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ORIGINAL PAPER

Does robotic-assisted computer navigation improve acetabular cup positioning in total hip arthroplasty for Crowe III/IV hip dysplasia? A propensity score case-match analysis

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Abstract

Aims Total hip arthroplasty (THA) in patients with hip-dislocation dysplasia remains challenging. This study aims to evaluate whether these patients may benefit from robotic-assisted techniques.

Methods We reviewed 135 THAs (108 conventional THAs and 27 robotic-assisted THAs) for Crowe type III or IV from January 2017 to August 2019 in our institution. Robotic-assisted THAs were matched with conventional THAs at a 1:1 ratio (27 hips each group) using propensity score matching. The accuracy of cup positioning and clinical outcomes were compared between groups.

Results The inclination of the cup for conventional THAs and robotic THAs was 42.1 ± 5.7 and 41.3 ± 4.6 ($p = 0.574$), respectively. The anteversion of the cup for conventional THAs was significantly greater than that of robotic THAs (29.5 ± 8.1 and 18.0 ± 4.6; $p < 0.001$), respectively. The ratio of the acetabular cup in the Lewinnek safe zone was 37% (10/27) in conventional THAs and 96.3% (26/27) in robotic THAs ($p < 0.001$). Robotic THAs did not achieve better leg length discrepancy than that of conventional THAs (-0.4 ± 10.9 mm vs. 0.4 ± 8.8 mm, $p = 0.774$). There was no difference in Harris Hip Score and WOMAC Osteoarthritis index between groups at the 2-year follow-up. No dislocation occurred in all cases at the final follow-up.

Conclusion Robotic-assisted THA for patients with high dislocation improves the accuracy of the implantation of the acetabular component with respect to safe zone.

Keywords Robot-assisted · Total hip arthroplasty · Dysplasia

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Introduction

Developmental dysplasia of the hip (DDH) is a complex syndrome characterized by morphological abnormalities of the acetabulum and femur. The diagnosis and classification of DDH were commonly based on the Crowe classification [1]. Surgical techniques for total hip arthroplasty (THA) in DDH remain challenging, especially for THA in Crowe III/IV.

Patients with Crowe III/IV often have severe dysplastic morphologies, including abnormal anteversion and inclination of the acetabular, and soft tissue retractions often require specific surgical techniques [2–4]. Notably, the identification of anatomical landmarks (e.g., transverse acetabular ligament) around the acetabular remains challenging. Therefore, it is remarkably hard to determine the orientation of the acetabulum, which may result in malposition. Malposition of the cup during THA was suggested to correlate with post-operative severe complications, such as dislocation

[5, 6], component impingement [7], and leg length discrepancy (LLD) [8]. Not surprisingly, the risk for loosening of the acetabular component and dislocation in THA has been shown to increase in patients with Crowe III and IV [9, 10].

To improve the precision of implanting cup in THA, various techniques have been introduced including pre-operative templating, manual guides, intra-operative bone landmarks, intra-operative navigation, and robotics [11, 12]. Recently, robotic-assisted THA has been suggested to improve the accuracy of cup implantation in primary THA and achieve better clinical outcomes compared to conventional THA [13–17]. However, there is a lack of data about the robotic-assisted THA for complicated cases, such as patients with Crowe III/IV. The present study therefore aims to compare the accuracy of acetabular cup positioning and short-term clinical outcomes between the robotic-assisted THA with the conventional THA for Crowe III/IV DDH.

Methods

Following Institutional Review Board approval, we reviewed 139 cases who underwent unilateral THA for Crowe III/IV DDH from January 2017 to August 2019 in our prospectively maintained institutional electronic DDH database. Patients with missing data for important variables (e.g., full leg length X-ray) and without a minimum of two year follow-up were excluded. Totally, 135 cases with 135 THAs met the inclusion and exclusion criteria, including 108 conventional THAs and 27 robotic-assisted THAs. The robot was introduced to our institution in August 2018. After that, THAs for DDH were routinely performed using robotic-assisted technique unless patients specifically request not to use it.

