Radiographic assessment of the cup orientation after total hip arthroplasty: a literature review

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Abstract: Optimal acetabular cup orientation is of substantial importance to good long-term function and low complication rates after total hip arthroplasty (THA). The radiographic anteversion (RA) and inclination (RI) angles of the cup are typically studied due to the practicability, simplicity, and ease of interpretation of their measurements. A great number of methods have been developed to date, most of which have been performed on pelvic or hip anteroposterior radiographs. However, there are primarily two influencing factors for these methods: X-ray offset and pelvic rotation. In addition, there are three types of pelvic rotations about the transverse, longitudinal, and anteroposterior axes of the body. Their effects on the RA and RI angles of the cup are interactively correlated with the position and true orientation of the cup. To date, various fitted or analytical models have been established to disclose the correlations between the X-ray offset and pelvic rotation and the RA and RI angles of the cup. Most of these models do not incorporate all the potential influencing parameters. Advanced methods for performing X-ray offset and pelvic rotation corrections are mainly performed on a single pelvic AP radiograph, two synchronized radiographs, or a two-dimensional/three-dimensional (2D-3D) registration system. Some measurement systems, originally developed for evaluating implant migration or wear, could also be used for correcting the X-ray offset and pelvic rotation simultaneously, but some drawbacks still exist with these systems. Above all, the 2D-3D registration technique might be an alternative and powerful tool for accurately measuring cup orientation. In addition to the current methods used for postoperative assessment, navigation systems and augmented reality are also used for the preoperative planning and intraoperative guidance of cup placement. With the continuing development of artificial intelligence and machine learning, these techniques could be incorporated into robot-assisted orthopaedic surgery in the future.

Keywords: Acetabular cup; radiographic angle; pelvic rotation; X-ray offset

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Introduction

Optimal acetabular cup orientation is of substantial importance to good long-term function and low complication rates after total hip arthroplasty (THA). Improper cup positioning always leads to limited range-of-motion, accelerated wear, and early dislocation postoperatively. Anteversion and inclination are two primary indicators of the cup orientation in THA (1), which can be measured on a plain radiograph (2,3) and were named the radiographic anteversion (RA) and inclination (RI) angles, respectively, by Murray (4) (*Figure 1*). In addition, the other two pairs of Murray angles, the anatomical anteversion (AA) and inclination (AI) angles and the operative anteversion (OA) and inclination angles, could be transformed into each other using trigonometric functions but were wrongly used in the literature.

Some specific ranges for the RA/RI angle recommended by Lewinnek *et al.* (3) and others (5,6) have also been widely accepted as the "safe zone" for cup placement in THA. However, to date, a plethora of different methods for measuring the cup orientation have been proposed and are inconsistent among each other. As a simple, cheap, and easily available imaging modality, the plain radiograph is still the mainstream tool for the postoperative assessment of cup orientation. Multiple radiographic measurement methods have been proposed since the 1970s.

However, there is a discussion to be had about the reliability and validity of these radiographic methods. Indeed, cup angle interpretation is multifactorial and dependent on both extrinsic and intrinsic factors (7). The cup orientation can only be correctly interpreted with reliable results after incorporating all the influencing factors into the calculation process. As the two most important extrinsic determinants of cup orientation, the X-ray offset and pelvis orientation have been analysed with different observational results in numerous previous studies. To minimize the effects of the X-ray offset and pelvic rotation on the radiographic evaluation of the cup orientation, other measurement methods involving complicated algorithms and advanced equipment and technology have also been developed for precisely assessing the cup orientation intra- or postoperatively. Different methods have their own pros and cons according to their applications and availability.

Although some studies have disclosed significant variation in the current assessment methods of cup orientation (8) and analysed the pitfalls of these methods on how to correctly determine the cup orientation in THA regarding pelvic rotation (9), a critical analysis of the reasons for this inconsistency, the effects of the X-ray offset and pelvic rotation, and the previously established correction methods is still lacking. The rest of this review is organized as follows. The section titled "*Radiographic measurement methods of cup angles*" presents the conventional measurement methods of the radiographic angles of the cup, including an overview of radiographic measurement methods based on the hip or pelvic antero-posterior (AP) and lateral radiographs and reliability and validity studies of the conventional measurement methods. In the section titled "Influencing factors of the radiographic angles of the cup", the influencing factors of the radiographic angles of the cup are introduced, the X-ray offset and the pelvic rotation. In the section titled "*Advanced methods for evaluating the X-ray offset and pelvic rotation*", we present some advanced methods for correcting the X-ray offset and pelvic rotation. Finally, in the "Discussion" section, we discuss the advantages and disadvantages of the various types of measurement methods used today and then summarize the challenges and future prospects in the radiographic assessment of cup orientation.

The radiographic measurement methods of the cup angles

Overview of the radiographic measurement methods

Most radiographic measurement methods of cup angles are performed on AP X-ray films, including hip and pelvic radiographs. Others use a lateral radiograph of the hip as the measurement tool.

Hip AP X-ray

Since McLaren proposed the earliest radiographic measurement method in 1973 (2), many researchers have developed different variants and measurement tools based on the original algorithm. All of these methods are based on a basic projection phenomenon in which the cup opening can be projected by a parallel beam from a circle to an ellipse on the X-ray film. The correspondence between the spatial circle and the planar ellipse can be interpreted with the cup anteversion, of which the arcsine value can be calculated with the shorter to longer axis of the ellipse projected onto AP X-ray film. Although the X-ray has no parallel beam in the real world, this relationship between the circle and ellipse persists on hip-centred AP radiographs, which was verified in an analytical study (10).

