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Validating a Modified Circle Theorem Method for the Measurement of Acetabular Cup Anteversion on Plain Radiography with Intra-Operative Data from Robotic Assisted Total Hip Arthroplasty

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ABSTRACT

This study aims to validate a modified circle theorem method for the calculation of true version of the acetabular component on anteroposterior x-rays with intra-operative version data derived from robotic assisted total hip arthroplasty (THA). Planar anteversion measurements recorded intraoperatively in 80 THAs were correlated to measurements on anteroposterior radiographs. The mean anteversion of the cohort measured by the robotic system and on plain radiography was 21.2° ± 2.0° and 19.9° ± 3.4° respectively and 97.5% of cases were in a 30% relative error. The correlation between the true and planar measurements of anteversion on plain radiographs was strong (Pearson correlation coefficient of 0.9422). We conclude that the circle theorem method can be validated with data from robotic guided THA.

Acetabular cup position affects stability, range of motion and impingement in total hip arthroplasty (THA) [1]. Inclination and anteversion are the two most commonly analyzed parameters of cup positioning [2]. Lewinnek et al proposed a safe zone for acetabular inclination of 15° ± 10° to minimize dislocation rates [3]. More recently, Dorr et al defined a safe zone for combined anteversion of the acetabulum and femur of 25° to 50° [4]. Following on from this, Nakashima et al demonstrated that THAs with a combined anteversion (Fig. 1) outside of the range of 40° to 60° were 5.8 times more likely to dislocate than those within this range [5].

Several methods have been developed to help surgeons correctly position the acetabular component intra-operatively. These methods can be divided into implantation with the assistance of anatomical landmarks [6], mechanical alignment guides [7], computer navigation [8] and robotic assistance [9]. Several studies have shown that navigation increases the percentage of components within the safe zone compared to non-navigated methods [8,10,11]. More recently, robotic technology has been developed to help surgeons not only with component positioning but also haptic conical reaming. Domb et al reported on a series in which 97.1% of cups were placed in the Lewinnek safe zones with robotic assistance compared to 80% of cups with mechanical alignment guides [9].

Several methods have been proposed to calculate acetabular cup version on antero-posterior cup radiographs [12–14]. The circle theorem method proposed by Kosiyatrakul et al is based on simple descriptive geometry and does not rely on conversion tables or complex computer calculations [15]. The method has yet to be validated on x-rays in patients with THA. The purpose of this study is to validate a modified circle theorem method for the calculation of true version of the acetabular component on anteroposterior x-rays of the pelvis with intra-operative version data derived from robotic assisted THA. To our knowledge, this type of validation has not been previously performed. The modification and methodology proposed are also more precise in defining the rim of an uncemented acetabular component.

Patients and Methods

Patient Selection

103 randomly selected patients who had undergone robotically assisted THA between the period of July 2012 and August 2014 were included in the study (Table 1). All patients had the same acetabular prosthesis implanted. The acetabular component was an uncemented titanium porous coated hemispherical cup (Trinity Corin, Circencester, United Kingdom).

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Plain Radiography

All patients had post-operative anteroposterior plain radiographs of the pelvis. Patients were excluded if they did not have well centered radiographs as obliquity can cause erroneous measurements [14]. Anteroposterior radiographs of the pelvis were taken with the X-ray beam centered on the pubic symphysis. Radiographs were considered well centered if the tip of the coccyx was centered within 2 cm of the pubic symphysis and the obturator foramen was symmetrical [15]. As a consequence of this exclusion criterion, 23 patients were excluded from the cohort leaving 80 patients eligible for inclusion in the study.

Surgical Technique

THA was performed with the MAKOplasty Total Hip Application (MAKO Surgical Corp., Fort Lauderdale, FL, USA), a robotic-guided computer navigation designed to place THA components with increased precision. It is based on a three-dimensional model of the patient's hip, reconstructed from CT.

Preoperative CT Scan

The preoperative CT scan has about ten times the radiation of a normal hip radiographic series [16]. Specialized software is used to create a patient specific virtual 3-D model of the pelvis and femur. Intra-operatively specific points are defined on the patient's anatomy to help the software determine the patient's pelvic position. The software accounts for the pelvic tilt by using the patient's anterior/posterior tilt when lying supine on the CT table. All inclination and version measurements use this tilt.

