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Clinical and surgical outcomes of robot-assisted versus conventional total hip arthroplasty: a systematic overview of meta-analyses

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- Robot-assisted total hip arthroplasty (THA), in comparison to conventional THA, improves radiographic outcomes, but it remains unclear whether it alters complication rates, clinical and functional outcomes, and implant survival.
- The purpose of this systematic overview was to summarize the findings of the most recent meta-analyses that compare clinical and surgical outcomes of robot-assisted versus conventional THA.
- Two readers independently conducted an electronic literature search, screening and data extraction from five electronic databases. Inclusion criteria were: meta-analyses evaluating robot-assisted versus conventional THA in terms of radiographic outcomes, clinical and functional scores, and complications and revision rates. The literature search returned 67 records, of which 14 were duplicates and 49 were excluded, leaving three meta-analyses published within the past two years for data extraction and analysis.
- The present overview of meta-analyses suggests that, compared to conventional THA (n = 3011), robot-assisted THA (n = 1813) improves component placement and reduces intraoperative complications. The overview also affirms that robot-assisted THA could extend surgery by 20 minutes, and increases risks of postoperative heterotopic ossification, dislocation, and revision. None of the meta-analyses found significant differences in clinical or functional scores between robot-assisted and conventional THA.
- Future studies and reviews should make a clear distinction between active and semi-active robotic assistance, address technology matureness, and describe the experience of surgeons with robotic assistance.

Keywords: clinical and radiographic outcomes; robotic surgical procedures; total hip arthroplasty

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Introduction

In an attempt to improve accuracy and consistency of implant placement during total hip arthroplasty (THA), multiple navigation technologies have been introduced over the past three decades,[1] which can be broadly characterized as computer-assisted navigation systems, or robot-assisted systems.[2] Robotic systems, which are utilized across many surgical subspecialties,[3] can be classified as either active systems, which work autonomously to perform the planned bone resections, or semi-active systems, which provide full control to the surgeon with live intraoperative feedback to limit deviation from the preoperative surgical plan.[4] Although robotic assistance in THA improves precision and accuracy,[5] it remains unclear whether it alters complication rates, clinical and functional outcomes, and implant survival.[6]

Over the last three years, numerous meta-analyses pooled data from published studies that compared outcomes of robot-assisted versus conventional THA. To the authors' knowledge, there is no published overview of these meta-analyses to summarize the latest evidence in terms of the effect of robot-assisted THA on rates of complications, clinical and functional outcomes, or implant survival. The purpose of this overview was therefore to summarize the findings of the most recent meta-analyses on the efficacy of robot-assisted versus conventional THA, and highlight any differences in surgical and clinical outcomes. This overview is expected to highlight gaps in the literature and help decision-makers justify clinical and economic benefits of robotic assistance.[7]

Material and methods

The protocol for this overview of systematic reviews and meta-analyses, including the search strategy and proposed methodology, was registered with PROSPERO (CRD42020181669).

Search strategy

The authors conducted an electronic literature search using Allied & Complementary Medicine™, Embase®, MEDLINE®, Web of Science, Cochrane Database of Systematic Reviews on 11 February 2020. Key words used to develop search strategy were ("hip" OR "knee") AND ("arthroplasty" OR "replacement") AND ("robot" OR "robot*") AND "meta-analysis" (see full search strategy in PROSPERO registration). While the original search strategy included both hip and knee arthroplasty, it was subsequently resolved that only results regarding primary THA would be included.

Two reviewers (JHM and KJC) independently performed the literature search described. Grey literature regarding robot-assisted THA was searched and an expert in the field (NK) consulted for other relevant publications not identified in the electronic search. Review registries were checked for ongoing reviews on the subject. Disagreements between reviewers were discussed and resolved by consensus.

Study selection and data extraction

Titles and abstracts of the studies were screened independently by two reviewers (JHM and KJC) to determine relevance according to the inclusion and exclusion criteria presented below.

Inclusion criteria

Original meta-analyses that:

- reported on studies evaluating robot-assisted, both active or semi-active, compared to conventional primary THA for any indication.
- presented results in terms of:
- radiographic outcomes (such as limb and joint alignment, component placement).
- clinical scores (such as Harris Hip Score (HHS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)).
- complication rates (intra- and postoperative complications).
- implant survival or revision rates (such as Kaplan-Meier, Cumulative Incidence Function).

