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Techniques and Technologies for the Intraoperative Assessment of Component Positioning, Leg Lengths, and Offset in Total Hip Arthroplasty: A Systematic Review

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ABSTRACT

Background: Many techniques and technologies exist for the intraoperative assessment of component positioning, leg lengths, and offset in total hip arthroplasty, but with limited comparative data. We conducted a systematic review of the available literature to evaluate the range of techniques and technologies for the intraoperative assessment of component position as well as leg lengths and offset in terms of accuracy, precision, surgical time, cost, and relationship to clinical outcomes.
Methods: A comprehensive search of the Embase and Medline databases from 1974 to 2023 was performed. We included controlled or comparative prospective clinical studies. Cochrane's risk-of-bias tool for randomized trials and Risk of Bias in Non-Randomized Studies – of Interventions tools were used by 2 independent reviewers to evaluate each study for risk of bias. We conducted both qualitative and quantitative analyses of the studies included. However, a meta-analysis was deemed not to be feasible due to heterogeneity.
Results: Our review included 25 studies with 52 intraoperative techniques and technologies. Mechanical guides and computerized navigation were most frequently evaluated in the included studies. Computerized navigation systems consistently showed the greatest accuracy and precision across all measures, at the cost of longer mean operative time. In contrast, freehand techniques demonstrated the poorest accuracy and precision. Insufficient data were found to reach any meaningful conclusions in terms of differences in overall surgical cost or clinical outcomes.
Conclusions: Evidence shows that computerized navigation systems are most accurate and precise in positioning components during total hip arthroplasty. Further research is needed to determine their health and economic impact and whether the accuracy and precision of navigated techniques are justified in terms of clinical outcomes.

Introduction and background

Total hip arthroplasty (THA) is one of the most common and successful procedures in orthopaedic surgery, with registry-reported 15-year survivorship approaching 95% and a meaningful proportion of patients reporting no awareness of the prosthesis once fully recovered [1]. Proper positioning and placement of components can affect the clinical outcomes of THA [2], both objective outcomes such as instability and other adverse events as well as patient-reported outcomes such as pain, satisfaction, and quality of life. One potentially important factor in achieving a high-performing 'forgotten' hip replacement is the accuracy and precision of component positioning, as well as patient-specific minimization of leg length discrepancy (LLD) and restoration of native hip offset [3].

Traditionally, the intraoperative assessment and optimization of these measures has primarily relied on a combination of anatomic

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landmarks (eg, the coronal and axial planes of the patient's pelvis to assess acetabular component position) and direct manual manipulation techniques (such as displacement of the trial femoral head in response to axial leg traction, sometimes known as the 'shuck test') [4,5]. More recently, additional techniques have been reported that rely on more specialized mechanical, image-based, and/or computer-based technologies.

Most, if not all, hip reconstruction surgeons will have one or more preferred techniques for intraoperative component positioning and assessment of leg lengths and offset, and these are likely to vary between surgeons given the number of different techniques reported. The choice of technique can be expected to vary depending on elements such as exposures during formal training, institutional and health care system factors, the preferred choice of surgical approach, and engagement with new technologies while in independent practice. We hypothesize that there are differences between these techniques in terms of the accuracy and precision of component positioning, relative value, and clinical outcomes.

While there is literature that compares and evaluates specific techniques, such as the accuracy of robotic-assisted THA vs manual-THA [6] and the effectiveness of minimally invasive surgery, computer-assisted surgery, and computer-assisted minimally invasive surgery [7]. To the best of our knowledge, there is no literature that systemically synthesizes the available evidence regarding the full range of intraoperative techniques and technologies for the assessment of component positioning, leg lengths, and offset, and their relative precision and accuracy in determining LLD, offset, and acetabular component positioning. Given this and the absence of a 'gold-standard' technique, it is difficult for arthroplasty surgeons and investigators to make informed, evidence-based decisions regarding the choice of techniques and/or technologies to optimize intraoperative component positioning in THA. Thus, the purpose of this study was to systematically review the current literature to determine the accuracy and precision of the range of intraoperative techniques and technologies for component positioning and restoration of leg lengths and offset in THA, as well as the relative value of these techniques and technologies in terms of impact on surgical time and cost, as well as both objective and patient-reported clinical outcomes.

Material and methods

This systematic review was conducted with adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Guidelines for Transparent Reporting of Systematic Reviews and Meta-Analyses [8]. No ethical approval or registration was needed as this study was a review of existing literature.

Search strategy and selection criteria

We searched electronic databases (Embase, Medline) for studies on THA-related leg length measurement, non-THA-related leg length measurement, component positioning, and offset measurement. Boolean operators, truncation, and wildcards were employed to enhance the search strategy and encompass variations in terminology. The complete search syntax is shown in Supplementary Figure 1. This search was performed on August 2, 2023, with no exclusion based on publication date.

The inclusion criteria were: a) studies of adult human participants 18 years of age or older; b) human participants of any sex; c) studies that evaluated techniques and/or technologies for the intraoperative assessment of component positioning, LLD, and/or offset compared to postoperative imaging; d) studies that included a comparative evaluation of two or more techniques and/or technologies for the intraoperative assessment of component positioning, LLD, and/or offset; e) prospective study design; f) the same surgical approach(es) used in all groups; g) studies with full text manuscripts available in English. The exclusion criteria were: a) immature study participants under the age of 18; b) cadaveric or animal studies; c) patients with marked pelvic or acetabular deformities such as developmental dysplasia of the hip; d) computer simulated arthroplasty; e) hip resurfacing arthroplasty; f) revision THA; g) cemented THA; h) hip hemiarthroplasty; i) in-vitro studies (pelvic models); j) techniques/technologies that were evaluated preoperatively (eg, assessment of native leg length and/or offset in the orthopaedic office setting) or post-operatively (eg, radiographic assessment of component positioning parameters after surgery was complete and patient had left the operating room); k) retrospective studies; l) studies that compare the accuracy of different implants or approaches; m) correlation studies between intraoperative positioning and surgical outcomes; o) studies that evaluate the relationship between 2 anatomical/radiographic measurements; p) conference/meeting abstracts, and case reports.

The citations identified during the search, including their titles and abstracts were exported into an electronic systematic review management software package (Covidence, Melbourne, Australia) for further screening. The screening and selection of studies were performed in 2 stages. First, 4 reviewers (C.C., I.B.H., R.H., and M.G.Z.) independently screened and reviewed the titles and abstracts for all studies, and irrelevant studies were excluded. Each citation was screened by 2 reviewers. The remaining studies underwent full text review, again with each screened for inclusion by 2 of the study authors. Disagreements were discussed between reviewers at all stages, and a final decision was made based on consensus between 2 reviewers. The PRISMA flow diagram of the screening and selection process is shown in Figure 1.