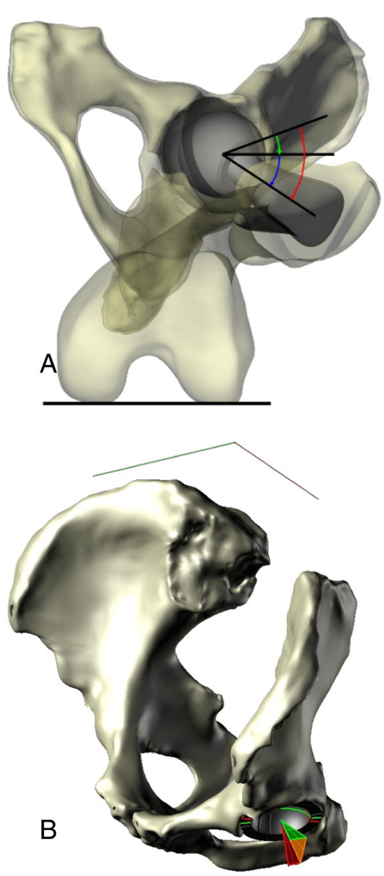

Fig. 1. (A) Projection in the Transverse plane of the THA. The combined anteversion (red) is the sum of the Acetabular Cup True Anteversion (Green) and of the Femoral Anteversion (Blue). (B) Difference between the True (Green) and planar (Red) Anteversions.

Table 1
Demographic Data.

Demographic characteristics	Number
Total Number of Cases	103
Age (Mean and range)	67.6 (43.8–79.1)
Male:Female	46:57
BMI(Mean ± Std Dev)	29.6 ± 5.3
Cup Size (Median and Range)	54 (42–60), 100% Corrin Trinity Cup
Stem	100% Corrin Metafix Uncemented femoral stem
Number with post-operative x-rays	103 (100%)
Number with inadequate centered x-rays	23 (22.3%)

Preoperative Planning

The depth, inclination and version of the cup in the acetabulum are positioned preoperatively in the computer-generated model to guide the robotic assisted reaming. The stem is positioned in the femoral canal to determine the correct site of femoral neck osteotomy so as to reconstruct the leg length and offset.

Surgical Approach

Patients underwent either an anterior or posterior approach for implantation of components. A posterior approach was chosen in those patients in whom the overhanging abdominal adiposity was considered to potentially increase wound complications. The anterior approach was performed on a traction table as described by Matta et al [17]. The posterior approach was performed as described previously [9].

Pelvic Array Placement

The first step in robotic THA was to place the three pelvic threaded pins into the thickest portion of the iliac crest (ipsilateral iliac crest in the cases that underwent a posterior technique, and contralateral iliac crest in those cases that underwent an anterior technique). The pins hold the pelvic array, which allows the robotic camera to visualize the exact 3D orientation of the pelvis.

Femoral Registration and Osteotomy

Femoral registration requires insertion of two screws; one large screw for holding the femoral array and a smaller screw to be used to

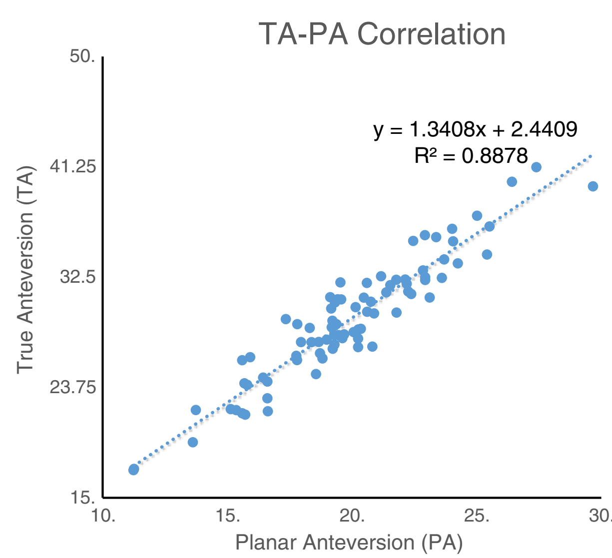

Fig. 2. Correlation found between the True Anteversion and the Planar Anteversion measured on X-rays.