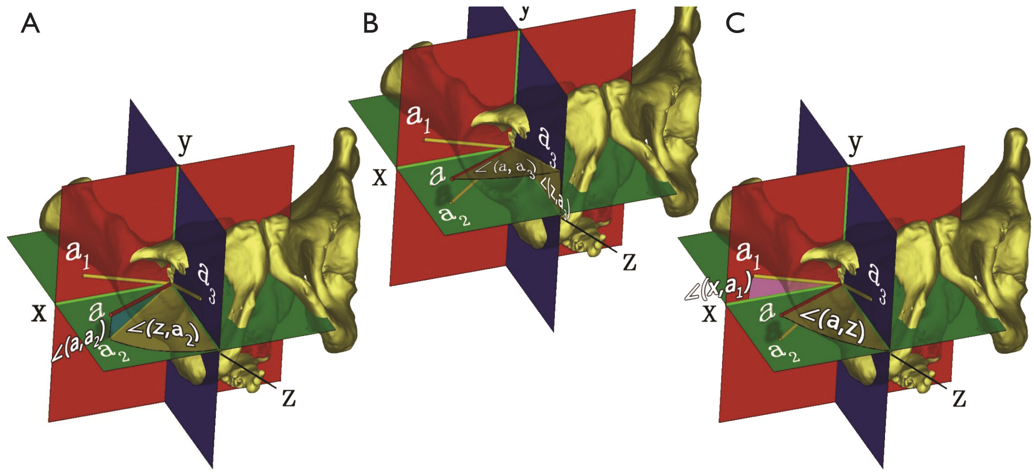

Figure 1 Three pairs of the acetabular/cup angles defined by Murray. x, y, and z are the transverse, anteroposterior, and longitudinal axis of the body. xz, xy, and yz constitute the axial, coronal, and sagittal plane, respectively. a represents the axis of the acetabular or cup, of which its projection in the axial, coronal, and sagittal plane are a1, a2, and a3, respectively. (A) The RA and inclination angles are indicated by ∠(a, a2) and ∠(z, a2); (B) the OA and inclination angles are indicated by ∠(a, a3) and ∠(z, a3); (C) the AA and inclination angles are indicated by ∠(x, a1) and ∠(a, z).

To calculate the cup anteversion, Ackland *et al.* used the general formula of the ellipse to calculate its shorter axis (11), while others developed similar methods (12-17). Visser *et al.* established a mathematical method combining the general formula of the ellipse and the trigonometric functions for the measurements (18). Additionally, other modified methods have been proposed according to basic geometrical relationships (19-22). Based on these algorithms, different measurement tools (23) and software (24,25) were established. Using McLaren's method, the RadLink software was developed to intraoperatively help place the cup within the target range (24). Zingg *et al.* incorporated the rotation matrix algorithm to evaluate the cup orientation with a C-arm intraoperatively (26).

Although these methods were used in hip AP radiographs (*Figure 2*), they were also performed on pelvic AP radiographs in other studies.

Pelvic AP X-ray

Similar to McLaren's study, Lewinnek also proposed a similar measurement method based on the same trigonometric relationship between the longer and shorter axis of the ellipse (3). Thereafter, others also used similar methods to measure the cup orientation intra- (5) or postoperatively (27,28); meanwhile, the TraumaCad software used by Schwarzkopf *et al.* (29) was developed based on these methods. However, all these studies performed measurements on the pelvic AP radiograph without considering X-ray divergence and the distorted silhouette of the cup opening.

Martell *et al.* developed a semi-automated computer-assisted technique, named the Hip Analysis Suite (HAS), for detecting polyethylene wear in THA based on edge detection (30). During measurement of the cup orientation, edge detection was used to help determine the edge of the ellipse projection of the cup opening. Barrack *et al.* also used the HAS to calculate the cup angles on pelvic AP radiographs (31). Penenberg *et al.* used Radlink to measure the intraoperative RA angle and compared it with the postoperative measurements obtained using Martell software (5). In another study, Callanan *et al.* (32) added an additional lateral radiograph to distinguish anteverted from retroverted cups. Importantly, the X-ray offset was not considered in many of these studies (5,30-32).

Lateral radiographs

In addition to the above-mentioned measurement methods involving AP radiographs, other methods have been performed on hip lateral radiographs, such as the cross-table lateral radiograph (13,14,33-39).

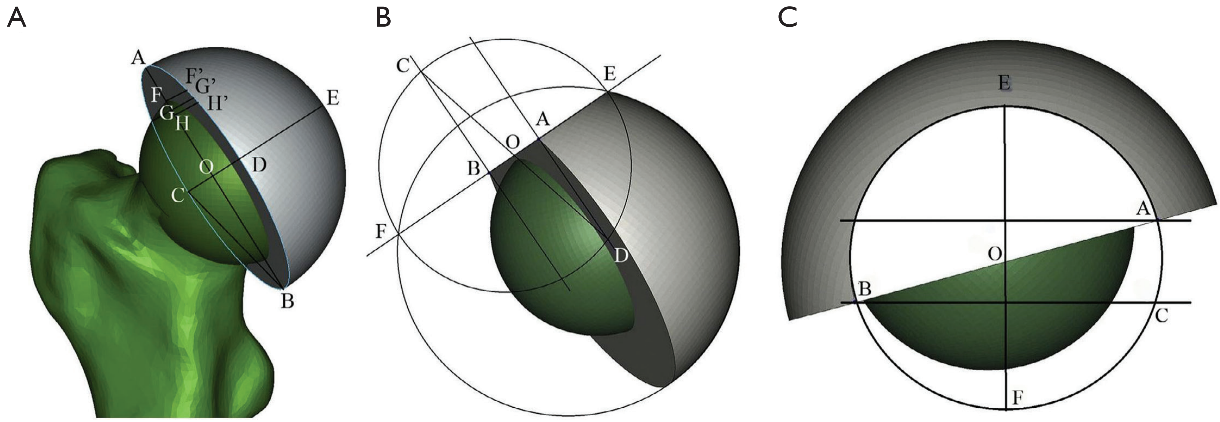

Figure 2 Some of previous radiographic measurement methods on the pelvic or hip AP radiograph (10). (A) The methods of Ackland (11), Hassan (15), and Pradhan (16) rely on different points acquired on the longer axis of the ellipse projection, which can be used to determine the shorter axis according to the general equation of ellipse. With Liaw's method (20), the RA angle is arcsine of the shorter to longer axis; (B,C) the methods of Kosiyatrakul *et al.*, Bachhal *et al.* and Fabeck *et al.* can be shown with another circle and a change of view. Details of the explanation can be found in *Figure 3* in (10).

