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Research article

The accuracy of cup anteversion measurement on postoperative pelvic radiographs: A comparative retrospective cohort study between DDH and non-DDH patients

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A R T I C L E I N F O

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Total hip arthroplasty
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Developmental dysplasia of the hip
Repeated-measures analysis of covariance
Image quality

A B S T R A C T

Rationale and objectives: Postoperative pelvic radiographs remain a vital tool for assessing cup orientation after total hip arthroplasty (THA), with the accuracy influenced by various factors. The objective of this study is to investigate the accuracy of cup anteversion measurement in developmental dysplasia of the hip (DDH) patients and others based on postoperative pelvic radiographs conducted under the current heavy workload conditions.

Materials and methods: Patients who underwent THA at our hospital with both postoperative X-ray and CT images from January 2020 to December 2022 were included in this retrospective cohort study. Virtual X-ray films were generated using digitally reconstructed radiographs (DRR) technology from CT images, with pelvic position perfectly controlled. Radiographic anteversion (RA) was measured on 3D-CT, virtual X-rays, and actual postoperative X-rays, abbreviated as RA_3D, RA_DRR, and RA_Xray, respectively. A repeated-measures analysis of covariance (ANCOVA) was utilized to evaluate the variations in RA within and between different groups across three methods. The Bland-Altman plot analysis showed the variations among methods in DDH and non-DDH patients, setting a clinically acceptable limits of agreement (LOA) at $\pm 5^{\circ}$.

Results: This study included 154 hip cases, with 63 DDH and 91 other diseases. Repeated-measures ANCOVA revealed a descending trend in RA across three methods, with differences of 2.64° (DDH) vs. 2.74° (others) from 3D to DRR, and 4.89° (DDH) vs. 1.07° (others) from DRR to X-ray. The group by methods interaction effect were significant ($p = 0.002$). Significant statistical differences in RA_Xray ($P = 0.035$) were observed between DDH and non-DDH patients, but not in RA_3D and RA_DRR. Bland-Altman plots showed 71.4 % of DDH patients exceeded the clinically acceptable LOA, compared to 36.3 % of other patients.

Conclusion: Our study indicated that under the current intense workload, the reliability of assessing cup anteversion using postoperative pelvic radiographs is challenged, especially in patients with DDH.

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1. Introduction

Cup orientation assessment is a critical aspect in the follow-up after total hip arthroplasty (THA), routinely performed on X-ray and CT images. CT scans, particularly three-dimensional CT (3D-CT), is considered the gold standard as it effectively controls confounding factors, mainly pelvic position and X-ray projection direction [1–3]. However, anteroposterior pelvic radiographs continue to be favored due to their notable advantages of lower radiation exposure and greater convenience [4,5]. Previous studies have highlighted reliability issues in using X-rays for the assessment of acetabular cup orientation, and it is generally believed that measurements of cup inclination are reliable, while assessments of cup anteversion are less dependable due to those confounding factors [6]. Efforts to refine X-ray measurement of acetabular cup anteversion have been successful [7,8], but their complexity has limited clinical adoption, keeping Lewinnek's method as the predominant and classic choice [9]. Research has revealed that radiographic anteversion changes by approximately 0.8° for each degree of pelvic tilt [10]. Compared with their counterparts, patients with developmental dysplasia of the hip (DDH) are more likely to exhibit increased lumbar lordosis, potentially impacting pelvic tilt and consequently leading to imprecise X-ray measurements of cup measurement [11], thereby adding complexity and challenges to the treatment [12]. Previous studies have found that in DDH patients during imaging, the pelvis tilts forward ($8.05^\circ \pm 3.57^\circ$) and rotates anteriorly in the transverse plane ($3.31^\circ \pm 1.41^\circ$) [13]. Furthermore, the increasing workload in radiology departments makes it nearly impossible to ensure that every patient is imaged in a standardized position [14]. It is particularly pronounced when postoperative patients face challenges in adhering to prescribed positioning protocols, thereby further complicating the accuracy of such measurements. Therefore, we believe that a significant correlation exists between the type of preoperative diagnosis and the accuracy of cup anteversion assessment on AP pelvic radiographs. To our knowledge, no study has investigated the accuracy of assessing cup orientation on AP pelvic radiographs among DDH and non-DDH patients.

