# Trigonometric Algorithm Defining the True Three-Dimensional Acetabular Cup Orientation

## Correlation Between Measured and Calculated Cup Orientation Angles

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**Background:** Acetabular cup orientation plays a key role in implant stability and the success of total hip arthroplasty. To date, the orientation has been measured with different imaging modalities and definitions, leading to lack of consensus on optimal cup placement. A 3-dimensional (3D) concept involving a trigonometric description enables unambiguous definitions. Our objective was to test the validity and reliability of a 3D trigonometric description of cup orientation.

**Methods:** Computed tomographic scans of the pelvis, performed for vascular assessment of 20 patients with 22 primary total hip replacements in situ, were systematically collected. On multiplanar reconstructions, 3 observers independently measured cup orientation retrospectively in terms of coronal inclination, sagittal tilt, and transverse version. The angles measured in 2 planes were used to calculate the angle in the third plane via a trigonometric algorithm. For correlation and reliability analyses, intraobserver and interobserver differences between measured and calculated angles were evaluated with use of the intraclass correlation coefficient (ICC).

**Results:** Measured and calculated angles had ICCs of 0.953 for coronal inclination, 0.985 for sagittal tilt, and 0.982 for transverse version. Intraobserver and interobserver reliability had ICCs of 0.987 and 0.987, respectively, for coronal inclination; 0.979 and 0.981, respectively, for sagittal tilt; and 0.992 and 0.978, respectively, for transverse version.

**Conclusions:** The 3D concept with its trigonometric algorithm is a valid and reliable tool for the measurement of cup orientation.

**Clinical Relevance:** By calculating the transverse version of cups from coronal inclination and sagittal tilt measurements, the trigonometric algorithm enables a 3D definition of cup orientation, regardless of the imaging modality used. In addition, it introduces sagittal tilt that, like pelvic tilt, rotates around the transverse axis.

The first total hip arthroplasty, introduced in 1962 by Sir John Charnley, had a dislocation rate of approximately 4.8% after 23 years, as reported in a large long-term cohort[1]. Since then, dislocation has remained one of the most common postoperative complications, with reported rates of 0.2% after 3 months, 0.8% after 1 year, and 4.76% after 10 years[2-4]. It is well known that acetabular cup orientation is of substantial importance to a well-functioning and stable total hip replacement[5-7]. Several studies have suggested that cup orientation should be within a specific zone in order to minimize the risk of dislocation. For instance, the widely accepted "safe zone" of Lewinnek is characterized by an inclination of 40° ± 10° and an anteversion of 15° ± 10°[5]. However, multiple methods for measuring cup orientation, involving different imaging modalities and various definitions for descriptive angles in different planes, have been introduced[7-10]. On the one hand, "inclination" is consistently considered to be the angle that represents cup orientation in
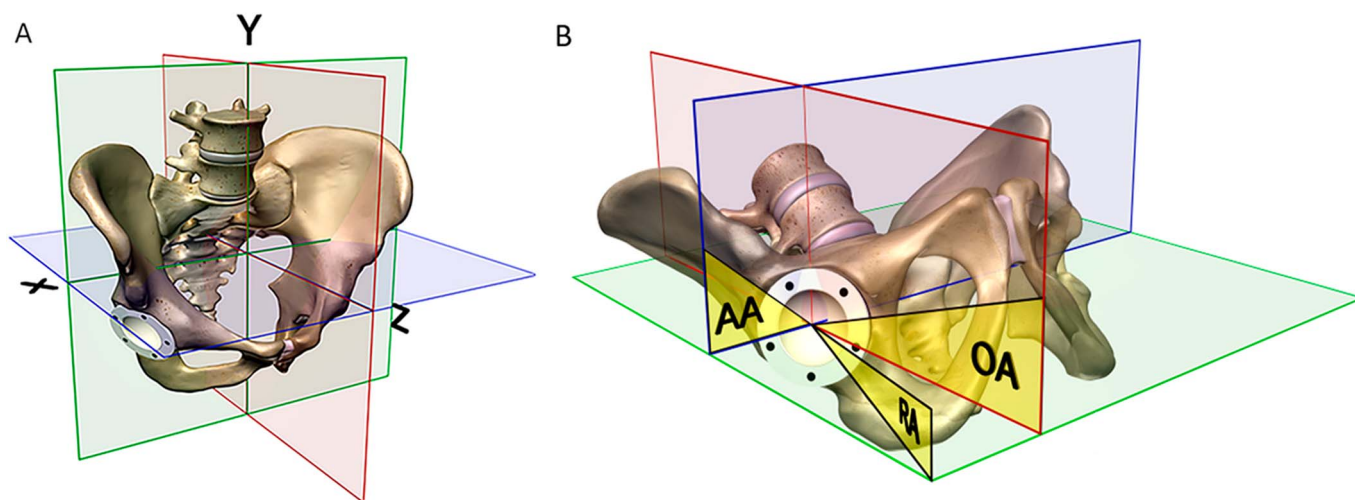
Fig. 1