The robotic-assisted THAs were matched with a conventional THAs at a 1:1 ratio using propensity score matching (PSM) based on the nearest neighbor matching without replacement within a caliper width of 0.2. Parameters were chosen for inclusion in the PSM calculation including age, gender, BMI, ASA score, side (left or right), and Crowe type. The standardized mean differences (SMD) were calculated to evaluate the balance of covariates between groups. The PSM analysis yielded 27 conventional THAs and 27 robotic-assisted THAs that were enrolled in the final analysis (Fig. 1).

Pre-operative planning

The decision-making process of pre-operative planning was made by at least 2 senior surgeons. The post-operative hip centre should be restored to the true socket as possible, and could be properly shifted upward when the bone volume was inadequate (in Crowe III cases), without using augment. For conventional cases, pre-operative templating was conducted by using Orthoview software (version 6.6.1, Materialise, Leuven, Belgium) with plain radiographs to determine component positions and sizing, level of the

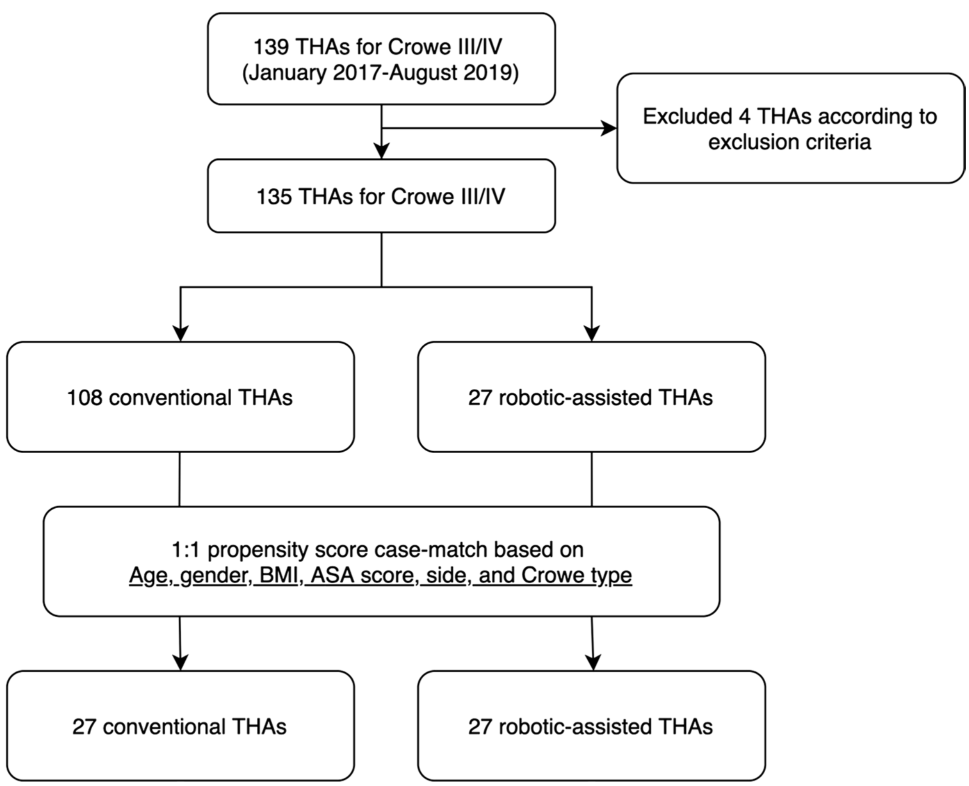

Fig. 1 Study flowchart

neck cut, and amount of leg shortening needed. Patients who were scheduled to undergo robotic-assisted THA completed a CT scan of the involved hip and ipsilateral knee at two weeks pre-operatively (Fig. 2A). In patients with robotic THA, pre-operative planning was performed by surgeons using the robotic system (Fig. 2B). The robotic system utilized the maximum amount of bone to place the 44-mm (or more) acetabular cup without intentionally retaining bone

