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Robotic-Arm Assisted versus Conventional Total Hip Arthroplasty via the Direct Anterior Approach: Acetabular Cup Positioning, Limb-Length Discrepancy, and Offset Restoration

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Abstract

Background

Robotic-arm assisted total hip arthroplasty (THA) aims to improve the precision of acetabular cup placement and limb-length restoration. Whether these radiographic advantages translate into clinically meaningful benefits over conventional THA via the direct anterior approach (DAA) remains incompletely characterized.

Methods

We retrospectively reviewed 330 consecutive patients who underwent primary unilateral THA via the DAA by a single surgeon-led team between January 2021 and January 2025 at a tertiary referral center. In total, 165 patients received MAKO robotic-assisted THA and 165 underwent conventional THA. Indications included osteonecrosis of the femoral head, developmental dysplasia of the hip, rheumatoid arthritis, osteoarthritis, ankylosing spondylitis, and femoral neck fracture. All postoperative radiographic measurements were performed independently by two attending radiologists using a picture archiving and communication system. Primary outcomes comprised acetabular anteversion and inclination, leg-length discrepancy (LLD), and hip offset parameters. Secondary outcomes included Lewinnek and Callanan safe-zone compliance, rates of absolute LLD exceeding 5 mm and 10 mm, total intraoperative blood loss, operative time, complications, and Harris Hip Scores (HHS) at a maximum follow-up of 3 years.

Results

Baseline demographics were well matched between groups (all $P > 0.05$). The robotic group demonstrated significantly greater accuracy in acetabular cup placement, with 94.6% of cups within the Lewinnek safe zone versus 84.2% in the conventional group ($P = 0.004$; OR = 3.24). The proportion of patients with absolute LLD > 5 mm was markedly lower in the robotic group (15.8% vs. 38.2%; $P < 0.001$; OR = 0.30). No between-group differences were observed for the Callanan safe zone, severe LLD (> 10 mm), or individual offset parameters. Robotic-assisted THA was associated with longer operative time (118.5 vs. 97.8 min; $P < 0.001$) and greater total intraoperative blood loss (285.6 vs. 160.3 mL; $P < 0.001$). HHS at final follow-up was comparable between groups (90.5 vs. 90.1; $P > 0.05$).

Conclusions

Robotic-arm assisted DAA THA improves the precision of acetabular cup positioning within the Lewinnek safe zone and reduces the incidence of moderate limb-length discrepancy compared with conventional THA. These radiographic gains are achieved at the expense of longer operative time and

greater blood loss, with no detectable difference in short-term functional outcomes. Long-term studies are needed to determine whether these improvements translate into reduced dislocation rates and improved implant survivorship.

Background

Total hip arthroplasty (THA) is among the most successful and cost-effective interventions in modern orthopedics, delivering predictable pain relief and functional restoration for end-stage hip disease. Despite its overall success, accurate acetabular cup positioning remains a cornerstone of durable outcomes, as malpositioning has been linked to dislocation, impingement, accelerated polyethylene wear, and aseptic loosening [1, 2, 3]. Alarmingly, between 38% and 47% of acetabular components implanted with conventional technique have been reported to lie outside the accepted safe-zone target [22], underscoring the persistent challenge of achieving consistent positional accuracy. Moreover, a substantial proportion of post-THA dislocations occur in hips where the acetabular component is positioned within the so-called safe zone [23], suggesting that static radiographic targets alone are insufficient predictors of stability and that combined anteversion—integrating both acetabular and femoral component orientation—may provide a more reliable biomechanical framework [23, 24].

Beyond component positioning, restoration of limb length and femoral offset are critical determinants of postoperative function, abductor mechanics, and patient satisfaction. Leg-length discrepancy (LLD) is one of the most common causes of patient dissatisfaction following THA and has been implicated in approximately 5% of all medical errors and up to 14% of malpractice litigations related to the procedure in the United States [25]. Although LLD of less than 10 mm is generally considered clinically well tolerated, even moderate discrepancies of 5–10 mm have been associated with perceived inequality, gait adaptation, lumbar compensation, and diminished patient-reported outcomes [25, 26]. Similarly, failure to restore femoral offset compromises abductor muscle function, reduces hip stability, and may contribute to abnormal gait mechanics [25].

The direct anterior approach (DAA) has gained increasing traction as a muscle-sparing alternative to traditional posterior or lateral approaches, with the purported advantages of more rapid early rehabilitation and lower dislocation risk [4]. However, the DAA introduces distinct challenges for acetabular component positioning: the supine patient posture and restricted operative field can obscure the anatomical landmarks that guide cup orientation in lateral approaches, potentially increasing the risk of malinclination and malversion [5]. Intraoperative fluoroscopy has been proposed as one solution, with studies demonstrating that fluoroscopic or radiographic guidance can reduce LLD beyond the 5 mm threshold to near zero in DAA THA [25], but this approach adds operative time, radiation exposure, and equipment demands.

Robotic-arm assisted systems have emerged as a more comprehensive technological response to these positioning challenges. The evolution of robotic THA has progressed from fully autonomous systems such as ROBODOC in the 1990s—which demonstrated improved femoral component positioning but

were associated with elevated soft-tissue injury and periprosthetic fracture rates—to the current generation of semi-active, haptically guided platforms [22]. Today, the MAKO system (Stryker Corporation, Kalamazoo, MI, USA) dominates the global market, offering preoperative three-dimensional (3D) CT planning coupled with intraoperative haptic guidance and real-time navigation [6, 7]. By constraining reaming and cup insertion within a preplanned trajectory, these systems aim to reduce the positional variability inherent to freehand technique [8]. Additional semi-active platforms, including ROSA (Zimmer Biomet, Warsaw, IN, USA), VELYS (DePuy Synthes, Raynham, MA, USA), and CORI (Smith & Nephew, Watford, UK), have entered the market, with the ROSA system specifically designed for the DAA and utilizing intraoperative fluoroscopic rather than CT-based navigation [22]. A comprehensive meta-analysis by Loke et al. reported that MAKO-assisted THA achieved Lewinnek and Callanan safe-zone compliance rates of 94.7% and 90.3%, respectively, compared with only 65.8% and 57.1% for conventional THA [9].

Critically, the intraoperative measurements provided by robotic systems have been validated against postoperative computed tomography. Nodzo et al. demonstrated strong correlations between intraoperative robotic and postoperative CT measurements for acetabular inclination (R^2=0.62), acetabular version (R^2=0.76), and combined anteversion (R^2=0.65), with mean deviations of only 1.6 mm for limb length and 0.5 mm for offset [23]. This level of accuracy lends credibility to the radiographic improvements reported across the literature and supports the use of robotic technology as a reliable tool for precision hip reconstruction.

