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ORIGINAL PAPER

Is the acetabular cup orientation after total hip arthroplasty on a two dimension or three dimension model accurate?

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Abstract
Purpose Malposition of the acetabular component in total hip arthroplasty (THA) is a common surgical problem that can lead to hip dislocation, reduced range of motion and may result in early loosening. The aim of this study is to validate the accuracy and reproducibility of a single x-ray image based 2D/3D reconstruction technique in determining cup inclination and anteversion against two different computer tomography (CT)-based measurement techniques.
Methods Cup anteversion and inclination of 20 patients after cementless primary THA was measured on standard anteroposterior (AP) radiographs with the help of the single x-ray 2D/3D reconstruction program and compared with two different 3D CT-based analyses [Ground Truth (GT) and MeVis (MV) reconstruction model].
Results The measurements from the single x-ray 2D/3D reconstruction technique were strongly correlated with both types of CT image-processing protocols for both cup inclination [R^2=0.69 (GT); R^2=0.59 (MV)] and anteversion [R^2=0.89 (GT); R^2=0.80 (MV)].
Conclusions The single x-ray image based 2D/3D reconstruction technique is a feasible method to assess cup position on postoperative x-rays. CT scans remain the golden standard for a more complex biomechanical evaluation when a lower tolerance limit (+/-2 degrees) is required.

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Keywords Cup orientation · Inclination / anteversion · CT-based measurement · 2D/3D reconstruction · Statistical shape model · Total hip arthroplasty · Quality measure · Error analysis

Introduction

Previous studies demonstrate that both short- and long-term results of total hip arthroplasty (THA) have been well associated with component positioning, and surgical experience indicates that the mal-orientation of the acetabular component in terms of anteversion and inclination is correlated with prosthetic impingement, dislocation, wear, osteolysis, and prosthetic loosening [1–5]. Accurate assessment of cup orientation is essential for evaluation of outcome after THA and is typically done on two-dimensional (2D) postoperative anteroposterior (AP) X-ray radiographs [6–13]. While plain pelvic radiographs can be easily obtained, their accurate interpretation is subject to substantial error, if the individual pelvis orientation with respect to the X-ray plate is not taken into consideration [6, 7, 12]. It is thus of special interest to develop improved methods to accurately measure the postoperative cup orientation for a reasonable follow-up and to detect cup loosening/migration as an important quality measure and the basis for any error analysis after THA.

The aim of this study is to validate the accuracy and reproducibility of a single X-ray image based 2D/3D reconstruction technique in determining cup orientation after THA by comparing this technique with measurements on postoperative computed tomography (CT) reconstructions of the pelvis with two different types of image-processing software and measurement protocols.

Patients and methods

In addition to the use of conventional postoperative radiographs of the patients, while conducting a prospective clinical trial to evaluate an imageless navigation system for THA, we have also prepared postoperative CTs of the pelvis to determine acetabular positions. This investigation was approved by the local Ethics Commission and by the Federal Office for Radiation Protection (Z5-22462/2-2007-008).

In the present paper, the radiological and CT-films of the first consecutive 21 patients of this study were evaluated. The demographical data is displayed in Table 1. The indication criteria for THA was primary osteoarthritis in all patients. Patients with dysplasia of the hip or post traumatic deformities of the pelvis or femur were excluded. Cementless, press-fit cups (Pinnacle®, DePuy, Warsaw, IN, US) and uncemented hydroxyapatite-coated straight shafts (Corail®, DePuy, Warsaw, IN, US) were used in all patients.

Following the hospital's standard, each patient had a standard two-dimensional (2D) AP pelvic radiograph (conventional overall view of both hips with the patient standing, the film-focus distance being 1,150 mm) one week postoperatively. The central beam was directed at the symphysis. In addition, an axial radiograph of the operated hip was taken. All patients had a pelvic CT scan three to five weeks after surgery.