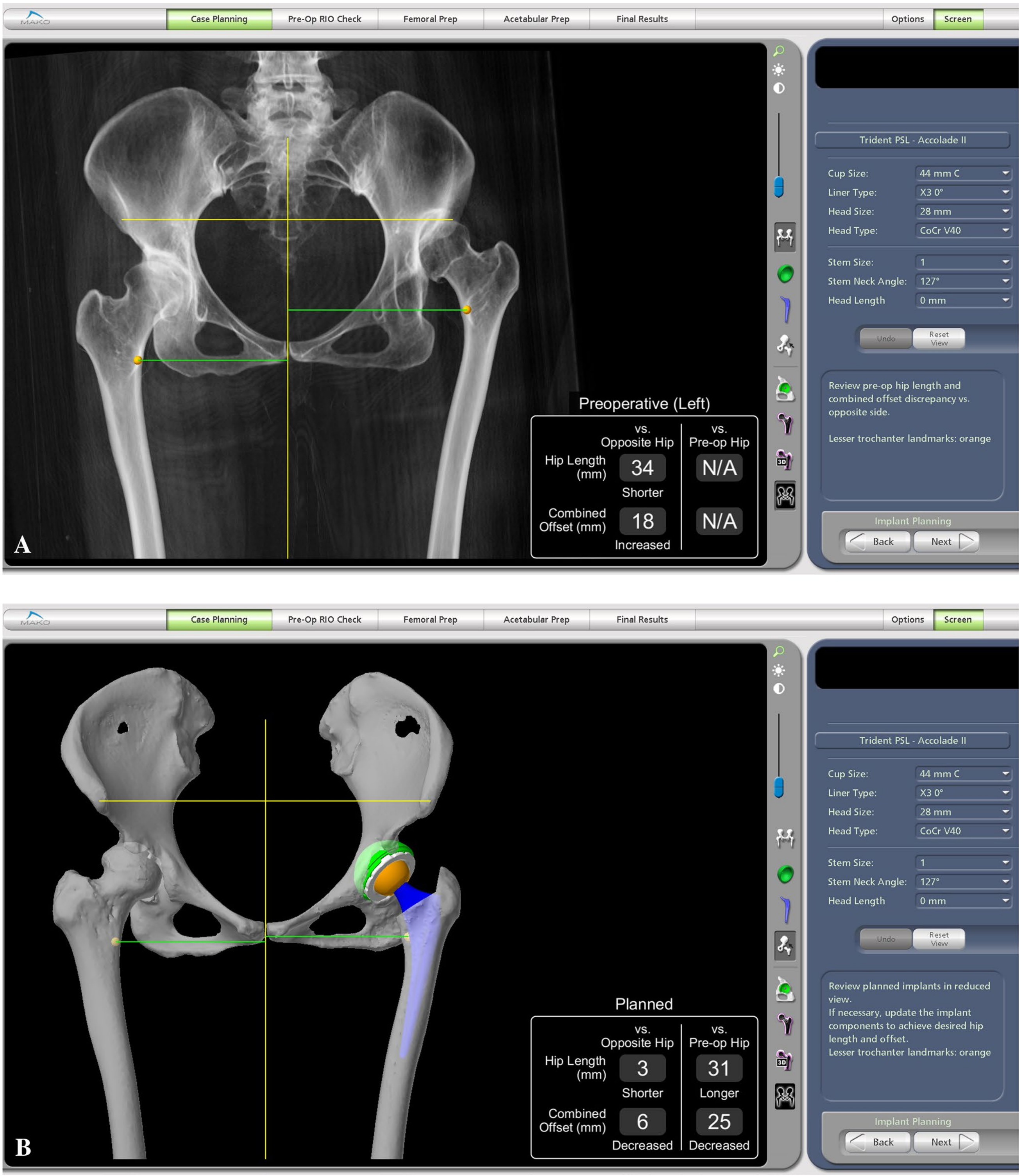

Fig. 2 Pre-operative planning. **A** pre-operative simulative X-ray. **B** Templating using robotic system

mass for future revisions. This type of surgery prioritized on achieving stability of the acetabular prostheses rather than leaving opportunity for subsequent interventions. The target orientation of the acetabular cup prosthesis was 20° of anteversion and 40° of abduction by the recommendation of Lewinnek [18].