Data extraction

Data extraction was performed independently by a single author. Study information that was extracted includes the following details: author, year of publication, study design, study location, study objectives, study groups, population description, selection criteria, follow-up duration, surgical approach, study comparator, evaluation method, reported measurement outcomes, analysis of surgical time, analysis of surgical cost, and reported clinical outcomes. Extracted data was exported to Excel spreadsheet software (Microsoft, Washington, USA) for manual review and aggregation.

Quality assessment

A modified version of Cochrane's risk-of-bias tool for randomized trials (RoB 2) was used to evaluate the quality of randomized control trials (RCTs) marked for inclusion in the systematic review (Table 1). This tool has 5 distinct domains to assess bias [9]. These domains were assessed by 2 reviewers for low risk of bias, some risk of bias, or high risk of bias. Disagreements were discussed, and a consensus was reached between the reviewers. These domains are: bias arising from the randomization process; bias due to deviations from intended interventions; bias due to missing outcome data; bias in measurement of the outcome; and bias in selection of the reported result [9]. An overall risk of bias score was assigned to each study based on the assessed results of all 5 RoB 2 risk of bias domains.

For non-randomized trials, a modified version of Cochrane's Risk of Bias in Non-Randomized Studies — of Interventions

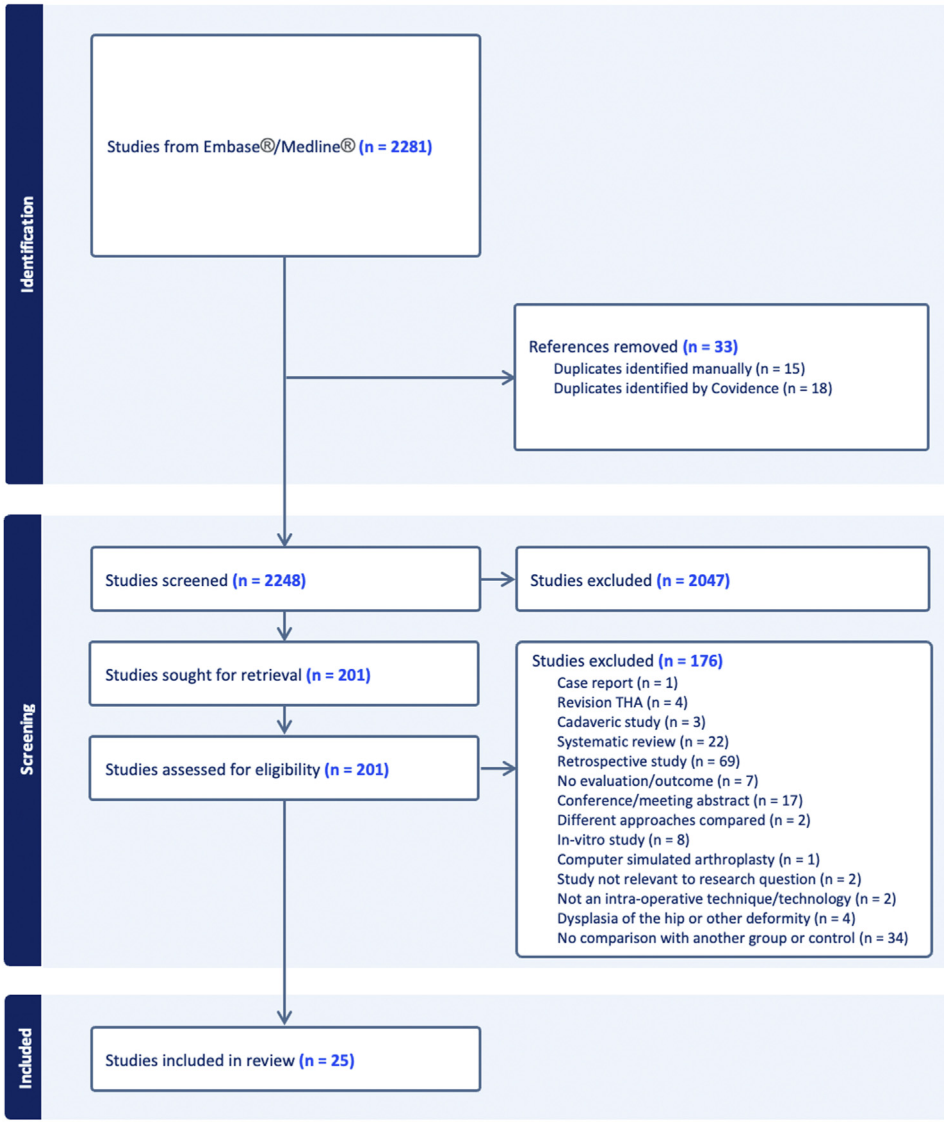

Figure 1. PRISMA flow diagram depicting selection process for study inclusion.

(ROBINS-I) tool was used as a quality evaluation (Table 2). This tool has 7 distinct domains to assess bias [10], and each domain was assessed by 2 reviewers for low, moderate, or serious risk of bias. Disagreements were discussed and a consensus was reached between the reviewers. These 7 domains are: bias due to confounding; bias in selection of participants into the study; bias in classification of interventions; bias due to deviations from intended interventions; bias due to missing data; bias in measurement of outcomes; and bias in selection of the reported result [10]. An overall risk of bias score was assigned to each study based on the assessed results of all 7 ROBINS-I risk of bias domains.

Outcomes

The component positioning, LLD, and offset achieved with each technique/technology in every study were evaluated for precision (the standard deviation of each measure as compared to the reference value) and accuracy (difference between the mean value achieved and the target/reference value), with the postoperative plain x-ray (XR) or computed tomography (CT) scan considered the gold standard. Additionally, surgical time and surgery cost were also considered as outcomes, where information was provided by the study. Clinical outcomes, encompassing objective measures such as complications and adverse events, as well as patient-reported outcomes such as satisfaction and stability following THA, were also areas of focus for our review.

Results

Selection of studies

Two thousand two hundred eighty-one citations were identified following our search, with 18 duplicates automatically removed. An additional 15 duplicates were manually identified and removed on initial screening. Out of the remaining 2248 studies under consideration for inclusion, 2047 were found to be ineligible based on title and abstract screening and were subsequently excluded. The 201 remaining studies were retrieved and screened in full text. Of these, 176 full-text studies did not meet our inclusion criteria and were thus considered ineligible. Consequently, 25 studies were identified for final inclusion in the review [4,5,11–33]. A PRISMA flow diagram

Table 1
RoB 2 assessment of bias for randomized studies.