Radiographic calculation of the acetabular cup inclination and cup anteversion from a single X-ray image based 2D/3D reconstruction technique

The postoperative AP radiograph was used to measure the cup orientation with a single image based 2D/3D reconstruction technique [14, 15]. In summary, underlying this method is a statistical shape model-based 2D/3D deformable registration algorithm that can reconstruct a patient-specific 3D-model from a single standard 2D AP pelvis radiograph (Fig. 1). Statistical shape modeling is an efficient way to represent the shape variations in collected data, which is typically parameterized by an average shape model and a set of principal shape modes. Based on a statistical shape model of the pelvis, the 2D/3D reconstruction method uses a three-stage sequential optimization procedure to estimate the affine transformation between the statistical shape model and the input image, as well as the weights for the principal shape modes by matching the silhouettes detected from the statistical shape model to contours extracted from the input radiograph [14]. Required input includes a digital radiograph, the pixel size, and the film-to-source distance. No specific calibration of the X-ray radiograph or a CT scan of the patient is required. After reconstruction, cup inclination and anteversion is then calculated with respect to the APP extracted from the reconstructed 3D model. This is done by first calculating the radiographic inclination and radiographic anteversion according to Widmer's method [10], and then transforming the computed cup orientation from the radiographic coordinate system to a coordinate system that is established on the derived APP to estimate the patient-specific cup orientation. Finally, the program calculates radiographic inclination and anatomical anteversion according to Murray's definitions [16].

Table 1 Demographical data of patients

Characteristics	Value
Mean age (range; SD)	66.8 (51–81; 7.3)
Gender (male/female)	10/11
Side (right/left)	8/13
Mean BMI (range; SD)	27.4 (20.5–40.4; 4.2)

SD standard deviation, *BMI* body mass index

CT-based calculation of the acetabular cup inclination and cup anteversion with "Ground Truth" (GT) image processing software

Cup orientation for each patient with respect to the APP was extracted from the postoperative CT using the GT image

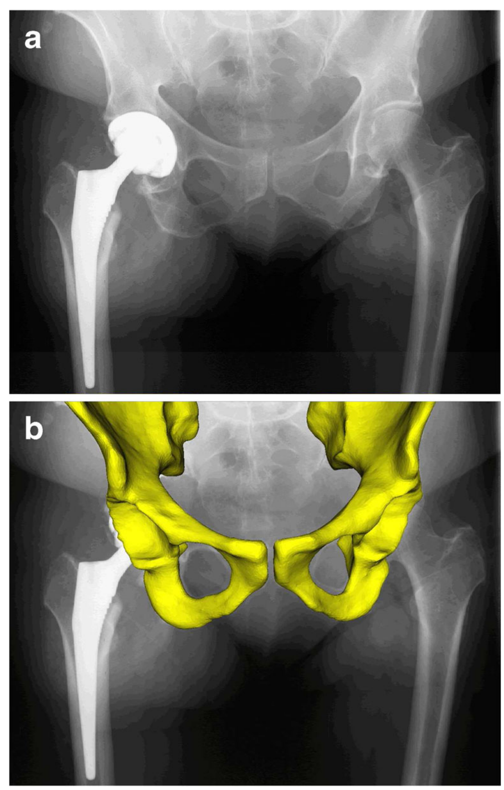

Fig. 1 To estimate the cup orientation, the 2D/3D reconstruction method first reconstructs a patient-specific 3D model from the X-ray radiograph by matching the statistical shape model of the pelvis to the X-ray radiograph. **a** The input X-ray radiograph. **b** The superimposition of the reconstructed 3D surface model (*yellow*) on the X-ray radiograph