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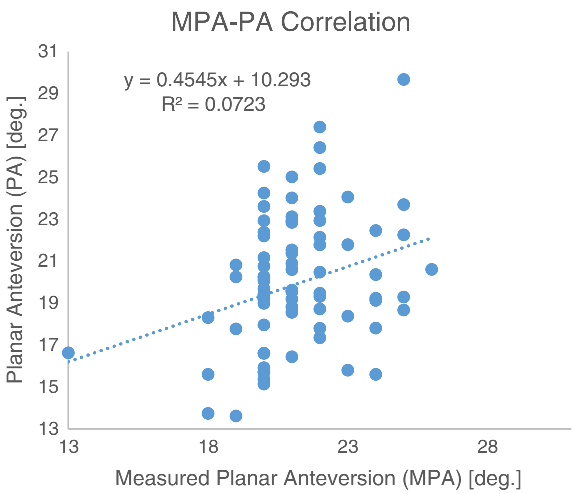

Fig. 3. Correlation found between the Planar Anteversion measured on X-rays and the operative anteversion measured with the robotic system.

verify accuracy of registration (check point). The screws are inserted to allow the femoral array to be easily visualized and do not interfere with femoral reaming. Femoral registration is accomplished by touching the probe to thirty two required points on the proximal femur as identified by the software. These points verify the anatomic geometry defined pre-operatively by the CT scan. Ideally, the femoral registration error should be less than 0.5 mm. If the registration error is more than 1 mm the verification fails and the surgeon must re-register the femur.

Acetabular Registration and Reaming

The pelvic check point (screw) is inserted outside the acetabular cavity in the bone just superior to the posterior–superior acetabulum rim. The probe is touched to the pelvic checkpoint to verify the registration. Thirty-two points on the acetabulum are identified by the software for the registration process and are touched using the probe to the bone surface. Verification is done by touching the probe to 8–10 points defined on the surface of the acetabulum. As with the femur, if the software displays a registration error of more than 1 mm the registration must be repeated. Reaming is started within 2 mm of the planned cup size; the surgeon must ream within ±10° of the planned cup position

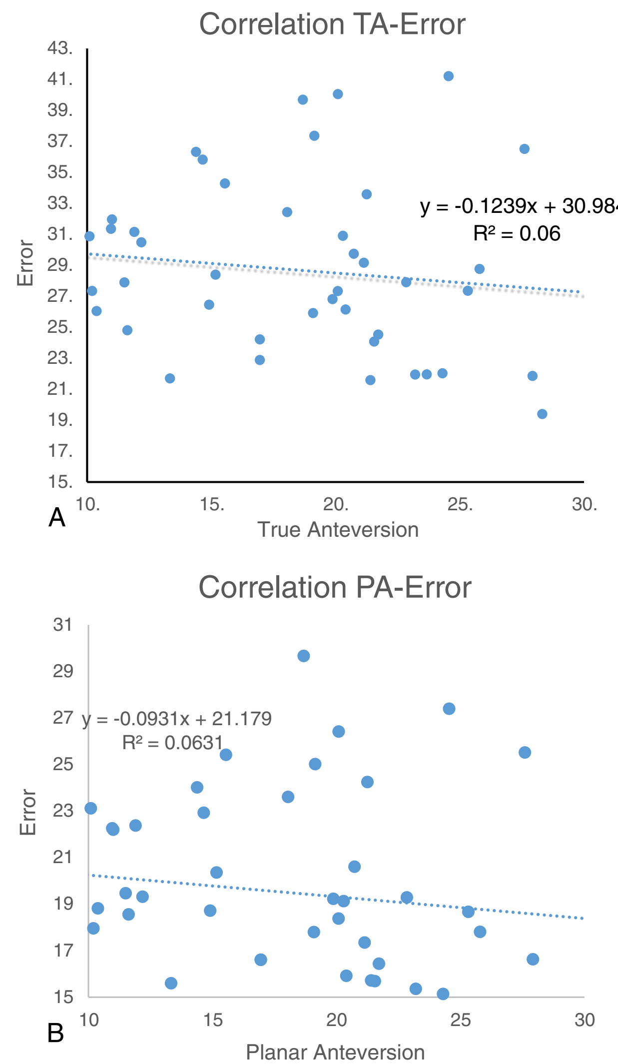

Fig. 5. Correlations found between (A) Error and True Anteversion and (B) Error and Planar Anteversion.

(constrained by virtual haptic tunnel). The reaming is line-to-line. The reaming is complete when the cup center of rotation numbers for superior/inferior, medial/lateral, anterior/posterior are zero and turn green. The

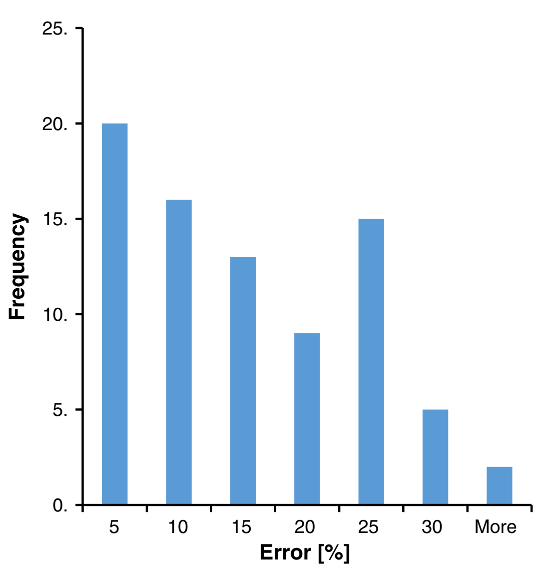

Fig. 4. Frequency distribution of the relative error ER.