Surgical techniques

Both robotic and conventional THA were performed in a lateral decubitus position using the standard posterolateral approach. For conventional THA, the surgical technique was descripted by our previous study [19]. For the robotic THA, Mako robot (Stryker, Mahwah, USA) was used for reaming the acetabulum during bone preparation and cup placement. Three reference pins were inserted into the iliac crest for attachment of the fixed pelvic array and a fixed adhesive electrode attached to the patellar of the operated leg for intra-operative assessment. The surgeon began the skin incision and preliminary exposure after attaching the pelvic arrays. Prior to hip dislocation, the proximal and distal femoral checkpoints were captured to measure the pre-operative leg length and hip offset. The surgeon then dislocated the joint and performed the femoral neck osteotomy. The position of the pelvis was confirmed by registering and verifying the position of patient-specific anatomical landmarks displayed on the screen. The accuracy of the registration was confirmed using the validation spheres. A surgeon-controlled robotic arm was used to guide cup positioning. With the help of the haptic arm, the planned volume bone was removed with the reamer. Then, the surgeon impacted the acetabular cup into the planned position. Finally, at least two acetabular screws and the liner were installed in place [20].

The femur was prepared manually. Hip stability was tested through the full range of movement after hip reduction. Leg length and offset were verified by manual and robotic before implantation of the final femoral stem and femoral head. The robotic system had problems in measuring the leg length if an osteotomy was performed. The extension length of leg (measured on trochanter) shown by robotic system need to subtract the length of osteotomy to obtain the actual extension length.

If reduction of the hip cannot be achieved after adequate soft tissue and tendon release, then a subtrochanteric transverse osteotomy was performed horizontally to remove a section of the femur [21, 22]. The purpose of the osteotomy was to shorten the femur to ease reduction, the distal and proximal ends of the femur were aligned without changing rotation, while the abnormal femoral anteversion was adjusted using the S-ROM prosthesis. For female DDH patients, our target combined anteversion was 50°, and their adjusted femur anteversion ranged from 20 to 30°. The osteotomy could restore the greater trochanter to its normal physiological/anatomical position, which facilitated the recovery of the gluteus medius function and helped prevent dislocation and restore gait.

Release was extremely important for surgical exposure, especially in patients with history of prior surgery and/or infection. There was no difference in the degree and sequence of release between the two groups. The soft tissue release begins with the tensor fasciae latae, the gluteus maximus tendon attached to iliotibial band, the short external rotators (and obturator externus and quadratus femoris), the reflected head of rectus femoris, the anterior capsule, and the iliopsoas tendon. A percutaneous adductor tenotomy at the groin could be performed if necessary, usually postoperatively.

All robotic-assisted THAs used the Trident (Stryker, USA) acetabular component. Conventional THAs used either Combicup (LINK, Germany) or Pinnacle (DePuy, USA). All cases utilized modular femoral stem (S-ROM; DePuy, USA) to adjust the anteversion of stem and leg length.

Clinical and radiographic evaluation

The clinical records and follow-up data of these patients were reviewed manually in detail to extract pertinent information that included age, gender, BMI, ASA score, Harris Hip Score (HHS) [23], Western Ontario and McMaster Universities (WOMAC) Osteoarthritis Index, LLD [24], relative LLD (RLLD) [25], implant information, intra-operative and post-operative complications, and readmission and reoperation. The surgery time was defined as the time from initial incision to final wound closure.

Radiographic measurements, including inclination and anteversion of the cup, and LLDs were conducted using OrthoView software version 7.0.3 (Meridian Technique Ltd, UK) by two observers according to a standardized technique [24, 26]. The proportion of hips within target zone of Lewinnek [18] (inclination, 30–50°; anteversion, 5–25°) and the safe zone of Callanan [27] (inclination, 30–45°; anteversion, 5–25°) were calculated. The relative limb length (RLL) and the RLLD were measured and calculated in full-length film at least three months post-operation [25]. The inter-observer reliability of the radiographic measurements indicated strong agreement, and the intraclass correlation coefficient was greater than 0.80 for all measurements [28]. The mean of the two measurements was used for analysis.

Statistical analysis

All of the statistical analyses were performed with the statistical software packages R (http://www.R-project.org, The R Foundation). Continuous variables were compared by the independent *t*-test or Mann–Whitney test and categorical variables were compared by the chi-square test or Fisher exact test. Logistic regression analysis was used to examine the association between the type of THA and radiographic measurements. Odds ratio (OR) with 95% confidence intervals (CIs) were reported. The reliability test was performed by calculating the intraclass correlation coefficient (ICC) [28]. A p-value less than 0.05 was considered significant.