Exclusion criteria

Meta-analyses that:

- reported outcomes for robot-assisted surgery for other joints without separating data regarding THA.
- were written in languages other than English, to avoid translation errors.

Full-text articles were retrieved if the article passed the first eligibility screening or if the title or abstract provided insufficient information to establish eligibility. Disagreements in screening decisions between the reviewers were discussed and resolved by review and consensus. The reference lists of all selected publications were checked for relevant studies that may have been missed in the electronic search.

Data extraction and quality assessment

Two reviewers (JHM and KJC) extracted characteristics of meta-analyses independently including: year of publication, journal, number and type of studies included, countries in which included studies were performed, intervention and comparator details, number of patients included per intervention and comparator, follow-up period, type of robot used, pooled outcomes recorded by at least three studies. Pooled outcome data reported by the meta-analyses included reported effect size and statistical significance. Results of data extraction were compared and where discrepancies were found, consensus was reached through review and discussion between the reviewers.

The same two reviewers (JHM and KJC) assessed the methodological quality of eligible studies according to the 16 domains outlined by A MeaSurement Tool to Assess systematic Reviews (AMSTAR-2).[8] Where there was disagreement between reviewers in their appraisal of study quality, consensus was achieved through review and discussion.

Interpretation of results

Methodological differences across meta-analyses made pooling or direct statistical comparison of results impossible. As a result, findings extracted from each meta-analysis were presented as reported and synthesized narratively, rather than normalized to a single comparable metric. Differences in outcomes were reported as weighted mean difference (WMD) or weighted odds ratio (WOR) and considered statistically significant if $p < 0.05$.

Results

Literature search

The electronic literature search returned 67 records, of which 14 were duplicates. A further 49 articles were excluded after reading their titles or abstracts (46 did not include THA; two did not include robotic assistance, and one was not written in English), and an additional article[9] was excluded after reading its full text, as it included < 3 studies per outcome of interest, leaving a total of three meta-analyses eligible for quality assessment and data extraction (Fig. 1).[2,10,11]