However, the patient position is poorly standardized and the X-ray beam angle used varies across studies that analysed cross-table lateral radiographs. The degree of contralateral hip flexion is inconsistent, with 45° (40,41), 90° (41,42), or some arbitrary degree (13) reported across studies. Furthermore, the beam direction used also varies, with 30° (13) or 45° reported (38,39). Herrlin *et al.* (13) and Ghelman *et al.* (43) determined that the inclination of the cup opening relative to the X-ray table could not represent the RA angle of the cup unless the cup opening was projected as a line onto the cross-table lateral radiograph, which was dependent on the RI angle of the cup and was difficult to achieve in clinical activities.

Another concern inherent to the cross-table radiograph was that flexion of the contralateral hip might cause pelvic extension or posterior tilt, which would result in increased acetabular anteversion to an unknown degree (35).

Reliability and validity assessment of the radiographic measurement methods

A variety of studies have been performed to test the reliability and validity of the various measurement methods using either the hip or pelvic AP or cross-table lateral radiograph to date. Some of them used phantom models to compare different measurement methods, while others compared the measurement results between radiographic and CT-based methods.

The inter- and intra-observer reliability of the Hassan method and the cross-table measurement method were verified in two studies without referencing other methods (44,45). In addition, most of the radiographic measurement methods established previously were compared with reference values either in a model test or from clinical studies. As shown in the summary in *Table 1*, most of the comparative or reliability studies reported previously did not use uniform study designs and outcomes in terms of the hip or pelvic radiographs, intra- or postoperative fluoroscopy, the standing or supine position, the reference plane (e.g., AP, axial or sagittal CT image, or the coronal plane of the body), the targeted angles of the cup (e.g., the RA, OA or AA angle), and the measurement technique used as the control reference. Most importantly, the X-ray offset was not incorporated into the calculation procedure when these methods were performed on the pelvic AP radiographs.

Influencing factors of the radiographic angles of the cup

The X-ray offset and pelvis orientation have been considered to be the two most important extrinsic influencing factors in the radiographic measurement of the cup orientation.

X-ray offset

The phenomena of the variable silhouette of the cup opening caused by variability in the relative position

Table 1 Reliability and validity studies of the radiographic measurement methods

Author	Study type	Radiographic measurement methods studied	Radiograph type/patient posture /reference plane	Reference method/plane	Reference angle	Recommendation
Haenle 2010 (46)	Phantom model	Ackland (11), Hassan (15), Pradhan (16), Modified Pettersson (19)	Hip AP radiograph/APP	Predefined value/ APP	RA angle	Modified Pettersson method (19)
Nho 2012 (47)	Prospective clinical trial	Lewinnek (3), Hassan (15), Liaw (20), Widmer (48), Ackland (11), Cross-table lateral radiograph (34)	Supine hip AP radiograph	Axial CT image	AA angle	Lewinnek (3), Hassan (15), Liaw (20), Woo and Morrey (34)
Marx 2006 (49)	Retrospective clinical trial	KH Widmer (48), Pradhan (16), McLaren (2), Hassan (15), Ackland (11)	NA	SurgiGATE CT navigation/APP	RA angle	KH Widmer (48)
Kalteis 2006 (50)	Retrospective clinical trial	KH Widmer (48) *vs.* VectorVision CT navigation	Standing pelvic AP radiograph; APP for CT	MeVisLab image software/APP	RA angle (transformed)	CT navigation
Bayraktar 2017 (51)	Retrospective clinical trial	MediCAD software using KH Widmer (48)	Standing pelvic AP radiograph	3D-MeVis 3D-CT software/APP	RA/RI angle	3D-CT method
Lu 2013 (52)	Retrospective clinical trial	Lewinnek (3)	Supine pelvic AP radiograph	3D-CT/supine coronal plane	RA/RI angle	Lewinnek (RA angle)
Nishino 2013 (41)	Retrospective clinical trial	Lewinnek (3) *vs.* Cross-table lateral radiograph	Supine pelvic AP radiograph	3D-CT/supine coronal plane	RA angle	Lewinnek
Westacott 2013 (53)	Retrospective clinical trial	TraumaCad using KH Widmer (48)	Supine pelvic AP radiograph	Axial/coronal CT image	AA/RI angle	AA angle underestimated by 12°
Nomura 2014 (54)	Retrospective clinical trial	Lewinnek (3), KH Widmer (48), Liaw (20), Pradhan (16), Cross-table lateral radiograph (34)	Supine pelvic AP radiograph	3D-CT image/ supine coronal plane	RA angle	KH Widmer (48)
Alzohiry 2018 (55)	Retrospective clinical trial	Lewinnek (3), Liaw (20), Hassan (15), KH Widmer (48), Ackland (11)	Supine pelvic and hip AP radiographs	Axial CT image	AA angle	Lewinnek and Liaw for pelvic/hip radiographs; Hassan for pelvic radiograph; KH Widmer and Ackland for hip radiograph
Snijders 2019 (40)	Retrospective clinical trial	Lewinnek (3), KH Widmer (48), Pradham (16), Ackland (11), Dorr (56), Wan (57), Liaw (20), Hassan (15), Cross-table lateral radiograph (34), Sagittal CT image/ OA angle	Supine pelvic AP radiographs	Axial CT image	AA angle	
Schwarzkopf 2017 (29)	Cadaveric experiment	TraumaCad *vs.* optical navigation	Pelvic AP radiograph/APP	3D-CT/APP	RA/RI angle	Navigation (RA angle)

Table 1 (*continued*)