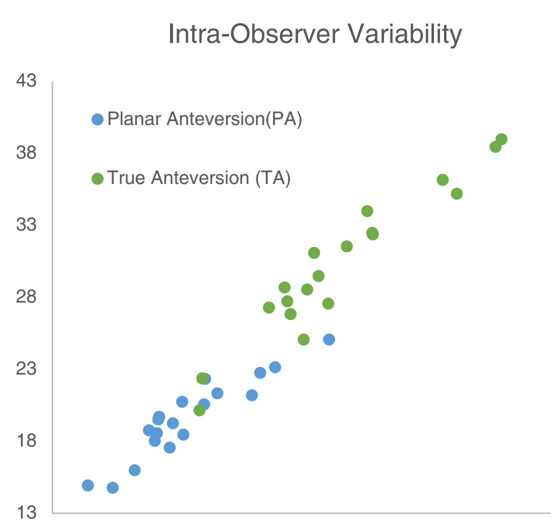

Fig. 6. Correlation between Intra-Observer measures.

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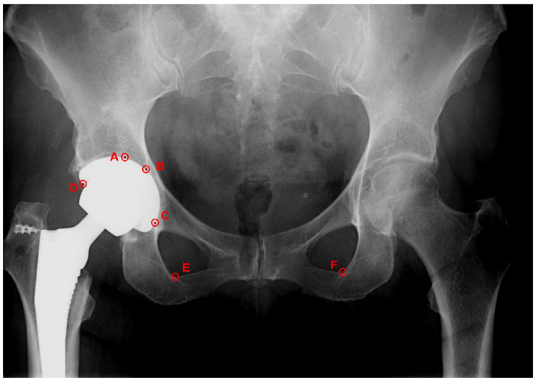

Figure A.1. Plain Antero-Posterior radiography with 6 landmark points used to calculate the Anteversion values.

3D model of the bone will also illustrate that the planned bone resection has been achieved when the green color of the acetabulum has been removed, showing white bone. Both methods confirm that the surgeon has reached the established acetabular center of rotation. The bone model will turn red when the surgeon has reamed more than 0.5 mm past the plan. When the surgeon has reamed 1 mm past the plan in any direction the power drill will turn off.

Acetabular Cup Implantation

The porous shell is loaded onto the robotic arm and inserted in the acetabulum through a haptic tunnel which keeps the cup inclination and anteversion within 3° of the plan as the cup is implanted. After implantation of the cup the plastic liner is inserted. After the liner is inserted the fit plane measurement can be done to confirm the cup position by touching the liner with the probe at five points. Femoral version is measured by detecting the position of the femoral broach relative to the femoral anatomy (based on CT landmarks, namely the medial and lateral epicondyles, taken pre-operatively). This final computer screen shows quantitative numbers of the entire reconstruction compared to the planned reconstruction.

Measurement of Acetabular Version

One of the authors measured acetabular version on appropriately centered post-operative anteroposterior x-rays. Measurements in 20 patients were repeated at a different time to determine intra-observer variability. Anteversion measurements were correlated with intra-operative data.

Anteversion Measurements

Each x-ray has been assigned a randomly generated identification code to isolate any information coming from the surgical procedure. The dataset composed by imaging data for a total of 80 THAs has been analyzed by two investigators. Geometrical constructs as proposed and measures of Planar Anteversion (PA) and True Anteversion (TA) have been calculated using the digital X-rays in Rhinoceros 3d (Robert McNeel & Associates, Seattle, WA). The achieved values of planar anteversion measured by the robotic system (MPA) at the time of the surgery are tested for correlation with the values of planar anteversion (PA) calculated with the proposed method on X-rays.

The Relative Error (ER) of the proposed circle theorem has been calculated as the difference $|PA - MPA|$ between the planar anteversion (PA) and the measured operative anteversion (MPA) divided by the measured operative anteversion $ER = |PA - MPA|/PA$.