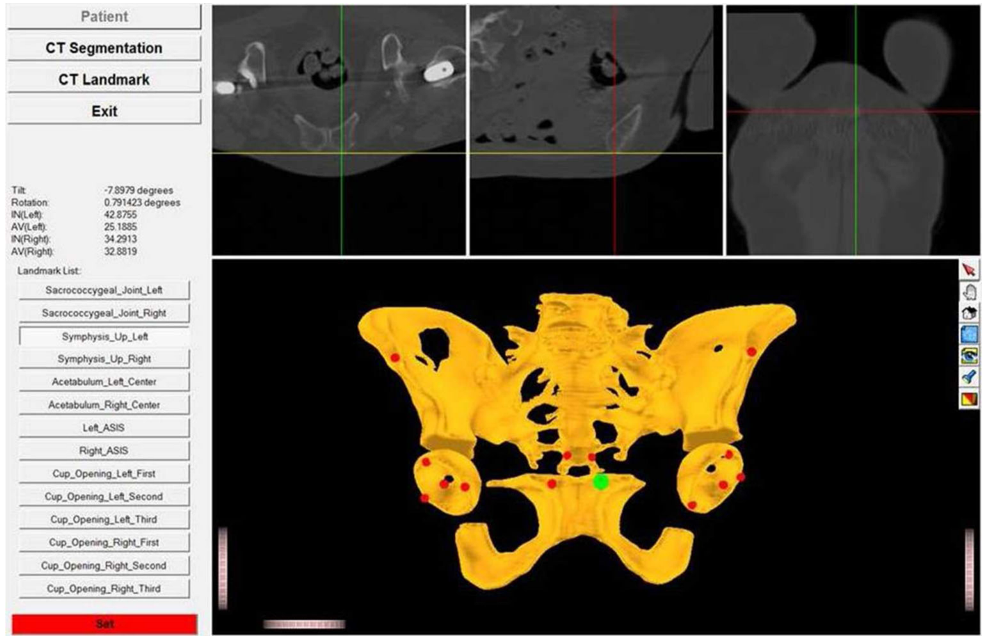

Fig. 2 Measuring the Ground Truth cup inclination and anteversion using a postoperative CT scan with the help of segmentation software

processing protocol [14, 15]. Four landmarks required in defining the APP (anterior superior iliac spines, pubic tubercles) were interactively picked from a model that was segmented from the postoperative CT scan using the commercially available software called Amira® (TGS-Europe, Paris, France). Then, three points on the cup opening rim were interactively picked to define the cup opening plane. Cup inclination and anteversion were calculated using the plane normal to the cup opening and the extracted APP (Fig. 2). The program calculated radiographic inclination and anatomical anteversion according to Murray's definitions [16].

CT-based calculation of the acetabular cup inclination and cup anteversion with 3D-MeVis image processing software

The position of the acetabular component was also evaluated by an independent external institute at MeVisLab (Bremen, Germany). The APP was extracted from the postoperative CT using 3D-MeVis image processing software. The normal vector of the sagittal plane is identical to the vector between both anterior superior iliac spine (ASIS) landmarks. To construct the transversal plane, the center point of the pubic tubercle (PT) landmarks was projected onto the vector between both ASIS landmarks. The vector from the center point to its projection was used to determine the normal vector of the transversal plane. The normal vector of the coronal plane was calculated as the cross product of the sagittal and transversal normal vectors. Subsequently, a plane parallel to the implant aperture was constructed. Its normal vector represents the implant axis. Cup anteversion and inclination angles were calculated by using the APP (Fig. 3). The cup position was measured twice by two independent examiners. Radiographic inclination and anatomical anteversion according to Murray's definitions were calculated [16].