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Author	Study type	Radiographic measurement methods studied	Radiograph type /patient posture/reference plane	Reference method/plane	Reference angle	Recommendation
Shin 2015 (58)	Retrospective clinical trial	Liaw (20) *vs.* Cross-table lateral radiograph (34)	Supine pelvic AP radiograph	PolyWare	RA angle	Liaw
Delagrammaticas 2019 (24)	Prospective clinical trial	RadLink	Intraoperative supine hip and pelvic PA radiographs	RadLink/ postoperative supine pelvic AP radiograph	RA angle	Intraoperative hip PA radiograph
Penenberg 2018 (5)	Prospective clinical trial	Radlink	Intraoperative supine pelvic AP radiograph	Martell HAS software/ postoperative supine pelvic AP radiograph	RA angle	95% of RA/RI angles within 5° of Radlink measurements
Harold 2019 (59)	Prospective clinical trial	RadLink (Ackland)	Intraoperative hip PA radiograph/standing coronal plane	3D SterEOS software/ postoperative standing plane	RA angle	
Amirouche 2016 (60)	Retrospective clinical trial	Modified Kosiyatrakul method (AA angle); Ackland	Postoperative pelvic AP radiograph/posture not reported	Intraoperative MAKO robot data	RA angle	
Ghelman 2009 (43)	Retrospective clinical trial	Cross-table lateral radiograph *vs.* Reformatted CT image	Posterior border of sacrum and ischium	Intraoperative navigation data	RA angle	Reformatted CT image

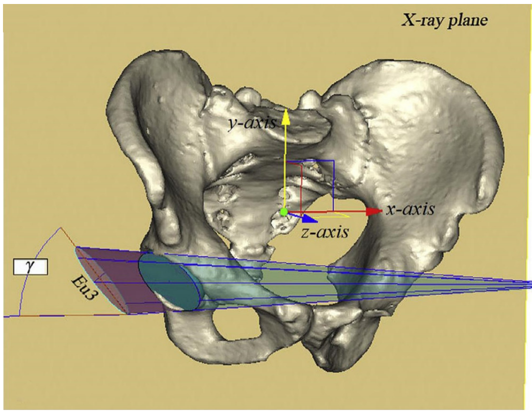

Figure 3 A cone model for correcting the X-ray offset and measuring the radiographic angles of the cup (10). Eu3 represents the ellipse projection of the cup opening.

between the cup and the X-ray beam source was disclosed in 1975, which was attributed to divergent rays or the X-ray offset in the pelvic AP radiograph (15,61). Pettersson *et al.* used the transverse translation of the X-ray source from the pelvic AP view to the hip AP view to judge the anteversion and retroversion of the cup (12), which was also used in later studies (16,62,63).

Goergen and Resnick proposed a correction factor of an additional 5° for the RA angle for the symphysis-centred pelvic AP radiograph relative to that of the hip AP radiograph, while the correction factor was variable with the varying relative position of the cup and X-ray offset (61). Other researchers had similar findings (11,16,48,62,63). Regardless of the incorrect interpretation of the Lewinnek method, Dorr *et al.*'s study only presented a predefined setting for the cup position and pelvic rotation (62).

In addition to the X-ray offset, after measuring radiographs of 152 THA procedures, Karl-Heinz Widmer found that the RA angle was also slightly dependent on the true cup inclination (48). Rueckl *et al.* aligned the intra- and preoperative pelvic postures on the radiographs and found that an additional 5° correction factor was needed to correct the intraoperative RI angle for the X-ray offset (64).

For the above-described studies, no theoretical evidence was presented to support these proposals. With CT-based measurements as the reference, Westacott *et al.* discovered a correlation between the RA/RI angles and their CT-derived counterparts (53). Widmer *et al.* (65) also stressed that the RA angle measured on the pelvic AP radiograph was nothing but a first approximation that needed to be corrected unless measured on the hip-centred AP radiograph.

Liaw *et al.* established a correction method for the X-ray offset in the pelvic AP radiograph by modifying Karl-Heinz Widmer's method (66). Furthermore, the relationship between the true RA angle and its estimated error on the pelvic AP radiograph was expressed as a curve dependent on the true RI angle. More specifically, Schwarz *et al.* performed a phantom model study to quantitatively investigate the influence of the X-ray offset on the cup angles (67). Based on the observation that translating the X-ray beam medially and cranially from the centre of the hip could decrease the RA angle of the cup, they established a modified method of differentiating between anteversion and retroversion of the cup by means of a second X-ray and correcting the RA angle by adding horizontal and vertical correction factors, which could be calculated in line with Liaw's correction method for the transverse X-ray offset and Tannast and Wan's method for pelvic tilt correction.

In contrast to the linear model of Schwarz *et al.*, Zhao *et al.* incorporated the influencing factors of X-ray offset into a mathematical model that involved the rotation matrix of the projection transformation between the spatial circle and its ellipse projection in the X-ray plane (68) (*Figure 3*). The varying rules between the X-ray position and the cup orientation in 3D space could be depicted as different types of surfaces or curves dependent on different groups of unknown variables in the formulae. Given the theoretical nature of Zhao *et al.*'s study, further *in vitro* experiments should be performed to verify their conclusions.

Pelvic rotation

Pelvic rotations involve the transverse, longitudinal, and anteroposterior axis of the body, which are referred to as tilt, axial rotation, and obliqueness, respectively, in this study for clarification. The intersubject variation of pelvic tilt was studied mostly with inconsistent results and influenced the cup orientation significantly, especially for pelvic AP radiographs, which cannot indicate the degree of individual pelvic tilt directly.

The lateral radiograph was the most convenient tool for measuring the pelvic tilt. Shon *et al.* measured the pelvic tilt among four postures using the lateral radiographs of 40 patients and found that the pelvis tilted posteriorly 26.5°, 8.4°, and 13.4° from the supine position to the sitting, standing, and lateral decubitus positions, respectively (69). Heckmann *et al.* incorporated the sacral slope into the evaluation of the relationship between the cup's AA angle and late dislocation after THA (70). After adjusting the gantry angle of the CT scan, Anda *et al.*'s cadaveric study presented a ratio of 0.5° variation in the acetabular AA angle to 1° of pelvic tilt (71). Lazennec *et al.* established a similar reformatted CT-based method to measure the AA angle after incorporating the pelvic tilt measured on the lateral radiographs of different postures (72).