Correlations between Operative (MPA) and Measured anteversion values on X-rays (PA and TA) and Intra-Observed measures are calculated.

Statistical Analysis

Correlations of 2 continuous variables were performed using Pearson correlation coefficient to test for intra-observer and inter-observer variability of measurements and correlation with intra-operatively recorded anteversion. Statistical analysis was performed using Microsoft Office Excel 2007 (Redmond, WA). Values of alpha < 0.05 were considered statistically significant.

Results

The planned planar anteversion ranged from 16° to 27° with an average value of 20.4° ± 1.5°. The values of planar anteversion measured with the Mako system, at the time of the surgery (MPA) ranged from 13° to 26° with an average value of 21.2° ± 2.0°. On the X-rays the average planar anteversion (PA) measured 19.9° ± 3.4° and ranged from 11.2° to 29.7°. The true anteversion (TA) ranged from 17.9° to 41.2° with average value of 29.1° ± 4.8°. The true anteversion (TA) correlated to the planar anteversion (PA) with a Pearson Correlation coefficient of 0.9422 (Fig. 2). The correlation between

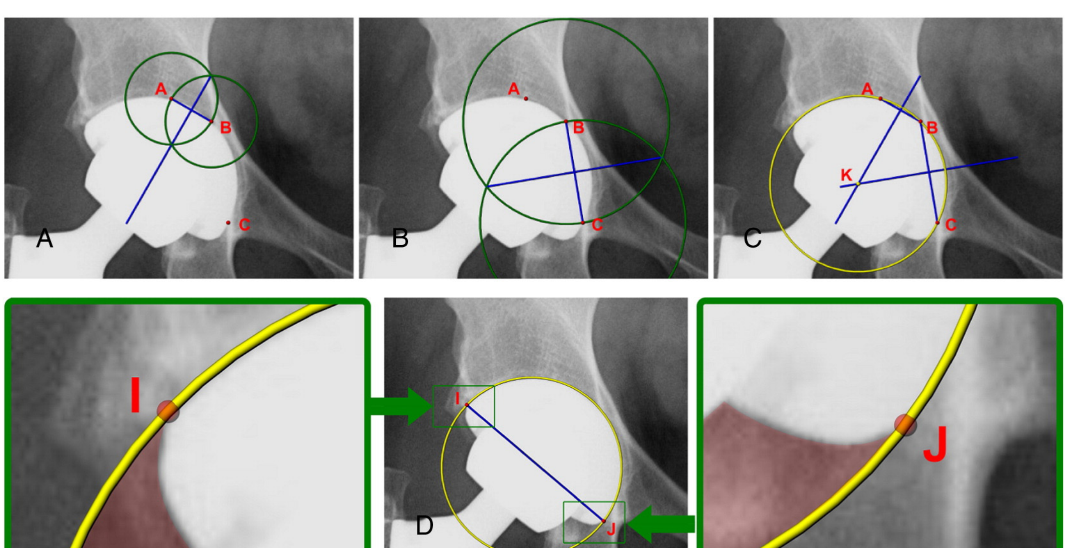

Figure A.2. (A, B and C) Steps to identify the Circumference approximating the Cup Trace; (D) Identification of the Cup edge,.

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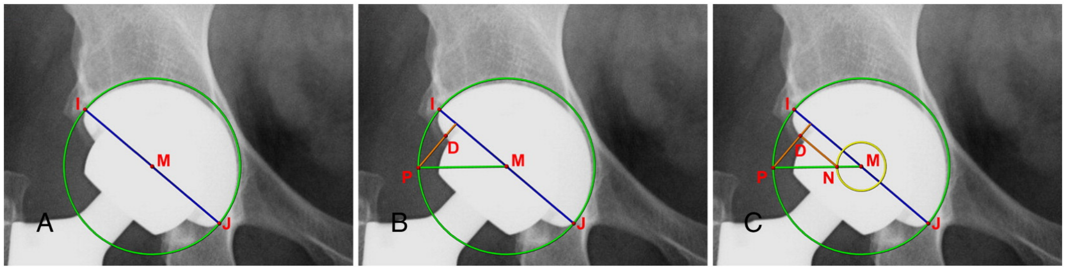

Figure A.3. Geometrical construction of the Cup Border.