The hypothesis of this study posits that, within the context of the current intense clinical workload, the accuracy of cup anteversion assessment using postoperative AP pelvic radiographs is challenged; and it differs between DDH and non-DDH patients.

2. Materials and methods

2.1. Study design and methodology

Patients who underwent total hip replacement surgery at our hospital from January 2020 to December 2022 and subsequently received both postoperative anteroposterior pelvic radiographs and CT scans were included in the study. Exclusion criteria included cases with poor image quality, characterized by inappropriate field of view (FOV) or motion artifacts, those who underwent hip surgery between CT and X-ray examinations, and cases with missing anatomical landmarks due to a history of pelvic bone surgery. Patients were divided into two groups: those with DDH and those with other diseases including femoral neck fractures, avascular necrosis of the femoral head, and primary hip osteoarthritis, as shown in Fig. 1. This retrospective study received approval from the local Institutional Review Board of Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine on September 17, 2022, under ethical clearance number SH9H-2022-T297-2, received a waiver for the requirement of informed consent.

2.2. Image acquisition

Postoperative AP pelvic radiographs were captured in a supine position using Kodak's DirectView DR7500 system (New York, USA), featuring a 130 cm source-to-film distance, 70 kV tube voltage, and 225 mA tube current, with the X-ray beam centered on the pubic symphysis. CT scans utilized a SOMATOM Definition Flash 128-slice scanner (SIEMENS, Germany), set at 120 kV tube voltage and 336 mA tube current, producing images with a slice thickness of 1.0 mm. All acquired data were formatted and stored in the DICOM standard.

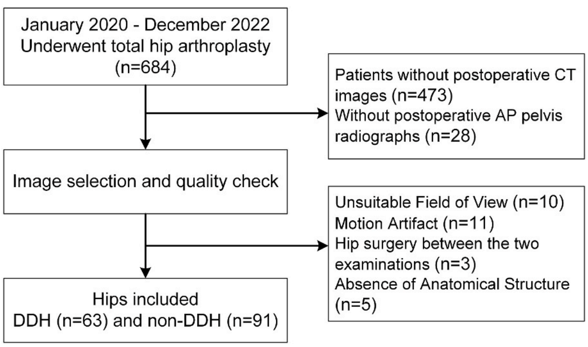

Fig. 1. Inclusion flow chart.

2.3. 3D-CT measurements and generation of virtual pelvic radiographs

In this research, we utilized Medraw software (Image Medraw Technology Co., Ltd., China) for processing CT images [15]. The software facilitated the execution of 3D-CT measurements and the generation of virtual anteroposterior pelvic radiographs. Three-dimensional models of the pelvis and prosthesis were reconstructed using different thresholds to reduce metal artifacts. A fitting circle was established by manually selecting 16 points on the rim of the 3D cup model to represent the plane of cup opening (Fig. 2A). Subsequently, by selecting the anterior pelvic plane (APP) as the reference plane, the software automatically calculates the radiographic cup anteversion on 3D-CT using a semi-automated method that was described in previous study [15], which was abbreviated as RA_3D.

Digitally reconstructed radiographs (DRR) were used to generate virtual X-ray films, enabling precise alignment of the X-ray beams perpendicular to the anterior pelvic plane (APP) (Fig. 2C). The X-ray beam was focused on the center of the triangle formed by the bilateral anterior superior iliac spines and the pubic symphysis, with a source-to-film distance maintained at 130 cm. To minimize the effect of metal artifacts on CT images, the fitting circle of the cup rim was directly projected onto the virtual X-ray film, facilitating the radiographic measurement of cup orientation (Fig. 2B). The disparities in cup orientation measurement between postoperative X-rays and CT scans are mainly due to two factors: the suboptimal positioning of the pelvis during X-ray imaging, and the magnification effects caused by the X-ray beam's offset. DRR technology facilitates the acquisition of virtual pelvic X-rays with impeccable control over pelvic positioning. Consequently, the differences observed between DRR and the gold-standard CT stem from the X-ray beam's offset, enabling us to separately evaluate the impact of these two factors.