In addition to lateral radiographs and CT scans, some anatomical studies have observed that the pelvic tilt could cause a change in the acetabular crossover on pelvic AP radiograph (71,73-75). Tannast *et al.* analysed six pelvic anatomical parameters from the pelvic AP radiographs of 104 patients, one of which showed the strongest correlation with the pelvic tilt measured on the lateral radiograph (76). By doing so, they established a mathematical correction model for estimating the pelvic tilt based on the postoperative pelvic AP radiograph.

Similar to the offset effect caused by X-ray translation, modifying the angle of the X-ray beam (11), such as the pelvic inlet view (5,15), can help with evaluating the difference between the anteversion and retroversion of the cup. When viewing towards the pelvic inlet, the abduction and anteversion angles were reduced for an anteverted cup but increased for a retroverted cup (12,77).

Table 2 summarizes the studies performed on the relationship between the pelvic rotations and the RA and RI angles of the cup using the above-mentioned radiographic measurement methods. Most of these studies were observational studies. Grammatopoulos *et al.* (81) used the EBRA software to evaluate the impact of the orientation of the pelvis between lateral decubitus and supine positions during the operation. Wolf *et al.* (87,88) performed a model test to establish a relationship between the pelvic rotation and the measurements of different angles of the cup. Derbyshire (89) developed a series of mathematical equations to evaluate the effects of different types of pelvic rotations on cup wear. Except for these three studies, researchers have only analysed one or two influencing factors, such as pelvic tilt and axial rotation. Similar to the effect of the X-ray offset, the interactive effect of the true RI angle of the cup and the pelvic rotation on the RA angle of the cup has also been observed in some studies (12,85). The X-ray offset was also incorporated into the effect of pelvic rotation on the measurement of the cup angles in some observational, *in vitro* phantom studies (57,83,84). However, these established methods or models did not analyse the synergetic effect of the pelvic rotation and X-ray offset in an accurate manner, which was merely approximated in some simulated or fitted models, regardless of other parameters influencing the calculation. Based on a previously established cone model, Zhao *et al.* established an equation for a cone and accurately analysed the effects of the pelvic rotations about each axis on the RA/RI angles after incorporating the X-ray offset and the position and orientation of the cup (90).

Advanced methods for evaluating the X-ray offset and pelvic rotation

Different from the traditional measurement methods, which were mainly performed on a single radiograph, some advanced methods incorporated more complicated equipment, algorithms and methods.

Single pelvic AP radiograph

Due to the inherent deficiency of X-ray film, it is difficult to accurately evaluate the pelvic tilt using a single pelvic AP radiograph; however, the X-ray offset can be corrected as much as possible with some complicated algorithms with or without edge detection.

Mathematical method

The earliest method involving a mathematical algorithm was proposed by Seradge in 1982 (91). His method was based on a series of geometric transformations with a specified parameter range in the model, which limited its application.

To reveal the effect of pelvic rotation on the cup angles, Jaramaz *et al.* (92) developed a new method of geometric reconstruction and measured the cup orientation using this new method and Seradge's method. When compared with the intraoperative navigation measurements, the results displayed a significant effect of pelvic rotation on the RA angle. No details of their method were disclosed.

Derbyshire also developed an advanced algorithm similar to Seradge's method (93). However, in this method, the RI angle needed to be corrected before the RA angle; furthermore, his derivation process was difficult to follow and conveniently interpret by the reader.

In Amiri *et al.*'s study, a multiplanar radiographic method was used to compensate for the X-ray offset (94). Using this method, the relationship between the measurement errors caused by the X-ray offset and the true cup orientation was established and simulated. In a study of the radiographic assessment of cup wear, Stuart

Table 2 Studies on the effect of the pelvic rotations on the RA and RI angles of the cup

Author	Study type	Pelvic rotation type	Targeted angle	Measurement method and plane	Features and results	Correction method
Pettersson 1982 (12)	Model test	Pelvic tilt	RA angle	Pelvic AP radiograph	Dependent on true RI angle	Correction factor
Thoren 1990 (78)	Model test	Pelvic tilt and axial rotation	RI angle	Pelvic AP radiograph	1) Vertical distance from symphysis to sacroiliac joint (1 mm change cause variation: left, 0.09°; right, 0.14°); 2) Horizontal distance from symphysis to coccyx midline (1 mm change cause variation: left, 0.11°; right, 0.22°)	Correction factor; linear relationship
Mellano 2015 (79)	Model test	Pelvic tilt and axial rotation	RI angle	Pelvic AP radiograph	1) Inlet view decreased RI angle, but outlet view increased it; 2) Obturator oblique view decreased RI angle, but iliac oblique view increased it	Correction factor; nomogram
Schwarz 2017 (80)	Model test	Pelvic tilt and axial rotation	RA/RI angle	TraumaCad 2.0/ Lewinnek *vs.* CT/APP	Dividing the errors into horizontal and vertical errors	Nomogram
Delagrammaticas 2018 (75)	Model test	Pelvic tilt and axial rotation	RA/RI angle	RadLink	Predefined AA and AI angles: 0° and 55°. For pelvic and hip radiographs, RA angle was prone to being influenced by pelvic axial rotation but the RI angle was more sensitive to pelvic tilt	Nonlinear relationship
Herrlin 1988 (14)	Clinical test	Pelvic tilt	AA/RI angle	Herrlin method	AA angle measured on the CT axial image.	Correction factor; tabluation
Grammatopoulos 2018 (81)	Retrospective clinical trial	Pelvic rotations about three axes	RA/RI angle	EBRA	Left hip: Pelvic tilt and axial rotation increased RI angle; RA angle was increased by pelvic tilt but decreased by pelvic axial rotation	Correlation coefficient
Liaw 2008 (82)	Retrospective clinical trial	Pelvic tilt and axial rotation	RA angle	McLaren/Lewinnek methods	Vertical and horizontal displacement of sacrococcygeal junction to symphysis.	Correction algorithm
Widmer 2018 (65)	Simulation test	Pelvic tilt and axial rotation	RA/RI angle	Basic trigonometric equation	Distance between mid-symphysis and mid-sacrum; rectangle around the pelvic inlet; X-ray offset considered	Linear relationship
Wan 2009 (57,83)	Model test	Pelvic tilt	RA/RI angle	Basic trigonometric equation	Computer navigation. X-ray offset considered. CT. Pelvic posterior tilt increased RA/RI angle, and pelvic anterior tilt decreased RA/RI angle. 1° of tilt changed RA angle by 0.8°	Correction factor; tabluation