Multiple randomized controlled trials (RCTs) have corroborated these radiographic advantages [10, 11, 12]; however, their clinical significance remains contested. Systematic reviews and meta-analyses of RCT-level evidence have consistently failed to demonstrate meaningful differences in Harris Hip Scores (HHS) or complication rates between robotic and conventional THA at short- to mid-term follow-up [13, 14]. A recent comprehensive meta-analysis by Llombart-Blanco et al. of 12 studies including 1,224 hips confirmed improved radiological outcomes with MAKO-assisted THA but found no significant differences in HHS (MD 0.61, 95% CI − 0.22 to 1.45) or intraoperative complications (OR 0.96, 95% CI 0.51–1.79) [26]. Interestingly, the same analysis found that Forgotten Joint Scores (FJS) favored the MAKO group (MD 5.99, 95% CI 4.10–7.88), although the difference did not exceed the minimally clinically important difference, raising questions about whether more sensitive patient-reported instruments may better capture the clinical impact of improved component positioning [26]. Furthermore, DAA-specific studies have shown improved component positioning with robotic assistance but comparable implant survival and adverse event profiles [15, 16].

Additional considerations include a well-documented learning curve—with proficiency reportedly attained after 7 to 35 cases—during which operative time and blood loss decline progressively [17, 18, 19]. More recent work using cumulative summation (LC-CUSUM) analysis has provided more granular estimates, suggesting that operative time stabilizes after approximately 22 cases, while femoral offset and limb-length preservation proficiency are achieved even earlier—after approximately 5 and 15 cases, respectively [24]. The rapid acquisition of offset and limb-length proficiency is clinically meaningful, as

these parameters directly influence soft-tissue balance and patient satisfaction. Cost-effectiveness remains a concern [20], particularly given that the radiographic precision gains have not yet translated into demonstrable reductions in revision rates or long-term complications.

Evidence specifically comparing robotic and conventional DAA THA performed by the same surgical team remains limited, and such data are essential to isolate the effect of the robotic platform from surgeon-related confounding. Furthermore, most comparative studies have focused on cup positioning alone, with fewer data on offset restoration and the full spectrum of radiographic outcomes in the DAA setting. Accordingly, we conducted this retrospective comparative study to test the hypothesis that MAKO robotic-assisted DAA THA would yield more precise acetabular cup placement and reduced limb-length discrepancy without compromising offset restoration or short-term clinical outcomes, relative to conventional DAA THA performed by the same surgeon-led team.

Methods

Study design and patient selection

This retrospective comparative cohort study was conducted at the Department of Sports Medicine and Adult Reconstructive Surgery, Nanjing Drum Tower Hospital, a tertiary academic referral center. The study protocol was approved by the institutional review board of Nanjing Drum Tower Hospital (approval number: 2025-0419-01; approval date: June 03, 2025) and was performed in accordance with the 1964 Declaration of Helsinki and its later amendments. Written informed consent was obtained from all patients prior to surgery. We reviewed the electronic medical records and radiographic archives of all consecutive patients who underwent primary unilateral THA via the DAA between January 2021 and January 2025. Patients were allocated to the robotic-assisted THA group or the conventional THA group based on the surgical instrumentation used. To minimize selection bias, all patients who received MAKO robotic-assisted THA during the study period were included, and consecutive patients who underwent conventional DAA THA by the same surgeon-led team during the same time frame were selected as controls.

Eligible patients were those with end-stage hip disease of any etiology—including osteonecrosis of the femoral head (ONFH), developmental dysplasia of the hip (DDH), rheumatoid arthritis (RA), primary or secondary osteoarthritis (OA), ankylosing spondylitis (AS), and displaced femoral neck fracture—who underwent primary unilateral THA via the DAA with either MAKO robotic assistance or conventional instrumentation and for whom complete clinical and radiographic follow-up data were available.

Patients were excluded if they had (1) neuromuscular dysfunction, active psychiatric illness, alcoholism, or substance abuse that could confound functional assessment; (2) a history of prior ipsilateral hip surgery or revision arthroplasty; or (3) active or chronic periprosthetic infection.

Surgical Technique

Conventional THA Group: All procedures were performed under spinal or general anesthesia with the patient in the supine position on a standard operating table. The DAA was used in all cases, performed through an interval between the sartorius and tensor fasciae latae muscles. The implants used in the conventional group were predominantly from Stryker Corporation (Kalamazoo, MI, USA), with a minority of patients receiving components from DePuy Synthes (Johnson & Johnson, New Brunswick, NJ, USA). No intraoperative fluoroscopic guidance was employed in any case.

Preoperative planning was performed by the senior surgeon using anteroposterior pelvic radiographs to estimate implant size, femoral neck osteotomy level, and anticipated limb-length adjustment. Intraoperatively, the acetabulum was reamed in a sequential fashion, and cup orientation was determined by the surgeon based on patient positioning, inserter alignment, the relationship between the component and anatomical landmarks (including the transverse acetabular ligament and acetabular rim), and tactile feedback. Following cup and liner insertion, the femoral canal was prepared and trial components were assembled. Joint stability and limb length were assessed by manual evaluation of capsular tension and by comparing the relative heights of the knees and heels, which guided the final selection of femoral stem and head dimensions.

Robotic-Arm Assisted THA Group: All procedures in the robotic group were performed using the MAKO robotic-arm system (Stryker Corporation, Kalamazoo, MI, USA). All implants were press-fit biological acetabular cups (Tritanium or Trident; Stryker) and femoral stems (Accolade II; Stryker), with ceramic femoral heads articulating against highly cross-linked polyethylene (HXLPE) liners.

Preoperatively, all patients underwent CT scanning of the pelvis, bilateral hips, and bilateral knees. The DICOM data were transferred to the MAKO engineering team for three-dimensional reconstruction of the pelvis and proximal femur. A collaborative preoperative planning session was held between the operating surgeon and the engineering team to determine implant sizes, target cup position, and anticipated limb-length and offset restoration.

Intraoperatively, a pelvic reference array with infrared reflective markers was secured to the anterior superior iliac spine using three cortical screws. Following hip exposure and dislocation, a femoral reference array was affixed to the intertrochanteric region via a single screw. Registration of the proximal femur and femoral head was then completed. Under navigational guidance, the femoral neck osteotomy level was marked and executed according to the preoperative plan. During femoral canal preparation, the system displayed the planned stem size in real time, and after trial stem insertion, dynamic feedback on femoral anteversion and offset was provided.

For acetabular preparation, the medial wall and acetabular rim were registered sequentially. Under MAKO RIO robotic-arm guidance, the acetabulum was reamed to the preplanned depth and diameter, and the cup was subsequently impacted. Throughout reaming and insertion, the system provided continuous visual feedback on cup inclination and anteversion, while haptic boundary constraints prevented deviation beyond the planned trajectory. After insertion of the acetabular component, liner, femoral stem, and trial head, the hip was reduced. The system then displayed the final combined anteversion, global

offset, and limb-length change, which guided the final head-length selection to optimize joint stability and soft-tissue tension.

Perioperative Management and Follow-up Protocol

All patients received standardized perioperative care, including multimodal analgesia, thromboprophylaxis, antiemetic therapy, and accelerated rehabilitation protocols. Mobilization with gait aids and progressive active and passive range-of-motion exercises was initiated on the first postoperative day under the supervision of physiotherapists.

Operative time and any intraoperative complications were prospectively documented. Total intraoperative blood loss was calculated for each patient from suction canister volumes, surgical swabs, and postoperative drain output, adjusted for irrigation fluid. Postoperative complications—including dislocation, periprosthetic fracture, infection, neurovascular injury, and venous thromboembolism—were recorded at each follow-up visit. Patients were reviewed at 3 months, 6 months, 1 year, 2 years, and 3 years postoperatively. At each visit, anteroposterior pelvic and lateral hip radiographs were obtained. The Harris Hip Score (HHS) was administered at the final follow-up to assess pain relief and functional recovery.

