CLINICAL ARTICLE

Reliability and Validity of Standing Lateral Radiograph Method for Measuring Acetabular Component Version: A Modified Cross-table Lateral Radiograph Method

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Objectives: To investigate the effect of the X-ray incidence angle on cup version measurements and the reliability and validity of standing lateral (SL) radiography for measuring cup versions.

Methods: Cup versions under different X-ray incidence angles were investigated by the 3D simulation analysis. Ninety-three patients, who underwent primary total hip arthroplasty (THA) with postoperative SL radiographs and CT scans between April 2020 and December 2021, were retrospectively analyzed. SL radiography was taken under naturally standing position, correcting for the measurement error of pelvic tilt in cross-table lateral (CL) radiography. Cup versions were measured on SL radiographs and CT images by two qualified orthopedic physicians. The intra- and inter-observer reliabilities were assessed by intra-class correlation coefficient. The consistency between radiographic and CT measurements was evaluated using Pearson correlation coefficient.

Results: No significant differences in cup version measurements were observed between groups of different X-ray incidence angles ($P = 0.663$) in the 3D simulation analysis. All measurements had excellent intra- and inter-observer reliabilities, with an intraclass correlation coefficient of >0.95. Mean cup version measurements from SL radiographs correlated well with those from CT scans ($r = 0.853$, $P < 0.001$). The mean difference between radiographic and CT measurements was $-0.49°$ (range $-12.62°$ to $10.37°$, SD $3.95°$), and the majority of differences were within the 95% limits of agreement.

Conclusion: The cup versions measured with SL radiography were close to the CT measurements. SL radiograph method is reliable and valid for measuring acetabular component version after THA.

Key words: Acetabular component version; Cross-table lateral radiograph; Hip dislocation; Standing lateral radiograph; Total hip arthroplasty

Introduction

Malposition of acetabular prosthesis after total hip arthroplasty (THA) has been associated with adverse clinical outcomes, including dislocation, impingement, polyethylene wear, pain, and diminished joint mobility.[1–4] Dislocation is the most frequent complication during the first 6 months after THA surgery.[5] A long-term cohort study reported a postoperative dislocation rate of 4.76%.[6] Although the number of revisions due to aseptic loosening has decreased, because implant design has improved, recurrent dislocation is still the most common indication for THA revision surgery, comprising 17%–22% of all revision procedures.[7] Thus, dislocation is a crucial factor for determining the efficacy of THA surgery. Accurate measurement of the

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acetabular component position contributes to the assessment of dislocation risk and guides prevention and treatment of dislocation following THA procedures.

The orientation of the acetabular component can be categorized into two angles: inclination angle and version angle.[8] While computed tomography (CT) scanning accurately evaluates the component position and is regarded as the golden standard technique,[9–11] plain radiographs continue to be commonly used due to the relatively low cost and radiation exposure.[12–14] Anteroposterior (AP) pelvic radiography is the standard method used for inclination angle measurement.[15] The component version was generally measured using AP radiographs[12,16,17] or cross-table lateral (CL) radiographs.[18,19] However, the optimal plain radiographic method for cup version measurement is not preferred.[15]

Most postoperative dislocations occur in the standing or sitting position, but the traditional "safe zone" and the previous method used to measure cup version are based on the supine position.[20] Pelvic tilt (PT) was reported to cause inaccuracy in cup version measurements, 1° of PT changed the cup version by an average of 0.8°.[21–24] Moreover, the cup version may move either into or out of the "safe zone" when changing from the supine to standing position, due to variation in PT.[20,25,26] Accordingly, the cup version, as assessed using previous supine radiographs, is not equivalent to postoperative functional cup version in the standing position. Supine radiography may lead to misinterpretation of the true risk of postoperative dislocation, and the traditional "safe zone" may not be applicable neither for preoperative planning, nor for intraoperative navigation of the implant position. Hence, to assess the true risk of postoperative dislocation and determine the functional "safe zone," the development of a new method for assessing cup versions in the standing position is required.