Study (year)	Bias arising from the randomization process	Bias due to deviations from intended interventions	Bias due to missing outcome data	Bias in measurement of the outcome	Bias in selection of the reported result	Overall bias
Kalteis et al. (2005)	Some concerns	Low	Low	Some concerns	Low	Some concerns
Leenders et al. (2002)	Low	Low	Low	Low	Low	Low
Parratte et al. (2007)	Low	Low	Low	Low	Low	Low
Sendtner et al. (2011)	Some concerns	Low	Low	Low	Low	Low
Gurgel et al. (2014)	Low	Low	Low	Low	Low	Low
Small et al. (2014)	Low	Low	Low	Low	Low	Low
Hamilton et al. (2019)	Low	Low	Low	Low	Low	Low
Ogawa et al. (2020)	Low	Low	Some concerns	Low	Low	Low
Mihalic et al. (2020)	Low	Low	Low	Low	Low	Low
Pongkunakorn et al. (2021)	Low	Low	Low	Low	Low	Low
Wang et al. (2023)	Some concerns	Low	Low	Some concerns	Some concerns	Some concerns
Kurosaka et al. (2023)	Low	Low	Low	Low	Low	Low
Wassilew et al. (2012)	Some concerns	Low	Low	Low	Low	Low
Weber et al. (2014)	Low	Low	Some concerns	Low	Low	Low

of these results, as well as exclusion reasons for full-text studies, are shown in Figure 1.

Risk of bias assessment

Using the RoB 2 tool for risk of bias assessment of the RCTs in our review, we found that 12 of 14 studies had 'low risk' of bias, and the other 2 studies had 'some concerns' over risk of bias (Table 1). The ROBINS-I tool was used for the 11 nonrandomized studies. Six of these studies had 'low risk' of bias, while 5 studies had 'medium risk' of bias (Table 2). In the case of RCTs, the domain 'bias due to randomization process' was the most frequently indicated source of risk, while for nonrandomized studies, the domain 'bias due to confounding' was the primary source of risk of bias. No studies had an overall 'high risk' of bias score with either tool.

Techniques and technologies identified

Out of the 25 records included in the study, a total of 52 intraoperative techniques and technologies were evaluated. These were grouped together based on technical and/or technological similarity. A freehand component placement technique that relied on manual manipulation without the use of mechanical aids, guides, or anatomical landmarks was assessed 9 times by 8 studies [4,11,12,22,23,25,26,29], the use of anatomic landmarks was assessed 4 times by 4 studies [5,14,16,20], mechanical guides were assessed 19 times in 15 studies [5,12–17,19,22,25–28,31,33], conventional fluoroscopy without computerized guidance was assessed 3 times by 3 studies [21,24,30], computerized navigation (nav) systems were assessed 16 times in 14 studies [4,11,13,17,18,20,21,23,24,27,28,30,32,33], and a robotic arm assisted surgery system was assessed once by 1 study [29]. Further description of techniques and technologies is shown in Supplementary Table 1.

A qualitative analysis was conducted by categorizing the studies. All interventions were first separated from their study group pairings to evaluate the accuracy and precision of each component's positioning technology and measurement technique. Interventions were then further divided into 2 groups, 1 focused on component positioning and the other on addressing LLD and offset restoration.

Component positioning

The first evaluation focused on the radiographic outcomes of acetabular component positioning with different techniques/technologies. Of particular interest to our study was the acetabular inclination and anteversion on postoperative imaging. The 2 radiographic measurement methods used in these studies were XR or CT scans. This synthesis is presented in Table 3. Outcome assessors used a variety of methods to calculate component positioning on postoperative imaging, including using analog or digital rulers and protractors to measure in relation to anatomical

Table 2
Robins-I assessment of bias for nonrandomized studies.

Study (year)	Bias due to confounding	Bias due to selection of participants	Bias in classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reported result	Overall bias
Naito et al. (1999)	Low	Low	Low	Low	Low	Moderate	Low	Low
Desai et al. (2011)	Low	Low	Moderate	Low	Low	Moderate	Low	Moderate
Epstein et al. (2011)	Moderate	Moderate	Low	Low	Low	Low	Low	Moderate
Barbier et al. (2012)	Low	Low	Low	Low	Low	Low	Low	Low
Meermans et al. (2015)	Low	Low	Low	Low	Low	Low	Low	Low
Iwakiri et al. (2017)	Serious	Low	Low	Low	Moderate	Low	Low	Moderate
Ogawa et al. (2018)	Low	Low	Low	Low	Low	Low	Low	Low
Takada et al. (2020)	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate
Agarwal et al. (2020)	Low	Low	Low	Low	Moderate	Low	Low	Low
Pongkunakorn et al. (2021)	Moderate	Low	Low	Low	Low	Low	Low	Moderate
Kolodychuk et al. (2022)	Low	Low	Low	Low	Low	Low	Low	Low

Table 3
Postoperative radiographic outcomes of acetabular component positioning studies.