Radiographic Assessment

All postoperative radiographic measurements were performed independently by two board-certified attending radiologists who were blinded to patient group allocation, using a picture archiving and communication system (PACS; GE Healthcare, Chicago, IL, USA). Standardized anteroposterior pelvic radiographs were used for all measurements. The following parameters were assessed: (1) Acetabular anteversion and inclination angles. Acetabular anteversion was measured on the anteroposterior radiograph using the ellipse method as described by Domb et al. [21]. Inclination was defined as the angle between the teardrop-interconnecting line and the long axis of the acetabular cup. (2) Leg-length discrepancy (LLD): the perpendicular distance from the lesser trochanter tip to the inferior teardrop line was measured bilaterally; LLD was calculated as the operative-side value minus the contralateral-side value, with negative values indicating shortening and positive values indicating lengthening of the operated limb. (3) Femoral offset: the center of the femoral head was identified using the concentric circle technique; femoral offset was defined as the perpendicular distance from the femoral head center to the long axis of the femoral medullary canal. (4) Acetabular offset: the perpendicular distance from the femoral head center to a vertical line passing through the ipsilateral teardrop (perpendicular to the inter-teardrop line).

Outcome Measures

The primary outcomes were the radiographic parameters detailed above. Secondary outcome measures included: (1) rate of acetabular cup placement within the Lewinnek safe zone (inclination 40 ± 10°, anteversion 15 ± 10°) [1]; (2) rate of placement within the Callanan safe zone (inclination 30°–45°, anteversion 5°–25°) [2]; (3) proportion of patients with absolute LLD exceeding 5 mm; (4) proportion of patients with absolute LLD exceeding 10 mm; (5) total intraoperative blood loss; (6) operative time; (7) intraoperative and postoperative complications, including dislocation; and (8) HHS at the final available follow-up.

Statistical Analysis

Data were managed in Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA) and analyzed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Continuous variables were tested for normality with the Shapiro–Wilk test and for homogeneity of variance with Levene's test. Normally distributed variables with equal variances were compared using independent-samples Student's t-test; Welch's t-test was used when variances were unequal. Non-normally distributed variables were compared with the Mann–Whitney U test. Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate. Effect sizes were reported as Cohen's d for parametric comparisons, r for non-parametric comparisons, and Cramer's V for chi-square tests. Odds ratios (OR) with 95% confidence intervals (CI) were computed for binary outcomes. All statistical tests were two-tailed, and a P value less than 0.05 was considered statistically significant.

Results

Baseline Characteristics

A total of 330 patients (165 robotic-assisted, 165 conventional) met the inclusion criteria and formed the study cohort. Baseline demographic and perioperative data are summarized in Table 1 and Fig. 1. The two groups were well matched with respect to age (64.2 vs. 64.4 years; P = 0.598), sex distribution (P = 0.652), and body mass index (23.7 vs. 23.6 kg/m²; P = 0.930). Patients in the robotic group had significantly longer operative times (118.5 ± 33.2 vs. 97.8 ± 22.7 min; P < 0.001) and greater total intraoperative blood loss (285.6 ± 231.9 vs. 160.3 ± 79.5 mL; P < 0.001) compared with the conventional group.

Table 1
Comparison of baseline characteristics between the rTHA and cTHA groups

Variable	rTHA (n = 165)	cTHA (n = 165)	P value
Sex (M/F, %)	67/98 (40.6/59.4)	62/103 (37.6/62.4)	0.652
Age (years)	64.22 ± 10.38	64.43 ± 14.32	0.598
BMI (kg/m²)	23.66 ± 3.55	23.63 ± 3.49	0.930
Total intraoperative blood loss (mL)	285.58 ± 231.90	160.30 ± 79.54	< 0.001
Surgical time (min)	118.45 ± 33.24	97.83 ± 22.68	< 0.001

Data are expressed as mean ± standard deviation or n (%). P values from chi-square test (sex) or Mann-Whitney U test (age, total intraoperative blood loss, surgical time) or independent samples t-test (BMI).

Radiographic Outcomes

The radiographic measurements are detailed in Table 2 and illustrated in Fig. 2. The robotic group exhibited significantly lower mean acetabular anteversion (10.05 ± 2.89° vs. 12.71 ± 2.44°; P < 0.001) and higher mean inclination (41.47 ± 4.02° vs. 36.36 ± 6.66°; P < 0.001) than the conventional group. The mean inclination in the robotic group was closer to the canonical 40° target, whereas the mean anteversion fell below the midpoint of the Lewinnek range. No significant between-group differences were detected for postoperative LLD, operative-side or contralateral acetabular and femoral offsets, or bilateral offset differences (all P > 0.05). A trend toward greater operative-side femoral offset was observed in the conventional group, although this did not reach statistical significance (P = 0.075).

Table 2
Comparison of radiographic measurements between the rTHA and cTHA groups

Parameter	rTHA	cTHA	Test	Statistic	P value
Anteversion (°)	10.05 ± 2.89	12.71 ± 2.44	M-W U	U = 7183	< 0.001
Inclination (°)	41.47 ± 4.02	36.36 ± 6.66	M-W U	U = 6450	< 0.001
Postoperative LLD (mm)	0.22 ± 6.01	0.02 ± 6.44	M-W U	U = 12883	0.400
Op-side acet. offset (mm)	36.36 ± 5.25	36.81 ± 5.13	M-W U	U = 13931	0.714
Op-side fem. offset (mm)	40.59 ± 9.11	42.30 ± 8.23	t-test	t = 1.785	0.075
Contra acet. offset (mm)	44.85 ± 6.73	43.88 ± 5.31	M-W U	U = 12895	0.408
Contra fem. offset (mm)	37.74 ± 9.50	38.84 ± 8.44	M-W U	U = 14241	0.469
Bilat. acet. offset diff. (mm)	-8.49 ± 7.59	-7.08 ± 5.75	M-W U	U = 15001	0.109
Bilat. fem. offset diff. (mm)	2.85 ± 10.36	3.46 ± 8.85	M-W U	U = 14554	0.278

Data are expressed as mean ± standard deviation. M-W U = Mann-Whitney U test; LLD = leg-length discrepancy; acet. = acetabular; fem. = femoral; contra = contralateral; bilat. = bilateral; op = operative-side.

Threshold and Categorical Outcomes

The results of the threshold and categorical analyses are presented in Table 3 and Figs. 3–5. The proportion of acetabular cups positioned within the Lewinnek safe zone was significantly higher in the robotic group (94.55% vs. 84.24%; P = 0.004; OR = 3.24; 95% CI: 1.47–7.16). In contrast, no significant difference was found for the Callanan safe zone (78.18% vs. 75.15%; P = 0.603). The rate of absolute LLD exceeding 5 mm was substantially lower in the robotic group (15.76% vs. 38.18%; P < 0.001; OR = 0.30; 95% CI: 0.18–0.51). For severe LLD exceeding 10 mm, the rates were low in both groups and did not differ significantly (5.45% vs. 8.48%; P = 0.387).