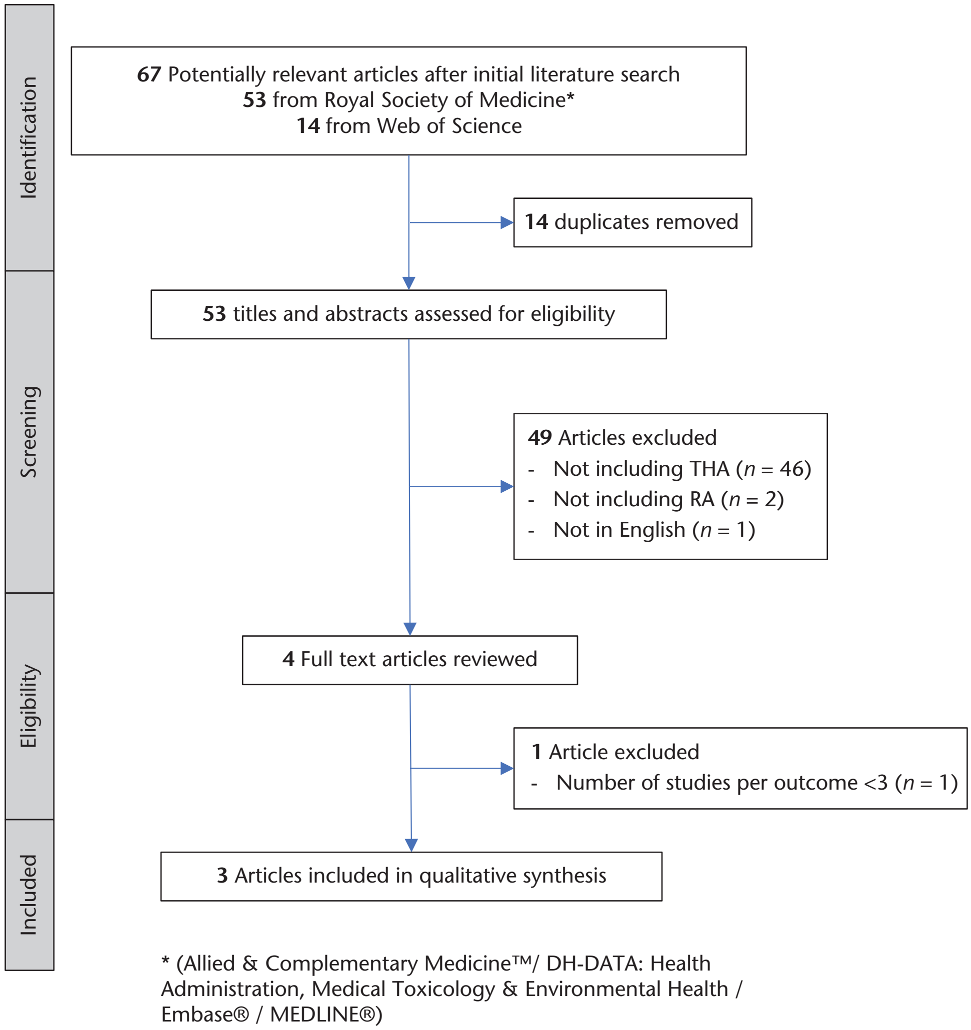

Fig. 1 Flowchart of the study selection procedure.
Note. THA, total hip arthroplasty; RA, robotic-assisted.

Characteristics of included studies

The three meta-analyses, all published within the past two years, assessed a total of 15 comparative studies reporting outcomes of 1813 hips that received robot-assisted THA and 3011 hips that received conventional THA. The majority of studies originated from the USA ($n = 7$),[5,12–17] and the most frequently used system was the ROBODOC which provides active assistance (THINK Surgical, Inc., Fremont, CA, $n = 8$ studies).[12,18–24] Of the 15 studies, five,[19,21,23–25] were included by all three meta-analyses, two[12,20] were included by both Han et al[2] and Karunaratne et al,[10] two[16,17] were included by both Han et al[2] and Chen et al,[11] five[5,14,15,18,22] were included only by Han et al,[2] and one[13] was included only by Karunaratne et al[10] (Table 1). It is worth noting that all three meta-analyses pooled results of older and possibly obsolete robotic systems with results of newer generations and enhanced robotic systems, which may be a methodological flaw. While the meta-analyses did not distinguish between outcomes of old (such as ROBODOC (ORTHODOC) and Caspar) and new (such as Mako) systems, which makes it impossible to present their results separately, inspection of forest plots revealed no consistent differences in outcomes of old versus new systems.

Quality assessment of included meta-analyses

According to AMSTAR-2, methodological quality was 'low' for Karunaratne et al[10] due to weakness in a critical domain, and 'critically low' for the remaining two studies[2,11] due to weaknesses in two or more critical domains (Table 2, Fig. 2). All three meta-analyses failed to apply appropriate methods for data synthesis; neither Han et al[2] nor Chen et al[11] prospectively published their review protocols in

Table 1. Characteristics of included studies

	Han et al, 2019[2]	Karunaratne et al, 2019[10]	Chen et al, 2018[11]
Journal	*Int J Med Robot Comp*	*Int Orthop*	*Postgrad Med J*
Population	THA	THA	THA
Intervention (robotic-assisted, hips)	817	474	522
Comparator (conventional, hips)	1536	481	994
Outcomes reported by ≥ 3 studies			
Radiographic outcomes	yes		yes
Clinical scores	yes	yes	yes
Complication and revision rates	yes		yes
Operation time	yes		yes
Follow-up (months, range)	(0–168)	(18–60)	(0–60)
Studies assessed			
Total (unique inclusions)	14 (5)	8 (1)	7 (0)
RCT	*5*	*4*	*2*
Cohort	*1*	*1*	*1*
Case-control	*8*	*3*	*4*
Robots			
ROBODOC	8	6	4
CASPAR	1	1	1
MAKO	5	1	2
Countries			
USA	6	2	2
Japan	4	3	3
Germany	3	2	1
Korea	1	1	1

Note. THA, total hip arthroplasty; RCT, randomized controlled trial.