the Measured Operative Anteversion (MPA) obtained from the robotic system and the Planar Anteversion (PA) calculated on X-rays, resulted in Pearson coefficient of 0.2688 for all the measures, and improved to 0.3907 for anteversion angles Higher than 22° (Fig. 3). Two cases with measured planar anteversion of about 11° in which the cup edge was poorly approximated by the drawn ellipse were discarded. The highest frequency of 25% was associated to percentage errors lower than 5%. The percentage error from 10 to 20 was observed with similar values of frequency (Fig. 4) and 72.5% of the measures contained an error less than 20%. Two of the samples showing a relative error greater than 20% were associated to intra-operative complications, so, the actual anteversion at the time of the surgery was not necessarily the reported value. The 97.5% of the measures had a relative error smaller than 30%. On 11 of the measures with an error greater than 20% we measured a relatively small angle of 15.7° ± 1.7°. The Pearson correlation coefficient between the true anteversion (TA) and the relative error (ER) for planar anteversion resulted in a value of −0.251(Fig. 5a), while the correlation between Planar anteversion (PA) and its Error (ER) resulted in a Pearson coefficient of 0.1741 (Fig. 5b). On 20 randomly selected subjects the Intra-observer variability resulted in Pearson correlation coefficients of 0.9277 and 0.9585 for the Planar (PA) and True Anteversion (TA) respectively (Fig. 6).

Discussion

This is the first study to our knowledge that has used information from robotic guided THA to validate a method of measuring acetabular version using plain radiography. The robotic data measured planar anteversion. We therefore measured planar anteversion using the method described by Ackland et al [13] to determine the validity of the robotic guided measurements. We found a strong correlation between the robotic guided measurements of planar version and the radiographic measurement of planar version. Using modified circle theorem we calculated the true anteversion and found this to be strongly correlated with the planar anteversion. We can therefore conclude that the true anteversion as measured using a circle theorem method can be validated with data from robotic guided THA.

The clinical relevance of these findings pertains to the ability to use a validated method to calculate planar and true anteversion using plain radiography. A validated method of calculating accurate planar version allows surgeons to verify that cup placement is within the safe zone of Lewinnek [3] or combined version of Dorr et al [4]. The clinical significance of true version still needs to be further elucidated. True version is planar version with reference to the coronal plane of the pelvis. As it incorporates a coronal plane adjustment it is of higher value than planar version. It may be of more significance in the setting of combined anteversion measurements as femoral stem version is also in relation to the coronal plane as defined by the transepicondylar axis of the femur [4]. However, the utility of the association is yet to be established. There have been several studies that have reported on calculating acetabular cup measurements based on CT, fluoroscopy and plain radiography [18–23]. Measurements based on CT have demonstrated good reproducibility and a high level of precision regardless of the position of the patient [18–20]. The main disadvantages of this method are the cost and increased risk of radiation exposure to the patient [21]. Fluoroscopic methods to determine anteversion are considerably longer to perform and are impractical for routine follow up in clinical practice [22]. Measurements using plain radiographs are inexpensive, easily available and can be incorporated into routine follow-up [21]. The main disadvantage with plain radiography is that x-rays need to be well centered as obliquity can lead to erroneous measurements [24].

There are several limitations of this study that need to be discussed. First is the use of robotic data as a basis of validating the circle geometry method. The robotic data are subject to error from bony landmark registration by the surgeon within a limit of 1 mm making it potentially less accurate than a CT validation method. However, robotic is often with less radiation exposure and can be used as a verification source for routine follow-up. The accuracy of component positioning using robotic assisted THA has been previously validated. Nawabi et al [25] conducted a cadaveric study where acetabular component positioning was compared in twelve cadavers, six with robotic assistance and six with manual implantation. The root-mean-square (RMS) error for the robotic-assisted system was within 3° for cup placement and within 1 mm for leg-length equalization and offset when compared to computer tomography (CT). The RMS error for manual implantation compared

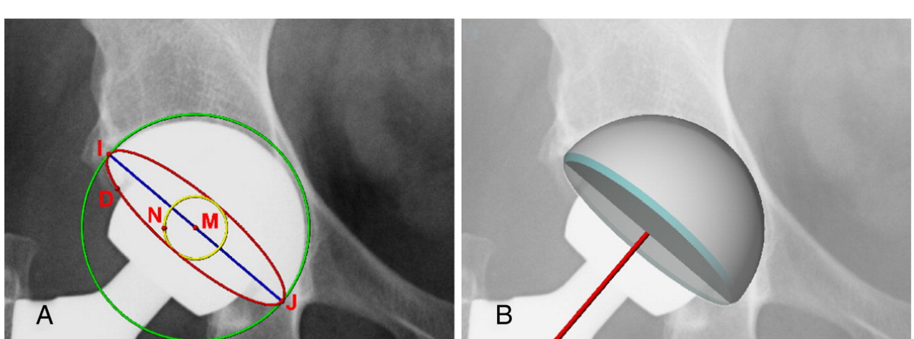

Figure A.4. (A) Constructed Cup Border and (B) Recaptured Tri-dimensional Cup.