Standing lateral (SL) radiography may be ideal because it enables the cup version to be measured in the standing position and PT to be assessed simultaneously. To our knowledge, the appropriate measurement method for cup version using SL radiography has not been studied yet. SL radiography could be considered as a variation of CL radiography, with the patients positioned from supine to standing position, and the X-ray incidence angle changed from 45° to 90°. The variation of the X-ray incidence angle causes the change in projected shape of the cup rim, which is the main difference between SL radiograph and CL radiograph. The cup version on CL radiograph is measured between the vertical line of the film and the line tangential to the opening face of the acetabular cup.[19] It is possible that the same method is applicable for SL radiograph, but it would be necessary to determine whether the change in the X-ray incidence angle significantly affects the cup version measurement in the lateral view. However, it is impractical to perform multiple lateral radiographs with different X-ray incidences on a single patient due to radiation exposure and ethical concerns. In a previous study, a 3D postoperative THA model was built, in which multiple parameters, including cup version, inclination, PT, and incidence, were independently adjusted.[24] Independent variables and confounding factors were controlled using a standard physical model.

Therefore, our study aimed: (i) to investigate whether the X-ray incidence angle significantly affects cup version measurements in lateral view, through 3D simulation analysis; and (ii) to evaluate the reliability and validity of SL radiography for measuring acetabular cup version.

Material and Methods

3D Simulation Validation

Four healthy volunteers (two men and two women) without pelvic deformity were recruited to undergo a pelvic CT scan. First, DICOM data were imported into the Geomagic Design X software (version 2016, 3D Systems Inc., Rock Hill, SC, USA) for 3D pelvis reconstruction. Subsequently, laser equipment was used to scan the titanium converge acetabular cups with a diameter of 48–52 mm (R3◊ Acetabular System, Smith & Nephew, Inc., Memphis, TN, USA) to establish the cup models. Finally, 3D postoperative models were generated by integrating the cup model with the pelvic model in Geomagic Design X. All models were established as described above.

In these 3D postoperative models, the actual cup versions and X-ray incidence angles can be independently set. The X-ray incidence angle was defined as the angle between the X-ray beam and the long axis of the 3D pelvic models on the anteroposterior plane. The X-ray beam was simulated by the built-in light source in the software; it centered on the acetabular cup along the sagittal plane and was parallel to the coronal plane of the 3D pelvic models. We adjusted the incidence angle in the range of 45°–90°, at intervals of 5°. The incidence angle of 45° and 90° corresponded to the CL radiograph and the SL radiograph, respectively. Five groups of actual cup versions were set from 10° to 30°, at intervals of 5°. Under different groups of incidence angles, five groups of actual versions were measured using the CL radiographic method[19] on the 3D models, respectively (Fig. 1). The aforementioned measurements were repeated for the four postoperative 3D models.

Clinical Measurement Validation

Patient Selection

The following inclusion criteria were applied: (i) unilateral primary cementless THA; (ii) age > 18 years old; and (iii) SL radiography and CT scanning 1 week after THA surgery. The following exclusion criteria were applied: (i) history of pelvic or spinal surgery, or history of pelvic or spinal deformity; (ii) simultaneous bilateral THA; and (iii) absence of postoperative SL radiographs and CT scans.