**Fig. 1-A** Illustration depicting the coronal plane (green), sagittal plane (red), and transverse plane (blue). X indicates the transverse axis, Y indicates the longitudinal axis, and Z indicates the sagittal axis. **Fig. 1-B** Illustration depicting the different definitions of anteversion introduced by Murray[10]. AA = anatomical anteversion in the transverse plane, with rotation around the longitudinal axis; OA = operative anteversion in the sagittal plane, with rotation around the transverse axis; and RA = radiographic anteversion in a projectional plane, with rotation around an axis in between the longitudinal and transverse axes.

the anatomical coronal plane. On the other hand, "anteversion" has been used to describe cup orientation in the anatomical transverse and sagittal planes as well as in different oblique planes[11]. For example, "anteversion" was measured on radiographs in the sagittal plane and on computed tomography (CT) scans in the transverse plane. It was measured on cross-lateral radiographs on a projectional plane or calculated from the ellipse that results from the cup projection on anteroposterior pelvic radiographs. In addition, a combination between the sagittal and transverse angles has been used intraoperatively[12-15]. Several of these methods disregard the fact that these measured angles are projections of a 3-dimensional (3D) cup on different 2-dimensional (2D) planes. In a recent study, Snijders et al. showed that a plethora of different definitions of anteversion for cup orientation leads to confusion with respect to guidelines for cup placement[16]. As there is no uniform method for the assessment of cup orientation in 3 dimensions, it is very difficult to compare or pool data from studies on the optimal cup position[6,7,17]. A uniform concept that is applicable with every 2D and 3D imaging method could fill this void.

Three-dimensional cup orientation can be defined and measured in the coronal, transverse, and sagittal planes (Fig. 1). Each angle rotates around an axis perpendicular to that particular plane. Thus, cup orientation can be defined by angles that describe inclination as the rotation around the sagittal axis in the coronal plane, version as the angle rotating around the longitudinal axis in the transverse plane, and tilt as the angle rotating around the transverse axis in the sagittal plane (Fig. 2, Video 1). Evaluation of cup orientation in the sagittal plane is highly recommended. First, adequate inclination and anteversion within the "safe zone" of Lewinnek could still be insufficient in the sagittal plane. Second, high-risk movements
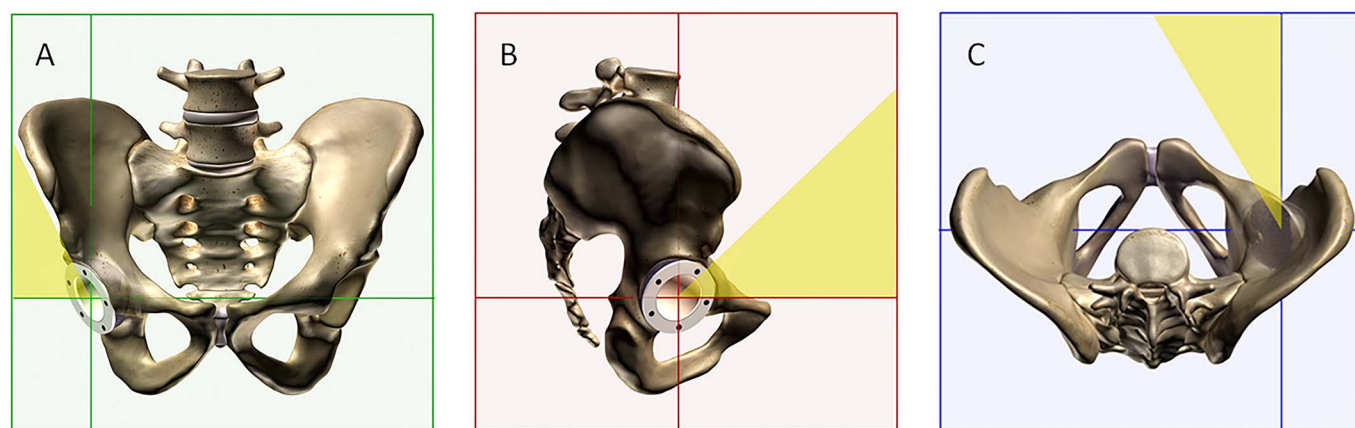


Fig. 2

Illustrations depicting coronal inclination (**Fig. 2-A**), sagittal tilt (**Fig. 2-B**), and transverse version (**Fig. 2-C**) of the cup.
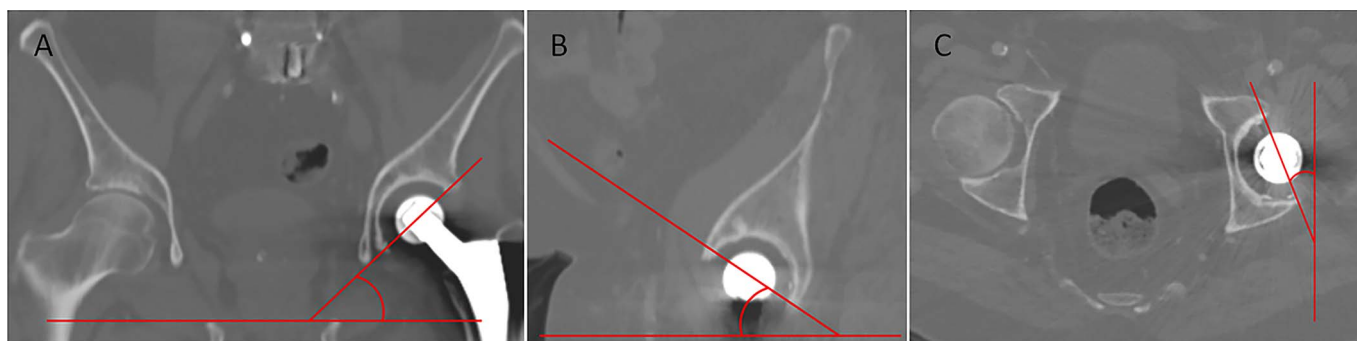
Fig. 3