Study (year)	Study design	Specific intervention/ reference	Pts	Surgical approach	Postoperative measurement method	Target cup inclination ±SD (°)	Postoperative cup inclination mean ± SD (°)	Target cup anteversion ±SD (°)	Postoperative cup anteversion mean ± SD (°)
Anatomical landmark studies									
Epstein et al. (2011) [14]	NP	TAL	33	Posterolateral	Pelvic, Lateral XR	45	41 ± 6.6	20	23.6 ± 9.9
Meermans et al. (2015) [16]	NP	TAL	100	Posterior	Pelvic, Lateral XR	40	38.5 ± 7.0	N/A	N/A
Agarwal et al. (2020) [5]	NP	TAL	19	Direct lateral Hardinge	CT	45	44.8 ± 4.9	5 to 25	23.8 ± 4.9
Fluoroscopy studies									
Hamilton et al. (2019) [30]	RCT	Fluoroscopy	100	Direct anterior	Pelvic XR	40	42.3 ± 4.1	20	21.8 ± 3.6
Freehand studies									
Kalteis et al. (2005) [23]	RCT	Manual Freehand	22	Anterolateral	CT	45	42.3 ± 7.0	15	24.0 ± 15.0
Sendtner et al. (2011) [11]	RCT	Manual Freehand	32	Anterior	CT	40-45	37.9 ± 6.3	15-20	23.8 ± 10.1
Pongkunakorn et al. (2021a) [12]	NP	Visual Estimation	107	Posterolateral	CT	N/A	N/A	N/A	24.6 ± 5.2[a]
Wang et al. (2023) [29]	RCT	Manual Freehand	36	Modified Hardinge	XR	40	38.02 ± 6.31	15	14.99 ± 8.13
Mechanical guide studies									
Parratte et al. (2007) [33]	RCT	Mechanical Angle Guide	30	Anterolateral	Full Pelvic CT	32 ± 7.1	34 ± 7.62	16.6 ± 10.4	16.2 ± 9.6
Epstein et al. (2011) [14]	NP	Mechanical Angle Guide	30	Posterolateral	Pelvic, Lateral XR	45	42 ± 6.0	20	29.5 ± 13.6
Gurgel et al. (2014) [13]	RCT	Mechanical Alignment Guide	20	Modified Hardinge	CT	40	42.2 ± 3.3	15	14.5 ± 8.3
Small et al. (2014) [15]	RCT	Standard Instrumentation	15	Posterior	CT	44.3	44.99 ± 9.0	20.4	29.01 ± 8.2
Small et al. (2014) [15]	RCT	PSI	15	Posterior	CT	44.2	46.42 ± 7.5	18.1	18.79 ± 7.2
Meermans et al. (2015) [16]	NP	Digital Protractor	100	Posterior	Pelvic, Lateral XR	40	38.3 ± 4.7	N/A	N/A
Iwakiri et al. (2017) [19]	NP	Cup Alignment Guide	60	Anterolateral	CT	N/A	39.0 ± 5.3	N/A	21.7 ± 6.4
Iwakiri et al. (2017) [19]	NP	Novel Mechanical Cup Navigator	76	Anterolateral	CT	N/A	40.6 ± 3.2	N/A	18.3 ± 4.6
Ogawa et al. (2020) [17]	RCT	Mechanical Angle Guide	22	Modified Watson-Jones	CT	40	N/A	15 or 20	N/A
Agarwal et al. (2020) [5]	NP	Mechanical Angle Guide	16	Direct lateral Hardinge	CT	45	44.2 ± 4.8	5 to 25	18.3 ± 5.2
Pongkunakorn et al. (2021b) [31]	RCT	Mechanical Angle Guide	32	Posterolateral	Pelvic XR	40	40.3 ± 7.9	20	19.1 ± 5.9
Pongkunakorn et al. (2021b) [31]	RCT	Smartphone Inclinometer	32	Posterolateral	Pelvic XR	40	41.2 ± 3.9	20	19.3 ± 3.8
Pongkunakorn et al. (2021a) [12]	NP	Digital Protractor	107	Posterolateral	CT	N/A	N/A	N/A	23.2 ± 8.2[a]
Pongkunakorn et al. (2021a) [12]	NP	Digital Protractor + Spirit Level	107	Posterolateral	CT	N/A	N/A	N/A	22.8 ± 6.9[a]
Computerized navigation studies									
Kalteis et al. (2005) [23]	RCT	Imageless Nav	23	Anterolateral	CT	45	45.0 ± 2.8	15	14.4 ± 5.0
Parratte et al. (2007) [33]	RCT	Imageless Nav	30	Anterolateral	Full pelvic CT	32 ± 4.8	34 ± 5.7	14.8 ± 4.6	14.4 ± 4.5
Sendtner et al. (2011) [11]	RCT	Imageless Nav	30	Anterior	CT	40-45	42.3 ± 3.8	15-20	24.5 ± 6.0
Gurgel et al. (2014) [13]	RCT	Imageless Nav	20	Modified Hardinge	CT	40	41.7 ± 3.0	15	17.4 ± 6.3
Hamilton et al. (2019) [30]	RCT	Fluoroscopic Nav	100	Direct anterior	Pelvic XR	40	40.4 ± 3.5	20	20.8 ± 3.0
Ogawa et al. (2020) [17]	RCT	Augmented Reality Nav	19	Modified Watson-Jones	CT	40	N/A	15 or 20	N/A
Kurosaka et al. (2023) [18]	RCT	Augmented Reality Nav	62	Modified Watson-Jones	XR	40	N/A	15 to 25	N/A
Kurosaka et al. (2023) [18]	RCT	Imageless Nav	64	Modified Watson-Jones	XR	40	N/A	15 to 25	N/A
Wassilew et al. (2012) [32]	RCT	Ultrasound Nav	40	Anterolateral	Full Pelvic CT	N/A	43.6 ± 3.4	N/A	15.9 ± 2
Wassilew et al. (2012) [32]	RCT	Imageless Nav	40	Anterolateral	Full Pelvic CT	N/A	46.3 ± 4.2	N/A	22.3 ± 3.8
Robotic-assisted studies									
Wang et al. (2023) [29]	RCT	Robotic-arm assisted surgery	35	Modified Hardinge	XR	40 to 45	41.37 ± 5.22	15 to 20	13.58 ± 5.39

R, randomized control trial; NP, nonrandomized prospective; TAL, transverse acetabular ligament; PSI, patient-specific instrumentation; Nav, computerized navigation; Pts, number of patients; SD, standard deviation; XR, X-ray; CT, computed tomography.

[a] These values represent femoral stem anteversion rather than acetabular cup anteversion.

reference points and/or the use of specialized radiographic analysis software. Four studies [20,24,27,28] only reported radiographic outcomes for acetabular positioning in terms of estimate error or mean error; 1 exclusively presented data through a box plot distribution [4]; and 1 only evaluated femoral anteversion [12], all of which were excluded from Table 3. The remaining studies encompassed all the technique/technology groups and included data on accuracy and/or positioning.

Overall, the computerized navigation-based techniques demonstrated the overall best accuracy and precision for both acetabular inclination (mean difference from target of 1.0 degrees, mean standard deviation [SD] 3.8 degrees) as well as anteversion (mean difference from target of 1.1 degrees, mean SD 4.4 degrees) (Table 4). All techniques demonstrated good accuracy for inclination (mean difference from target 1.0 to 1.9 degrees) with modest variation in precision (mean SD 3.8 to 6.5 degrees). In contrast, there was greater variation in accuracy between techniques for acetabular version, where freehand techniques demonstrated particularly poor performance (mean difference from target of 9 degrees). Similarly, greater variation was seen in precision between techniques (mean SD: 4.4 to 9.6 degrees). It is worth noting that data were only available from 1 study for the fluoroscopy and robotic-arm assisted techniques.

Leg length discrepancy and offset

For the second group of interventions, LLD and acetabular, femoral, and combined offset were the radiographic outcomes of interest. Eight studies are synthesized and presented in Table 5. Some radiographic data were reported as differences compared to the contralateral limb, while some data were reported as mean change between preoperative and postoperative radiographic measurements on the ipsilateral limb. Two studies [22,26] only reported LLD measurement values in terms of patients in each 1cm range from -3cm to +3cm LLD and were thus excluded from the synthesis in Table 5. All of the technique/technology groupings were represented in this synthesis, although data were only available from 1 or 2 studies for each.

