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RESEARCH

Robotic-arm assisted total hip arthroplasty correlates with superior acetabular bone preservation: a cup-to-head ratio and volumetric analysis

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Abstract

Preservation of acetabular bone stock during primary total hip arthroplasty (THA) is increasingly important, particularly in younger patients with higher lifetime revision risk. Robotic-arm assisted THA has the potential to improve reaming precision and minimize unnecessary bone removal; however, comparative data using robust surrogate measures of acetabular bone preservation remain limited. This prospective observational cohort study included 101 consecutive primary THAs performed by a single surgeon between January 2024 and January 2025. Fifty hips underwent conventional manual THA (CTHA) and 51 hips underwent robotic-arm assisted THA (RTHA) using a CT-based robotic platform. Native femoral head diameter was measured intraoperatively and implanted acetabular cup size was recorded. Acetabular bone resection was assessed using linear (c–f), relative ((c–f)/f), and volumetric ($(c^3–f^3)/f^3$) surrogate indices. Cup-to-head diameter ratio was analyzed as an independent measure of cup proportionality. The RTHA group demonstrated significantly smaller linear (1.63 ± 1.09 mm vs. 3.30 ± 1.45 mm), relative (0.03 ± 0.02 vs. 0.07 ± 0.03), and volumetric (0.10 ± 0.07 vs. 0.23 ± 0.11) indices of acetabular bone resection compared with the CTHA group (all $p < 0.001$). The median cup-to-head ratio was significantly lower in RTHA (1.02 [IQR 1.02–1.04]) than CTHA (1.07 [IQR 1.06–1.09]; $p < 0.001$), with a large effect size ($r = 0.64$). RTHA may be associated with greater preservation of native acetabular bone compared with CTHA, as reflected by reduced linear, relative, and volumetric surrogate indices of reaming. These findings indicate that CT-based planning with semi-autonomous haptic control enables more anatomically precise acetabular preparation with improved bone conservation.

Keywords Robotic-arm assisted surgery · Acetabular bone preservation · Cup-to-head diameter ratio · Volumetric bone resection · CT-basedsurgical planning · Bone stock conservation

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Introduction

Total hip arthroplasty (THA) remains one of the most successful orthopaedic procedures for end-stage hip arthritis, widely regarded as the operation of the century [1]. There is a projected increase in the incidence of revision THA which is set to double by 2026 [2, 3]. Younger age at the time of primary THA is consistently associated with an increased risk of revision surgery [4]. In the Asian context, it is well published that more than 50% of total hip arthroplasties are performed in patients younger than 60 years, most commonly as a consequence of pre-existing hip disorders such as avascular necrosis, developmental dysplasia, post-traumatic arthritis, and sequelae of childhood hip disease [5].

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Published series report revision rates ranging from 4% to 33% in patients younger than 30 years, which are substantially higher than the 7-15% revision rates observed in older patient populations despite longer follow-up durations [6]. This demographic shift underscores the growing importance of preserving native bone stock at the index procedure, particularly on the acetabular side where revision reconstruction remains technically demanding [7]. Excessive reaming can alter the hip's center of rotation, compromise cup stability, and predispose to impingement or periprosthetic fracture [6, 8, 9].

Conventional manual techniques rely on tactile feedback and visual landmarks for acetabular preparation, which can lead to variability in reaming depth and orientation whereas, recent advances in computer-assisted and robotic arm-assisted technologies aim to improve the precision of component positioning and bone conservation [10–12]. By following a pre-operative plan derived from computed tomography, robotic systems enable controlled and reproducible reaming while maintaining the acetabular center within the anatomic boundaries [13]. This technology therefore allows preservation of acetabular bone that is particularly relevant in younger patients undergoing THA, where minimizing bone loss at the index procedure can facilitate future revision surgery [14, 15].