Multiplanar reconstruction of CT scans, illustrating the method of measurement of coronal inclination (**Fig. 3-A**), sagittal tilt (**Fig. 3-B**), and transverse version (**Fig. 3-C**) of the acetabular cup.

for a posterior dislocation often consist of adduction and hip flexion, with the latter movement involving rotation around the transverse axis in the sagittal plane. Third, pelvic tilt also involves rotation around the transverse axis and solely affects relative 3D cup orientation.

For the present study, we developed a mathematical algorithm that describes the relationships between the 3D cup-orientation angles in the anatomical planes. Because most modern cups are hemispherical, mathematical modeling could be used to calculate cup orientation in the 3 perpendicular planes. In order to implement this trigonometric mathematical 3D algorithm, it is necessary to examine the effect of measuring errors on the results of the algorithm. Moreover, because radiographic transverse imaging is impossible to achieve, this algorithm can only be verified with 3D CT before it can be applied with 2D radiographic images in daily practice.

The purpose of the present study was to test definitions of cup orientation derived from a trigonometric algorithm defined with respect to the 3 anatomical planes. First, the validity of the algorithm was tested by correlating measured and calculated 3D cup-orientation angles. Second, we evaluated the intraobserver and interobserver reliability of the 3D cup-orientation measurements necessary as input for the algorithm.

## Materials and Methods
### Study Procedures
After approval from the institutional review board, the patient archiving and communications system (PACS) was systematically searched for CT angiogram images of the pelvis that were acquired between January 2013 and August 2016 and showed a total hip replacement in situ, a cup with a circumferential reference perpendicular to the cup axis, and complete visualization of the pelvis. The exclusion criteria were previous ipsilateral hip surgery other than primary total hip arthroplasty, malignant disease localized in the pelvis or femur, and images that were part of an incomplete series or that showed substantial contrast artifacts in the region of interest. By protocol, scans were acquired with the patient in the supine position with use of a 16-channel multidetector CT system (Siemens Healthcare; slice thickness, 0.5 mm).

Clinical and radiographic charts were reviewed by 1 observer for inclusion and exclusion, and demographic data were collected.

After manual localization of the center of the femoral head of the total hip replacement on the transverse CT images, multiplanar reconstructions were acquired for the coronal, transverse, and sagittal planes with use of MeVisLab (MeVis Medical Solutions). Next, 3 blinded observers independently

| TABLE I Demographic Data | |
|---|---|
| No. of patients (no. of hips) | 20 (22) |
| No. of female patients | 11 (55%) |
| Age* (yr) | 75.7 ± 7.1 (62-88) |
| Left-sided total hip arthroplasty (no. of hips) | 13 (59.1%) |
| Approach (no. of hips) | |
| Direct lateral | 9 |
| Posterolateral | 7 |
| Anterolateral | 3 |
| Unknown | 3 |
| Type of cup (no. of hips) | |
| RM Pressfit cup (Mathys Bettlach) | 17 (77.3%) |
| PF (Zimmer) | 1 (4.5%) |
| Morscher (Zimmer) | 1 (4.5%) |
| Exeter all-polyethylene cup (Stryker) | 1 (4.5%) |
| Monoblock cup of unknown design | 2 (9.1%) |
| Cup fixation (no. of hips) | |
| Cemented | 3 (13.6%) |
| Uncemented | 19 (86.4%) |
| Cup type (no. of hips) | |
| Monoblock | 22 (100%) |
| Modular system | 0 (0%) |
| Cup size† (mm) | 54 (46-60) |

*The values are given as the mean and the standard deviation, with the range in parentheses. †The values are given as the median, with the range in parentheses.