Overall, the computerized navigation techniques demonstrated the greatest accuracy and precision for both leg lengths (mean difference from target of 1.0 degrees, mean SD 2.0 degrees) as well as combined offset (mean difference from target of 1.4 degrees, mean SD 1.0 degrees). Conversely, freehand techniques had the worst performance for both length lengths and offset, with mean differences from target of over 7 degrees and mean SD approaching 7 degrees. Interestingly, the robotic arm-assisted technique's performance was inferior to all but the freehand technique in terms of both accuracy and precision of leg length and offset restoration.

Surgical time and cost

Operative time analysis between interventions was reported in 17 of 25 studies [11,13,15–21,23,24,28–33] (Table 6). Mean operating time for computer-navigated THA was typically higher than the comparative surgical methodology without nav, as evidenced in 7 studies [11,13,21,23,24,30,33]. However, in 2 studies, the navigation system resulted in a very minor decrease in operative time when compared to the study's nonnavigated surgical group [17,20]. Overall, navigation resulted in a mean increase in case length of 9.3 minutes when compared to manual fluoroscopy and 13.3 minutes when compared to freehand or mechanical device techniques. Robotic arm techniques were associated with a mean increase in operative time of 41 minutes as compared to freehand techniques, although this was derived from a single study [29].

Only 2 of 25 studies reported cost data [16,18]. Meermans et al. reported on the cost associated with the use of a digital inclinometer in 100 hip arthroplasty cases [16], and Kurosaka et al. provided the relative cost of 2 different navigation systems. [18]. However, in both cases, the authors reported the incremental cost of the devices themselves, but not differences in overall surgical case cost or episode of care costs.

Clinical outcome analysis

Clinical outcomes were reported in 12 of 25 studies [5,11–18,22,31,32]. These were largely limited to the reporting of adverse events [5,11–18,31,32], with only 1 study reporting patient-reported outcomes in the form of University of California, Los Angeles (UCLA) activity scores [22]. Across all included studies, there were a total of 4 postoperative dislocations [5,12,15,31], 4 intraoperative femoral fractures [13,18], 2 esthetic pin scar complaints [17], 1 postoperative surgical site infection [18], and 1 postoperative distal deep vein thrombosis [18]. Given the low number of adverse events and likely heterogeneity across studies, it is difficult to draw any conclusions regarding associations between the choice of technique/technology for intraoperative assessment and the risk of experiencing a perioperative adverse event.

Table 4
Accuracy and precision of different technique/technology types.

Technique/technology type	Acetabular inclination		Acetabular version		Leg-length restoration		Combined offset restoration	
	Accuracy (mean difference from target in degrees)	Precision (mean standard deviation in degrees)	Accuracy (mean difference from target in degrees)	Precision (mean standard deviation in degrees)	Accuracy (mean difference from target in degrees)	Precision (mean standard deviation in degrees)	Accuracy (mean difference from target in degrees)	Precision (mean standard deviation in degrees)
Anatomic landmarks	1.9	6.2	3.6	7.4	N/A	N/A	N/A	N/A
Fluoroscopy	2.3	4.1	2.3	3.6	2.0	3.6	4.6	2.4
Freehand techniques	2.1	6.5	9.0	9.6	7.7	6.9	7.2	6.8
Mechanical guides	1.5	5.7	3.1	7.3	2.3	2.6	4.0	4.8
Computerized navigation	1.0	3.8	1.1	4.4	1.0	2.0	1.4	1.0
Robotic-arm assisted surgery	N/A	5.2	N/A	5.4	3.8	8.3	6.4	8.1

Table 5
Postoperative radiographic outcomes for LLD and offset studies.

Study (year)	Study design	Specific intervention	Pts	Surgical approach	Postoperative measurement method	LLD mean ± SD (mm)	Acetabular offset mean ± SD (mm)	Femoral offset mean ± SD (mm)	Combined offset mean ± SD (mm)
Kolodychuk et al. (2022) [24]	NP	Fluoroscopy	99	Anterior	Pelvic, Lateral XR	3.4 ± 3.0			6.1 ± 4.5
Kolodychuk et al. (2022) [24]	NP	Imageless Nav	60	Anterior	Pelvic, Lateral XR	1.6 ± 1.7			1.4 ± 1.7
Wang et al. (2023) [29]	RCT	Robotic-Arm Assisted Surgery	35	Modified Hardinge	XR	3.77 ± 8.31	3.54 ± 5.09[a]	2.84 ± 7.86[a]	6.37 ± 8.13[a]
Wang et al. (2023) [29]	RCT	Manual Freehand	36	Modified Hardinge	XR	8.39 ± 9.11	4.08 ± 6.72[a]	2.46 ± 7.67[a]	4.33 ± 6.59[a]
Weber et al. (2014) [21]	RCT	Fluoroscopy	61	Anterolateral	Pelvic XR	0.6 ± 4.1		3.6 ± 0.2	3.1 ± 0.2
Weber et al. (2014) [21]	RCT	Imageless Nav	55	Anterolateral	Pelvic XR	0.4 ± 2.2		2.0 ± 0.2	1.4 ± 0.2
Barbier et al. (2012) [25]	NP	Novel Mechanical Measurement Device	32	Posterolateral	Pelvic XR	2.31 ± 2.64[a]			3.96 ± 4.79[a]
Barbier et al. (2012) [25]	NP	Manual Freehand	26	Posterolateral	Pelvic XR	6.96 ± 4.72[a]			10.16 ± 7.05[a]

RCT, randomized control trial; NP, nonrandomized prospective; XR, X-ray; Nav, computerized navigation; LLD, leg length discrepancy; Pts, number of patients.
[a] These values represent mean change on postoperative imaging when compared to preoperative imaging.

Discussion

The success of THA procedures is at least partly dependent on achieving appropriate component positioning and adequate restoration of leg lengths and offset. While there are a number of techniques and technologies used by surgeons for the intraoperative assessment of these parameters, there is no one gold standard, and there is a paucity of comparative evidence spanning the full range of available techniques. This review synthesized data from 25 studies, to the authors' knowledge, representing the most comprehensive analysis to date of the range of techniques and technologies for intraoperative assessment of component positioning and LLD/offset. We found that computerized navigation techniques consistently provided the greatest accuracy and precision for acetabular component positioning, as well as restoration of leg lengths and offset. While all techniques were fairly accurate for acetabular inclination, there was greater variability in accuracy for the remaining parameters. Freehand techniques that did not rely on the use of any mechanical guides or anatomical landmarks were associated with the poorest accuracy and precision.