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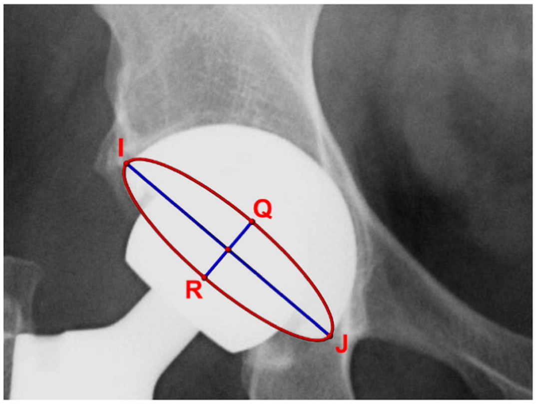

Figure A.5. Geometrical dimensions used to calculate the Planar Anteversion.

to robotic-assistance was five times higher for cup inclination and 3.4 times higher for cup anteversion ($P < 0.01$). The mean difference for acetabular version between CT and robotic assisted THA was 1.4° ± 1.0° (0.2–3.7) with an RMS error of 1.72°. Dorr et al [26] also conducted a cadaveric study to validate the accuracy of acetabular component positioning in robotic assisted THA. They reported that compared to postoperative CT the average absolute error was 1.3 ± 1.4° for inclination.

The robotic data use horizontal and pelvic tilt from the preoperative planning CT that may potentially differ from the patient position on the operating table causing error in the measurements recorded. With respect to the circle theorem small rotations in the AP pelvis x-ray may be a source of error. The circle theorem method also has numerous steps but after familiarity the steps can be performed in a few minutes.

Conclusion

The modified circle method allows for the identification of the rim, and calculation of acetabular cup version on well centered anteroposterior radiographs of the pelvis with respect to version measurements from robotic assisted THA. This simplistic geometrical approach is well suited to template designs and quick evaluation for reference in cases where cup orientation is critical to the THA stability and postoperative success.

Appendix A. Measurement technique

1) Identification of the Landmarks on the X-Ray.
   Three points (A, B, C) are randomly selected on the circular edge of the cup. One point (D) is selected on the edge of the liner in proximity of the femoral head (non-circular portion of the projected profile) and two points are identified on the lower extremities of the Obturator foramen (E, F) (Fig. A.1).
2) Identification of Cup Edge
   The center of the circle approximating the cup trace is positioned at the intersection of the bisectors of the two chords AB and BC; two circles with radius AB respectively centered in A and B are used to draw the bisector of the first chord (Fig. A.2a). Similarly the second bisector is evaluated with two circles of radius BC centered in B and C (Fig. A.2b). The circle representing the cup's trace is traced with center at the intersection K of the two bisectors with radius KA (Fig. A.2c). Unless the projection is obtained with any axis perpendicular or parallel to the cup edge, the cup edge is projected as an ellipse; its major axis is obtained by the conjunction of the points I and J identified as the points where a strong change in curvature is observed. Unlike the circle used to approximate the cup edge, this