**TABLE II Measured and Calculated Values of Coronal Inclination***

| | Coronal Inclination (deg) | | | | | |
| | Observer 1 | | Observer 2 | | Observer 3 | |
| Case | Measured | Calculated | Measured | Calculated | Measured | Calculated |
|---|---|---|---|---|---|---|
| 1 | 30.83 | 31.87 | 30.63 | 31.01 | 30.31 | 30.63 |
| 2 | 38.31 | 39.75 | 37.81 | 39.79 | 39.75 | 39.27 |
| 3 | 52.22 | 51.30 | 51.66 | 50.76 | 51.94 | 50.44 |
| 4 | 64.21 | 65.14 | 63.36 | 63.74 | 63.20 | 64.58 |
| 5 | 46.2 | 44.43 | 44.24 | 54.75 | 46.72 | 52.39 |
| 6 | 43.23 | 42.72 | 44.38 | 42.06 | 43.80 | 44.32 |
| 7 | 38.65 | 38.77 | 39.73 | 39.73 | 39.26 | 37.50 |
| 8 | 36.42 | 32.98 | 32.46 | 33.28 | 31.52 | 35.42 |
| 9 | 48.16 | 47.02 | 48.20 | 46.39 | 47.54 | 47.56 |
| 10 | 45.25 | 44.85 | 45.84 | 46.65 | 44.00 | 42.21 |
| 11 | 28.69 | 29.52 | 29.18 | 29.47 | 28.76 | 28.81 |
| 12 | 37.12 | 38.74 | 36.73 | 29.41 | 37.23 | 37.32 |
| 13 | 33.07 | 34.32 | 31.96 | 30.97 | 32.80 | 33.48 |
| 14 | 46.72 | 47.01 | 43.18 | 45.79 | 45.68 | 46.20 |
| 15 | 54.83 | 52.08 | 53.40 | 49.80 | 52.05 | 50.06 |
| 16 | 52.70 | 52.86 | 52.74 | 51.23 | 53.38 | 52.32 |
| 17 | 26.08 | 26.83 | 26.92 | 39.38 | 25.76 | 26.21 |
| 18 | 44.83 | 42.87 | 44.63 | 41.04 | 43.75 | 41.05 |
| 19 | 48.04 | 48.42 | 48.56 | 47.88 | 47.85 | 45.89 |
| 20† | 41.62 | 37.47 | 45.43 | 82.17 | 42.19 | 27.70 |
| 21 | 41.80 | 41.91 | 41.38 | 40.92 | 39.54 | 41.26 |
| 22 | 49.99 | 50.53 | 48.96 | 49.16 | 49.41 | 48.64 |

*Differences between calculated and measured angles were evaluated with use of the intraclass correlation coefficient (ICC). For coronal inclination, the ICC was 0.953 (95% CI, 0.923-0.971). †Case excluded.

measured the inclination in the coronal plane, tilt in the sagittal plane, and version in the transverse plane for all cups in random order with use of a HOROS Medical Image Viewer (Horos v2.0.2; Horos project). For interobserver reliability, 1 blinded observer measured the angles at 3 different settings within a 2-week interval. Coronal inclination and sagittal tilt were defined as the angle between the line through the longitudinal axis of the ellipse of the rim of the cup and the horizontal, whereas transverse version was defined as the angle between the longitudinal axis of the ellipse of the rim of the cup and the sagittal axis (Fig. 3). Therefore, positive angles represented anterior sagittal tilt (also referred to as antetilt) and anterior transverse version (also referred to as anteversion of the cup). Last, a trigonometric algorithm that was developed in-house for the assessment of 3D cup orientation was used for calculation of the 3D angles (see Appendix). In this algorithm, the angles measured in 2 perpendicular planes were used to calculate the parameter in the third plane. Hence, for each patient, 3 calculations were derived, whereby inclination, version, and tilt were each subsequently determined on the basis of the 2 others. For anteriorly oriented cups, the following equations were used:

1. $Inclination = \arctan\left(\dfrac{\tan Version}{\tan Tilt}\right)$

2. $Version = \arctan(\tan Tilt \times \tan Inclination)$

3. $Tilt = \arctan\left(\dfrac{\tan Version}{\tan Inclination}\right)$

For retroverted and retrotilted cup orientations, the following equations were used:

1. $Inclination = \arctan\left(\dfrac{\tan(90 - Version)}{\tan(90 - Tilt)}\right)$

2. $Version = 90 - (\arctan(\tan(90 - Tilt) \times \tan Inclination))$

3. $Tilt = 90 - \left(\arctan\left(\dfrac{\tan(90 - Version)}{\tan Inclination}\right)\right)$

**Statistical Analysis**

For practical purposes and calculation of the different angles with use of the algorithm, data were imported into Excel 2010

| TABLE III Measured and Calculated Values of Sagittal Tilt* | | | | | | |
|---|---|---|---|---|---|---|
| | Sagittal Tilt *(deg)* | | | | | |
| | Observer 1 | | Observer 2 | | Observer 3 | |
| Case | Measured | Calculated | Measured | Calculated | Measured | Calculated |
| 1 | 27.23 | 26.29 | 25.8 | 25.47 | 26.75 | 26.46 |
| 2 | 46.94 | 45.47 | 46.46 | 44.43 | 46.25 | 46.74 |
| 3 | 30.34 | 31.17 | 30.72 | 31.54 | 25.37 | 26.58 |
| 4 | 28.02 | 27.03 | 27.51 | 27.12 | 29.12 | 27.66 |
| 5 | 22.99 | 24.29 | 31.53 | 22.89 | 25.49 | 21.31 |
| 6 | 19.59 | 19.92 | 19.42 | 20.92 | 19.29 | 18.97 |
| 7 | 48.52 | 48.40 | 49.03 | 49.03 | 47.4 | 49.19 |
| 8 | 7.13 | 8.09 | 7.66 | 7.43 | 7.56 | 6.53 |
| 9 | 44.1 | 45.24 | 43.57 | 45.38 | 44.62 | 44.60 |
| 10 | 20.82 | 21.09 | 28.62 | 27.94 | 20.08 | 21.27 |
| 11 | 21.05 | 20.40 | 21.3 | 21.07 | 21.13 | 21.09 |
| 12 | 12.33 | 11.65 | 10.61 | 13.92 | 11.67 | 11.63 |
| 13 | 12.12 | 11.57 | 10.79 | 11.21 | 11.35 | 11.06 |
| 14 | 30.71 | 30.45 | 30.71 | 28.47 | 30.88 | 30.42 |
| 15 | 20.99 | 22.98 | 18.88 | 21.26 | 18.27 | 19.51 |
| 16 | 34.36 | 34.21 | 33.82 | 35.27 | 33.87 | 34.89 |
| 17 | 22.46 | 21.80 | 22.77 | 14.55 | 22.25 | 21.85 |
| 18 | 15.01 | 16.02 | 15.56 | 17.53 | 14.2 | 15.54 |
| 19 | 25.62 | 25.33 | 27.42 | 27.98 | 24.6 | 26.12 |
| 20† | −1.5 | −1.29 | 2.76 | 0.39 | −1.39 | −1.26 |
| 21 | 16.05 | 15.99 | 16.37 | 16.62 | 15.55 | 14.67 |
| 22 | 32.94 | 32.44 | 31.66 | 31.48 | 31.81 | 32.51 |