Table 2. Evaluation of the quality of meta-analyses on RA THA using AMSTAR-2

First author, year	Han et al, 2019[2]	Karunarante et al, 2019[10]	Chen et al, 2018[11]
Intervention	**THA**	**THA & TKA**	**THA**
1. Research questions and criteria included PICO	N	Y	Y
2. Published review protocol prior (c)	N	Y	N
3. Explained study design inclusion criteria	N	N	Y
4. Comprehensive literature search strategy (c)	P	Y	P
5. Performed study selection in duplicate	Y	Y	Y
6. Performed data extraction in duplicate	Y	Y	Y
7. Excluded studies listed and justified (c)	N	Y	N
8. Included studies described in adequate detail	P	P	P
9. Included studies assessed for RoB (c)	Y	Y	P
10. Reported sources of funding for studies	N	N	N
11. Appropriate methods for data synthesis (c)	N	N	N
12. Assessed impact of RoB in each study	Y	Y	N
13. Considered RoB when interpreting results (c)	N	Y	N
14. Observed heterogeneity & impact explained	N	Y	N
15. Investigated publication bias (c)	Y	Y	N
16. Reported own conflict of interests & funding	Y	Y	Y
Number of critical weaknesses	4	1	5
Result (AMSTAR-2)	Critically low	Low	Critically low

Note. THA, total hip arthroplasty; TKA, total knee arthroplasty; RA, robotic-assisted; AMSTAR-2, A MeaSurement Tool to Assess systematic Reviews; PICO, Population Intervention Comparator Outcome; RoB, risk of bias; c, critical.

advance, listed or justified excluded studies, or considered risk of bias when interpreting their results.

Radiographic outcomes

Chen et al[11] reported on radiographic outcomes, which could not be considered because they had fewer than three clinical studies on each outcome. Han et al[2] reported on radiographic outcomes, including acetabular cup inclination, cup anteversion, stem alignment, cup safe zones (Lewinnek and Callanan) and leg length discrepancy (> 3 or > 10 mm). They found that robot-assisted THA improved both cup inclination (WMD, 2.47°; p = 0.03) and stem

Fig. 2 Critical AMSTAR-2 domains for the assessment of the meta-analyses.

Note. AMSTAR-2, A MeaSurement Tool to Assess systematic Reviews; PICO, Population Intervention Comparator Outcome; RoB, risk of bias; c, critical.

alignment (WMD, 0.4°; $p = 0.02$), as well as positioning within the Lewinnek safe zone (WOR, 11.05; $p < 0.001$) and the Callanan safe zone (WOR, 7.63; $p < 0.001$) (Table 3).

Functional outcomes

Han et al[2] reported weighted HSS, Postel-Merle d'Aubigné (PMA) and pooled different scores (HSS, PMA and Japanese Orthopedic Association (JOA)). Karunaratne et al[10] reported weighted PMA and pooled HHS and modified HHS together. Chen et al[11] did not report any weighted scores, but pooled different scores (HSS, PMA and JOA). None of the meta-analyses found statistically significant differences in clinical scores between robot-assisted and conventional THA (Table 3).

Complications and survival

Both Han et al[2] and Chen et al[11] found that robot-assisted THA decreased intraoperative complications (respectively: WOR, 0.32; $p = 0.006$ and WOR, 0.12; $p < 0.001$). Chen et al[11] found that robot-assisted THA decreased overall complications (WOR, 0.42; $p = 0.03$), whereas Han et al[2] found no significant difference. Han et al[2] reported that robot-assisted THA increased dislocation (WOR, 2.28; $p = 0.02$) and revisions (WOR, 2.88; $p = 0.03$), and Chen et al[11] likewise reported that robot-assisted THA increased heterotopic ossification (WOR, 1.94; $p = 0.04$) (Table 3).

Operation time

Both Han et al[2] and Chen et al[11] found that robot-assisted THA extends operation time by about 20 minutes. Han et al[2] found a statistically significant difference (WMD, 20.72 minutes; $p = 0.002$), while Chen et al[11] did not (WMD, 23.21 minutes) (Table 3).

