] Even as the debate continues over what the ideal "safe zone" is, nonetheless, our study has shown that robotics, in particular the MAKO-THA, is able to ensure increased reproducibility in component placement, which enables surgeons to achieve their target placement with confidence, notwithstanding the consensus on what the optimal "safe zone" may be.

Surgical duration for THA beyond 87 min places patients at higher risks of overall complications, particularly related to wound complications and sepsis [42]. In our study, even though MAKO-THA had greater mean

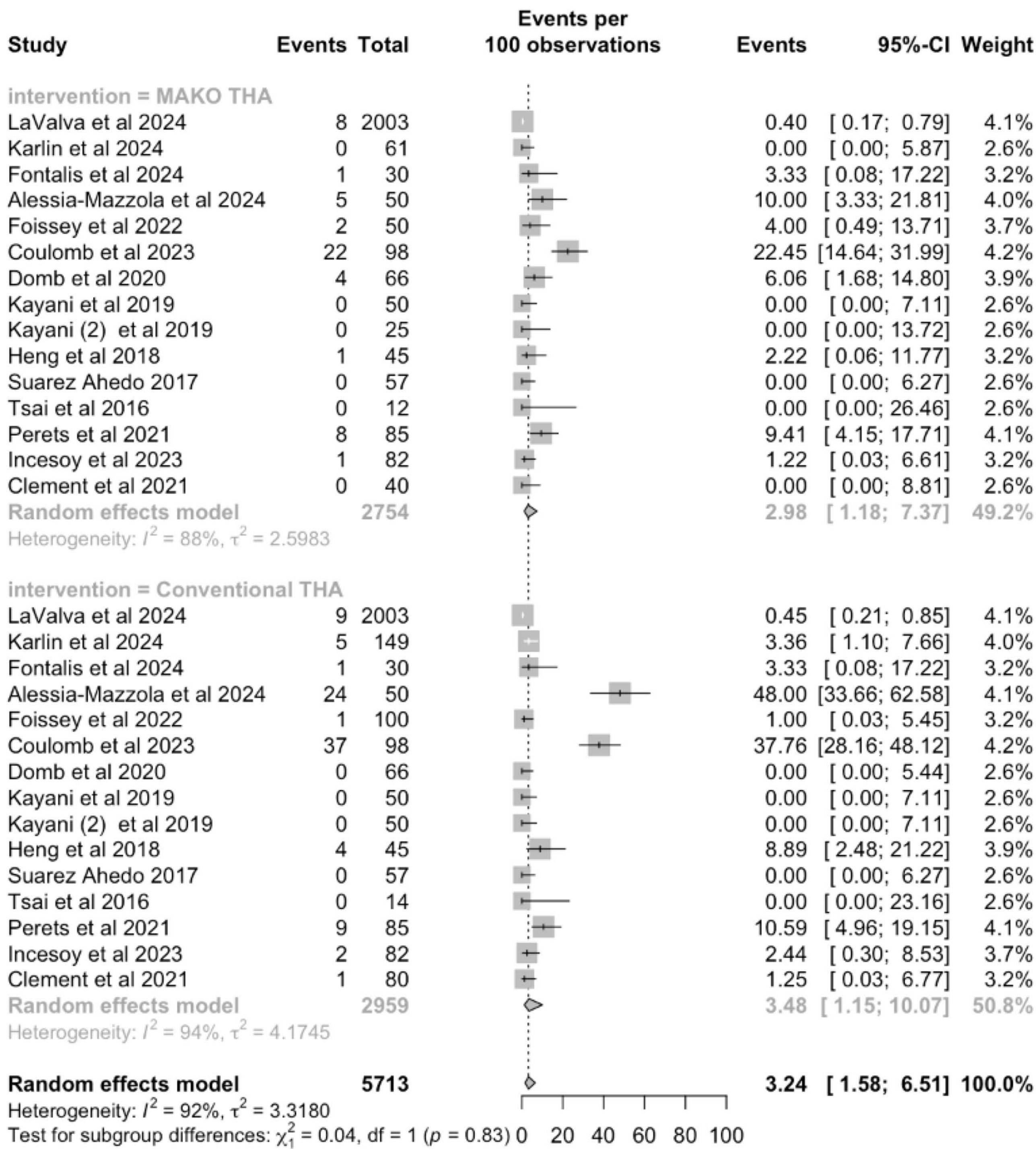

Fig. 9 Complications

surgical durations, likely secondary to registration and calibration of the robot and pins, this was not significantly different from conventional THA and not greater than 87 min. Our complications rates reported seem to agree with such findings and are in alignment with what has been previously reported in literature [37, 48].

The findings of our study are limited by a few factors. Due to paucity of data, we were unable to provide pooled clinical outcomes at various time-points, be it 1-year, 5-year or 10-years postoperatively. This should be explored in further studies. We were unable to assess other radiographic parameters other than the Lewinnek-and-Callanan zones due to limited reporting. Another important metric in assessing total joint arthroplasty is survival– however our relatively short mean follow-up does not make it favourable to compare survival between both groups. A separate parameter that might introduce heterogeneity in our study is the surgeon experience that was difficult to monitor in the present study.

Our meta-analysis also consisted of mainly non-randomized studies, which may introduce heterogeneity, although efforts were made to ensure reliability of data by assessing and only including studies that had a low-moderate risk-of-bias and ensuring no publication bias was present. Subgrouping between retrospective and prospective studies were also done to ensure comparability between the two types of studies.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13018-025-05866-1.

Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

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Author contributions
Study design: Ryan Loke, Chan Yang Kai, Lim Yao Hui Search strategy and screening of articles: Ryan Loke, Chan Yang Kai, Lim Yao Hui Risk of bias assessment: Ryan Loke, Chan Yang Kai Data collection: Ryan Loke, Chan Yang Kai, Lim Yao HuiData analysis and interpretation: Ryan Loke, Lim Yao Hui Tables and figures: Ryan Loke, Chan Yang Kai, Lim Yao Hui Drafting of manuscript: Ryan Loke, Chan Yang Kai, Lim Yao Hui Critical revision of manuscript for intellectually important content: Dr Barry Tan Wei Loong All authors provided critical conceptual input, interpreted the data analysis, read and approved the final draft of the manuscript have accessed and verified the data were responsible for the decision to submit the manuscript.

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Data is provided within the manuscript or supplementary information files, and other data will be made available on reasonable request.

Declarations

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Not applicable.

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All authors provided critical conceptual input, interpreted the data analysis, read and approved the final draft of the manuscript have accessed and verified the data. were responsible for the decision to submit the manuscript.

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The authors declare no competing interests.

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