Table 2 (*continued*)

Table 2 (*continued*)

Author	Study type	Pelvic rotation type	Targeted angle	Measurement method and plane	Features and results	Correction method
Zhu 2010 (84)	Retrospective clinical trial	Pelvic tilt	RA/RI angle	Basic trigonometric equation	Computer navigation. X-ray offset considered. 1° of tilt changed RA angle by 0.8°	Linear relationship
Lembeck 2005 (85)	Clinical test	Pelvic tilt	RA/RI angle	Basic trigonometric equation	Inclinometer and a sonographic tracking system. 1° of pelvic tilt lead to 0.7° of variation in RA angle. Dependent on true RI angle	Correction factor; algorithm; nonlinear relationship
Rutherford 2019 (86)	Model test	Pelvic tilt	RA/RI angle	Basic trigonometric equation	A mechanical alignment and a transverse acetabular ligament method were used to determine the RA angle. Relevant algorithms about pelvic rotations were used	Linear relationship
Wolf 2015 (87,88)	Model test	Pelvic rotations about three axes	RA/RI angle	Basic trigonometric equation	A kinematic model for calculating the intraoperative cup orientation after incorporating the pelvic rotation during the THA	Nonlinear relationship
Vigdorchik 2017 (7)	Analytical study	Pelvic rotations about three axes	RA/RI angle	Basic trigonometric equation	For true RA/RI angles of 15° and 50°, 1° of pelvic tilt lead to 0.77° change for RA angle and 0.17° for RI angle, while pelvic axial rotation induced RI angle change with an 1:1 ratio, but did not affect RA angle	Mathematical model
Derbyshire 2018 (89)	Analytical study	Pelvic rotations about three axes	RA/RI angle	Basic trigonometric equation	Matrix algorithm have been developed to evaluate the effect of the pelvic rotation on the RA and RI angles of the cup	Mathematical model

Kerrigan introduced the cone model to calculate the RA/RI angles of the cup and their true value in 3D space (95). Nevertheless, to reduce the computational difficulty, a simplified situation was simulated with the X-ray beam source directing at the cup's centre, which was similar to the hip-centred AP radiograph.

Based on the related algorithms of projection transformation and monocular computer vision (96-98), Zhao *et al.* generalized a mathematical model of the cone from a hip-centred AP radiograph to a pelvic AP radiograph (10). Based on the ellipse projection, the true RA and RI angles of the cup could be calculated according to the established model. Sarry *et al.* established an accurate 2D method using only one pelvic AP radiograph to estimate cup wear. According to their method, the cup orientation was calculated with an algorithm in computer vision with the pose estimation based on the back projection of a 3D circle from the ellipse (99).

Einzel-Bild-Roentgen-Analyse (EBRA)

Based on a series of radiographs, EBRA was a computer-aided method for assessing the migration of arthroplasty implants. The superiority of this method was that only a single pelvic AP radiograph was needed and a specified range of the pelvic rotation could be compensated using its algorithm (100-102). However, a significantly distorted pelvis could not be corrected with this method. Langton *et al.* validated EBRA for measuring the RA and RI angles of the cup by comparing it to the lateral radiographic method (103).

Lee *et al.* (104) also validated the EBRA method with the navigation measurements and tested the RA angle measured on a false profile view with that of EBRA. Their results showed a correlation between the results of two groups with a moderate correlation coefficient of 0.56.

Grammatopoulos *et al.* used EBRA to measure the cup angles in the lateral decubitus position intraoperatively and in the supine position postoperatively. The mean differences in the RA and RI angles were 1° and −2°, respectively (105). In contrast to Vigdorchik *et al.* (7), Wang *et al.* used computer-aided design (CAD) software to create computer-generated pelvic AP radiographs following THA to calculate the posture-integrated RA angle after simulated pelvic rotations were applied (106). Their measurements were based on the EBRA method using the APP as a reference. In line with their established formula, 1° of pelvic tilt could induce a 0.8° change in the RA angle with predefined RA and RI angles of 15° and 40°, respectively.

Two synchronized roentgen tubes

In addition to the previously described methods used in pelvic AP radiographs, there were also other types of radiographic methods used for assessing cup orientation. Different from those using one X-ray beam source, some other methods were based on two roentgen tubes either at right angles to take the AP and lateral radiographs simultaneously or at an acute angle against each other in front of the body, which enabled calculations of the movements of the implants in 3D space. Similar to EBRA, these systems were also used for evaluating implant migration or wear. During the evaluation, the cup orientation was an essential determinant for calculating wear.

Radio stereometric analysis (RSA)

Baldursson *et al.* (107) and Selvik (108) developed the RSA technique using two synchronized roentgen tubes at a 35°–40° angle to each other in front of the body. The original method was based on the configuration of several tantalum markers inserted in the bone (109). In Valstar *et al.*'s study (110), a new measurement method was developed based on the geometry of the implant, which was also called model-based RSA. In their *in vitro* experiment, the accuracy of the measurement of the cup orientation was approximately 0.35° on average.

Borlin *et al.* incorporated a semi-automatic edge detection algorithm into the model-based RSA system to determine the outline and orientation of the cup (111). In a further study by Sarry *et al.*, they modified their previously established single X-ray-based system by using two roentgen tubes in front of the body, similar to the setup of the RSA system (112).

Devane *et al.* (42,113,114) modified the RSA method by taking the pelvic AP and hip cross-table radiographs simultaneously. Afterwards, the authors developed PolyWare software based on the RSA method and preoperative CT scan data (115). During measurements, two simultaneous ray tracers were used to simulate the AP and lateral radiographs from the CT-derived 3D model to compensate for the pelvic rotation postoperatively.