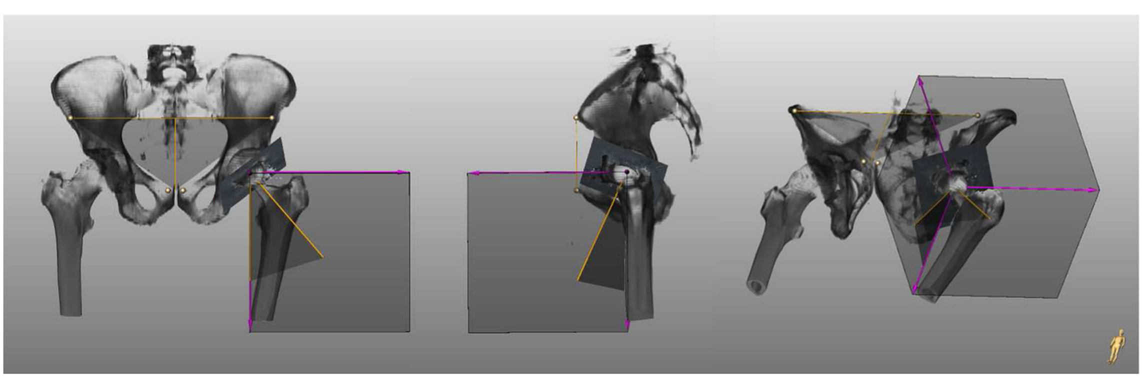

Fig. 3 The software developed by MeVis for measuring inclination and anteversion from a postoperative CT scan. The surface model was interactively segmented using the image-processing software

Table 2 Comparison of the measurements from the 2D/3D reconstruction technique on pelvis X-ray to the CT measurement Ground Truth and MeVis of the present study (degree difference; Δ)

Comparison	Method	Mean (SD)	min / max	95 % confidence interval (CI)
Δ MV-2D/3D	Incl (rad)	−1.6 (2.2)	−5.9 to 1.9	−2.64 to −0.60
	AV (anat)	−1.1 (2.8)	−4.8 to 3.7	−2.40 to 0.18
Δ GT-2D/3D	Incl (rad)	−1.4 (1.8)	−3.7 to 2.7	−2.23 to 0.57
	AV (anat)	−0.7 (2.1)	−5.5 to 3.1	−1.66 to −0.57
Δ MV-GT	Incl (rad)	−0.2 (1.9)	−5.0 to 2.7	−1.08 to 0.65
	AV (anat)	−0.4 (1.7)	−3.0 to 2.0	−1.20 to 0.35

Statistical methods

All analyses were performed with Microsoft Excel® 2010 and IBM SPSS Statistics® 21.0 software. The assumption of data normality was tested with the Shapiro-Wilk test, and average deviations of measurements from the single X-ray based 2D/3D reconstruction technique to the Ground Truth and to the MeVis analysis were compared with a two-tailed Student's t-test. The Pearson correlation coefficient was used to determine association of measurements from different techniques.

Pearson's correlation coefficient 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 (0.81–1.00) [17]. The graphical Bland-Altman analysis [18, 19] was used for both parameters to detect potential systematic errors in the method by plotting the difference between the two measurement techniques (2D/3D reconstruction-based measurement vs. postoperative CT scan-based measurement) against their averages.

Results

Comparing the acetabular cup measurements from the 2D/3D reconstruction technique to those obtained from the Ground Truth CT measurement protocol, a mean deviation of 1.4°± 1.9° (range −2.7°–3.7°; 95% CI −2.23 to −0.57) was found for inclination and a mean deviation of 0.6°±2.2° (range −3.1°–5.5°; 95 % CI −1.66 to 0.29) for anteversion (Table 2). The measurements from the single X-ray image based 2D/3D reconstruction technique showed good correlation for inclination (R^2=0.71) and excellent correlation for anteversion (R^2=0.89) when compared to the Ground Truth CT analysis (Fig. 4).