A total of 93 patients were retrospectively selected between April 2020 and December 2021, including 39 men and 54 women with a mean age of 58.1 years (range, 19–87 years) and body mass index of 23.7 kg/m^2 (range, 15.8–33.3 kg/m^2) at the time of the operation. Indications for THA

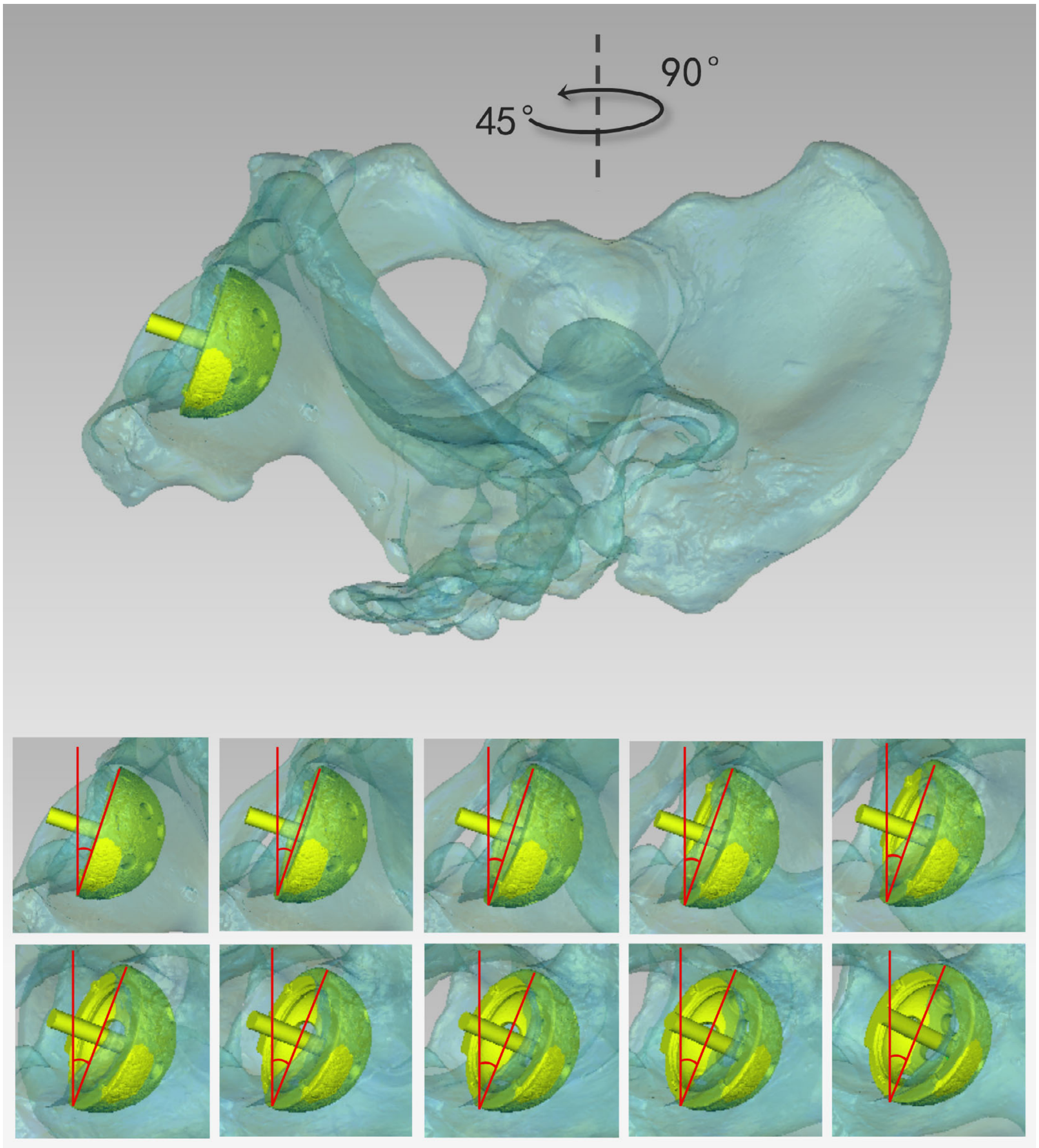

Fig. 1 Cup version measurements under different X-ray incidence angles on the 3D models. Ten groups of X-ray incidence angles were set from 45° to 90°, at intervals of 5°. Five groups of actual versions were set from 10° to 30°, at intervals of 5°. Different groups of cup versions were measured under different X-ray incidence angles