While previous investigations have quantified bone removal by comparing acetabular component sizes between hip resurfacing and THA, few have examined bone preservation among different modes of THA [16–18]. Suarez-Ahedo et al. [19] introduced the acetabular cup-to-native femoral head diameter ratio as an indirect, reproducible measure of bone resection, reporting smaller ratios with robotic-arm-assisted THA compared to conventional THA.

The present prospective cohort study builds upon this conceptual framework by incorporating intraoperative femoral head measurements and introducing a volumetric analogue of the cup-to-head relationship to better approximate relative acetabular bone removal. By normalizing acetabular reaming to native patient anatomy, this approach allows meaningful comparison across varying femoral head sizes and provides a three-dimensional surrogate for bone preservation. The primary aim of this study was to compare acetabular bone preservation between conventional and robotic-arm assisted THA using linear, relative, and volumetric indices of bone resection. We hypothesized that robotic-arm assisted THA would demonstrate significantly reduced acetabular bone removal compared with conventional manual techniques, reflecting more anatomically precise reaming.

Methods

This investigation was designed as a prospective observational cohort study conducted at a single, high-volume academic arthroplasty center. Patients undergoing either primary robotic-assisted or conventional manual total hip arthroplasty (THA) between January 2024 and January 2025 were enrolled following approval from the institutional ethics committee (SIEC/2023/531). The study protocol and reporting adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [20].

All procedures were performed by a single senior arthroplasty surgeon. Robotic-assisted cases utilized a CT-based robotic platform (Mako system, Stryker Orthopaedics, Fort Lauderdale, FL), while conventional cases employed identical implant systems without robotic assistance. Surgical planning data were obtained from the Mako planning software, and radiological measurements were retrieved from the institutional Picture Archiving and Communication System (PACS). Demographic and clinical variables were prospectively collected from the institutional joint replacement registry.

Patient selection

All patients undergoing primary manual or robotic-assisted THA during the study period were eligible for inclusion. Indications for surgery included avascular necrosis of the femoral head, primary osteoarthritis, post-traumatic arthritis, femoral neck fractures treated with THA, unilateral developmental dysplasia of the hip, and degenerative arthritis secondary to childhood hip disorders such as Perthes disease and slipped capital femoral epiphysis (SCFE).

A total of 101 consecutive patients met the inclusion criteria. Of these, 50 patients underwent conventional THA (CTHA), while 51 patients underwent robotic-assisted THA (RTHA), and all were included in the final analysis.

Surgical technique

All procedures were performed using an uncemented Accolade II femoral stem and an uncemented Trident hemispherical acetabular component. All patients underwent a routine preoperative CT scan to facilitate image-based surgical planning using Mako 4.0 software, irrespective of whether the definitive procedure was performed manually or with robotic assistance.

All patients were operated in the lateral decubitus position via the posterior approach. The femoral neck was resected the femoral head diameter was measured using vernier calipers, with the diameter noted in millimeters.

The acetabulum was prepared using sequential reaming technique in manual THA, with cup size decided based on best Antero-Posterior capture of the trial cup and based on coverage. The robotic surgical technique is described below.

Express workflow for robotic THA

Optical array pins were placed in the ipsilateral iliac crest for the pelvic array. The express workflow involves only acetabular registration. An electrocardiogram tab was placed over the lateral epicondyle of the femur prior to skin preparation. A stockinette was then used in the draping process, secured with sterile cling roll, while ensuring that the tab remained palpable. Pelvic pins, as well as pelvic and femoral checkpoints, were placed using the technique described in the enhanced workflow. Hip dislocation was performed after initial registration of the LLD, and femoral neck osteotomy was then performed. The remaining steps of acetabular registration, preparation, trial and definitive component insertion were performed similarly to that of the enhanced workflow. The acetabular cup size is determined from the Mako software, based on the guidelines for component positioning on the CT-based plan. The surgeon then selected the optimal size and position of the components considering the centre of rotation of the hip, length of the leg and combined offset. These measurements were used to guide execution of the acetabular reaming, which was a single ream with reamer size 1 mm smaller than the planned acetabular component size. Following this, the femur was broached, trialled, and definitive components were inserted freehand by the surgeon. The surgeon was able to measure the change in leg length and combined offset at any time during the procedure with either the trial or definitive components in situ by reducing the hip and registering with the pointer the palpable tab on the distal ECG Lead reference point and divot on the proximal femoral checkpoint from which the software calculates leg length and combined offset values.