Table 3
Clinical threshold analysis between the rTHA and cTHA groups

Threshold	rTHA (%)	cTHA (%)	χ^2	OR (95% CI)	P value	Sig.
|LLD| >5 mm	15.76	38.18	14.24	0.303 (0.18–0.51)	< 0.001	Yes
|LLD| >10 mm	5.45	8.48	0.75	0.622 (0.26–1.48)	0.387	No
Lewinnek safe zone	94.55	84.24	8.09	3.242 (1.47–7.16)	0.004	Yes
Callanan safe zone	78.18	75.15	0.27	1.185 (0.71–1.98)	0.603	No

|LLD| = absolute leg-length discrepancy; OR = odds ratio; CI = confidence interval; Sig. = significance (P < 0.05).

To provide a comprehensive visual overview of the magnitude and direction of all between-group comparisons, a forest plot of effect sizes was constructed Fig. 6. This plot summarizes the standardized effect size and 95% confidence interval for each outcome measure, allowing direct comparison of the relative impact of robotic assistance across all radiographic, clinical, and functional endpoints.

Functional Outcomes

The mean duration of follow-up was up to 3 years. At the final follow-up assessment, HHS values were comparable between the robotic and conventional groups (90.5 ± 6.8 vs. 90.1 ± 6.5; P > 0.05), indicating equivalent short-term functional outcomes.

Discussion

In this retrospective comparative cohort of 330 DAA THA procedures performed by a single surgeon-led team, robotic-arm assistance improved the precision of acetabular cup placement within the Lewinnek

safe zone and reduced the proportion of patients with moderate limb-length discrepancy (> 5 mm) relative to conventional instrumentation. These radiographic benefits were achieved at the cost of longer operative times and greater intraoperative blood loss, while hip offset restoration and short-term functional outcomes, as measured by the HHS, were indistinguishable between groups.

The rate of Lewinnek safe-zone compliance in the robotic group (94.6%) was nearly identical to the 94.7% reported in a recent meta-analysis of MAKO-assisted THA by Loke et al. [9] and closely aligns with the 95%–100% range described in the Llombart-Blanco meta-analysis of 1,224 hips [26]. In contrast, the conventional group rate (84.2%) was substantially higher than the pooled 65.8% observed across historical controls [9]. This discrepancy is likely multifactorial. First, the conventional procedures in the present series were all performed by an experienced high-volume surgeon, which may have raised the baseline performance ceiling compared with multi-surgeon pooled analyses. Second, the DAA-specific learning curve and the absence of fluoroscopic guidance in the conventional arm may have influenced cup orientation differently than in posterior-approach cohorts. Nonetheless, the 10-percentage-point absolute improvement in Lewinnek compliance is clinically meaningful, as cup malposition has repeatedly been linked to dislocation risk and polyethylene wear [1, 3].

A nuanced finding of the present study is the divergent behavior of inclination and anteversion in the robotic group. While mean inclination (41.5°) clustered tightly around the 40° target, mean anteversion (10.1°) was notably lower than the 15° midpoint of the Lewinnek range and also lower than in the conventional group (12.7°). This pattern is consistent with observations from the Llombart-Blanco meta-analysis, which found greater cup anteversion in the MAKO group compared with conventional THA (MD 1.53°) but at levels that varied substantially across studies depending on planning philosophy [26]. In the present cohort, the preoperative planning protocol may have systematically targeted a more conservative anteversion, possibly to mitigate anterior impingement risk in the supine DAA position. Whether this lower anteversion compromises long-term stability—particularly in the setting of reduced posterior soft-tissue tension—cannot be determined from the present data and warrants longer-term surveillance. Importantly, accumulating evidence suggests that the static Lewinnek safe zone is an imperfect predictor of stability, as a substantial proportion of dislocations occur in cups positioned within the safe zone [23]. A more comprehensive biomechanical approach, incorporating combined anteversion—the sum of acetabular and femoral anteversion—may better characterize the risk of impingement and instability [23, 24]. The observation underscores an important distinction: robotic technology improves the precision with which a target is achieved, but the clinical quality of the result ultimately depends on the appropriateness of the preoperative plan itself.

Failure to demonstrate a significant difference in Callanan safe-zone compliance is worth examining. The Callanan criterion is more restrictive with respect to inclination (30°–45° versus 30°–50°) but equally permissive for anteversion (5°–25°). In the present cohort, the robotic group's inclination distribution was centered at approximately 41°, well within the Callanan range, but the relatively low anteversion values likely reduced the overall Callanan hit rate. The Loke et al. meta-analysis reported 90.3% Callanan compliance for MAKO THA versus 57.1% for conventional THA [9], a difference far larger than observed

here. This gap probably reflects differences in patient mix, surgical approach, implant selection, and the learning-curve stage of the participating centers. It is also notable that the Llombart-Blanco meta-analysis identified significant mismatches between preoperative planning and final cup placement after MAKO-assisted THA [26], suggesting that intraoperative adjustments—whether due to soft-tissue constraints, bone quality, or surgeon judgment—may partially explain the variability in safe-zone compliance rates across studies.

The reduction in moderate LLD (> 5 mm) from 38.2% to 15.8% represents one of the most clinically relevant findings of this study. The clinical significance of this reduction should not be underestimated: LLD has been identified as one of the most common causes of patient dissatisfaction following THA, accounting for approximately 5% of all medical errors and up to 14% of malpractice litigations related to the procedure in the United States [25]. While LLD of less than 10 mm is generally considered well tolerated, even moderate discrepancies of 5–10 mm have been associated with perceived inequality, gait adaptation, lumbar compensation, and diminished patient-reported outcomes [25]. The ability of the robotic system to display dynamic limb-length changes intraoperatively—and to guide head-length selection accordingly—likely accounts for this improvement. Importantly, the rates of severe LLD (> 10 mm) were low in both groups and did not differ significantly, suggesting that experienced surgeons using either technique can usually avoid clinically important limb-length inequality. It is worth noting that even more impressive LLD control has been reported with intraoperative fluoroscopic guidance in DAA THA, with one study achieving 0% of patients with LLD exceeding 5 mm using wireless digital radiography and digital templating software [25]. These data align with prior reports of reduced LLD with robotic assistance [9, 13] and extend the evidence specifically to the DAA setting.

Offset restoration was broadly comparable between groups, with no significant differences in acetabular or femoral offsets on either the operative or contralateral side, nor in bilateral offset differences. The trend toward greater operative-side femoral offset in the conventional group (P = 0.075) should be interpreted cautiously; it may reflect differences in implant geometry between the two groups (all Stryker implants in the robotic group versus a mix of manufacturers in the conventional group) or simply stochastic variation. That robotic assistance did not demonstrably improve offset restoration is perhaps unsurprising, given that offset is heavily constrained by femoral canal geometry, implant design, and native anatomy—factors that are largely independent of instrumentation. Nevertheless, recent work by Delaigue et al. using LC-CUSUM analysis demonstrated that femoral offset preservation within 2 mm is achieved relatively rapidly in the MAKO learning curve—after approximately 5 cases—suggesting that proficiency in offset restoration is acquired early and may not differ substantially from experienced conventional practice once the learning curve is surmounted [24]. These findings are consistent with those of Maldonado et al., who reported no meaningful differences in combined offset restoration between MAKO workflow protocols [7].