2.4. Radiographic cup anteversion measurements

Both postoperative and virtual AP pelvic radiographs were used to measure radiographic cup anteversion using Lewinnek's method [16,17], denoted as RA_Xray and RA_DRR, respectively (Fig. 2D and E). The main differences between RA_3D and RA_DRR are mainly caused by the divergence of the X-ray beam. Similarly, the differences between RA_DRR and RA_Xray are mainly caused by the pelvic position.

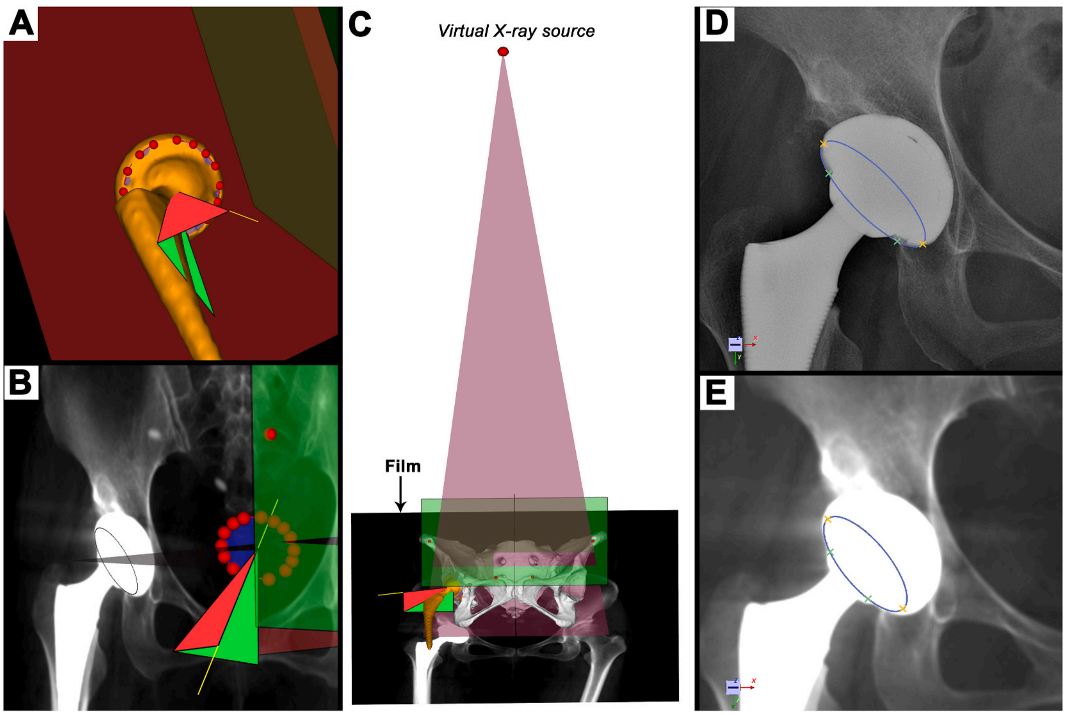

Fig. 2. Generation of virtual X-ray films and measurement of cup anteversion (A) Sixteen points were selected around the rim of the cup model. (B) The fitting circle along the cup's rim was precisely projected onto the virtual pelvic radiographs. (C) Detailed three-dimensional models of both the pelvis and the prosthesis were reconstructed. The virtual X-ray beam was aligned perpendicular to the anterior pelvic plane (APP) at a source-to-film distance of 130 cm to create virtual pelvic radiographs. (D) and (E) displayed the measurements of cup anteversion as captured on actual post-operative pelvic radiographs and corresponding virtual pelvic radiographs.

2.5. Statistical analysis

Statistical analyses were conducted using SPSS (version 24.0, IBM Corp., Armonk, New York, USA) and R software (version 4.3.2, R Foundation for Statistical Computing, Vienna, Austria). Continuous variables were summarized using means and standard deviations (SD), while categorical variables were described through frequencies. The normality of data distribution and the homogeneity of variances were evaluated using the Kolmogorov-Smirnov and Levene's tests, respectively. Baseline characteristics of the participants were compared using independent-samples t-tests for continuous variables and the Chi-square ($\chi 2$) test for categorical variables. To assess the changes in RA within and between different groups across various measurement methods, a repeated-measures analysis of covariance (ANCOVA) was employed. Upon identifying significant interaction effects between the group and measurement methods, simple effects analyses were performed to explore specific differences at individual levels, applying Bonferroni correction for multiple comparisons. The Bland-Altman plot illustrated the differences among RA_Xray with RA_DRR, and RA_DRR with RA_3D in DDH and non-DDH patients. The limits of agreement (LOA) were set at ±1.96 times the SD of the differences, with a clinically acceptable LOA defined as ±5° [10]. Statistical significance was set at a p-value of less than 0.05 (two-tailed) for all analyses.