Results

The patient characteristics are shown in Table 1. There was no significant difference in age, gender, BMI, ASA score, and Crowe type between robotic-assisted THAs and conventional THAs. The quality of PSM was considered balanced (all SMD < 0.2). The number of Crowe IV was 20 (74.1%) and 17 (63%) for conventional THAs and robotic THAs, respectively.

The clinical and radiographic measurements are presented in Table 2. The inclination of the cup for conventional THAs and robotic THAs was 42.1° ± 5.7° and 41.3° ± 4.6° ($p = 0.574$), respectively. The anteversions of the cup for conventional THAs were significantly greater than those of robotic THAs with 29.5° ± 8.1° and 18.0° ± 4.6° ($p < 0.001$), respectively. The ratio of acetabular cups in the safe zone of Lewinnek was 37% (10/27) in conventional THAs and 96.3% (26/27) in robotic THAs ($p < 0.001$). Comparing with robotic-assisted THAs, conventional THAs were more likely to out of the safe zone (OR for out of Lewinnek's safe zone: OR: 44.2, 95% CI [5.2, 377.4] than robotic-assisted THA). Additionally, robotic THAs did not achieve better LLD (− 0.4 mm ± 10.9 mm vs. 0.4 mm ± 8.8 mm, $p = 0.774$) and RLLD (0.0 mm ± 7.8 mm vs. − 0.4 mm ± 6.2 mm, $p = 0.817$) than that of conventional THAs. There was no difference in HHS and WOMAC index between groups at the follow-ups.

When stratified by Crowe type (Table 2), the results remained robust; robotic THAs had greater ratios of cups in Lewinnek's and Callanan's safe zone than conventional THAs. Robotic THAs did not achieve better LLDs compared with conventional THAs in both Crowe III and IV.

Although there was a trend towards longer surgical time for robotic THA than conventional THA (133.2 ± 45.1 min vs. 114.8 ± 19.5 min; $p = 0.095$). There was no intra-operative complication in both groups. No dislocation occurred in all cases by the last follow-up. No case experienced nerve injury post-operatively. Two cases with conventional THAs had wound exudation, which healed after pressure dressing.

Discussion

To improve the accuracy and precision of the acetabular component position in THA, there are several recent studies on the application of the robotic technique in the simple primary THA [11, 13–15, 29]. However, to our best knowledge, there is limited data on the robotic THA for severe pelvic deformities such as high hip dislocation. The present study revealed that the robotic-assisted THA achieved more accurate anteversion of the cup than the conventional technique, while the procedure time was slightly longer.

The explanation may be that the acetabular morphology of Crowe types III and IV often have greater original anteversion than normal [4], which could confuse surgeons to decide cup positioning intra-operatively. Thus, surgeons may sacrifice cup positioning to achieve better acetabular coverage. In addition, reaming these immature sockets, which are limited in size and bone volume, to a size large enough to implant a 44-mm acetabular cup is the greatest challenge

Table 1 Patient characteristics

Variables	Conventional THA	Robotic THA	Standardized mean difference	*P*-value
Age (year)	44.56 ± 9.53	43.04 ± 8.92	0.1645	0.5482
BMI (kg/m^2)	22.87 ± 3.11	24.34 ± 4.60	0.3743	0.1750
Female	27	27	0.0000	1.000
Side			0.1538	0.7781
Right	9 (33.3%)	11 (40.7%)		
Left	18 (66.7%)	16 (59.3%)		
Crowe type			0.3288	0.3713
III	6 (22.2%)	10 (37%)		
IV	21 (77.8%)	17 (63%)		
ASA score			0.2774	1.0000
1	0 (0%)	1 (3.7%)		
2	27 (100%)	26 (96.3%)		
Preoperative HHS	58.4 ± 13.6	63.0 ± 13.0	-	0.269

Table 2 Clinical and radiograph evaluation stratified by Crowe type. Cup anteversion: measured by the Lewinnek method, LLD: measurement of LLD by TD-LT method in pelvic X-rays, RLLD: measurement of the length discrepancy of the distal sacroiliac joint to the ankle between the two limbs in full-length x-ray, HHS&WOMAC@2020: HHS and WOMAC scores at follow-up in 2020 (at least 1 year postop), HHS&WOMAC@2021: HHS and WOMAC scores at follow-up in 2021 (at least 2 years postop)