Comparative measurements and ratios

The primary outcomes of interest were quantitative indices reflecting the extent of acetabular bone resection during total hip arthroplasty. Measurements were derived from intraoperative data and surgical records as follows:

- **Femoral head diameter (f, mm):**
- The native femoral head diameter was measured intraoperatively after femoral neck resection using Vernier callipers across the largest dimension of the femoral head. This value served as a surrogate for the native acetabular diameter and was used as the baseline for comparative calculations. A single assessor performed two measurements after femoral head resection, taking care to avoid measurements over osteophytes; averages were used when different values were obtained.
- **Acetabular cup diameter (c, mm):**
- The outer diameter of the implanted acetabular shell, as recorded in the operative log and confirmed from the implant database.
- **Absolute difference (c − f, mm):**
- Represents the linear difference between the implanted cup and the native femoral head diameters, indicating the circumferential extent of acetabular bone removed beyond the native anatomic size.
- **Relative difference ratio ((c − f)/f):**
- The ratio based on absolute difference normalized to the native femoral head size. This ratio allows for comparison across varying head sizes in different patients.
- **Volumetric ratio ($(c^3 - f^3)/f^3$):**
- An estimation of volumetric difference of acetabular reaming relative to the estimated native acetabular volume. This parameter serves as a three-dimensional surrogate for total bone volume removed. It must be noted, volumetric bone resection was approximated using a cubic ratio as described, assuming acetabular and femoral head geometry is near-hemispherical. This is only a ratio and does not directly estimate volume of bone removed in reaming process, but is valid for hemispherical cups.
- **Cup-to-Prosthetic Femoral Head ratio (c/h):** Defined as the ratio between the implanted acetabular cup and the prosthetic femoral head diameter.
- **Cup-to-head diameter ratio (c/f):**
- Defined as the implanted acetabular cup diameter divided by the size of the native femoral head (h). This ratio provides an index of cup oversizing relative to the chosen femoral head.

These parameters were analyzed as continuous variables. The linear (c − f), relative ((c − f)/f), and volumetric ($(c^3 - f^3)/f^3$) indices were considered the principal surrogate measures of acetabular bone resection, while the cup-to-head diameter ratio (c/h) was analyzed as an independent comparative metric of cup proportionality between robotic-arm assisted (RTHA) and conventional THA (CTHA) groups.

Statistical analysis

Descriptive statistics were calculated for all continuous and categorical variables. Continuous data are presented as mean ± standard deviation (SD) for normally distributed variables and as median with interquartile range (IQR) for non-normally distributed data. Categorical data are expressed as frequencies and percentages.

Table 1 Demographic and clinical characteristics

Variable	CTHA (n = 50)	RTHA (n = 51)	p-value
Age (years)	51.37 ± 13.14	43.24 ± 13.10	**0.003***
Male, n (%)	28 (56.0%)	39 (76.5%)	**0.049** †
Female, n (%)	22 (44.0%)	12 (23.5%)	
Pathology, n (%)			**< 0.001**†
AVN	22 (44.0%)	41 (80.4%)	
OA	6 (12.0%)	7 (13.7%)	
Post-traumatic arthritis	2 (4.0%)	2 (3.9%)	
AS	0 (0.0%)	1 (2.0%)	
Femoral neck fracture	6 (12.0%)	0 (0.0%)	
Other	14 (28.0%)	0 (0.0%)	

*Mann Whitney-U test; †Chi-square test

Normality of distribution was assessed using the Shapiro-Wilk test. For normally distributed continuous variables, comparisons between the conventional total hip arthroplasty (CTHA) and robotic-arm assisted total hip arthroplasty (RTHA) groups were made using the independent samples t-test. For non-normally distributed data, the Mann-Whitney U test was applied. The Chi-square or Fisher's exact test (where appropriate) was used to compare categorical variables such as gender distribution and underlying pathology between groups.