We acknowledge several limitations of our study. Most of the studies included in this review were single-center studies of relatively low patient population sizes, and data from 1 or 2 studies were available for some of the technique/technology groups. This could be a result of our study inclusion criteria, which excluded all retrospective studies and studies without comparative groups/controls to increase the quality of literature for synthesis. Additionally, the surgical approach in each study varied, although there was no variation between study groups within individual studies. Regardless, this could lead to inherent biases due to systemic differences in the various surgical approaches for THA. The surgeons for each of these studies also varied in experience, thus introducing bias between surgeons and their intraoperative techniques and technologies for component positioning. For example, in Kolodychuk et al., the study authors found a learning curve of 31-35 cases before the navigation system was more accurate in cup placement when compared to conventional fluoroscopy, as well as decreasing surgical time [24]. This observation suggests the possibility for bias and differences in study outcomes based on surgeon experience with a given technique, which was generally not reported in the included studies. Furthermore, only studies published in English were included in the search results of this systematic review, which might have led to selection bias and left out valuable studies published in other languages. While techniques and technologies were aggregated into similar groups for the purposes of analysis, there nevertheless may be differences between individual techniques and technologies within groups that could result in meaningful differences within the groups. While our review focused on acetabular component positioning as well as length lengths and offset, an additional parameter that may affect outcomes is femoral component version. However, we elected to exclude this because of the limited ability to assess this parameter without dedicated cross-sectional imaging and thus the limited number of studies that assessed it. Studies that included cemented implants were excluded from our review to reduce heterogeneity and enhance uniformity. While contemporary THA in North America is dominated by the use of cementless implants, we acknowledge that our findings may not be directly applicable to cemented fixation. This systematic review tackled an extremely broad subject, and for practical reasons, study selection criteria was strict to aggregate studies that would be relevant for comparison. Due to these reasons, the included studies had disparities in population sizes for each intervention type, resulting in varying degrees of evidence and certainty across the analyses. Additionally, meta-analyses could not be performed due to variations in techniques and technologies. Although many studies were published on the techniques surrounding mechanical angle guides and computerized navigation, the specific mechanical guides and navigation systems varied, as well as the measurement method (XR or CT). At present, there remains no single, universal gold standard for the assessment of component position. The measured parameters can vary depending on the imaging technology used, the position of the patient, the reference points and measurement tools used, and the experience of the assessor. As a result, some of the differences in accuracy and/or precision between studies could be attributable to these factors rather than the techniques/technologies themselves. We further acknowledge that by limiting our search strategy to prospective studies, we may have failed to identify and include data that could be inconsistent with or contradict the findings of the present study. Similarly, we may have failed to identify certain techniques, for example, the use of intraoperative flat plate XR (as distinct from intraoperative fluoroscopy). However, retrospective data are higher risk of bias as compared to prospectively collected evidence and would thus be overall less likely to meaningfully change the conclusions drawn from the included higher-quality studies.

While differences were seen between techniques in terms of both accuracy and precision for the range of component positioning and

Table 6
Cost, time, and outcome analysis of all included studies.

Study (year)	Study design	Interventions	Pts	Cost analysis	Operative time mean ± SD (range) (min)	*P*-value	Clinical outcome analysis
Kalteis et al. (2005) [23]	RCT	Manual Freehand	22	N/A	77.0 ± 21.8 (40-120)	.137	N/A
		Imageless Nav: Vector-Vision CT-Free Hip 3.1 (BrainLAB, Germany)	23	N/A	85.3 ± 13.9 (62-102)	.137	N/A
Naito et al. (1999) [26]	NP	Shuck Test	32	N/A	N/A	N/A	N/A
		Intraoperative Pin and Caliper	32	N/A	N/A	N/A	N/A
Leenders et al. (2002) [4]	RCT	Manual Freehand	50	N/A	N/A	N/A	N/A
		SurgiGATE CT-Nav (Medivision, Switzerland)	50	N/A	N/A	N/A	N/A
		Freehand after Nav Introduction	50	N/A	N/A	N/A	N/A
Parratte et al. (2007) [33]	RCT	Mechanical Angle Guide	30	N/A	+0[a]	N/A	N/A
		Imageless Nav (Praxim Medivision, France)	30	N/A	+12 (8-20)[a]	N/A	N/A
Sendtner et al. (2011) [11]	RCT	Manual Freehand	32	N/A	62 (57-75)	N/A	No complications or postoperative dislocations (first 6 weeks postoperatively)
		Imageless Nav: Hip Unlimited 5.0 (BrainLab, Germany)	30	N/A	85 (76-96)	N/A	No complications or postoperative dislocations (first 6 weeks postoperatively)
Desai et al. (2011) [22]	NP	Shuck Test	50	N/A	N/A	N/A	Postoperative UCLA Score (mean 3.98 ± 1.38)
		Novel Judd Pin Guide	50	N/A	N/A	N/A	Statistically significant higher postoperative UCLA Score (mean 6.05 ± 1.36)
Epstein et al. (2011) [14]	NP	Mechanical Angle Guide	30	N/A	N/A	N/A	No dislocations minimum 3 months postoperation.
		TAL	33	N/A	N/A	N/A	No dislocations minimum 3 months postoperation.
Barbier et al. (2012) [25]	NP	Manual Freehand	32	N/A	N/A	N/A	N/A
		Novel Mechanical Measurement Device	26	N/A	N/A	N/A	N/A
Gurgel et al. (2014) [13]	RCT	Mechanical Angle Guide	20	N/A	105	N/A	1 intraoperative proximal femoral fracture
		Imageless Nav: OrthoPilot (Aesculap, Germany)	20	N/A	114.8	N/A	1 intraoperative proximal femoral fracture
Small et al. (2014) [15]	RCT	Standard Instrumentation	15	N/A	88	N/A	1 anterior dislocation
		Patient-specific instrumentation	15	N/A	95	N/A	No complications or postoperative dislocations.
Meermans et al. (2015) [16]	RCT	TAL	100		52	.19	No complications or postoperative dislocations.
		Digital Inclinometer (WR 300 Digital Angle Gauge)	100	£40 initial cost + £0.80 each sterile camera drape	50	.19	No complications or postoperative dislocations.
Iwakiri et al. (2017) [19]	RCT	Mechanical Alignment Guide	60	N/A	103.0 ± 21.3	.195	N/A
		Novel Mechanical Cup Navigator	76	N/A	100.6 ± 23.8	.195	N/A
Ogawa et al. (2018) [27]	RCT	Goniometer	54	N/A	N/A	N/A	N/A
		Novel Augmented Reality Navigation (AR-Hip)	54	N/A	N/A	N/A	N/A
Hamilton et al. (2019) [30]	RCT	Fluoroscopy	100	N/A	+0*	N/A	N/A
		Fluoroscopic Nav: Surgeon's Checklist (Radlink, USA)	100	N/A	+>2*	N/A	N/A
Takada et al. (2020) [28]	NP	Goniometer	30	N/A	95.3 ± 18.7 (66-147)	N/A	N/A
		Imageless Nav: HipAlign (OrthAlign, USA)	30	N/A	95.3 ± 18.7 (66-147)	N/A	N/A
Ogawa et al. (2020) [17]	RCT	Mechanical Angle Guide	22	N/A	44 ± 12 (31-84)	N/A	2 Esthetic Pin Scar Complaints (group not specified)
		Novel Augmented Reality Navigation (AR-Hip)	19	N/A	43 ± 7 (34-89)	N/A	2 Esthetic Pin Scar Complaints (group not specified)