	Conventional THA	Robotic THA	*P*-value
Total cohort (n = 54)			
Cup inclination	42.1 ± 5.7	41.3 ± 4.6	0.574
Cup anteversion	29.5 ± 8.1	18.0 ± 4.6	< 0.001
Lewinnek's safe zone	10 (37.0%)	26 (96.3%)	< 0.001
Callanan's safe zone	10 (37.0%)	26 (96.3%)	< 0.001
LLD (mm)	− 0.4 ± 10.9	0.4 ± 8.8	0.774
RLLD (mm)	0.0 ± 7.8	− 0.4 ± 6.2	0.817
HHS@2020	93.4 ± 4.3	93.2 ± 3.5	0.836
HHS@2021	93.5 ± 3.9	94.5 ± 3.3	0.313
WOMAC@2020	17.2 ± 13.4	17.7 ± 11.3	0.876
WOMAC@2021	15.1 ± 11.5	13.4 ± 7.4	0.512
Crowe III (n = 16)			
Cup inclination	40.4 ± 4.4	41.7 ± 4.3	0.586
Cup anteversion	30.7 ± 5.9	18.4 ± 3.2	< 0.001
Lewinnek's safe zone	3 (42.9%)	10 (100.0%)	0.015
Callanan's safe zone	3 (42.9%)	10 (100.0%)	0.015
LLD (mm)	− 2.7 ± 10.2	2.3 ± 7.6	0.284
RLLD (mm)	1.5 ± 5.1	3.2 ± 6.1	0.576
HHS@2020	93.5 ± 4.2	93.0 ± 4.1	0.820
HHS@2021	94.2 ± 3.4	94.6 ± 2.7	0.781
WOMAC@2020	18.3 ± 13.0	16.2 ± 14.6	0.779
WOMAC@2021	14.8 ± 13.6	12.9 ± 9.1	0.737
Crowe IV (n = 38)			
Cup inclination	42.6 ± 6.1	41.1 ± 4.8	0.413
Cup anteversion	29.2 ± 8.7	17.8 ± 5.3	< 0.001
Lewinnek's safe zone	7 (35.0%)	16 (94.1%)	< 0.001
Callanan's safe zone	7 (35.0%)	16 (94.1%)	< 0.001
LLD (mm)	0.3 ± 11.3	− 0.7 ± 9.4	0.773
RLLD (mm)	− 0.4 ± 8.4	− 2.6 ± 5.3	0.364
HHS@2020	93.4 ± 4.4	93.4 ± 3.3	0.953
HHS@2021	93.3 ± 4.1	94.5 ± 3.7	0.378
WOMAC@2020	16.8 ± 13.9	18.5 ± 9.6	0.678
WOMAC@2021	15.2 ± 11.2	13.6 ± 6.5	0.619

of high-dislocation DDH and the greatest advantage of robot-assisted surgery [16, 30, 31]. Numerous studies have indicated THAs in high dislocation had worse outcomes including the loosening of the acetabular component and post-operative dislocation. Sochart et al. reviewed 60 THAs for congenital dislocation and suggested 22 cases (37%) had acetabular loosening [32]. Chougle et al. assessed 292 cemented THA which were performed for DDH with a mean follow-up of 15.7 years. They showed the survival rate of group IV was only 15.6% at 20 years, which was significantly lower than the low-dislocation group [9]. One of the primary reasons for the high failure rate is that it is difficulty to identify the orientation around the acetabulum, which results in malposition of the acetabular component. It is known that the rate of loosening of the acetabular component and post-operative dislocation are higher in THA for high hip dislocation such as Crowe IV [4] compared to those for mild deformity such as Crowe type I [5, 6]. One of the possible reasons is that in cases with severe pelvic deformity, it is difficult to identify the orientation around the acetabulum [7], and acetabular components may be likely to be malpositioned [8]. The present study favored the above view, which showed only 37% THAs were in the Lewinnek safe zone when using the conventional technique.