Conclusions of meta-analyses

All three meta-analyses concluded that postoperative clinical results were equivalent, with both Chen et al[11] and Karunaratne et al[10] calling for further studies to ascertain long-term outcomes. Both Chen et al[11] and Han et al[2] further concluded that while robot-assisted THA requires longer operation times, it incurs fewer intraoperative complications and better radiographic outcomes. Chen et al[11] also concluded that robot-assisted THA increases likelihood of heterotopic ossification, while Han et al[2]

Table 3. All reported outcomes of THA using robotic assistance and conventional instrumentation

		Han et al, 2019[2]				Karunaratne et al, 2019[10]				Chen et al, 2018[11]			
	Unit	*n**	Effect size	p-value	Favours	*n**	Effect size	p-value	Favours	*n**	Effect size	p-value	Favours
Radiographic outcomes													
Cup inclination (degrees)	WMD	4	–2.47	0.003	RA								
Cup anteversion (degrees)	WMD	4	–1.63	0.600									
Stem alignment (degrees)	WMD	6	–0.40	0.020	RA								
Cup safe zone Lewinnek	WOR	4	11.05	< 0.001	CI								
Cup safe zone Callanan	WOR	4	7.63	< 0.001	CI								
LLD (> 3 or > 10 mm)	WOR	4	0.74	0.280									
Clinical scores													
Pooled HHS, PMA & JOA score	WMD	10	0.01	0.970						3	0.09	0.380	
Pooled mHHS and HHS	WMD					4	–2.90	n.r.					
PMA score	WMD	4	0.06	0.860		4	–1.25	n.r.					
HHS	WMD	4	0.04	0.980									
Complications and revision													
Intraoperative complication	WOR	9	0.32	0.006	RA					5	0.12	< 0.0001	RA
Nerve palsy	WOR	3	4.47	0.110									
Thigh pain	WOR	3	0.32	0.030	RA								
Heterotopic ossification	WOR	4	1.44	0.290						3	1.94	0.040	CI
Dislocation	WOR	6	2.28	0.020	CI								
Total complications	WOR	7	0.83	0.480						5	0.43	0.030	RA
Revision rate	WOR	3	2.88	0.030	CI								
Operation time (minutes)	WMD	8	20.72	0.002	CI					3	23.21	0.090	

*Number of studies assessing an outcome.

Note. THA, total hip arthroplasty; RA, robotic-assisted; CI, conventional instrumentation; WMD, weighted mean difference; WOR, weighted odds ratio; HHS, Harris Hip Score; PMA, Postel-Merle d'Aubigné; JOA, Japanese Orthopaedic Association; mHHA, modified Harrris Hip Score; LLD, leg length discrepancy; n.r., not reported.

concluded that it is associated with a higher incidence of dislocations and revisions.

Discussion

The present overview of meta-analyses suggests that, compared to conventional THA, robot-assisted THA grants more accurate cup inclination and stem alignment, higher likelihood of component placement within safe zones, and fewer intraoperative complications. The overview also affirms that robot-assisted THA extends operation times by about 20 minutes, and increases risks of postoperative heterotopic ossification, dislocation, and revision. None of the meta-analyses found significant differences in clinical or functional scores between robot-assisted and conventional THA.

The two meta-analyses[2,11] that reported on radiographic outcomes found that, compared to conventional THA, robot-assisted THA enabled more accurate and reproducible acetabular cup placement within the Lewinnek safe zone[26] and the Callanan safe zone.[27] The validity of both safe zones has been challenged,[28–30] because subluxations and dislocations have also been observed for cups that were placed within the safe zones. As a result, several additional safe zones have been proposed that show an improved accuracy of component positioning,[29–31] but these were not used in the studies assessed by the meta-analyses. Moreover, a recent systematic review on acetabular cup positioning and risk of dislocation suggested that it is difficult to draw any conclusions regarding definitive target zones for cup positioning due to high heterogeneity among studies with inconsistent measurement techniques and different surgical approaches.[32] The authors therefore believe that ideal cup placement should be determined considering spino-pelvic parameters, such as pelvic tilt and functional anteversion, which could be facilitated by a robotic system.[33–35]

The meta-analyses revealed more accurate stem placement with robot-assisted THA, but there remains inconsistency in standards for classification of stem alignment.[11] Leg length discrepancy (LLD) remains one of the most common causes of patient dissatisfaction after THA, though there is no consensus as to whether the cut-off should be 3 mm, 5 mm or 10 mm.[2,11] The three meta-analyses found no statistically significant differences in LLD between robot-assisted and conventional THA, either in terms of absolute difference or proportion of outliers.[2,11] Robotic systems provide an accurate way to assess LLD that may help surgeons make intraoperative adjustments and/or improve their preoperative planning or component positioning.

