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The Relationship of Cup Inclination and Anteversion in the Coronal Plane with Ante-Inclination in the Sagittal Plane

Exposing the Fallacy of Cup Safe Zones

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Background: This study aimed to establish an equation for calculating cup ante-inclination (AI) from radiographic cup inclination and anteversion, to validate this equation in a total hip arthroplasty (THA) cohort, and to test whether achieving previously described radiographic cup inclination and anteversion targets would also satisfy sagittal cup AI targets.

Methods: A mathematical equation linking cup AI, radiographic inclination (RI), and anteversion (RA) was determined: tan(AI) = tan(RA)/cos(RI). Supine and standing anteroposterior and lateral radiographs of 440 consecutive THAs were assessed to measure cup RI and RA and spinopelvic parameters, including cup AI, using a validated software tool. Whether orientation within previously defined RI and RA targets was associated with achieving the AI target and satisfying the sagittal component orientation (combined sagittal index, 205° to 245°) was tested.

Results: The cups in the THA cohort had a measured mean inclination (and standard deviation) of 43° ± 7°, anteversion of 26° ± 9°, and AI of 34° ± 10°. The calculated cup AI was 34° ± 12°. A strong correlation existed between measured and calculated AI ($r = 0.75$; $p < 0.001$), with a mean error of 0° ± 8°. The inclination and anteversion targets were both satisfied in 194 (44.1%) to 330 (75.0%) of the cases, depending on the safe zone targets that were used, and 311 cases (70.7%) satisfied the AI target. Only 125 (28.4%) to 233 (53.0%) of the cases satisfied the AI target as well as the inclination and anteversion targets. Satisfying inclination and anteversion targets was not associated with increased chances of satisfying the AI target.

Conclusions: Achieving optimal cup inclination and anteversion does not ensure optimal orientation in the sagittal plane. The equation and nomograms provided can be used to determine and visualize how the 2 planes used for evaluating the cup orientation and the pertinent angles relate, potentially aiding in preoperative planning.

Acetabular component (cup) orientation is among the factors influencing the range of motion, stability, wear behavior, and patient-reported outcomes following total hip arthroplasty (THA)[1-4]. In recent years, evidence has shown that traditional targets for acetabular component position may not predict dislocation risk, and there is a question whether a universal safe zone exists[1,5,6]. Spinopelvic alignment and mobility (the dynamic interaction of the lumbar spine, pelvis, and hip in the sagittal plane) are associated with the dislocation risk and outcome after THA[4,7]. In studying the sagittal spinopelvic characteristics, the sagittal orientation of the cup and of the proximal femur have been examined in detail, and it has been shown that the sagittal functional hip position and orientation, defined as the combined sagittal index (CSI), is a predictor of impingement and dislocation after THA[8-10]. A standing CSI range of 205° to 245° is associated with a reduced dislocation risk[8,11].

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Radiographic cup inclination and anteversion measured on anteroposterior pelvic radiographs[12], and cup ante-inclination (AI) values measured on lateral spinopelvic views, are angular measurements of the cup axis as projected onto different planes used for measurement[4,10]. Given that all 3 cup orientations are measurements of the same object, a simple trigonometric equation interlinking all 3 will exist. Previous work has provided a complex description, based on 3-dimensional (3D) transformation matrices, which is challenging to use clinically and is dependent on measurements involving biplanar radiography and outputs[13], which are not the standard of care in most arthroplasty centers. A simple equation would help surgeons during their preoperative planning, in which they aim to identify a cup orientation that satisfies both sagittal and coronal targets[8,11]. To date, it is unknown if being within the targets for inclination and anteversion is associated with also being within the targets for AI and CSI.

The aims of this study were to establish a simple equation for calculating sagittal cup AI from cup anteversion and inclination (coronal measurements), to demonstrate its clinical utility in vivo in patients who had both supine and standing anteroposterior pelvic and lateral spinopelvic radiographs after THA, and to test whether achieving commonly used radiographic cup inclination and anteversion targets would also satisfy sagittal cup AI and CSI targets.

Materials and Methods

Study Design

Equation

Radiographic inclination (RI) is the angle between the longitudinal axis and the cup axis when this is projected onto the coronal plane. Radiographic anteversion (RA) is the angle between the cup axis and the coronal plane[12], and AI is the angle between the longitudinal axis and the cup axis when the latter is projected onto the sagittal plane[9]. A trigonometric equation relating RI and RA to AI was established using the definitions of these angles by Murray[12]. The equation was derived by considering a unit vector normal to the acetabular cup face; thus, based on the definitions by Murray, the radiographic anteversion and inclination could be defined. Based on these definitions, the relationship of AI to RA and RI was formed (see Appendix). The final equation is $\tan(AI) = \tan(RA)/\cos(RI)$, and the relationship of RI, RA, and AI is illustrated in Figure 1. The trigonometric analysis and derivation of the formula are provided in the Appendix.