Our results suggested robotic-assisted THA could improve the accuracy of cup position, which is consistent with previous studies. Domb et al. conducted a matched-pair-controlled study including 50 conventional THAs and 50 robotic-assisted THAs. In their study, they indicated the robot allowed for improvement in placement of the cup in safe zones [13]. Gupta et al. clarified the accuracy of acetabular cup inclination and anteversion in the obese patient with robotic-assisted computer navigation [15]. Kamara et al. reported that the robotic-assisted THA improved the precision of acetabular component positioning during the learning curve significantly and immediately [11]. They found robotic-assisted THA provided accurate and reproducible placement of the acetabular cup within safe zones for inclination and version in the obese patient [15]. Wataru et al. performed a CT base study showing that the robot-assisted technique reduced the cup position error and cup inclination error from the pre-operative targets in DDH THA [33]. To the best of our knowledge, we present the first study that directly examines the benefits of robotic-assisted THA in patients with high dislocation. However, whether the improvements in acetabular positioning will improve clinical outcomes for patients remains unproven.

The LLD following THA is more likely to occur in patients with DDH [34]. For primary THA, there have been several methods to measure leg length intra-operatively, such as marking pelvis and femur, comparing leg length (knee and ankle) directly in trial reduction, and intra-operative fluoroscopy [35, 36]. However, THA in patients with high dislocation aimed to recover leg length but not to correct it, which made these mentioned methods for intra-operative measurement maybe not suitable [34]. Therefore, the balance of leg length remains challenging. The present study found robotic-assisted THA achieved slightly better LLD than conventional THA, which may be another support for robotic THAs.

There was no nerve injury in the present study. Lower limb nerve injury is one of the major complications following THA, especially in high dislocation and revision THA [19, 37, 38]. Many studies have suggested the extension of limb lengthening more than 10% of the femur or 3 cm had a higher risk of nerve injury [39]. To reduce the incidence of nerve injury, Kong et al. [19] monitor nerve function and inform the surgeon of ongoing changes in a timely manner by using neuromonitoring technician intra-operatively. They found the use of intra-operative nerve monitoring which showed a trend towards reduced nerve injury in THA for Crowe IV DDH patients [40].

We need to consider whether robotic-assisted surgery is worthwhile and can benefit patients. Previous studies [11, 13, 15, 29] have suggested that robotic-assisted THA can effectively improve the imaging results in terms of acetabular anteversion and inclination, and lower limb length discrepancy. However, the ability of robotic-assisted THA to improve clinical outcomes and functional scores remains unknown due to the lack of relevant evidence [17, 41, 42]. In terms of complications, robotic-assisted THA does not increase the incidence [13, 17, 29], but has its own specific pin-site-related complications [43]. Given the additional cost, the benefit of robotic-assisted THA is not obvious for the regular patient with osteoarthritis or osteonecrosis of the femoral head. However, in patients with high hip dislocation, which requires excellent reaming and impaction techniques, we believe that robotic assistance can be of great help.

There were several limitations of this study that should be considered. First, the study was a single-institution study and all cases were performed by one surgeon (and some planning surgeons); thus, its findings may not be generalizable. Second, the sample size was not big due to the low prevalence of high-dislocation dysplasia. Third, several confounders could affect clinical outcomes. However, we performed a PSM analysis to the minimum potential bias. Lastly, we only evaluated clinical outcomes at the one and two year follow-ups; thus, whether robotic-assisted THA had benefits in the long term remains uncertain.

In conclusion, robotic-assisted THA for patients with high dislocation improves the accuracy of the implantation of the acetabular component with respect to the safe zone. Further studies with larger cohorts are required to evaluate whether the improvements in acetabular positioning will improve clinical outcomes in the long-term follow-up.

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Author contribution Wei Chai: conceptualization, investigation, methodology, writing—review and editing.

Chi Xu and Ren-Wen Guo: formal analysis, methodology, software, visualization, writing—original draft.

Xiang-Peng Kong and Jun Fu: methodology, validation, visualization, data curation, writing—review and editing.

Pei-Fu Tang and Ji-Ying Chen: conceptualization, investigation, supervision, writing—review and editing.

Data availability The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval The study was approved by the IRB of PLA General Hospital (S2019-052–01), and had been performed in accordance with the ethical standards in the 1964 Declaration of Helsinki.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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