In another study, Yuan *et al.* (116) also used a similar radiographic setup as Devane *et al.* (42,113,114) but incorporated the reference frame into the modified RSA system to establish a transformation between the phantom and cage radiographs for further calculations. With this system, the RA angle of the cup was measured using the ischiolateral method of Tiberi *et al.* (38,39) in subsequent studies (117,118).

Teeter *et al.* (118) used the RSA system to compare the change in the cup angles between supine and standing positions. The anteversion and RI angle increased 12° and 16.2° from supine to standing, respectively. The cup anteversion, however, was also measured with the ischiolateral method (39).

EOS system

Different from the RSA system, pelvic AP and lateral radiographs were taken using two roentgen tubes orthogonal to each other in the EOS system (119). Lazennec *et al.* introduced the 2D EOS system to measure the cup orientation (120). With this system, the OA and RI angles of the cup, which were also named the frontal and sagittal inclination angles in their study, were measured (121).

Thereafter, Journé *et al.* aimed to verify the accuracy of this system by comparing it with CT-derived measurement (122). However, in this phantom study, the AA angle of the cup was measured with the CT-based method, and the differences in the anteversion and RI angles between the two methods were 3.9° and 2.6°, respectively. Tokunaga *et al.* also measured the AA and RI angles by using the EOS and 3D-CT methods (123). The mean differences in the AA and RI angles were 0.1° and 2.3°, respectively, between the two methods. Bendaya *et al.* also used the EOS system to evaluate the cup angles (124). Nevertheless, the AA angle that they reported was actually the OA angle of the cup.

In contrast to the misuse in the previous three studies, Polkowski *et al.* used the same definition of cup anteversion in the sagittal plane when comparing the measurement results using both the standing EOS and supine CT methods (125). Their results showed that the difference between the standing and supine OA angles was almost greater than 5°.

After simulating the standing radiograph using the intraoperative C-arm, Harold *et al.* compared the intraoperative measurements of the RA and RI angles of the cup using RadLink with those of the postoperative EOS system (59). Their results showed that the differences in the RA and RI angles were 3.3° and 0.3°, respectively, on average.

2D-3D registration method

In addition to the various radiographic measurement tools and methods mentioned above, the CAD technique was also introduced to develop a more accurate method.

Penney *et al.* established a preoperative CT-based 2D-3D registration method for evaluation of the RA and RI angles postoperatively (126). Using the postoperative CT-based 3D-3D registration method as the gold standard, they validated the superior accuracy of this new 2D-3D method to the radiographic method.

In contrast to the 2D-3D registration using one single AP radiograph, Kobayashi *et al.* (127) developed a 2D-3D matching procedure based on a biplanar X-ray system and the preoperative CT image. However, no details of the measurement method were reported in their study. Craiovan *et al.* developed a vector arithmetic method based on 2D-3D registration, while the X-ray offset was not considered in their system (128).

Zheng *et al.* proposed a 2D-3D registration method and the associated software called "HipMatch" for cup placement in THA (129). They validated this with *in vitro* experiments and cadaveric and clinical studies of THA operations (130,131). In their further modified system, a statistical shape model was used to substitute the preoperative CT-based 3D model to perform the 2D-3D registration with the postoperative pelvic AP radiograph (132).

To evaluate the effect of pelvic rotation, both Blendea *et al.* (133) and Tannast *et al.* (134) used 2D-3D matching software to align the preoperative pelvic 3D model to the postoperative pelvic X-ray. Blendea *et al.* (133) determined a linear negative correlation between the pelvic flexion and the RI angle, while Tannast *et al.* (134) presented two nomograms of the relationships between the pelvic tilt and longitudinal rotation and the RA and RI angles.

In a clinical study, Steppacher *et al.* validated an automated 2D-3D registration algorithm by using the HipNav navigation software to measure the cup orientation (131). Nevertheless, the X-ray offset was also neglected by the Ackland algorithm used in their method. In another clinical study, Yun *et al.* used 2D-3D matching software to compare the difference in the RA angles between the supine and standing positions and found that there was a negative correlation of the pelvic longitudinal rotation with the RA angle of the right cup but a positive correlation with the left cup in both supine and standing positions (135,136).

Discussion

The plain radiograph remains the mainstream tool for evaluation of the cup orientation intra- or postoperatively.

Most of these algorithms were developed based on the ellipse projection from the circle of the cup's opening, which can be connected with each other via the general equation of the ellipse. However, these methods can only be used in standardized hip-centred AP radiographs without considering other biases from the inherent and extrinsic factors, such as the pelvic rotation and X-ray offset. As most evaluation methods of the cup orientation were performed in a retrospective manner, the pelvic AP radiograph might be superior to the hip AP radiograph in terms of viewing the bilateral hips to evaluate the pelvic rotation.

With regard to the X-ray offset, most of the methods used for the pelvic AP radiograph will definitely lead to errors in measurements. Although some studies aimed to find the most accurate method by comparing previous methods with CT-based measurements, their methods and results were not reliable if the pelvic AP radiograph was analysed without considering the X-ray offset. Moreover, the pelvic AP radiographic method was considered to be the reference standard in some comparative studies. Even in some recent studies using advanced equipment, such as the RSA system, the original ellipse method was still used for measuring the RI angle on the pelvic AP radiograph without incorporating the X-ray offset (118).

Those investigations concentrating on the difference between the postoperative pelvic AP radiographic measurements and their intraoperative counterparts or postoperative hip AP radiograph-derived results actually aimed to reveal the effects of the X-ray offset and establish a relationship between the cup orientation and the radiographic angles measured on the pelvic AP radiograph. Additionally, some *in vitro* experiments on phantom models were carried out to establish a linear relationship between the true radiographic angles and their projected counterparts. In addition to the X-ray offset caused by the variable cup positions, the influencing effects from the cup itself were also addressed by some researchers, which meant that the varying measurements of the radiographic angles of the cup would be changed depending on the different true RI angles of the cup (48). By establishing a mathematical cone model that included the potential influencing factors of X-ray offset and position, Zhao *et al.* studied the relationship between the variable orientations and positions of the cup and its RA and RI angles measured on pelvic AP radiographs (68).