Table 6 (*continued*)

Study (year)	Study design	Interventions	Pts	Cost analysis	Operative time mean ± SD (range) (min)	*P*-value	Clinical outcome analysis
Agarwal et al. (2020) [5]	NP	TAL	19	N/A	N/A	N/A	No complications or postoperative dislocations.
		Mechanical Angle Guide	16	N/A	N/A	N/A	1 dislocation
Mihalic et al. (2020) [20]	RCT	TAL	42	N/A	70 ± 13	N/A	N/A
		Electromagnetic Nav: GUIDING STAR E-HIP (ekliptik, Slovenia)	42	N/A	70 ± 10	N/A	N/A
Pongkunakorn et al. (2021b) [31]	RCT	Mechanical Angle Guide	32	N/A	122 ± 28	.069	1 posterior dislocation. No SSI
		Novel Smartphone Inclinometer	32	N/A	136 ± 34	.069	No complications or postoperative dislocations.
Pongkunakorn et al. (2021a) [12]	NP	Visual Estimation	107	N/A	N/A	N/A	One dislocation, no SSI. (all interventions performed in succession, same patients)
		Digital Protractor	107	N/A	N/A	N/A	One dislocation, no SSI.
		Digital Protractor + Spirit Level	107	N/A	N/A	N/A	One dislocation, no SSI.
Kolodychuk et al. (2022) [24]	NP	Fluoroscopy	99	N/A	62 ± 24	.305	N/A
		Imageless Nav: HipAlign (OrthAlign, USA)	60	N/A	75 ± 17	.305	N/A
Wang et al. (2023) [29]	RCT	Surgical Robotic-Arm: TRex-RX (Longwell Co., China)	35	N/A	118.11 ± 24.09	<.001	N/A
		Manual Freehand	36	N/A	77.22 ± 13.96	<.001	N/A
Kurosaka et al. (2023) [18]	RCT	Novel Augmented Reality Navigation (AR-Hip)	62	Approx. USD $500 per procedure	45 ± 9	.1	1 postoperative SSI, 1 postoperative distal DVT, 1 intraoperative fracture, 1 intraoperative pin loosening
		Imageless Nav: HipAlign (OrthAlign, USA)	64	Approx. USD $1000 per procedure	48 ± 10	.1	1 intraoperative fracture, 1 intraoperative pin loosening
Wassilew et al. (2012) [32]	RCT	Ultrasound Nav: OrthoPilot THAplus 3.0 (Aesculap, Germany)	40	N/A	73.2 ± 14.1 (51-90)	N/A	No complications or postoperative dislocations.
		Imageless Nav: OrthoPilot THAplus 3.0 (Aesculap, Germany)	40	N/A	67.3 ± 11.5 (48-93)	N/A	No complications or postoperative dislocations.
Weber et al. (2014) [21]	RCT	Fluoroscopy	61	N/A	64 (43-115)	<.001	N/A
		Imageless Nav: Hip 6.0 Prototype (Brainlab, Germany)	55	N/A	77 (51-126)	<.001	N/A

RCT, randomized controlled trial; NP, nonrandomized prospective; Nav, computerized navigation; SSI, surgical site infection; DVT, deep vein thrombosis; TAL, transverse acetabular ligament; Pts, number of patients; UCLA, University of California, Los Angeles.
[a] These operative time analyses represent an increase in time compared to the other intervention.

anatomic parameters, it is unclear to what extent these differences might be clinically significant or be associated with differences in clinical outcomes. The concept of the Lewinnek et al. and Callanan et al. safe zones [34,35] that were used as safe acetabular positioning guidelines in many of these studies has been shown in more recent literature to be unreliable predictors of prosthetic hip joint stability and clinical outcomes [36,37]. A recent study ascertained that Lewinnek's "safe zone" does not have any direct effect on patient-reported functional outcome scores [38]. Additionally, it determined that there were no strong correlations between the absolute position of the cup and functional outcome scores [38]. However, in terms of tribology, a cup inclination of 40º is favorable for avoiding impingement and accelerated wear [39]. Therefore, regardless of the validity of Lewinnek and Callanan's "safe zones," precise and accurate component positioning is clinically important, and using a technology or technique to improve the reliability of component positioning is beneficial to patient outcomes.

Similarly, there remains an incomplete understanding of the relationship between leg length, offset restoration, and clinical outcomes. Residual LLD after primary THA has been associated with back pain and sciatica, neuritis, gait disorders, general dissatisfaction, dislocation, and early loosening of components [40]. Historically, authors have suggested that LLD cannot be eliminated after THA and can only be mitigated [41]. However, the findings of this review suggest that contemporary navigation technology may be close to eliminating residual LLD, considering the mean differences of 1.0mm. Nevertheless, the criteria for acceptable LLD post-THA is not well defined, with 1 review finding that up to 10mm of LLD is well tolerated by most patients [40]. Femoral offset, the perpendicular distance from the center of rotation of the femoral head to the long axis of the femur, was found to adversely affect implant longevity and side-to-side imbalance of abductor muscle strength [42]. This strength imbalance was suggested to be a plausible explanation for post-THA patient-perceived LLD [42]. Evidence suggests that the target goal of femoral offset restoration to reduce polyethylene liner wear is said to be within 5mm of native hip offset [43]. These findings carry implications when assessing the clinical relevance of radiographically significant LLD and offset measurements. They also play a pivotal role in determining whether the additional advantages offered by a more precise intraoperative measurement system translate into tangible clinical benefits. Further research is encouraged to identify the difference between radiographic and clinical significance in LLD and offset discrepancies to identify the best intraoperative measurement method to improve patient outcome and satisfaction.

Nevertheless, the present study demonstrates that technological evolution has contributed to improving the precision and accuracy of hip replacement surgery. It encompasses a logical progression of technology and techniques in THA—from the initial reliance on surgeon's estimates (freehand) to the identification and use of anatomical landmarks (eg, the transverse acetabular ligament), mechanical guides, digital guides, and beyond. Many of these techniques and technologies were specifically developed to address perceived limitations in the precision and accuracy of component positioning, and given that most medical devices will undergo some degree of testing and validation to confirm effectiveness prior to introduction into clinical use, it is reasonable to expect each successive generation of technology to provide some incremental benefit. In some cases, a technology may provide further benefit by combining the benefits of multiple previous generations of techniques. For example, many computer navigation systems combine the use of multiple anatomic reference points with the digital equivalent of a mechanical guide.