Primary outcome measures included the difference between acetabular cup and native femoral head diameters (c–f), the relative ratio ((c–f)/f), and the volumetric analogue ((c^3–f^3)/f^3), representing surrogate indices of acetabular bone resection. In addition, the cup-to-head diameter ratio (cup diameter ÷ prosthetic femoral head diameter) was analyzed to assess proportional cup sizing between groups.

Given that the cup-to-head ratio data were non-normally distributed (Shapiro-Wilk $p = 0.036$ for RTHA, $p = 0.0006$ for CTHA), a Mann-Whitney U test was used to compare medians. The effect size (r) was computed and interpreted according to Cohen's criteria (0.1 = small, 0.3 = medium, 0.5 = large). A two-tailed p-value < 0.05 was considered statistically significant.

Power and sample size estimation

A post-hoc power analysis was performed based on the observed difference in cup-to-head ratio between groups (mean ± SD = 1.07 ± 0.03 for CTHA vs. 1.02 ± 0.02 for RTHA). With $\alpha = 0.05$ and the observed effect size ($r = 0.64$), the achieved power ($1 - \beta$) exceeded 0.95, indicating a high probability of detecting a true difference between groups. Given the total sample of 101 hips (50 CTHA, 51 RTHA), this study was adequately powered to detect a medium-to-large effect size (Cohen's $d \geq 0.5$) for the primary outcome measures.

Results

A total of 101 hips were analyzed, including 50 conventional THA (CTHA) and 51 robotic-arm assisted THA (RTHA). The summary table of demographic variables are tabulated in Table 1. Acetabular cup size was compared with the native femoral head as a surrogate of acetabular bone resection using the following metrics: c − f (mm), (c − f)/f (relative difference), and the volumetric analogue ($c^3 - f^3$)/f^3 (Table 2).

Comparative analysis of acetabular and femoral head dimensions is presented in Table 2. The mean native femoral head diameter was significantly larger in the RTHA group compared with the CTHA group (49.67 ± 3.20 mm vs. 46.42 ± 3.41 mm, $p < 0.001$), reflecting the younger and more male-predominant cohort in the robotic group. Despite this, the implanted cup diameter was only marginally larger in RTHA (51.29 ± 3.37 mm) than in CTHA (49.72 ± 3.77 mm; $p = 0.029$*), resulting in a markedly smaller difference between cup and head diameters (c – f = 1.63 ± 1.09 mm for RTHA vs. 3.30 ± 1.45 mm for CTHA; $p < 0.001$*).

When normalized to the native femoral head, the relative difference ((c – f)/f) was significantly lower in the robotic group (0.03 ± 0.02) compared with the conventional group (0.07 ± 0.03; $p < 0.001$). The volumetric ratio ((c^3 – f^3)/f^3) demonstrated an even greater variation, with mean values of 0.10 ± 0.07 for RTHA and 0.23 ± 0.11 for CTHA ($p < 0.001$). These findings indicate that single-time robotic-arm assisted reaming conserved native acetabular bone stock compared to manual sequential reaming.

Table 2 Cup-head metrics and volumetric comparison

Measure	Description	CTHA (Mean ± SD) (n = 50)	RTHA (Mean ± SD) (n = 51)	p-value *
Native femoral head (f), mm	Native femoral head diameter	46.42 ± 3.41	49.67 ± 3.20	**< 0.001**
Cup outer diameter (c), mm	Implanted acetabular cup diameter	49.72 ± 3.77	51.29 ± 3.37	**0.029**
c - f, mm	Difference between cup and native head diameters	3.30 ± 1.45	1.63 ± 1.09	**< 0.001**
(c - f)/f	Relative difference between cup and head diameters	0.07 ± 0.03	0.03 ± 0.02	**< 0.001**
(c^3 - f^3)/f^3	Relative volumetric difference (surrogate for acetabular bone resection)	0.23 ± 0.11	0.10 ± 0.07	**< 0.001**