*Differences between calculated and measured angles were evaluated with use of the intraclass correlation coefficient (ICC). For sagittal tilt, the ICC was 0.985 (95% CI, 0.975-0.991). †Case excluded.

(Microsoft). Statistical analyses were performed with use of IBM SPSS Statistics 23 (IBM). The continuous angles were assessed and were expressed as the mean and the standard deviation, with the range in parentheses. Box plots were used to identify any outliers. For validity analysis, differences between the measured and calculated angles per case for the 3 observers were assessed with use of the intraclass correlation coefficient (ICC) and corresponding 95% confidence interval (CI) with a 2-way mixed-effects model for absolute agreement. For intra-observer and interobserver reliability, measured and calculated angles were compared within and between the observers with use of the ICC, with a 1-way random-effects model for intraobserver reliability and a 2-way mixed-effects model for interobserver reliability.

## Results

### Demographics

Twenty-two total hip replacements on CT scans of 20 patients met the inclusion criteria. All CT angiograms had been requested for vascular assessment. The primary total hip replacements had been implanted between 2002 and 2016. Demographic characteristics and cup types are shown in Table I.

### Validity and Reliability Analyses

Data were normally distributed, and there was only 1 outlier. This outlier was excluded because, in this outlier, 2 angles were around 0°. Therefore, the measuring error affected the calculated results to a great extent. The mean coronal inclination, sagittal tilt, and transverse version that were measured on the multiplanar reconstructions for 21 total hip replacements by 3 observers (thus, for 63 measurements), were 42.82° ± 9.18° (range, 25.76° to 64.21°), 25.67° ± 11.09° (range, 7.13° to 49.03°), and 27.05° ± 12.01° (range, 10.75° to 54.79°), respectively. The calculated angles were 42.90° ± 8.95° (range, 26.21° to 65.14°) for coronal inclination, 25.55° ± 11.09° (range, 6.53° to 49.19°) for sagittal tilt, and 27.26° ± 12.34° (range, 9.62° to 54.74°) for transverse version. Tables II, III, and IV show the measured and calculated angles per case and per observer.

Correlation analysis of 63 measured and calculated 3D angles revealed an ICC of 0.953 (95% CI, 0.923 to 0.971) for

**TABLE IV Measured and Calculated Values of Transverse Version***

| | Transverse Version (deg) | | | | | |
| | Observer 1 | | Observer 2 | | Observer 3 | |
| Case | Measured | Calculated | Measured | Calculated | Measured | Calculated |
|---|---|---|---|---|---|---|
| 1 | 39.61 | 40.77 | 38.81 | 39.23 | 40.41 | 40.77 |
| 2 | 52.15 | 53.56 | 51.64 | 53.60 | 51.95 | 51.47 |
| 3 | 25.12 | 24.40 | 25.89 | 25.17 | 21.39 | 20.37 |
| 4 | 13.85 | 14.42 | 14.41 | 14.64 | 14.83 | 15.72 |
| 5 | 23.4 | 22.14 | 23.44 | 32.21 | 20.17 | 24.18 |
| 6 | 21.08 | 20.74 | 21.34 | 19.81 | 19.72 | 20.05 |
| 7 | 54.62 | 54.74 | 54.18 | 54.18 | 54.79 | 53.07 |
| 8 | 10.91 | 9.62 | 11.58 | 11.94 | 10.57 | 12.21 |
| 9 | 42.08 | 40.95 | 42.18 | 40.38 | 42.06 | 42.08 |
| 10 | 20.92 | 20.65 | 27.25 | 27.92 | 21.95 | 20.73 |
| 11 | 34.2 | 35.12 | 34.6 | 34.92 | 35.1 | 35.15 |
| 12 | 15.24 | 16.11 | 18.38 | 14.09 | 15.16 | 15.21 |
| 13 | 17.46 | 18.25 | 17.62 | 16.99 | 16.88 | 17.30 |
| 14 | 28.97 | 29.22 | 30.02 | 32.33 | 29.83 | 30.28 |
| 15 | 16.64 | 15.13 | 16.12 | 14.25 | 15.45 | 14.44 |
| 16 | 27.38 | 27.51 | 28.28 | 27.00 | 27.4 | 26.51 |
| 17 | 39.26 | 40.18 | 27.08 | 39.58 | 39.73 | 40.29 |
| 18 | 16.11 | 15.10 | 17.74 | 15.75 | 16.2 | 14.81 |
| 19 | 23.05 | 23.32 | 25.13 | 24.61 | 23.93 | 22.51 |
| 20† | −1.15 | −1.33 | 0.38 | 2.72 | −0.73 | −0.81 |
| 21 | 17.77 | 17.84 | 18.72 | 18.44 | 17.6 | 18.63 |
| 22 | 28.08 | 28.54 | 28.06 | 28.23 | 28.64 | 27.99 |