3. Results

3.1. Comparisons between the DDH and non-DDH patients

The study included 154 hip cases, aged 62.24 ± 12.38 years, with a gender ratio of 49 males to 105 females, and 74 left to 80 right hips. Among them, 63 had DDH and 91 had other diseases. Baseline analysis showed a significant age difference ($p < 0.001$) between the groups, where other patients undergoing THA were roughly 7.4 years older than DDH counterparts. Other indicators showed no significant differences, as shown in Table 1.

3.2. Differences in RA by measurement method and group

Normality of data was confirmed by the Shapiro-Wilk test, and homogeneity of variances was verified by Levene's test. The repeated-measures ANCOVA results of RA in the two groups by three measurement methods were shown in Table 2. A descending trend in RA values was observed across the results measured on 3D, DRR, and Xray, with differences of 2.64° (DDH) vs. 2.74° (others) from 3D to DRR, and 4.89° (DDH) vs. 1.07° (others) from DRR to X-ray. The group by methods interaction effect were significant ($p = 0.002$). Significant statistical differences in RA_Xray ($P = 0.035$) were observed between DDH and non-DDH patients, but not in RA_3D and RA_DRR. In the other patients, significant statistical differences were evident between 3D and DRR measurements ($p < 0.001$), whereas the difference between DRR and Xray was not statistically significant ($p = 0.441$). Conversely, in the DDH patients, all the results demonstrated significant statistical differences ($p < 0.001$), as detailed in Fig. 3.

3.3. Concordance: RA_Xray vs. RA_DRR, RA_DRR vs. RA_3D

The Bland-Altman plot revealed poor agreement between RA_Xray and RA_DRR among DDH patients, with the majority of cases, 45 (71.4 %), exceeding the clinically acceptable LOA. In contrast, among non-DDH patients, the agreement between RA_Xray and RA_DRR was relatively good, with 33 (36.3 %) patients exceeding the clinically acceptable LOA (Fig. 4A). Correspondingly, the Bland-Altman plot revealed excellent agreement between RA_DRR and RA_3D among all patients, with a mean difference of −2.7° and all observed differences residing comfortably within the clinically acceptable LOA (Fig. 4B).

4. Discussion

In this study, we utilized repeated-measures ANCOVA to assess the variation of RA in the three methods between DDH and non-DDH patients, with an adjustment for the baseline age disparities between the two groups. By comparing 3D vs. DRR and DRR vs. X-ray, we successfully distinguished the varying impacts of X-ray projection and patient pelvic position on the accuracy of cup

Table 1
Baseline patient characteristics.

	Others	DDH	Difference between two groups	t/χ2	p
	n = 91	n = 63			
	M±SD/Ratio	M±SD/Ratio	mean (95 % CI)		
age	65.29 ± 10.32	57.84 ± 13.80	7.44 (3.39–11.50)	3.635	<0.001
Gender (female: male)	58:33	47:16		2.206	0.155
position (left: right)	42:49	32:31		0.321	0.571
True cup orientation					
RA	20.53 ± 9.24	21.59 ± 9.64	−1.05 (−4.09∼1.99)	−0.681	0.497
RI	43.96 ± 10.04	45.88 ± 7.36	−1.92 (−4.69∼0.85)	−1.296	0.197

DDH, developmental dysplasia of the hip; M±SD, means and standard deviations; RA, radiographic anteversion; RI, radiographic inclination.

Table 2
Results of repeated-measures ANCOVA on RA.