Operative time was approximately 20 minutes longer in the robotic group, and total blood loss was nearly 80% greater. The operative-time difference is consistent with the existing literature and reflects the additional time required for reference array placement, registration, and system initialization [9, 10].

Recent LC-CUSUM analysis has provided a more precise estimate of the learning curve for operative time, suggesting stabilization after approximately 22 cases [24], which falls within the broader 7–35 case range previously reported [17, 18, 19]. The substantial difference in blood loss warrants closer scrutiny. The wide standard deviation in the robotic group (231.9 mL) suggests that a subset of cases drove the overall increase. Possible contributing factors include the additional screw-based fixation of the pelvic reference array, the learning-curve effect during early robotic cases, and potentially longer soft-tissue retraction time. That said, blood loss in both groups remained well within acceptable limits for primary THA, and no transfusion-related complications were recorded.

Short-term functional outcomes, as assessed by the HHS at up to 3 years, were nearly identical between groups (90.5 vs. 90.1). This equivalence is consistent with the broader literature: multiple systematic reviews and meta-analyses of RCTs have failed to detect meaningful differences in HHS or other patient-reported outcomes between robotic and conventional THA at follow-up intervals of 1–3 years [13, 14, 15]. The Llombart-Blanco meta-analysis of 1,224 hips similarly found no significant difference in HHS (MD 0.61, 95% CI − 0.22 to 1.45) [26]. The likely explanation is a ceiling effect: modern THA, regardless of technique, achieves such high levels of function that further increments are difficult to demonstrate with generic scoring instruments. Interestingly, the same meta-analysis found that Forgotten Joint Scores (FJS) favored the MAKO group (MD 5.99, 95% CI 4.10–7.88), although the difference did not exceed the minimally clinically important difference [26]. This finding raises the intriguing possibility that more sensitive patient-reported outcome measures, such as the FJS, which captures the subjective sense of having a natural joint, may detect subtler benefits of improved positioning that the HHS is not designed to capture. Whether the radiographic advantages of robotic assistance translate into reductions in revision surgery, dislocation, or late polyethylene wear—endpoints that require a decade or more of follow-up—remains the central unresolved question in the field.

This study has several limitations that merit acknowledgment. First, its retrospective, non-randomized design introduces the potential for selection bias, although the well-matched baseline demographics and single-surgeon-team design mitigate this concern somewhat. Second, the heterogeneity of implant manufacturers in the conventional group, while reflective of real-world practice, introduces variability in offset geometry and cup design that may have influenced radiographic comparisons. Third, the absence of intraoperative fluoroscopy in the conventional arm, while standard practice in many centers, may have contributed to the between-group differences observed; a study comparing robotic assistance with fluoroscopy-guided conventional THA would provide a more stringent test of the robotic platform's incremental value, particularly given that fluoroscopy has been shown to reduce LLD > 5 mm to near-zero rates [25]. Fourth, follow-up extending to only 3 years is insufficient to evaluate implant survivorship, late dislocation, or wear-related outcomes. Fifth, postoperative CT was not obtained for validation of component position, which would have enabled more precise assessment of combined anteversion and femoral stem version; however, previous work has demonstrated strong correlations between intraoperative robotic measurements and postoperative CT for these parameters [23]. Sixth, the single-institution setting and the learning-curve period inherent in adopting a new technology may limit the generalizability of these findings. Finally, it is important to recognize that even with robotic assistance,

discrepancies between preoperative planning and final implant position can occur [26], and intraoperative clinical judgment remains essential.

Strengths of the investigation include the same surgeon-led team design, which eliminates inter-surgeon confounding; the use of two independent, blinded radiologists for all measurements, which enhances the reliability of the radiographic data; and the comprehensive assessment of multiple outcome domains-cup positioning, limb length, offset, complications, and functional scores-providing a broad view of the comparative effectiveness of the two approaches.

Conclusion

Robotic-arm assisted DAA THA improves the accuracy of acetabular cup placement within the Lewinnek safe zone and substantially reduces the incidence of moderate limb-length discrepancy compared with conventional instrumentation. These radiographic gains are accompanied by longer operative times and greater intraoperative blood loss, whereas hip offset restoration and short-term functional outcomes at up to 3 years are equivalent. Whether the improvements in component positioning translate into clinically meaningful reductions in dislocation, wear, and revision rates will require long-term, ideally randomized, comparative effectiveness data.

Declarations

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Not applicable.

Author contributions

QJ contributed to the conception and design of the study, analysis and interpretation of data, manuscript drafting and revision, and statistical analysis. YY contributed to data acquisition, statistical analysis, and critical revision of the manuscript. DC participated in data acquisition and provided administrative. ZX contributed to data analysis and interpretation, critical revision of the manuscript, and administrative, technical, or material support. All authors read and approved the final manuscript.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to patient privacy concerns and institutional data protection policies of Nanjing Drum Tower Hospital, but are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

The study protocol was approved by the institutional review board of Nanjing Drum Tower Hospital (approval number: 2025-0419-01; approval date: June 03, 2025) and was performed in accordance with the 1964 Declaration of Helsinki and its later amendments. Written informed consent was obtained from all patients prior to surgery.

Consent for publication

Written informed consent for publication of de-identified clinical data and images was obtained from the patients whose images are presented.

Competing interests

The authors declare no competing interests.