*Mann Whitney-U test

Table 3 Distribution of prosthetic femoral head sizes

Head size (mm)	CTHA (n = 50)	RTHA (n = 51)	Total (n)
28 mm	10 (20%)	5 (9.8%)	15 (14.9%)
32 mm	24 (48%)	17 (33.3%)	41 (40.6%)
36 mm	16 (32%)	29 (56.9%)	45 (44.5%)

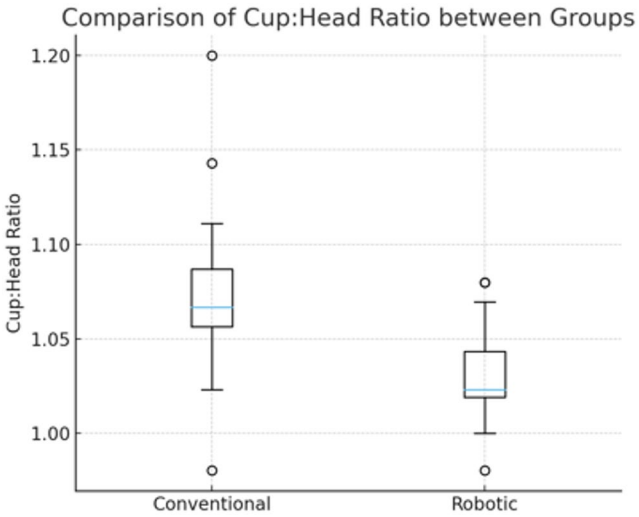

Fig. 1 Box plot showing variations in the cup: head size ratios between the two groups

Distribution of prosthetic femoral head sizes

The distribution of femoral head sizes implanted in both groups is summarized in Table 3. Although both techniques predominantly used 32 mm and 36 mm heads, there was a clear shift toward larger head diameters in the robotic cohort. Specifically, 56.9% of RTHA cases utilized a 36 mm head compared with only 32% in the CTHA group, while the use of smaller 28 mm heads was less frequent with robotic assistance (9.8% vs. 20%). This pattern likely reflects improved cup positioning and stability achieved through precise robotic reaming, allowing surgeons to safely accommodate larger femoral heads that enhance range of motion and reduce dislocation risk.

Overall, the robotic group exhibited narrow cup-head proportionality and lower volumetric resection indices, confirming that robotic-arm assistance enables accurate anatomic reaming and maximizes acetabular bone preservation without compromising implant stability.

The cup-to-native head ratio (c/f), representing the acetabular cup diameter divided by the native femoral head diameter, was significantly lower in the robotic-assisted group compared to the conventional group. The median cup: head ratio was 1.02 (IQR 1.02–1.04) in the robotic group and 1.07 (IQR 1.06–1.09) in the conventional group, demonstrating a highly significant difference ($U = 322.5$, $p < 0.001$) (Fig. 1). The calculated effect size was large ($r = 0.64$), indicating a substantial reduction in cup oversizing with robotic assistance. This suggests that robotic arthroplasty achieves more consistent and anatomically proportionate acetabular sizing compared to the conventional technique.

The median C/H ratio was 1.50 [IQR 1.44–1.56] in the robotic cohort and 1.56 [IQR 1.50–1.56] in the conventional cohort. Normality testing using the Shapiro-Wilk test demonstrated non-normal distributions in both groups ($p < 0.001$ for both); therefore, between-group comparison was performed using the Mann–Whitney U test. There was no statistically significant difference in the C/H ratio between the robotic and conventional groups ($p = 0.170$). This indicates comparable prosthetic femoral head size selection across cohorts.