	3D	DRR	Xray	Repeated-measures ANCOVA		
	M±SD	M±SD	M±SD	F	p*	η^2
Others	20.54 ± 9.24	17.80 ± 9.18	17.16 ± 9.14			
DDH	21.59 ± 9.64	18.94 ± 9.58	13.43 ± 8.26			
group				0.133	0.716	0.001
method				20.231	<0.001	0.118
method*age				8.93	0.003	0.056
method*group				10.073	0.002	0.063

Mauchly's W = 0.021, $p < 0.001$, p* was adjusted by Greenhouse-Geisser correction. DDH, developmental dysplasia of the hip; M±SD, means and standard deviations; ANCOVA, analysis of covariance; RA, radiographic anteversion; 3D, three dimensional; DRR, digitally reconstructed radiographs.

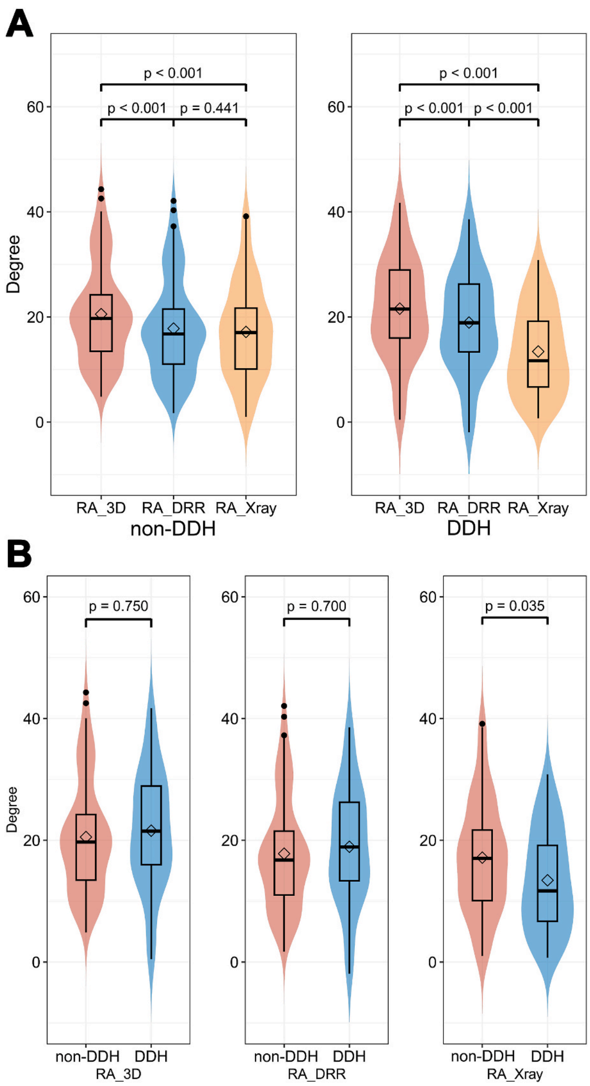

Fig. 3. Post-hoc comparisons following repeated measures ANCOVA 3D, three dimensional; DRR, digitally reconstructed radiographs; RA, radiographic anteversion; DDH, developmental dysplasia of the hip; ANCOVA, analysis of covariance. The combined violin and box plots showed the distribution of RA values across different measurement methods and within groups, with ⋄ indicating the mean value. *P*-values had been adjusted in accordance with the baseline age. A presented the analysis of inner-group comparisons across various methods, meticulously adjusted using Bonferroni correction. B presented the analysis of inter-group comparisons across various methods.