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Figures

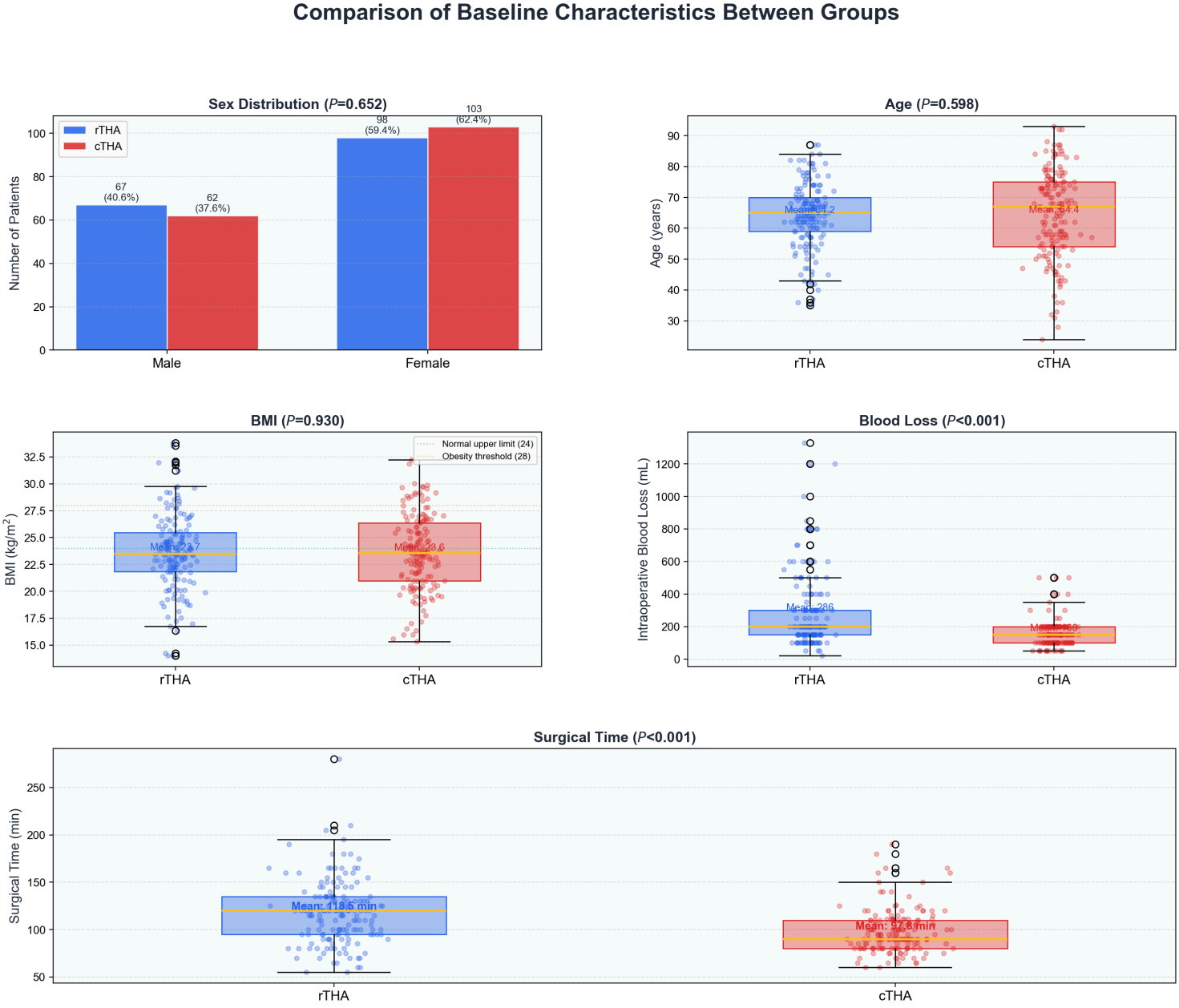


Figure 1

Comparison of baseline characteristics between the rTHA and cTHA groups. (A) Sex distribution; (B) Age; (C) BMI; (D) Total intraoperative blood loss; (E) Surgical time. Box plots show median, IQR, and range; individual data points are jittered for visualization.

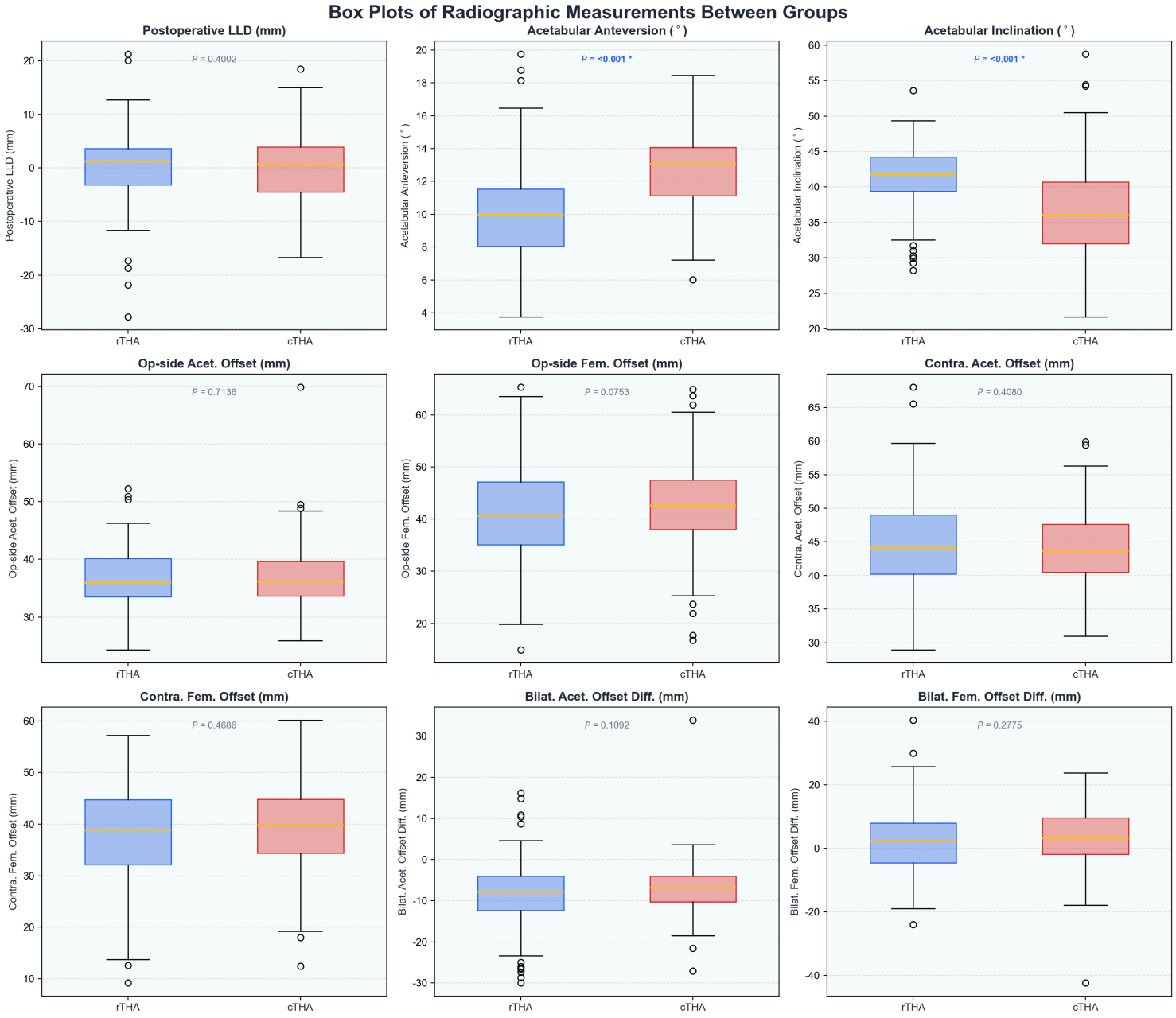


Figure 2

Box plots comparing radiographic measurements between the rTHA and cTHA groups. (A) Acetabular anteversion; (B) Acetabular inclination; (C) Postoperative LLD; (D) Operative-side acetabular offset; (E) Operative-side femoral offset; (F) Contralateral acetabular offset; (G) Contralateral femoral offset; (H) Bilateral acetabular offset difference; (I) Bilateral femoral offset difference. * P<0.05.