Furthermore, pelvic rotation is another important influencing factor that has been extensively studied previously. Some studies were conducted on a phantom model, while others measured the intraoperative cup orientation and pelvic rotation using a navigation system. Most of these studies only determined a rough, linear relationship between the cup angles and pelvic rotation. Meanwhile, there were also some mathematical simulation studies on this issue. However, the X-ray offset was neglected in most of these studies and was not incorporated into the established models. As the pelvic obliqueness and axial rotation could be viewed and adjusted when the pelvic AP radiograph was taken, the pelvic tilt became the only uncertain parameter that could not be evaluated on the pelvic AP radiograph but still significantly influenced the radiographic evaluation of the cup angle when the patient's posture varied between the supine, standing and even lateral decubitus positions. Prior studies paid much attention to the effects of the pelvic tilt, most of which aimed to determine the difference in the RA and RI angles of the cup between the supine and standing positions. Additionally, some correction factors were proposed to varying degrees in different studies, while some descriptive models were deduced with linear or nonlinear relationships between the pelvic rotation and anatomical parameters acquired from the pelvic AP radiograph. Unfortunately, for those mathematical models presented with analytical equations or formulae, not all essential parameters were incorporated (85).

To be honest, both the effects of the X-ray offset and pelvic rotations actually depend on several parameters, including the spatial orientation and position of the cup and the X-ray source (e.g., the vertical and transverse distances between the cup's centre and the X-ray source, and the distance of the X-ray source relative to the X-ray plane) and the diameter of the cup's opening circle. As most of the previous studies did not report all the details of these important parameters, it is inappropriate to perform a direct comparison among these results under different conditions. The best way to do so is to reveal the changing rules of the effects of the X-ray offset and pelvic rotations on the radiographic angles of the cup in the form of figures, such as curves or surfaces, which enable the analysis of all the potential influencing factors under different situations. In another analytical study, Zhao *et al.* simulated different types of pelvic rotations and their effects on the RA and RI angles of the cup using a mathematical cone model (90). In contrast to previously established models simulating pelvic rotations, Zhao *et al.*'s model incorporated the X-ray offset and other influencing factors. The quantitative relationship between different types of pelvic rotation and the RA and RI angles of the cup can be determined by adjusting the different positions and true orientations of the cup.

With regard to methods to correct the X-ray offset or pelvic rotation, various types of techniques and equipment have been developed that can be classified into one or two radiograph-based methods or 3D-CT model-based methods. If the measurement was performed on the pelvic AP radiograph, the opening circle of the cup was the most easily identifiable target on the radiograph that could be connected with its spatial counterpart. A few algorithms have been established based on the related geometric transformation. However, most of them have limitations or preconditions. Based on computer vision technology, Zhao *et al.* used a cone model to address this question in their theoretical study (10). However, there were limitations to their algorithm. First, the pelvic rotation cannot be corrected by their model. Second, the ellipse silhouette of the cup opening has to be outlined manually. For radiographs of THA lacking the circular marker of the cup opening, an automatic edge detection technique can be used to improve the accuracy and expedite the process of outlining the ellipse, as has been used in Sarry *et al.*'s study (99). Regarding the bias from the pelvic rotation, although the EBRA system could provide compensation to some degree, the X-ray offset was not incorporated in this system.

In addition to the algorithms and techniques used for pelvic AP radiographs, some advanced techniques and equipment, which were developed mainly for evaluating prosthesis migration or wear, could also be used as an alternative to measuring cup orientation. With regard to the RSA system, there have been mainly three types of variants since its arrival: the model-based RSA, the 3D-CT-based RSA with cross-table radiograph, and the reference marker-based RSA with cross-table radiograph. Although no comparative studies were performed to identify the most accurate of the three variants, their characteristics can also be distinguished from one other. The model-based RSA combined projection transformation and edge detection. Although the 3D-CT-based RSA system utilized 2D-3D registration, the cross-table lateral radiograph used in this system has the potential bias of causing the pelvic posterior tilt via contralateral hip flexion (42,113,114). A similar problem exists in the latest RSA variant system. Without using the cross-table radiograph, the EOS system substitutes the pelvic AP and lateral radiographs. However, no algorithms for projection transformation and edge detection were used in this system, and the measured cup angles primarily included the RI and OA angles, the latter of which was difficult to precisely recognize and measure from the lateral view because of the rounded, impossibly identifiable vertices of the ellipse (121).

The 2D-3D registration method seems to be the most accurate measurement method for determining the RA and RI angles of the cup. The advantage of this method is that both the X-ray offset and pelvic rotation can be evaluated based on the reconstructed 3D model, with which the RA and RI angles were measured as the ground truth. To increase the accuracy of 2D-3D registration, Kobayashi *et al.* (127) introduced a potential alternative with 2D-3D registration and biplanar X-ray in the standing posture, but no further studies have been performed on it.

Challenges and future prospects in radiographic assessment of the cup orientation

In addition to postoperative evaluation, precisely determining the cup orientation intraoperatively may be the optimal measure for preventing late complications related to malpositioning of the cup. In a clinical study, Steppacher *et al.* validated an automated 2D-3D registration algorithm by using HipNav navigation software to determine the cup orientation intraoperatively (131). Nevertheless, the X-ray offset was neglected by the version of Ackland's method used in their study. Yamada *et al.* verified that the accuracy of the cup placement in a preoperative CT-based 2D-3D registration system was superior to that of the paired-point matched system in THA when compared with the postoperative CT scan (137).

Different from CT-based navigation, some imageless navigation systems were also developed to improve cup positioning in THA (138,139). Furthermore, augmented reality technology has also been used as a powerful alternative to the current navigation system for cup placement (140-142). With the rapid development of artificial intelligence, machine learning, and computer vision (143,144), the collection, processing, and integration of pre-, intra-, and postoperative multimodal data could be performed in a more efficient and accurate manner, which could then be incorporated into robot-assisted orthopaedic surgery system in the field of intelligent orthopaedics in the future (145,146). Before that, however more high-quality theoretical, *in vitro*, and clinical studies should be performed in a robust manner.

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Footnote

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