The adoption of new techniques and technologies in medicine in general and hip arthroplasty in particular should be evaluated with consideration of impact on both cost and clinical outcomes. High-value interventions that either improve outcomes and the same or lower cost are typically attractive to all stakeholders in the health care system. However, the introduction of technologies that increase cost requires a more careful evaluation to ensure that it is justified by the impact on outcomes. Unfortunately, only 2 of 25 studies reported any cost data [16,18], and none reported differences in overall surgical case cost or episode of care costs. However, the computerized navigation technologies that were associated with increased accuracy and precision also resulted in increased mean surgical case time. Given the marked costs associated with operating room time as well as the inevitable additional costs of acquiring and supporting computerized technology, additional study is warranted to better understand the overall value of these technologies with respect to THA.

Conclusions

In summary, there are a range of techniques and technologies available for the intraoperative assessment of component positioning, leg lengths, and offset during THA. While freehand techniques are the least equipment and resource intensive, they are also associated with the poorest accuracy and precision. Conversely, computerized navigation technologies appear to consistently provide the greatest accuracy and precision across all component and anatomic parameters, at the cost of increased operating room time. However, there is a paucity of data concerning the impact of these different techniques, as well as the associated differences in accuracy and precision, on both the overall surgical cost as well as clinical outcomes. Thus, future studies of these techniques and technologies should include economic evaluations of both surgical and episode-of-care costs, as well as reporting of adverse events and patient-reported outcomes. Such investigations are crucial to aid surgeons and healthcare systems in making informed decisions regarding how component positioning is optimized during THA.

Conflicts of interest

M. Zywiel is a paid consultant for DePuy Synthes, ZImmerBiomet, and OPEXC Inc. and is an editorial board member of CORR and Expert Review of Medical Devices. All other authors declare no potential conflicts of interest.

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CRediT authorship contribution statement

Cedric Chung: Writing – original draft, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Ibrahim Bin Hazzaa:** Writing – review & editing, Validation, Investigation, Data curation. **Raja Hakim:** Writing – review & editing, Validation, Investigation, Data curation. **Michael G. Zywiel:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

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# ▲	Searches
1	(acetabul* component or acetabul* cup or acetabul* implant or acetabul* offset or fem#r* component or fem#r* stem or fem#r* implant or fem#r* offset).tw.
2	(inclination or abduction or version or anteversion or retroversion or position* or placement).tw.
3	(THA or THR or Total Hip* or Hip Arthroplast* or Hip Replacement? or Hip Prosthesis).tw.
4	(Precision or Evaluat* or Accurac* or Assess* or reliability or validity or reproducibility).tw.
5	(THA or THR or Total Hip* or Hip Arthroplast* or Hip Replacement? or Hip Prosthesis).tw.
6	(evaluat* or accurac* or assess* or Precision or reliability or validity or reproducibility).tw.
7	(leg-length discrepanc* or leg-length inequalit* or leg-length difference* or limb-length discrepanc* or limb-length inequalit* or limb-length difference* or LLD).tw.
8	measur*.tw.
9	6 and 7 and 8
10	5 and 6 and 7 and 8
11	Arthroplasty, Replacement, Hip.sh.
12	1 and 2 and 4
13	(child* or pediatric* or paediatric* or neuro* or depression or depressed).tw.
14	9 not 13
15	(acetabul* or fem#r*).tw.
16	(offset or hip offset).tw.
17	3 and 6 and 8 and 15 and 16
18	3 or 11
19	(canine or dog or cow or bovine or horse or equine or monkey or primate or sheep or ovine).tw.
20	12 and 18
21	11 and 12
22	20 not 19
23	21 not 19
24	(1 and 2 and 3 and 4) not 19
25	remove duplicates from 10
26	remove duplicates from 22
27	remove duplicates from 14
28	remove duplicates from 17
29	25 or 26 or 27 or 28
30	limit 29 to english
31	remove duplicates from 30

Supplementary Figure 1. Search strategy used

Supplementary Table 1
List of all techniques and technologies for intraoperative component positioning identified in the present study

Anatomic landmark techniques
Use of specific anatomic structures as an intraoperative landmark for component positioning
Examples:
Transverse acetabular ligament (TAL)
Fluoroscopy
Use of intraoperative fluoroscopy or continuous X-ray technology to assist in component positioning, without adjunct digital measurement tools
Freehand Technique [a]
The visual estimation of component positioning in THA without specific mechanical or computerized guides
Examples:
Shuck test
Visual estimation of angle between leg axis and metal rod of stem inserter handle
Direct manual manipulation of components without anatomical landmarks or mechanical guides/aids
Mechanical guides
The use of a physical mechanical guide to assist with intraoperative component positioning
Examples:
Intraoperative Pin and Caliper
Cup Positioning Guide
Patient Specific Instrumentation
Protractor
Goniometer
Smartphone Inclinometer
Novel mechanical guide attached to a pelvic lateral positioner in the anatomic pelvic plane (APP)
Mechanical angle guide
Computerized navigation systems
he use of computerized navigation systems intraoperatively to assist in component positioning
Examples:
Imageless navigation systems
Vector-Vision CT-Free Hip 3.1 (BrainLab, Germany)
Hiplogics Universal Protocol (PRAXIM Medivision, USA)
Hip Unlimited 5.0 (BrainLab, Germany)
Orthopilot THAplus 3.0 software (Aesculap, Germany)
HipAlign (Orthoalign Inc., USA)
Hip 6.0 Prototype (BrainLab, Germany)
CT-based navigation
Surgigate System (Medivision, Switzerland)
Augmented reality (AR) navigation
Novel AR-based portable navigation system (Japan)
AR-hip (Zimmer Biomet, Japam)
Fluoroscopic navigation software
Surgeon's Checklist positioning software (Radlink Inc., USA)
Electromagnetic navigation
Guiding Star E-Hip module (Ekliptik, Slovenia)
Ultrasound navigation
Orthopilot THAplus 3.0 software with ultrasound probe (Aesculap, Germany)
Robotic-arm assisted surgery systems
The use of an intraoperative robotic-arm assisted surgery system for component positioning
Example:
TRex-RS Robotic Arm (Longwell Company, China)

[a] All techniques included in this category met one or more of the following criteria: were explicitly described as using freehand technique, described performing the surgery without any mechanical or computerized guides or aids, did not describe using any specific anatomic reference point for positioning (for example, the transverse acetabular ligament), and/or only referenced using the “shuck test” (which does not involve any mechanical guides) to assess the appropriateness of component positioning.