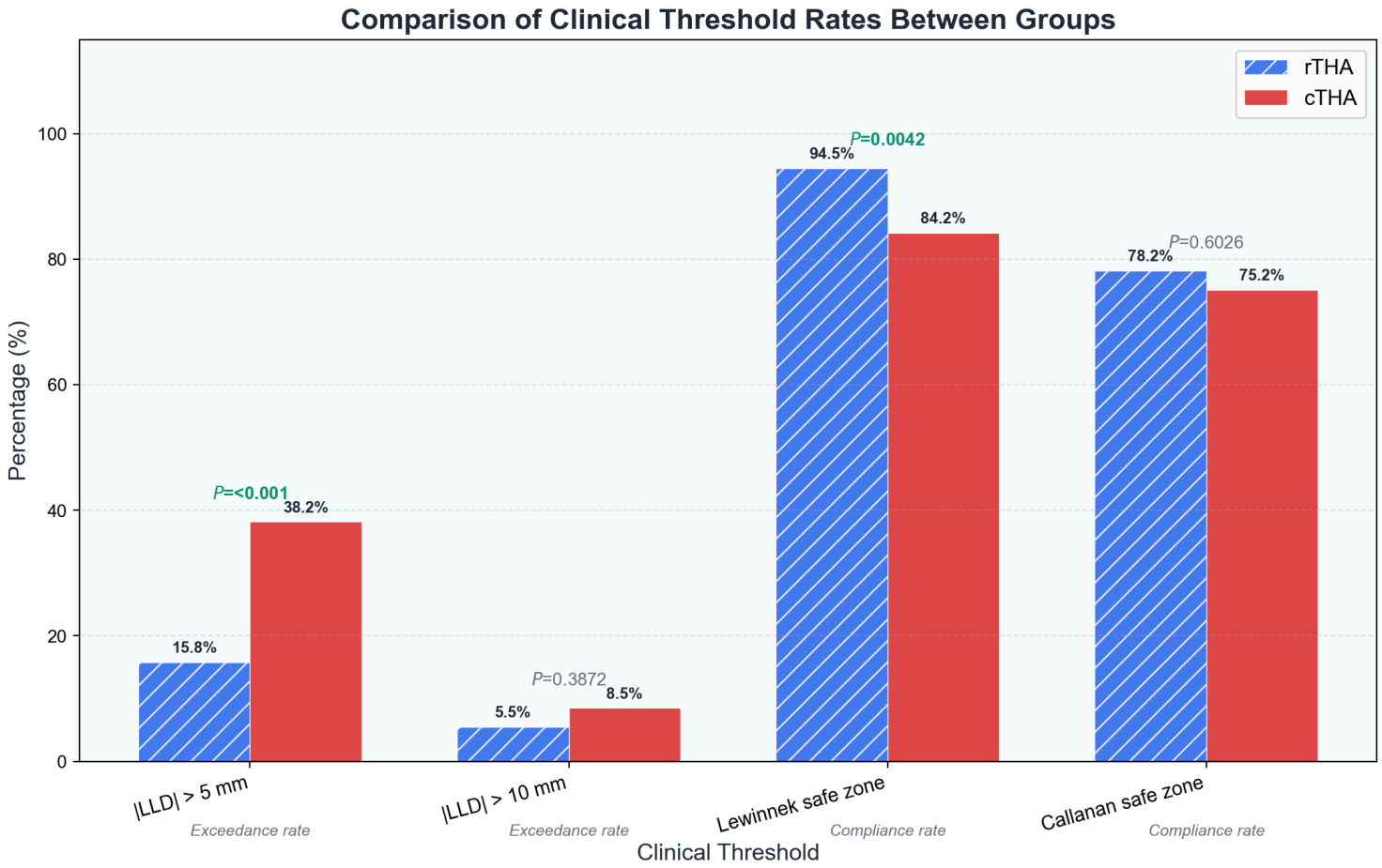


Figure 3

Comparison of clinical threshold compliance rates between the rTHA and cTHA groups. Blue bars represent the rTHA group; red bars represent the cTHA group. Solid bars indicate statistically significant differences (P<0.05); translucent bars indicate non-significant differences. P values are shown above each pair.

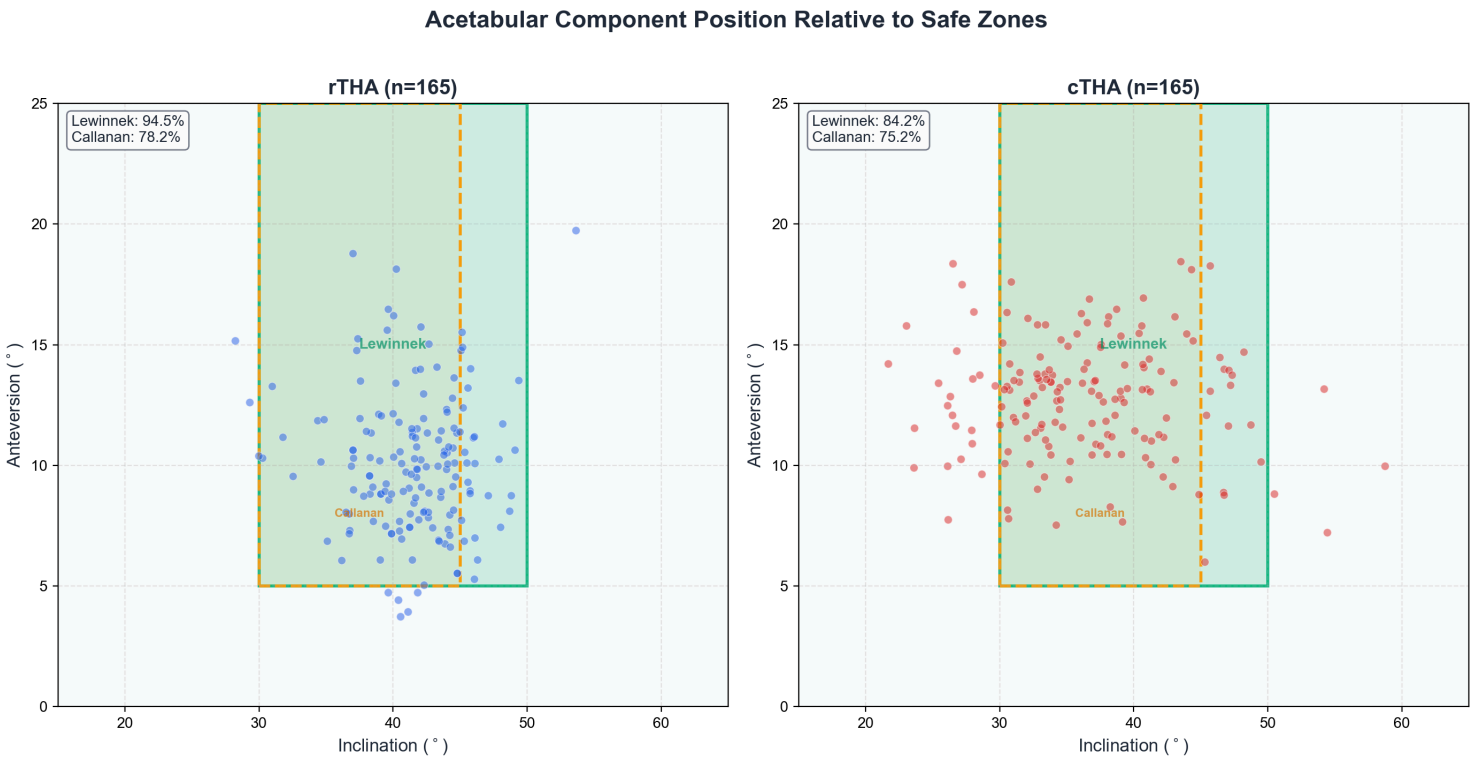


Figure 4

Scatter plot of acetabular component positioning relative to the Lewinnek and Callanan safe zones. The shaded areas represent the Lewinnek safe zone (inclination 40±10°, anteversion 15±10°) and Callanan safe zone (inclination 30°–45°, anteversion 5°–25°). Each point represents one patient.