Discussion

The most important finding of this prospective cohort study is that robotic-arm assisted total hip arthroplasty resulted in significantly reduced acetabular bone resection compared with conventional manual THA, as demonstrated by smaller absolute (c–f), relative ((c–f)/f), and volumetric ((c^3–f^3)/f^3) indices. Despite the robotic cohort exhibiting larger native femoral head diameters, observed differences were not simply a reflection of patient size but rather of surgical technique with the aid of image-based planning. Although excessive reaming may result in medialized cups with potential impingement, fracture risk and changes in the centre of rotation, these parameters are not exclusively reported in this study. There were no intra-operative fractures in any case in this study.

These findings corroborate those of Suarez-Ahedo et al. who first reported that the ratio of implanted cup diameter to the native femoral head diameter can serve as a quantitative surrogate for acetabular bone resection [19]. By extending their framework to a larger, heterogenous dataset including cases of osteoarthritis, avascular necrosis, post-traumatic arthritis, and femoral neck fractures, our analysis confirms the reproducibility of this metric across diverse pathologies.

The lower linear, relative and volumetric ratios in the RTHA group reflect more conservative reaming and improved adherence to pre-planned anatomy, likely attributable to the robotic system's ability to maintain the reamer's center within the anatomic acetabular walls [11]. This translates into better preservation of subchondral bone stock, which may benefit long-term implant stability and easier future revision procedures. The observed difference in mean cup diameter by approximately 1.5 mm smaller in RTHA appears modest numerically but represents a clinically meaningful reduction in circumferential bone removal, especially when considered volumetrically [21]. Our volumetric ratio (c^3–f^3)/f^3 analysis provides a more sensitive

reflection of total acetabular bone reamed. Consistent with prior literature comparing bone resection in resurfacing versus THA [22–24], the smaller volumetric values observed in the robotic group underscore the potential of technology-assisted THA to minimize unnecessary bone removal without compromising component stability.

Demographically, our robotic cohort included relatively younger patients due to the higher frequency of AVN, and paralleling the trend of adopting technology-assisted arthroplasty for higher-demand cases [5, 25, 26]. Although differences in age distribution may partially influence cup size selection, statistical control for native femoral head diameter and pathology ensures that the observed differences are attributable primarily to the surgical technique rather than patient anatomy. Reducing acetabular bone loss at primary THA has implications for implant survivorship, restoration of biomechanics, reducing blood loss during surgery and revision complexity [18, 27–29]. With robotic systems providing millimeter-level feedback and consistent reaming trajectories, these results suggest an evolving paradigm toward precision-based arthroplasty emphasizing anatomic conservation [30–32].

This study has some limitations. Volumetric bone resection was approximated using a cubic ratio as described, assuming acetabular and femoral head geometry is near-hemispherical. This is only a ratio and does not directly estimate volume of bone removed in reaming process but is valid for hemispherical cups. However, by replicating the methodology of Suarez-Ahedo et al. [19] and expanding the dataset to include multiple pathologies and volumetric modeling, our study strengthens the external validity of the cup-to-head ratio as a reliable surrogate for bone preservation. Absolute values of bone volume reamed are difficult to accurately estimate with current robotic software or planning.

Conclusion

Robotic-arm assisted total hip arthroplasty was associated with significantly greater preservation of native acetabular bone compared with conventional manual techniques, as reflected by reduced linear, relative, and volumetric surrogate indices of reaming. These findings indicate that CT-based planning with constrained robotic execution enables more anatomically precise acetabular preparation. Given the increasing number of younger patients undergoing primary THA, improved bone preservation at the index procedure may be clinically relevant for future revision surgery. Further longitudinal studies are required to determine the impact of these findings on implant survivorship.

Author contributions AA: Conceptualization; Writing - review & editing; PM: Writing - original draft; Investigation; TJ: Writing - original draft; Formal analysis; MA: Writing - review & editing; Investigation; VBN: Writing - review & editing; AVGR: Writing - review & editing; Conceptualization; Supervision.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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