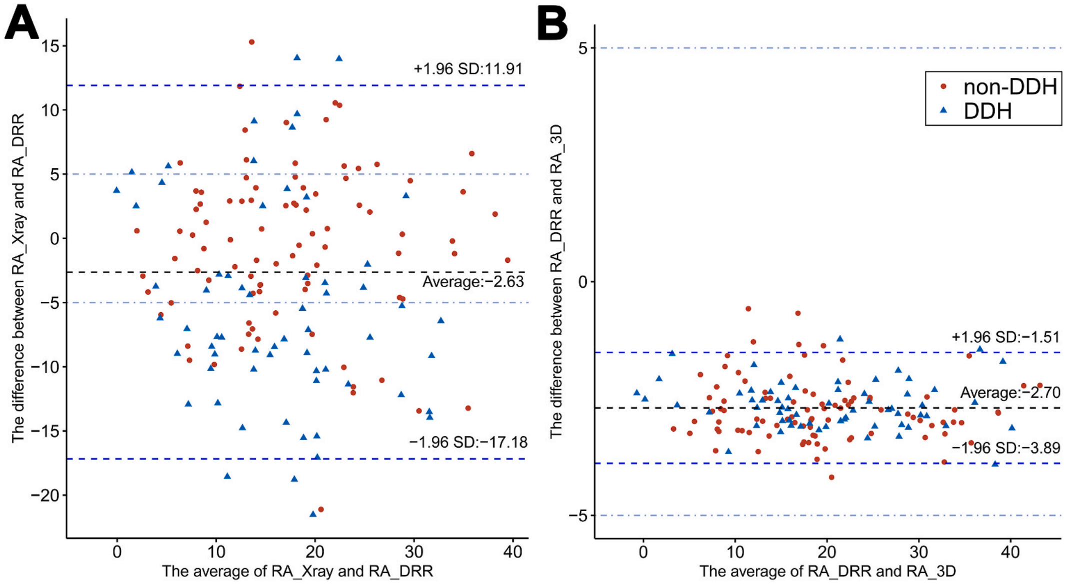

Fig. 4. Bland-Altman analysis: Agreement Among RA_Xray vs. RA_DRR, and RA_DRR vs. RA_3D in DDH and non-DDH patients 3D, three dimensional; DRR, digitally reconstructed radiographs; RA, radiographic anteversion; DDH, developmental dysplasia of the hip.

anteversion using postoperative X-ray in the two groups. A descending trend in RA values was noted across 3D, DRR, and X-ray methods, showing a 2.64° difference in DDH versus 2.74° in others from 3D to DRR, and 4.89° in DDH versus 1.07° in others from DRR to X-ray. The interaction between group and method was significant ($p = 0.002$). Notably, the anteversion differences between the real postoperative X-ray (RA_Xray) and virtual X-rays (RA_DRR) varied across the two groups (DDH, $p < 0.001$; others, $P = 0.441$). Additional findings from Bland-Altman plots showed 71.4 % of DDH patients exceeded the clinically acceptable LOA, compared to 36.3 % of other patients. These findings highlight the challenges in cup anteversion assessment on postoperative pelvic X-ray after THA under the current intense workload, emphasizing the necessity to take into account specific patient-related factors in the follow-up.

Postoperative anteroposterior pelvic radiographs remain a crucial tool in the follow-up after THA [4,5]; in this study, a majority of the patients lacked postoperative CT images, which may be related to the higher radiation exposure and the significant artifacts in the images after prosthesis implantation. With the increasing workload in radiology department [14], ensuring standard positioning for X-ray procedures in all patients proves challenging, notably during the initial post-surgery days due to pain at the operation site. Consequently, understanding the reliability of postoperative X-ray assessments of cup anteversion is crucial for surgeons, aiding them in selecting appropriate methods during patient follow-ups. Earlier studies suggest that measurements of cup inclination are reliable, while the measurements of cup anteversion continues to be debated [6]. In our study, the variation in measuring cup inclination across three methods was less than one degree, and no significant statistical differences were observed between the DDH and non-DDH patients, corroborating earlier research findings [18].