included femoral head osteonecrosis in 38 hips (40.9%), osteoarthritis in 38 hips (40.9%), and femoral neck fracture in 17 hips (18.2%). Four experienced orthopedic surgeons performed all operations using a posterolateral approach. All prostheses were selected from the R3 Acetabular System and POLARSTEM Cementless Stem System (Smith & Nephew, Inc., Memphis, TN, USA). Patient information is summarized in Table 1. This study was approved by the ethics committee of our institution (approval number: SYS-EC2-SOP-008-01.0-A05).

Image Examinations

One week after THA, images including SL radiographs and CT scans were obtained to measure the acetabular component version. When patients were unable to stand steadily 7 days after THA, examination was postponed until patients could stand firmly, to avoid irregular posture and other safety issues.

For SL radiography, patients were instructed to stand naturally still, with their feet together; which corrected for measurement errors of PT variations and patients'

TABLE 1 The demographics of the patients (n = 93)

Parameters	Value of number
Age (years) (range)	58.1 (19 to 87)
Gender (male/female)	39/54
BMI (kg/m^2) (range)	23.7 (15.8 to 33.3)
Operated side (left/right)	44/49
Preoperative diagnosis (n, %)	
Femoral head osteonecrosis	38 (40.9)
Osteoarthritis	38 (40.9)
Femoral neck fracture	17 (18.2)
Type of prosthesis (n, %)	
R3◊ Acetabular cup (Smith & Nephew)	93 (100)
POLARSTEM◊ cementless stem (Smith & Nephew)	93 (100)

Abbreviation: BMI, body mass index.

indisposition of hip flexion in CL radiography. The radiation beam was centered over the greater trochanter and intersected the longitudinal axis of the body at a right angle. Imaging ranged from the upper edge of the sacrum to the lower edge of the stem (Fig. 2).

For CT scanning, patients were in the supine position with the bilateral hip joints in neutral position. All standardized radiographies and CT scanning were performed by the same group of radiology technicians.

Cup Version Measurements

Radiographic version was defined as the cup version measured on the standing radiograph. It represented the angle between the tangential line of the cup opening face and the vertical line of the longitudinal axis of the body. The tangential line of the cup opening face was determined by connecting the two points formed after intersection of the fitting equal circle of the cup outer edge with the lower elliptical arc of the cup opening face (Fig. 3(A)). CT version was defined as the angle between the line through the most anterior and posterior points of the cup and the horizonal line on the sagittal plane according to a previous study (Fig. 3(C)).[9] As the PT during supine CT was different from that during SL radiography and cup version measurement would be affected by variations in PT,[24,25] we adjusted the PT of the CT images (Figure 3(B)) to be consistent with that of the SL radiographs (Figure 3(A)) before measuring the CT version. PT was defined as the angle between a horizontal line and a line connecting the upper border of the symphysis with the sacral promontory according to previously reported literature.[27]

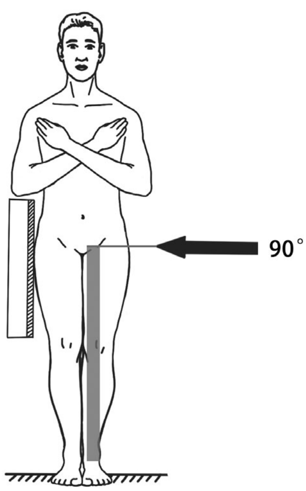

Fig. 2 Radiographic method for standing lateral radiography. Patients naturally stood with their feet together and the radiation beam was centered over the greater trochanter, with an X-ray incidence angle of 90°

Radiographic measurements of the cup version and PT were performed using an image-processing system in our hospital. The cup version and PT measured on CT imaging were performed using syngo.*via* (version 20A; Siemens Medical Solutions Inc., Erlangen, Germany). All measurements were performed by two observers, who were blinded to the patients' information and the other observers' values. All images were randomly assigned to each observer by a research assistant who did not participate in the reliability assessment.