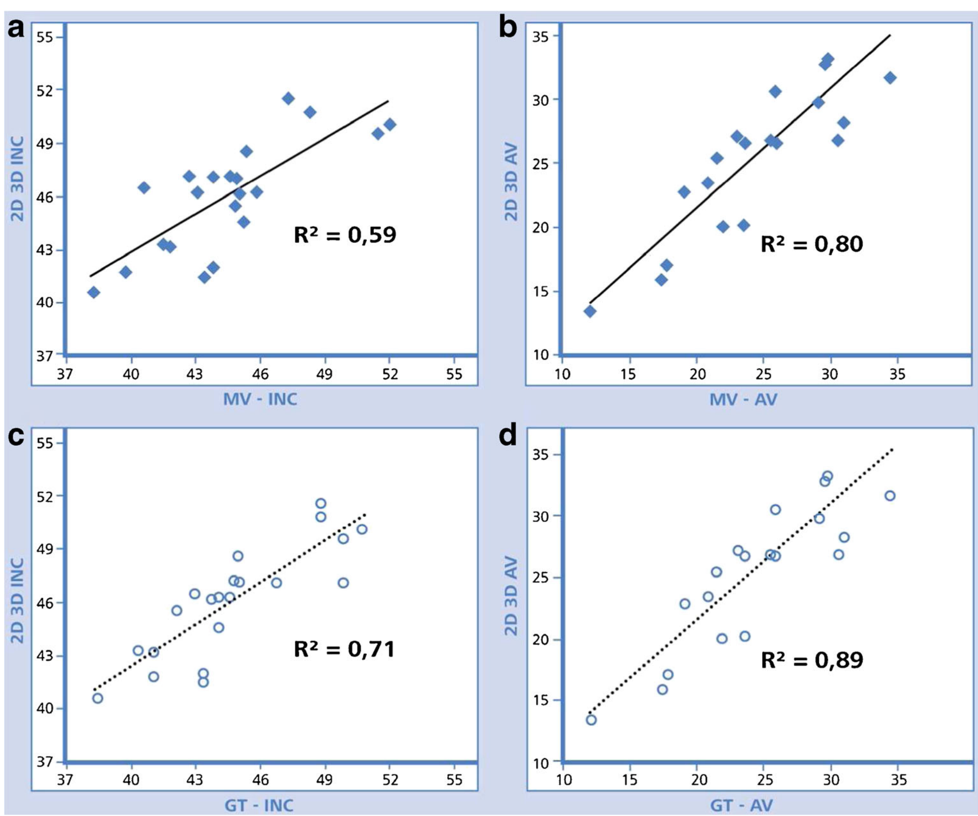

Fig. 4 Correlation between inclination measurements (*INC*) and anteversion measurements (*AV*) in degrees of the 2D/3D reconstruction technique with MeVis (*MV*) (**a**, **b**) and Ground Truth (*GT*) (**c**, **d**)

Comparing the acetabular cup measurements from the 2D/3D reconstruction technique to those obtained from the MeVis CT measurement protocol, a mean deviation of 1.6°±2.2° (range −1.9°–5.9°; 95 % CI −2.64 to −0.60) was found for inclination and a mean deviation of 1.1°±2.8° (range −3.7°–4.8° 95 % CI −2.40 to 0.18) for anteversion (Table 2). The measurements from the single X-ray image based 2D/3D reconstruction technique showed moderate correlation (R^2= 0.59) for inclination and good correlation for anteversion (R^2= 0.80) when compared to the MeVis CT analysis (Fig. 4).

Both CT-measurement image processing protocols (MeVis and Ground Truth) were strongly correlated to each other for both inclination (R^2=0.72) and anteversion (R^2=0.92). The differences between the cup orientation obtained from the 2D/3D reconstruction technique and those obtained from CT-based techniques were within −5.9° and 2.7° (95 % CI −1.80 to 0.65) for cup inclination and within −3.0° and 2.0° (95 % CI −1.20 to 0.35) for cup anteversion (Table 2).

A comparison of the measurement validity for cup anteversion between the results obtained with the 2D/3D measurement technique and other measurement techniques on plain radiographs, as published in the literature, is displayed in Table 2.

The Bland-Altman approach (Fig. 5) was used to illustrate agreement of both evaluation methods by plotting the differences of the two measurements on the vertical axis against the mean of both measurements on the horizontal axis. Note the dotted lines in the graph, which correspond to the 2.5th and 97.5th percentiles of differences assuming normal distribution (mean±1.96 SD). Therefore, it can be expected that 95 % of the individual differences for 2D/3D-GT are located in an interval of 5.0° to −2.2° for inclination and 4.9° to −3.5° regarding anteversion and for 2D/3D-MV in an interval of 6.0° to −2.8° for inclination and 6.6° to −4.4° regarding anteversion. Discrepancy between 2D/3D-GT and 2D/3D-MV measurements does not considerably increase with the averages of both methods and no systematic clusters of examiner values are obvious from the graphs. No systematic error was detected for the CT measurement methods as the means of the measurement pairs were spread evenly and randomly for both inclination and anteversion (Fig. 5).