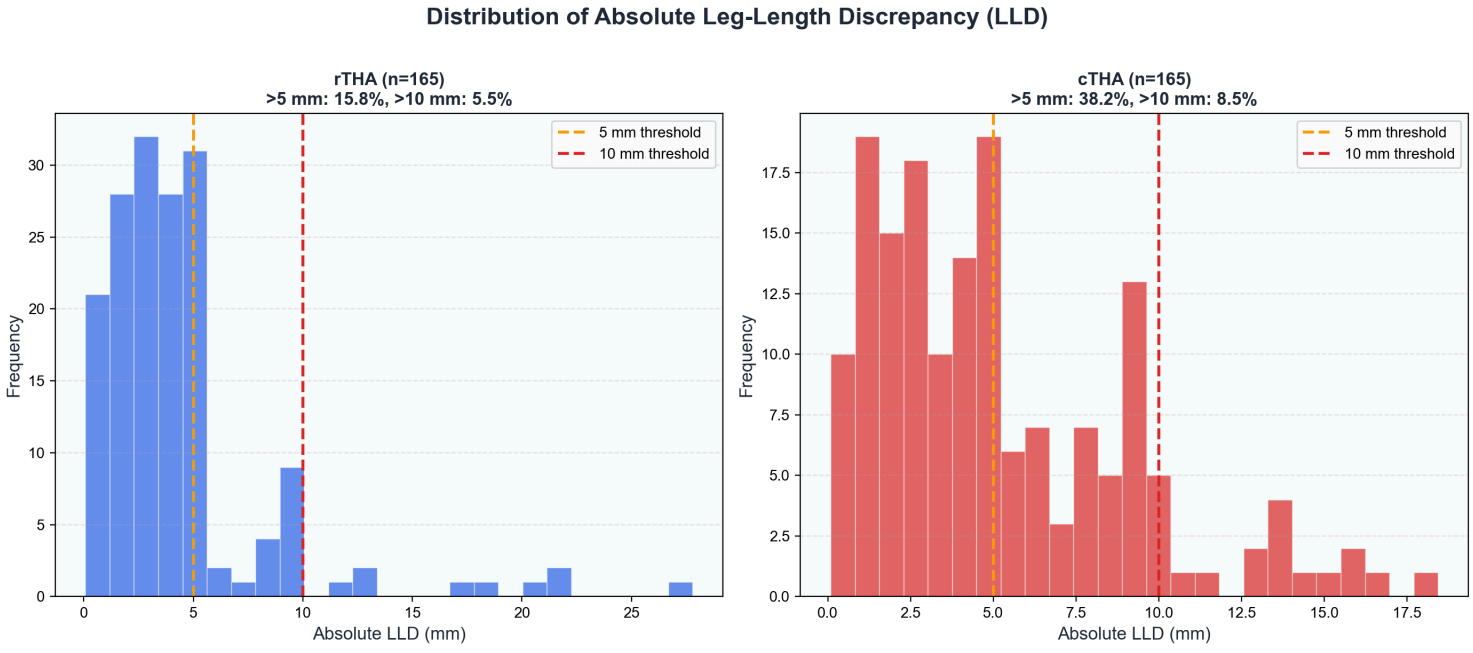


Figure 5

Distribution of absolute leg-length discrepancy (LLD) in the rTHA and cTHA groups. The vertical dashed lines indicate the 5 mm and 10 mm thresholds. The rTHA group shows a tighter distribution with fewer outliers beyond the 5 mm threshold.

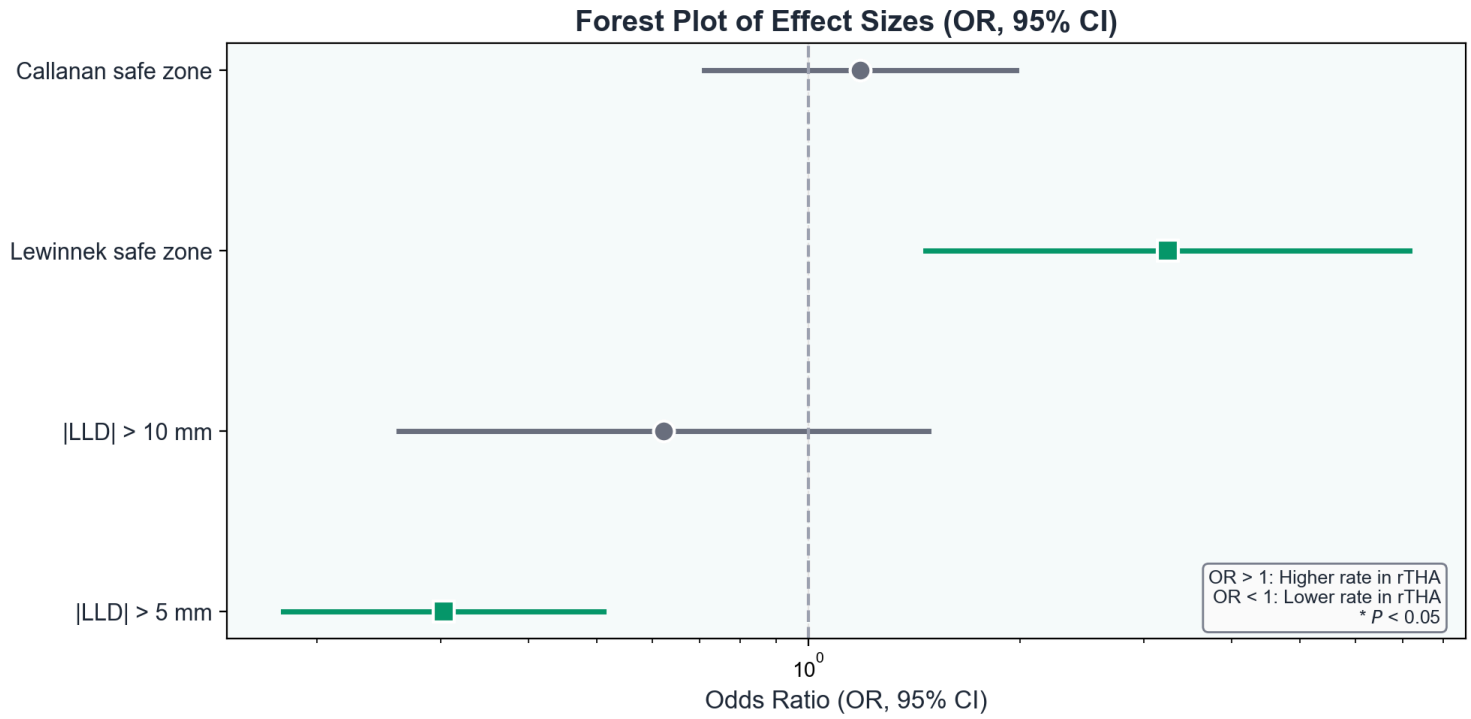


Figure 6

Forest plot of effect sizes for all significant and non-significant comparisons between the rTHA and cTHA groups. Cohen's d is used for parametric comparisons; r is used for non-parametric comparisons; Cramer's V is used for chi-square tests. Positive values favor the rTHA group; negative values favor the cTHA group.