Reliability and Accuracy Assessment

Reliability refers to the consistency of the measurements. Intra-observer reliability for each method was assessed based on the measurements from one examiner who performed the reassessment 4 weeks later. Inter-observer reliability for each method was assessed using the measurements from the same two examiners. Accuracy was defined as the proximity to the reference standard. CT is known as an accurate method to ascertain the true cup version.[9] We analyzed the agreement between radiographic measurements and CT measurements to evaluate the accuracy of the measuring method on SL radiographs.

Statistical Analysis

In the 3D simulation analysis, measurements for each group of versions at different incidences were evaluated using the two-way analysis of variance (ANOVA). Intra- and inter-observer reliabilities of all measurements were calculated using the intraclass correlation coefficient (ICC) and 95% confidence interval (CI). The two-way random effects intraclass correlation model and absolute agreement were used to calculate ICC. ICC of 1 indicated perfect reliability, while ICC of 0 indicated no reliability. To determine convergent validity, version measurements were compared between radiographs and CT scans using the paired *t*-test. The correlation between mean radiological and CT measurements was evaluated with Pearson's correlation coefficient (r). Correlation was characterized as poor (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), good (0.61–0.80), or excellent (0.81–

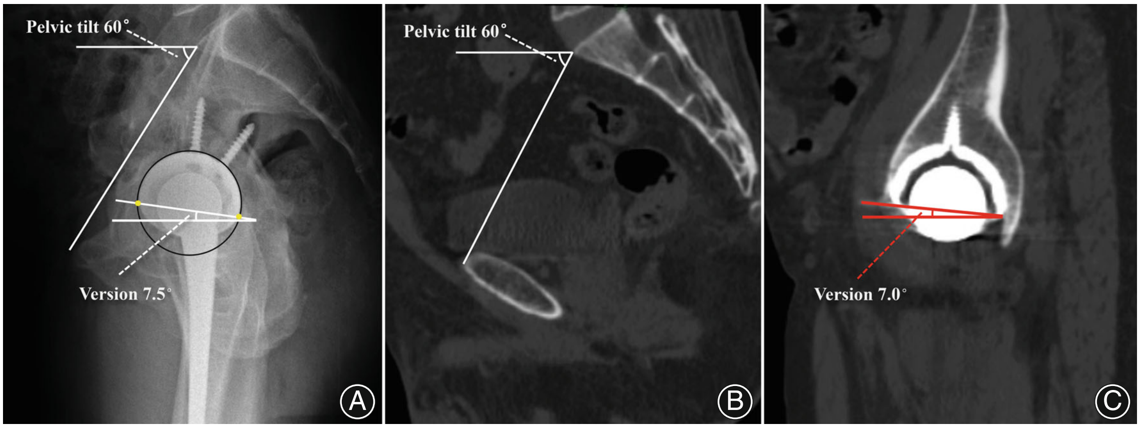

Fig. 3 Methods for measurement of cup version on radiographs and computed tomography (CT) scans. (A) Cup version measuring method on a standing lateral (SL) radiograph. Cup version was measured between the vertical line of the body's longitudinal axis and the tangential line. The line tangential to the cup opening face was determined through two intersecting points of the cup's edge fitting circle and the opening face's elliptical arc. (B) Pelvic tilt was adjusted to the value on radiographs before cup version measurement was performed on CT images. Pelvic tilt was defined as the angle between a horizontal line and a line connecting the upper border of the symphysis with the sacral promontory. (C) Cup version measurement on CT images after pelvic tilt adjustment. Cup version was defined as the angle between the line through the most anterior and posterior points of the cup and the horizonal line