*Differences between calculated and measured angles were evaluated with use of the intraclass correlation coefficient (ICC). For transverse version, the ICC was 0.982 (95% CI, 0.971-0.989). †Case excluded.

**TABLE V Results of Intraobserver Reliability Analysis***

| Parameter | Measurement 1† (deg) | Measurement 2† (deg) | Measurement 3† (deg) | ICC‡ |
|---|---|---|---|---|
| Coronal inclination | 43.14 ± 9.16 (26.08-64.21) | 42.95 ± 9.10 (26.04-64.08) | 42.90 ± 8.84 (27.02-63.55) | 0.987 (0.974-0.994) |
| Sagittal tilt | 24.45 ± 12.41 (−1.50-48.52) | 24.39 ± 12.42 (−1.82-48.14) | 24.70 ± 12.35 (−0.72-47.17) | 0.979 (0.959-0.991) |
| Transverse version | 25.76 ± 13.49 (−1.15-54.62) | 25.79 ± 13.47 (−0.77-53.86) | 26.36 ± 13.49 (−0.74-54.16) | 0.992 (0.983-0.996) |

*Differences between multiple measurements made by one observer were evaluated with use of the intraclass correlation coefficient (ICC). †The values are given as the mean and the standard deviation, with the range in parentheses. ‡The values are given as the ICC, with the 95% CI in parentheses.

**TABLE VI Results of Interobserver Reliability Analysis***

| Parameter | Observer 1† (deg) | Observer 2† (deg) | Observer 3† (deg) | ICC‡ |
|---|---|---|---|---|
| Coronal inclination | 43.14 ± 9.16 (26.08-64.21) | 42.79 ± 9.05 (26.92-63.36) | 42.57 ± 9.13 (25.76-63.20) | 0.987 (0.974-0.994) |
| Sagittal tilt | 24.45 ± 12.41 (−1.50-48.52) | 25.13 ± 12.29 (0.38-49.03) | 23.91 ± 12.32 (−1.39-47.40) | 0.981 (0.962-0.991) |
| Transverse version | 25.76 ± 13.49 (−1.15-54.62) | 26.04 ± 2.76 (2.76-54.18) | 25.59 ± 13.68 (−0.73-54.79) | 0.978 (0.956-0.990) |

*Differences between multiple measurements made by 1 observer were evaluated with use of the intraclass correlation coefficient (ICC). †The values are given as the mean and the standard deviation, with the range in parentheses. ‡The values are given as the ICC, with the 95% CI in parentheses.

coronal inclination, 0.985 (95% CI, 0.975 to 0.991) for sagittal tilt, and 0.982 (95% CI, 0.971 to 0.989) for transverse version (Tables II, III, and IV). The ICCs for intraobserver and interobserver reliability of the measured angles for 21 total hip replacements were 0.987 (95% CI, 0.974 to 0.994) and 0.987 (95% CI, 0.974 to 0.994), respectively, for coronal inclination; 0.979 (95% CI, 0.959 to 0.991) and 0.981 (95% CI, 0.962 to 0.991), respectively, for sagittal tilt; and 0.992 (95% CI, 0.983 to 0.996) and 0.978 (95% CI, 0.956 to 0.990), respectively, for transverse version (Tables V and VI).

## Discussion

The present study showed excellent correlation between measured and calculated angles for the assessment of 3D cup orientation with respect to the 3 anatomical perpendicular planes (Figs. 1 and 2). The proposed trigonometric algorithm can calculate the "true" (gold standard) transverse version in a valid and reliable way on the basis of the coronal inclination and the sagittal tilt. Similarly, coronal inclination can be calculated from sagittal tilt and transverse version, and sagittal tilt can be calculated from coronal inclination and transverse version. Theoretically, the ICC should be 1 in the case of perfect readings, and, in the present study, the ICC approached 1 for all 3 calculated angles (Tables II, III, and IV). The data suggest that the algorithm is usable in everyday practice. The minor measurement error of the readings is clinically irrelevant. An exception in the present study was the outlier case in which both transverse version and sagittal tilt were around 0°. In that case, the minor measuring error affected the proportion between the 2 angles greatly, giving a result ranging from 27.70° to 82.17° of coronal inclination (Tables II, III, and IV). Therefore, we recommend using the algorithm with caution in cases in which 2 angles are approaching 0°.