Based on the findings of the current overview, robotic assistance has no added benefit in terms of clinical and functional scores at 5 to 14 years.[2,10,11] It should be noted, however, that the use of different scoring systems across studies complicates evaluation of any pooled results. Han et al[2] noted that in a study by Bargar et al,[18] robotic assistance yielded significantly better pain scores (Health

Status Questionnaire and Harris Pain Scores) as well as WOMAC scores at a mean follow-up of 14 years (robot-assisted THA, 13.9±2.7 years; conventional THA, 14.2±4.7 years).

In the meta-analysis by Chen et al[11] the rates of infection, nerve palsy and deep vein thrombosis were comparable between robot-assisted and conventional THA. Han et al[2] revealed significantly higher dislocation and revision rates with robotic assistance. It is worth noting, however, that studies published after 2003 observed lower dislocation rates following robot-assisted THA.[20] This decrease might be attributable to the inclusion of five studies[19,21,23–25] that followed a posterolateral approach, which provides better retraction of the gluteus medius and minimus muscles, thereby granting improved access for robotic milling and avoiding injury to the abductor tendon and greater trochanter.[23] It is noteworthy that studies evaluating active robot-assisted THA reported outcomes at 1.5 to 14 years,[12,18–25] whereas studies evaluating semi-active robot-assisted THA reported outcomes at only 0 to 2 years.[5,13–17] The long-term outcomes of semi-active robot-assisted THA are therefore yet to be determined.

Both of the meta-analyses that assessed operation time indicated that robot-assisted THA took longer than conventional THA, possibly because robotic systems require registration or placement of positioning pins, as well as the learning curve for new users. The latter has not been addressed in the meta-analyses which did not consider the level of experience of the surgeons. There are few reports on the learning curve of robot-assisted THA.[2] One study observed a significant learning curve, with operation time decreasing from 79.8 minutes (1st to 35th case) to 69.4 minutes (71st to 105th cases),[36] whereas another study found surgeons were able to grasp the technology after only 10 procedures.[5] A third study compared one surgeon's experience switching from conventional to robot-assisted THA, and found that over the course of 100 surgeries, it took 14 surgeries to become 'proficient', beyond which there were no significant differences in operation time or HHS.[37]

The findings of this overview of meta-analyses should be interpreted with the following considerations and limitations in mind. First, only three meta-analyses fulfilled the inclusion criteria, and their quality was either 'low' or 'critically low'. Moreover, all three meta-analyses included nine case-control studies and one cohort study in addition to five randomized controlled trials. Second, only one meta-analysis[10] differentiated between active and semi-active assistance, whereas results from both systems were pooled in the other two meta-analyses.[2,11] Moreover, all three meta-analyses pooled results of older and possibly obsolete robotic systems with results of newer generations and enhanced robotic systems. This may be problematic as blending results across different robotic assistance techniques and generations may invalidate the data syntheses performed. Third, there was heterogeneity in terms of surgical approaches, and it is impossible to differentiate the effect of surgical approach from that of robotic assistance. Fourth, it is impossible to account for the effect of learning curves and experience in the included meta-analyses. Fifth, only the Lewinnek et al[26] and Callanan et al[27] safe zones for acetabular component positioning were assessed, while newer safe zones were not accounted for. Safe zones enable quantitative assessments of how well surgeons followed their preoperative plans, and hence how to improve their techniques and targets for future operations. Sixth, 'human error' remains a major weakness in THA,[6] since it is impossible to implant perfectly positioned components in every patient with their varying biological environments, diverse anatomy, and pathology. It is unknown whether and in how many cases surgeons might have diverted from the preoperative plan, and how this affected the reported outcomes. Seventh, technology has evolved greatly over the last two decades and is still evolving very fast.[7] Therefore the question arises whether data can be pooled for technologies of different generations and working methods.

Conclusion

The present overview of meta-analyses suggests that robot-assisted THA could improve the accuracy of component positioning and reduce intraoperative complications. The overview also affirms that robot-assisted THA extends surgery by 20 minutes, and increases risks of postoperative heterotopic ossification, dislocation, and revision. None of the meta-analyses found significant differences in clinical or functional scores between robot-assisted and conventional THA. Future studies and reviews should make a clear distinction between active and semi-active robotic assistance, address technology matureness, and consider surgeon experience.

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