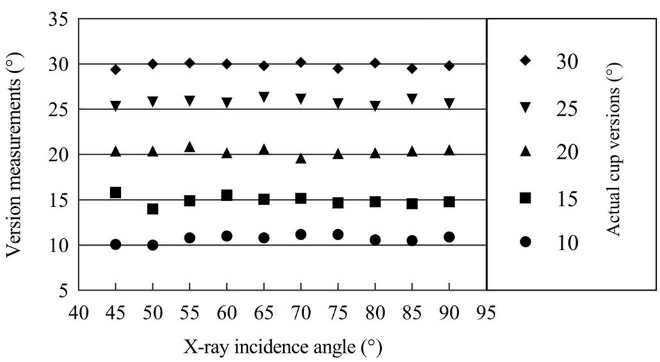

Fig. 4 Mean measurements of various actual cup versions under different X-ray incidence angles in four 3D models. No statistically significant differences in version measurements were observed between different groups of X-ray incidence angle (ANOVA, $F = 0.192$, $P = 0.663$)

1.00).[28] Bland–Altman plots illustrated differences between methods. If differences were within the 95% limits of agreement (95% LoA), they were clinically acceptable and measurements by the two methods were considered to have good agreement. Statistical analyses were conducted using SPSS for Windows (version 25.0; SPSS Inc., Chicago, IL, USA), and statistical significance was set at $P < 0.05$.

Results

3D Simulation Analysis

In the 3D simulation, cup version measurements for each group of actual versions under different X-ray incidence angles are shown in Fig. 4. No significant differences in cup version measurements were observed between the different groups of X-ray incidence angles (ANOVA, F = 0.192, $P = 0.663$).

Reliability Analysis

Intra- and inter-observer reliabilities were satisfactory for the measurement of cup version on radiographs (0.957 and 0.973, respectively; $P < 0.001$) and on CT scans (0.943 and 0.968, respectively; $P < 0.001$) (Table 2).

Accuracy Analysis

Mean cup version angle was 15.75° (SD 10.15°, range − 14.28° to 37.37°) for SL radiographs and 15.26° (SD 10.18°, range − 14.15° to 37.25°) for CT images. There was no significant difference (paired t-test, $t = 1.195$, $P = 0.235$) in the mean version measured with radiography or CT. There was a positive correlation (I = 0.853, $P < 0.001$) between radiographic versions and CT versions (Fig. 5). Individual differences between the radiological and CT values are shown in Bland–Altman plots (Fig. 6). The mean difference was −0.49° (SD 3.95°, range: −12.62° to 10.37°) and most differences (88/93, 95%) were within the 95% LoA.

Subgroup Analysis

The mean radiological measurement error correlated poorly with patient body mass index (<24.5 kg/m^2: $r = 0.93$, $P < 0.001$; >24.5 kg/m^2: $r = 0.93$, $P < 0.001$), age (18–45 years old: $r = 0.94$, $P < 0.001$; 46–69 years old: $r = 0.92$, $P < 0.001$; >69 years old: $r = 0.91$, $P < 0.001$), and sex (male: $r = 0.93$, $P < 0.001$; female: $r = 0.93$, $P < 0.001$). Similarly, neither preoperative diagnosis (femoral head osteonecrosis: $r = 0.96$,

TABLE 2 Intra- and interobserver reliability of each measurement

	Intra-observer reliability		Inter-observer reliability	
	ICC	95% CI	ICC	95% CI
Radiograph	0.957	0.932 to 0.968	0.973	0.956 to 0.992
CT scan	0.943	0.911 to 0.956	0.968	0.957 to 0.989

Abbreviations: CI, confidence interval; ICC, intraclass correlation coefficient.