The validity of this 3D concept provides improvements for the evaluation of optimal cup positioning in total hip arthroplasty and offers great potential for future comparative studies. The definitions are applicable to both radiographic and CT imaging as long as 2 orthogonal projections can be acquired (radiographs) or simulated (CT). While a craniocaudal radiograph of the pelvis is technically impossible, the algorithm has the potential to accurately calculate the transverse version with use of cup orientation angles on 2 radiographs, allowing for easily accessible postoperative feedback. Anteroposterior and lateral radiographs have to be made following the recommendation of Tannast et al.[18]. Specifically, standardized radiographs must be made with the patient in the standing position with the generator at 1.20 m and with the central beam directed to the midpoint between the upper border of the symphysis and the center between both anterior superior iliac spines. The lateral radiograph should be centered on the cranial tip of the contralateral greater trochanter, with the total hip replacement near the detector. After measurement of the sagittal tilt and coronal inclination, the transverse version can be calculated with use of equation number 2 for anteriorly oriented cups, as described in the Materials and Methods section (Fig. 4). The diverging radiation beam, however, presumably results in a larger measuring error. A future study should validate if the algorithm is also applicable with radiographs. If so, then these practical measurements can be performed without the extra radiation and additional cost of CT imaging, making 3D evaluation of cup orientation available for large cohorts. Moreover, the 3D concept could be helpful for establishing a consensus by enabling pooling of different studies that evaluate cup orientation in 2 orthogonal planes.

Murray, in 1993, clearly showed that the definitions for inclination and "anteversion" depend on the evaluation method
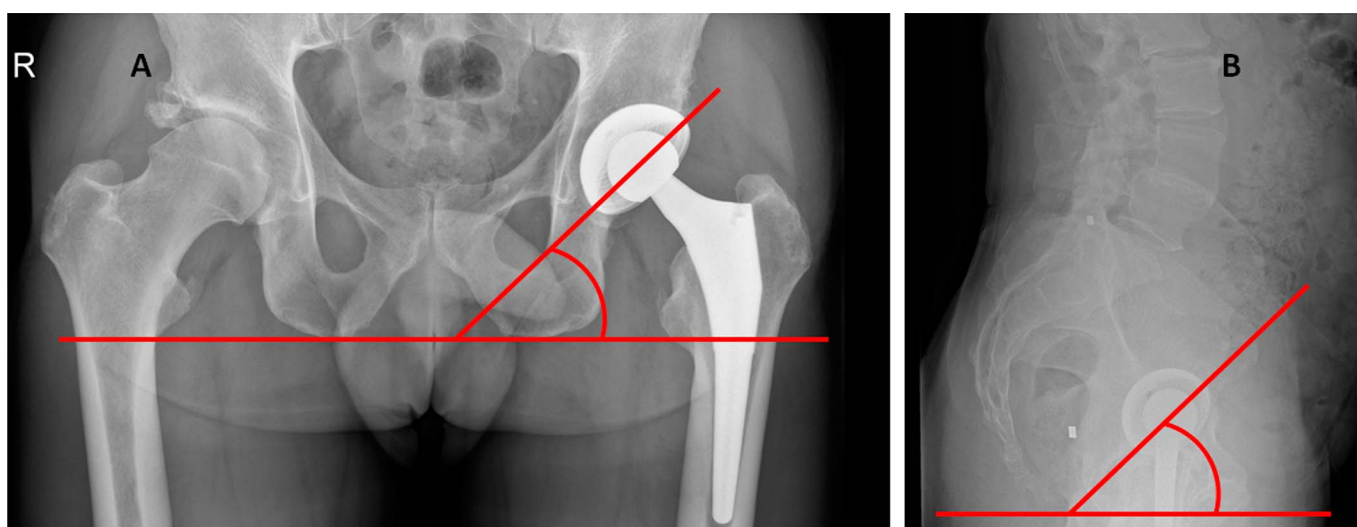


Fig. 4

Anteroposterior and lateral radiographs illustrating an example of how to calculate transverse version on the basis of coronal inclination and sagittal tilt according to the equation for anteriorly oriented cups as described in the Materials and Methods section:

*Version* = arctan(tan *Tilt* × tan *Inclination*)

*Version* = 39.6° = arctan(tan 39.2 × tan 44.6)

used (radiographic, anatomical, and direct observation at surgery)[10]. Direct comparison of inclination is possible because the definitions introduced by Murray for the 3 perspectives are basically equal. On the contrary, the different definitions of anteversion, which represent distinct spatial angles, are not interchangeable (Fig. 1)[10]. The transverse "anteversion" angle is a different spatial angle than the sagittal "anteversion" angle. Unfortunately, many previous studies have involved the use of different imaging methods and different definitions for anteversion, making it difficult to compare the recommendations[6,7,13,14,19-21]. Subsequent meta-analyses evaluating cup anteversion pooled these different outcomes of the spatial angles[22-27]. Thus, there is a lack of consensus for optimal cup orientation[16]. A consensus definition for preoperative planning, intraoperative placement, and postoperative evaluation of cup orientation would be useful. We recommend the evaluation of cup orientation in all 3 anatomical planes. These definitions are also applicable intraoperatively. These spatial angles provide unambiguous definitions and are interchangeable between different imaging modalities.