Discussion

We evaluated whether cup inclination and anteversion can be accurately measured with a single X-ray image based 2D/3D reconstruction technique in comparison to CT-based 3D reconstructions of the pelvis with two different image-processing protocols. We found that the 2D/3D X-ray cup measurements have a sufficient accuracy for daily clinical practice, but CT scans remain the gold standard for a more complex biomechanical evaluation when a lower tolerance limit (±2°) is required.

This study has some limitations: first, only one type of pressfit cup was used. Second, the landmark choice in determining the anterior pelvis plane as well as the cup opening plane and prosthesis segmentation of the analysed CT

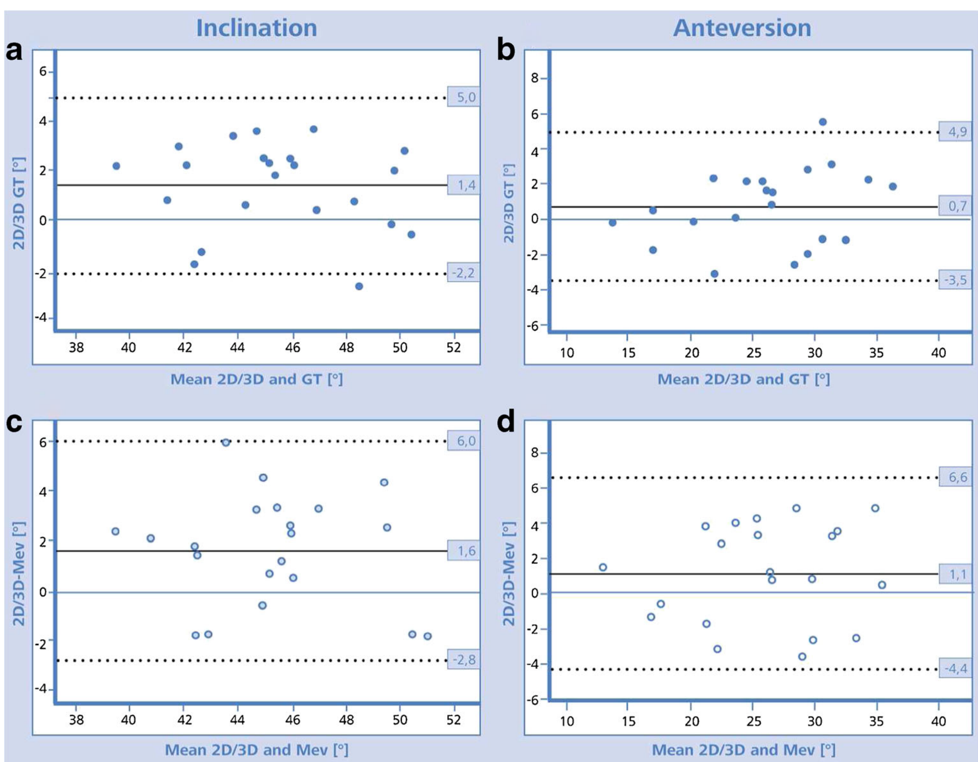

Fig. 5 Bland-Altman plots showed that the means of the measurements were spread evenly and randomly for inclination and anteversion. CT-based measurement techniques MeVis (**a**, **b**) and Ground Truth (**c**, **d**) against the reconstruction technique averages and 2D/3D-MV and 2D/3D-GT

contribute to differences between the CT measurements. Third, our study is limited by numbers.