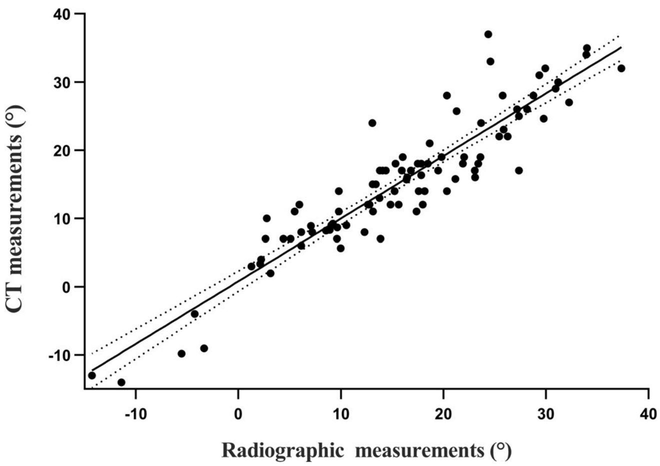

Fig. 5 Scatter plot of mean radiographic and computed tomography (CT) measurements with the correlation slope. The correlation coefficient between mean radiographic and CT measurements was $r = 0.853$ ($p < 0.001$)

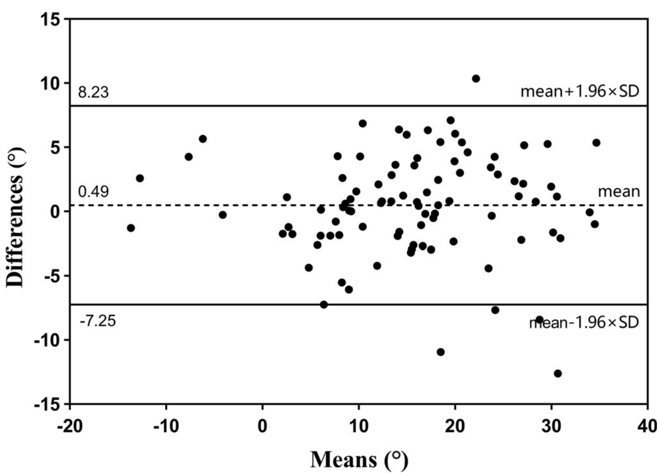

Fig. 6 Bland–Altman graph showing differences between mean radiographic and computed tomography measurements of the cup version. The dashed line represents the mean difference between measurements, and the straight lines represent the 95% limits of agreement (mean ± 1.96 SD)

$P < 0.001$; osteoarthritis: $r = 0.92$, $P < 0.001$; femoral neck fracture: $r = 0.87$, $P < 0.001$), nor the operative side (left: $r = 0.91$, $P < 0.001$; right: $r = 0.94$, $P < 0.001$) were associated with inaccuracy in the mean radiological measurements.

Discussion

Accurate measurement of the acetabular component version is of great importance in assessing surgical outcomes and risk of dislocation. Due to cost and radiation exposure, it is essential to be able to evaluate cup versions in daily clinical practice without CT imaging. However, it is possible that highly accurate X-ray imaging would be required, and there is currently no general consensus on the best technique to be applied.[15] In this study, we proposed SL radiography as a novel method to measure the acetabular component version, based on its accuracy and validity.

Effect of X-ray Incidence Angles

Our 3D simulation analysis revealed that the X-ray incidence angle had no significant effect on acetabular cup version measurement. This result indicates that measuring the acetabular cup version by calculating the angle between the acetabular cup opening tangent and the horizontal line on CL radiographs is also applicable to SL radiographs. However, due to the two-dimensional nature of X-ray images, the elliptical opening of the acetabular cup was not clearly displayed on the SL radiograph and determining the tangent of the opening of the acetabular cup was difficult. In the 3D model measurements, we observed that the two intersection points of the fitting circle of the cup outer edge and the lower elliptical arc of the cup opening face coincided with the most anterior and posterior points of the acetabular cup. Therefore, the tangential line of the cup-opening face could be determined by connecting the two intersecting points. The cup version on the SL radiograph was thus measured between the tangential line of the cup opening face and the vertical line of the longitudinal axis of the body.