Moreover, there are reasons to believe that malplacement around the transverse axis is important for the mechanism of dislocation. If the cup orientation is in the "safe zone" of Lewinnek for inclination and anteversion, it might not be "safe" enough for sagittal tilt (Fig. 5). Most hip and pelvic movements (pelvic tilt as well as hip flexion and extension) take place around the transverse axis. Opposing pelvic movements around the transverse axis could be protective against dislocation during certain hip movements. For example, posterior pelvic tilt enhances the containment of the femoral head when there is also hip flexion. The joint reaction forces remain more opposed to each other. However, there is a wide variety between patients in terms of the dynamics of anterior and posterior pelvic tilt[28]. In addition, the amount of pelvic tilt in particular positions differs widely[28]. Theoretically, 1° of anterior pelvic tilt decreases the sagittal tilt of the cup by 1°. In a previous study, Lembeck et al. stated that 1° of pelvic tilt affected anteversion by 0.7°[29]. On the basis of our validated algorithm, however, that statement is not correct. Pelvic tilt changes the amount of transverse version depending on the amounts of coronal inclination and pelvic tilt and follows a tangential function (i.e., equation 2 for anteriorly oriented cups as described in the Materials and Methods section) (Fig. 5). From a kinematic point of view, there is no argument for neglecting the sagittal tilt. Thus, this 3D concept has important clinical relevance for defining the orientation around the transverse axis.

This 3D concept has some limitations when used for the analysis of cup positioning. First, the algorithm cannot be applied to cups that lack a circumferential reference perpendicular to the acetabular axis. Fortunately, almost all modern cups have a circular wire that provides this reference.

A second limitation is that the trigonometric algorithm is only applicable for planes that are perfectly orthogonal. Consequently, cross-lateral views cannot be used. On the other hand, innovative biplanar radiography techniques provide
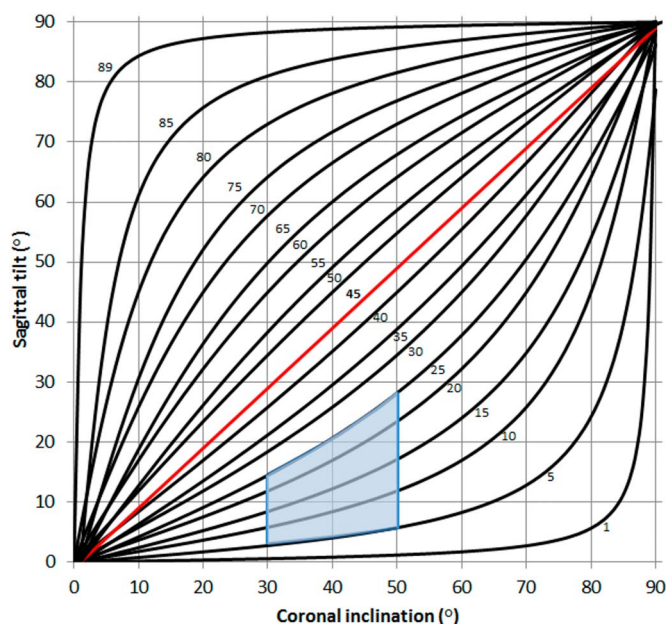


Fig. 5

Three-dimensional surface diagram demonstrating the mathematical interrelation between coronal inclination, sagittal tilt, and transverse version. If 1 of the angles is 45°, the other 2 angles are identical. The red line demonstrates the direct comparison of sagittal tilt and transverse version at a coronal inclination of 45°. The blue area demonstrates the "safe zone" of Lewinnek.

opportunities to use this algorithm for the systematic assessment of 3D cup orientation in patients undergoing total hip arthroplasty. Although additional lateral pelvic radiographs expose the patient to a relative high radiation dose compared with cross-lateral pelvic radiographs, this supplementary radiograph is only required one time postoperatively in addition to the standard anteroposterior pelvic radiograph. In addition, most of these patients are >50 years of age, thereby theoretically diminishing the long-term risk of the higher radiation dose.

A third limitation is that patient positioning has an impact on 3D cup orientation as pelvic tilt changes in different positions[30,31]. Kyo et al. established a difference of <10° of pelvic tilt in 83% to 90% of patients between the standing and supine positions[32]. Measuring and calculating the 3 angles with radiographic imaging with the patient in the standing position might give different results than for the 3 angles in the supine position because of this change in pelvic tilt.

In conclusion, the trigonometric equations provided in the present study can be used to calculate the third 3D orientation angle with use of the orientation angles in the 2 other anatomical planes. Transverse version is often a dominant factor for stability, and this value can now be calculated from the coronal (inclination) and sagittal (tilt) planes. Thus, this 3D concept provides unambiguous definitions of cup orientation regardless of the imaging modality, and it could provide the opportunity for easily accessible 3D postoperative feedback. Future studies are required to determine the reliability of this 3D concept with anteroposterior and lateral pelvic radiographs

and might be beneficial to ultimately guide intraoperative cup positioning.

## Appendix

(eA) An explanation of the trigonometric algorithm rationale and a table showing transverse version for given coronal inclinations and sagittal tilts are available with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSOA/A50). ■

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