The uncertainty in the accuracy of X-ray measurements of cup anteversion can be attributed to differences in how acetabular cup orientation is defined, the selection of reference planes, and the direction of X-ray projection. According to Murray [16], cup anteversion is categorized into radiographic, operative, and anatomical anteversion (RA, OA, and AA), all of which are interconvertible; the reference planes, including the SCP (supine coronal plane) and APP (anterior pelvic plane), are largely aligned when standing. In past research,CT has been chosen for the preferred standard, with various definitions of anteversion angles such as RA [19–21], AA [18], OA [3]; reference planes include SCP [18,19,21], APP [3,20], revealing a 1–8° variance between X-ray measurements and the gold standard. In this study, the gold standard is defined as the RA based on the APP plane from 3D-CT, and consistent with the classic method proposed by Lewinnek [17]. The RA obtained from postoperative pelvic X-ray measurements is based on the SCP. Assessing its difference from the gold standard allows for the exploration of the impact of X-ray projection direction and pelvic position. Differing from earlier studies, we applied repeated-measures ANCOVA, which facilitated a finer distinction of the impacts caused by X-ray projection direction and pelvic positioning across two group patients, while concurrently controlling for age as an intergroup confounding factor. Meanwhile, this approach reduces the risk of Type I errors (false positives) arising from multiple statistical comparisons. Our findings indicated a similar impact from X-ray projection on both DDH and other patient groups, measured at 2.64° and 2.74° respectively. Conversely, the effect of pelvic position showed notable differences, with an impact of 4.89° in DDH patients compared to 1.07° in others. Further Bland-Altman plots demonstrated that the majority of DDH patients (71.4 %) exceeded the clinically acceptable LOA caused by pelvic position, whereas the situation was relatively better in other patients, with only 36.3 % exceeding this range. DDH patients are more likely to exhibit lumbar lordosis and tend to have anteriorly tilted pelves in the supine position [22], which can reduce the cup anteversion measured on supine pelvic radiographs. The Office of the National Health Commission of China has issued a notice on the "Clinical Pathway for Accelerated Recovery in Orthopedic Surgeries (2023 Edition)," which includes an annex, "Clinical Pathway for Accelerated Recovery in Total Hip Arthroplasty." This guideline mandates postoperative imaging assessments, specifically anteroposterior pelvic radiographs and lateral views of the femoral neck on the affected side. However, based on the findings of our study, we contend that under the current high-intensity workload, relying solely on X-ray evaluations for postoperative acetabular cup positioning is insufficient, especially for DDH patients. For these patients, more stringent control of pelvic positioning during imaging or the addition of CT scans is essential. The incidence of DDH is 2%–4% [23], making it the second most common cause of hip arthritis. Moreover, patients are typically younger at the time of surgery, thus ensuring better surgical outcomes is vital for their postoperative quality of life [24]. Similarly, in our study, the DDH patients were about 7.4 years younger at the time of surgery compared to patients with other diseases. These findings above underscore the importance of strictly controlling the quality of pelvic X-rays or employing more precise methods like CT for the postoperative follow-up of THA in DDH patients. With the advancement of artificial intelligence technology in the medical field [25], it could serve as an effective tool for measuring acetabular cups in postoperative X-ray films, quickly addressing the challenges associated with pelvic positioning and X-ray beam offset during the imaging process.

Our study has some limitations. Firstly, this study is a retrospective cohort study with some missing baseline information for certain patients, potentially leading to confounding factors more than age. This warrants a more rigorous, prospective research design to elucidate additional influencing factors. Secondly, this study collected data only from one research center, and its results may not be applicable to hospitals that have strict requirements for X-ray imaging. However, with the surge in outpatient visits in China, the quality of X-ray images is inevitably affected. These results could provide valuable insights for hospitals experiencing intense workloads, particularly for major comprehensive hospitals. Thirdly, in our study, we included a relatively small sample size of patients, which becomes even smaller when divided into different subgroups, potentially insufficient for conducting analyses with statistical significance. Conducting subgroup analyses with such limited sample sizes may lead to inadequate statistical power, rendering it challenging to draw reliable conclusions. Finally, the absence of postoperative pelvic CT scans in a substantial portion of the patient cohort during imaging follow-up may introduce a degree of selection bias. This reflects the clinical reality that postoperative CT is often not the preferred modality for THA follow-up by surgeons. Highlighting the limited reliability of postoperative pelvic X-ray evaluations in determining the acetabular cup angle, particularly amidst high clinical workloads, could assist clinicians in choosing more suitable imaging techniques for THA follow-up, especially for patients with DDH.

5. Conclusion

In conclusion, this study demonstrated that under high workload conditions, the reliability of assessing cup anteversion using postoperative pelvic radiographs in DDH patients is compromised, highlighting the need for more stringent imaging positioning protocols or alternative modalities like CT for precise evaluation. These findings underscore the challenges in post-THA assessments, particularly for DDH patients, and suggest a reevaluation of current imaging practices to improve surgical outcomes. Future research should focus on optimizing imaging techniques and exploring the impact of imaging accuracy on long-term THA success, taking into account the specific needs of DDH patients.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Xiaomin Li: Writing – original draft, Software, Formal analysis, Data curation. **Yang Qu:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Liao Wang:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Songtao Ai:** Writing – original draft, Resources, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e31141.

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