Reliability and Validity of the Proposed Method

The previously reported radiographic methods for measuring cup versions used primarily AP and CL radiographs. Nho *et al.*[29] reported that correlation coefficients between AP radiographic methods and CT images ranged from 0.763 to 0.788. Nunley *et al.*[19] also found a strong correlation

($P = 0.820$, $P < 0.001$) between versions on CT scans and serial CL radiographs, but the variability with CL radiographs exceeded 10° for 20% of the patients; therefore, they concluded that precise analysis of the acetabular cup version was limited with CL radiographs. Snijders *et al.*[30] compared 10 radiographic anteversion methods and found that correlations between radiographic and CT image versions ranged from 0.528 to 0.771 for the AP radiographic method, and 0.562 for the CL method. In this study, the intra- and inter-observer ICC of the radiographic measurements was greater than 0.95. The versions measured using the proposed method correlated well with CT measurements ($r = 0.853$, $P < 0.001$), and the correlation coefficient was higher than that reported in previous studies. Furthermore, the differences were almost within the 95% LoA.

The difference between our results and the previous results may be explained in part by the following: one recent study concluded that previous version measurement methods represented different projection angles around different axes on different reference planes, which was inconsistent with the "golden standard" CT scans,[30] thus possibly explaining why the accuracy of the previous methods was relatively low. However, in this study, we used the same sagittal plane for both our method and CT scanning method, which enabled direct comparisons. In addition, although our method was based on the standing position, while the CT scan was performed in the supine position, we adjusted the PT of the CT image to be consistent with that of the radiograph, prior to CT version measurement. However, with regard to CL radiographs, version measurements may be overestimated due to the variation in PT generated by flexion of the uninvolved hip joint during examination.[31] In our study, patients stood naturally without bilateral hip flexion during SL radiography, which rarely caused pelvic tilt. What is more, all patients successfully and smoothly underwent SL radiography 7 days after THA in the present study. We have, therefore, demonstrated that SL radiography is practicable to be performed on patients nearly 7 days after THA, and cup version measured on SL radiograph is showed satisfactory accuracy and reliability, with clinically acceptable measurement errors.

Limitations

This study has some limitations. We developed a method to measure cup version on SL radiographs and demonstrated that it was accurate and reliable for clinical evaluation. However, this manual measurement procedure with several sequential steps would require a certain amount of time. Further development of software may be required to automate and streamline the procedure. Additionally, measurements would be difficult in individual patients with undesirable cup abduction angle. If the cup was excessively abducted, its lateral projection on the radiograph would closely approximate a circle. This would make it difficult to determine the longest axis of the opening face for the measurement.

Conclusions

The X-ray incidence angle has no significant effect on cup version measurement in the lateral view, and thus CL radiographic method is also applicable to SL radiographs. The cup versions measured with SL radiography were close to the CT measurements. SL radiography is a reliable and accurate technique for measuring acetabular cup versions. Future studies should explore a reliable and valid method of measuring the femoral stem version on SL radiograph, thus accomplishing the assessment of the functional combined anteversion on single plain radiograph. Moreover, we expect this approach to be applied in multicenter study with large sample size and long duration of follow-up to investigate the relationship between functional combined anteversion and dislocation, so a functional safe zone can be established as a reproducible guide for the prevention of dislocation after THA.

Acknowledgments

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Authors' Contributions

Wenhui Zhang, Jie Xu, and Ruofan Ma were responsible for study conception and design; Wenhui Zhang and Zhiqing Cai performed experiments;

Hao Sun and Zhiqing Cai contributed to acquisition of data;

Meiyi Chen supervised statistical analyses; Wenhui Zhang, Meiyi Chen, and Jie Xu interpreted the data; Wenhui Zhang drafted the manuscript; Hao Sun and Deng Li critical revised and edited the manuscript; Ruofan Ma supervised this study and is responsible for the integrity of the data and the accuracy of the analyses.

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