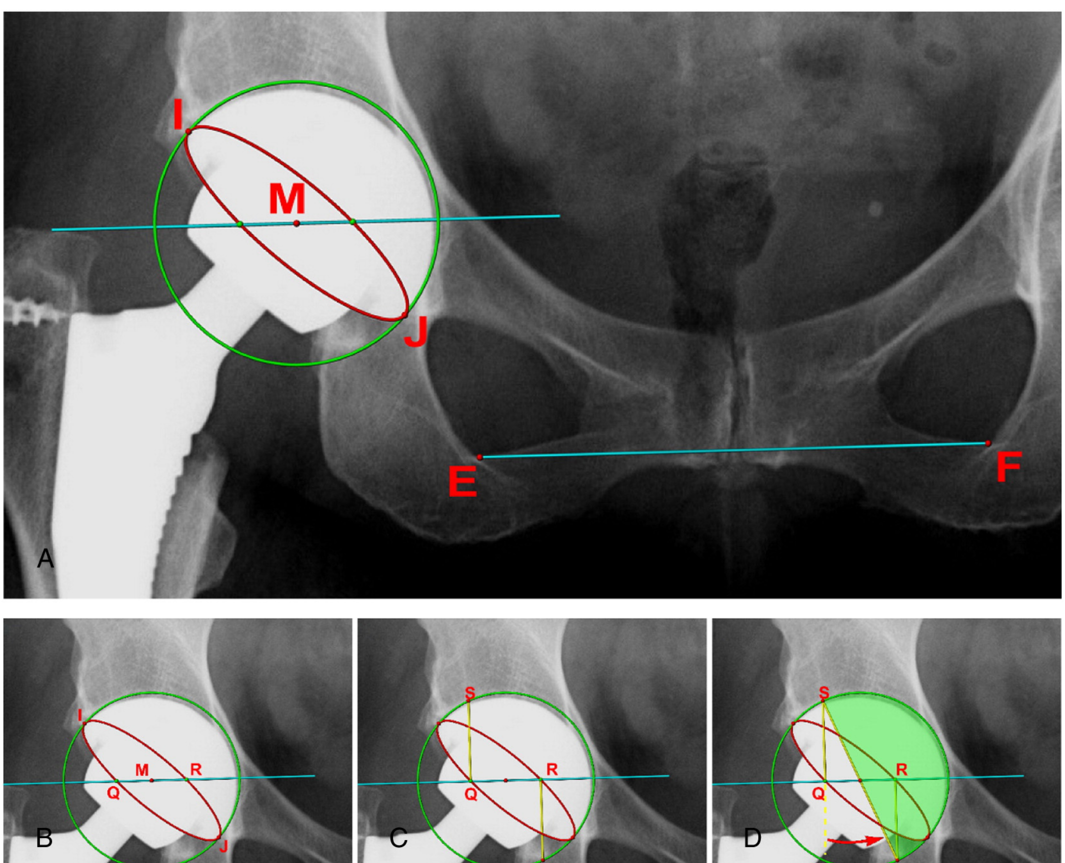

Figure A.6. Geometrical construction to calculate the True Anteversion.

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ellipse has a radius of curvature variable that results in the gaps observed from the created circle and the cup projection (Fig. A.2d).

3) Identification of the Cup Border.
The ellipse representing the projection of the cup edge is generated assuming the line IJ as major axis; the minor axis is evaluated from the landmark D, considering that the ellipse can be seen as a circle with diameter IJ (green in Fig. A.3a) scaled in the direction perpendicular to the line IJ: tracing the perpendicular line to IJ passing through D; the point P is the "unscaled" homologous of D (Fig. A.3b). The minor diameter is evaluated as the diameter of the circle centered in M and passing through the intersection N of the line PM with the line parallel to IJ passing through D (Fig. A.3c).
Knowing the mayor axis IJ and the minor axis with dimension equivalent to 2*NM it is possible to draw the ellipse representing the cup edge (Fig. A.4a) and use this in the following steps to calculate the anteversions. The tridimensional reconstruction shows the derived cup in transparency with the X-ray image; the red axis is the obtained tridimensional cup axis while the blue surface represents the derived fillet that differentiates the denominated cup and liner edges (Fig. A.4b).

4) Calculation of the Cup Anteversion.
The Anteversion as proposed by Ackland et al [13] can be calculated as "Planar anteversion" or as "True Anteversion" according to the reference planes adopted. The "Planar anteversion" can be easily calculated using the measured dimensions of the ellipse's axis (Fig A.5) with the relationship $\alpha_{planar} = \arcsin(RQ/IJ)$ and represents the angle formed by the mediolateral axis and the cup axis projected on the plane passing through the mediolateral axis and the line RQ. The "True Anteversion" because it is associated to the transverse plane requires a geometrical construct: The first line used as representation of the transverse plane is traced passing through the point M and parallel to the line joining the two landmarks E and F of the obturator foramen (Fig.A.6a); the points Q and R of intersection of the transverse line with the ellipse are respectively the projection of the point of intersection of the posterior and anterior edges of the cup with the transverse plane (Fig. A.6b). Considering the spherical shape of the cup, the previously created circle with diameter IJ (in green) is re-used as representative of the transversal section of the cup. The intersection S of the line perpendicular to the transverse line and passing through Q with the superior edge of the circle is the visualization of the actual intersection with the transverse plane with the posterior edge; similarly from the point R, with a perpendicular line is obtained the actual intersection of the anterior edge (Fig. A.6c). Joining the obtained points S and T it is possible to visualize the intersection of the cup edge with the transverse plane, and the angle formed by the points QST is the angle α_{true} of True Anteversion (Fig. A.6d).

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