The precondition of applying the single image-based 2D/3D reconstruction method for measuring cup orientation does not depend on whether the cup is uncemented or cemented, rather, it depends on the shape of the opening surface of the acetabular cup. Nonetheless, such a limitation can be addressed if a CAD model of the implant is available. With such a model, a 2D/3D registration can be used with the input X-ray radiograph.

Accurate assessment of the acetabular cup orientation is an important postoperative quality measure and an important part of error analysis [1–5]. Postoperative CT scan-based methods are regarded as the most reliable methods for measuring postoperative cup orientation; however, they carry the risks of additional radiation and expense [6, 7, 12, 20]. Widmer reported a protractor for measuring the anteversion of acetabular cups on radiographs [6]. Other studies reported that errors in measuring the cup position with various radiographic measurement methods could be high, exceeding 20°, due to the wide variability in individual pelvic orientation relative to the X-ray plate during image acquisition [6, 7, 12, 21–25]. A variety of radiological measurement methods to determine acetabular anteversion after THR have been described and comparatively analysed with CT scans [17, 25, 26].

When comparing our own data with these results, the accuracy to assess cup anteversion with the help of the radiographic 2D/3D technique is comparable to Lewinnek's method, Liaw's method and Woo and Morrey's method and more accurate than McLaren's method, Ackland, Bourne and Uhthoff's method, Pradhan's method, Widmer's method and Hassan's method (Table 3).

Correlation and comparability between X-ray measurements with CT measurements have been validated by the senior author in the past, but so far the accuracy of this 2D/3D measurement method has not yet been validated in comparison to a 3D-CT reconstruction model from an independent institute with blinded examiners [14, 15]. The two independent CT measurement protocols used in this study show the same trend and maximum differences of −5° for inclination and −2° for anteversion.

The present study demonstrates that the single X-ray image based 2D/3D reconstruction technique is a helpful procedure to measure cup inclination and anteversion on plain radiographs in everyday clinical practice. We found mean differences below 2° and maximum differences of −6° for inclination and −6° for anteversion between the radiographic 2D/3D and the CT-measurement protocols, which seem clinically acceptable for a first assessment of cup position. No specific calibration of the X-ray radiograph is required for these

Table 3 Reported validity of plain radiograph measurements compared with CT measurements for cup anteversion

Author	Publication	Method for measuring cup anteversion	Definition	Referenced plane of CT	Mean error in degrees (SD)	Range in degrees
Hassan et al. [1995]	JOA	Hassan's method AP radiographs	Not known	Not known	−2.5	−0.8 to −3.4
Marx et al. [2006]	AOTS	McLaren's method	Radiographic anteversion (for all)	APP (for all)	−14.5 (10.5)	Not known
		Ackland's method			−14.3 (10.3)	
		Pradhan's method			−14.5 (10.2)	
		Widmer's method			−6.4 (10.8)	
		Hassan's method AP radiographs (for all)			−14.4 (10.2)	
Ghelman et al. [2009]	CORR	Woo's method from cross-table lateral radiographs	Radiographic anteversion	Radiographic coronal plane	8.7	−10.7 to 25
Nho et al. [2012]	JBJS	Lewinneck's method	Anatomic anteversion	Radiographic coronal plane	0.10	Not known
		Widmer's method			7.66	
		Hassan's method			0.69	
		Ackland, Bourne and Uhthoff's method			11.14	
		Liaw's method			−1.68	
		Woo and Morrey's method AP radiographs (for all)			−1.28	
Lu et al. [2013]	CORR	Lewinneck's method AP radiographs	Radiographic anteversion	Radiographic coronal plane	0.55 (3.14)	Not known
Present study		2D/3D method AP radiographs	Anatomic anteversion	APP 3D reconstruction	−1.1 (2.8)	−4.8 to 3.7
		2D/3D method AP radiographs	Anatomic anteversion	APP Ground Truth	−0.7 (2.1)	−5.5 to 3.1

measurements. CT remains, however, the gold standard to accurately determine acetabular cup position when a lower tolerance limit (±2°) is required for a more complex biomechanical evaluation.

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Conflict of interest The authors declare that they have no conflict of interest.

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