Validation by Modeling

A 3D computer model of a generic cup was created using MATLAB (version 2021b; The MathWorks) and was placed into a Cartesian coordinate system in which the x axis was directed horizontally right to left, the y axis was directed horizontally anterior to posterior, and the z axis was directed inferiorly to superiorly. The initial plane of the cup face was in the x-y plane, with the axis normal to the cup face pointing straight down. The cup was placed in the left hip; first, a rotation of RA about the x axis was applied, followed by a rotation of RI about the y axis. The final orientation of the normal axis vector was projected onto the y-z (i.e., sagittal) plane. Then the angle between this projected vector and the vector pointing straight down ($[0, 0, -1]^T$) was determined from the inverse cosine of the dot product of these 2 vectors to

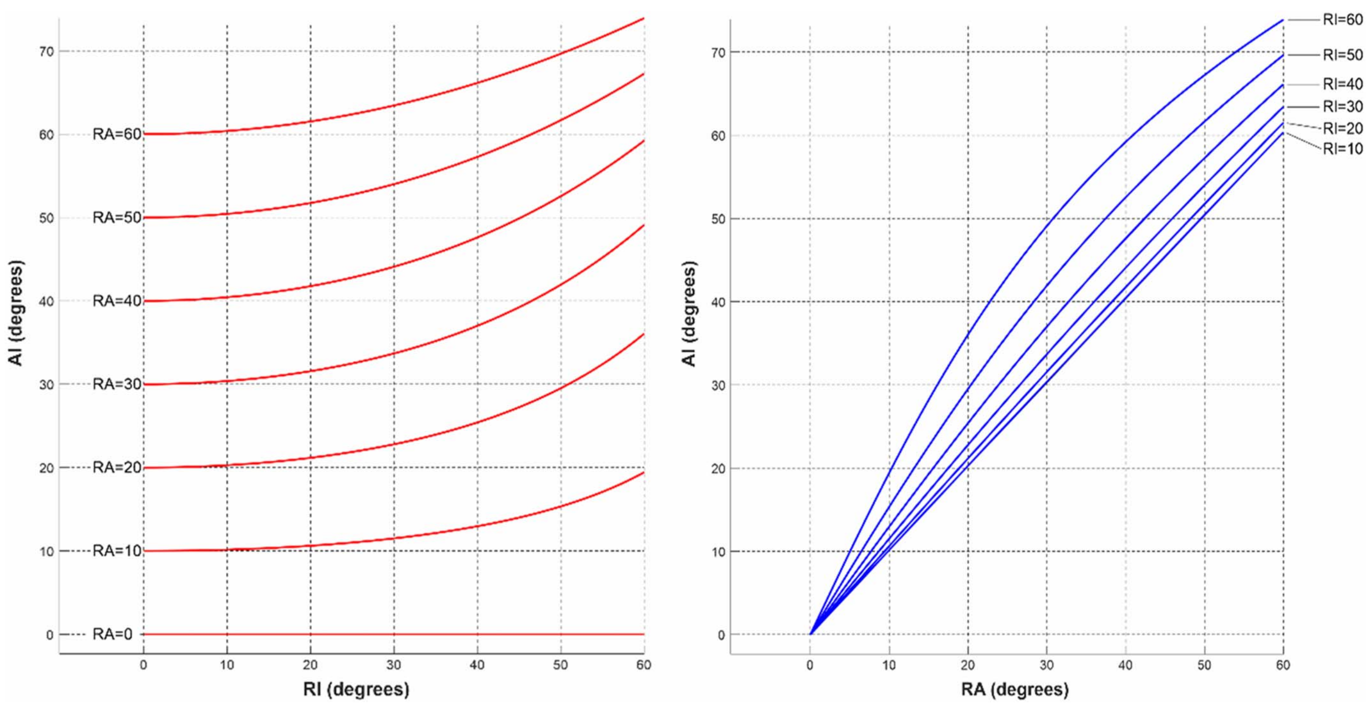

Fig. 1

Nomograms illustrating the interaction between radiographic cup inclination and anteversion in the coronal plane (left) and cup AI in the sagittal plane (right).

TABLE I Demographic Characteristics and Diagnoses for the Study Cohort

Demographic characteristics	
No. of hips*	440
Gender*	
Male	203
Female	237
Age at surgery† *(yr)*	66 ± 12
Body mass index† *(kg/m²)*	28 ± 5
Diagnosis*	
Primary osteoarthritis	367
Secondary osteoarthritis due to:	
Developmental dysplasia	45
Osteonecrosis	19
Legg-Calvé-Perthes disease	9

*The values are given as the number of hips. †The values are given as the mean and the standard deviation.

give the AI value determined from the 3D modeling; this was called AI_model. Note that because the inverse cosine function defaults to giving positive angle values, the sign of the AI angle was set to be the same as the applied RA value. This process was performed for RI values ranging from 20° to 60°, and for each RI value for RA values ranging from −20° to 20°. For each combination of RI and RA, AI was also calculated from the simple equation given above; this was called AI_eqn. For each combination of RI and RA, the 2 values of AI were compared.

Clinical Validation

The trigonometric equation was also validated in clinical practice, investigating the radiographic anteroposterior and sagittal cup orientations in a prospective diagnostic cohort study of 440 consecutive patients who had undergone unilateral THA. This part of the study was performed at 2 tertiary academic centers and was approved by the institutional review boards (Heidelberg University Hospital and the Ottawa Hospital).

Study Population

All patients underwent unilateral THA for end-stage hip osteoarthritis in the supine or lateral decubitus position, through a posterior approach (n = 89), a direct anterior approach (n = 149), a direct lateral approach (n = 192), or an anterolateral approach (n = 10). All THAs were performed by 1 of 8 fellowship-trained surgeons. Inclusion criteria were an age of ≥18 years and a diagnosis of unilateral primary or secondary hip osteoarthritis. Exclusion criteria were the inability to complete questionnaires or perform basic tasks without aid, having defective radiographs due to technical reasons, or lack of consent[14].

A cementless acetabular cup with a highly cross-linked polyethylene inlay was used in 437 cases (190 Allofit cups, 236 G7 cups, and 11 Trabecular Metal cups; all Zimmer Biomet) and a cemented cup, in 3 cases (Mueller low-profile cup; Zimmer Biomet). The demographic cohort details are outlined in Table I.

Radiographic Assessment

Biplanar low-dose radiographs (EOS Imaging System; EOS Imaging) of the lumbar spine, pelvis, and femur were acquired in the standardized standing position postoperatively. Standardized radiographic measurements were performed for cup orientation

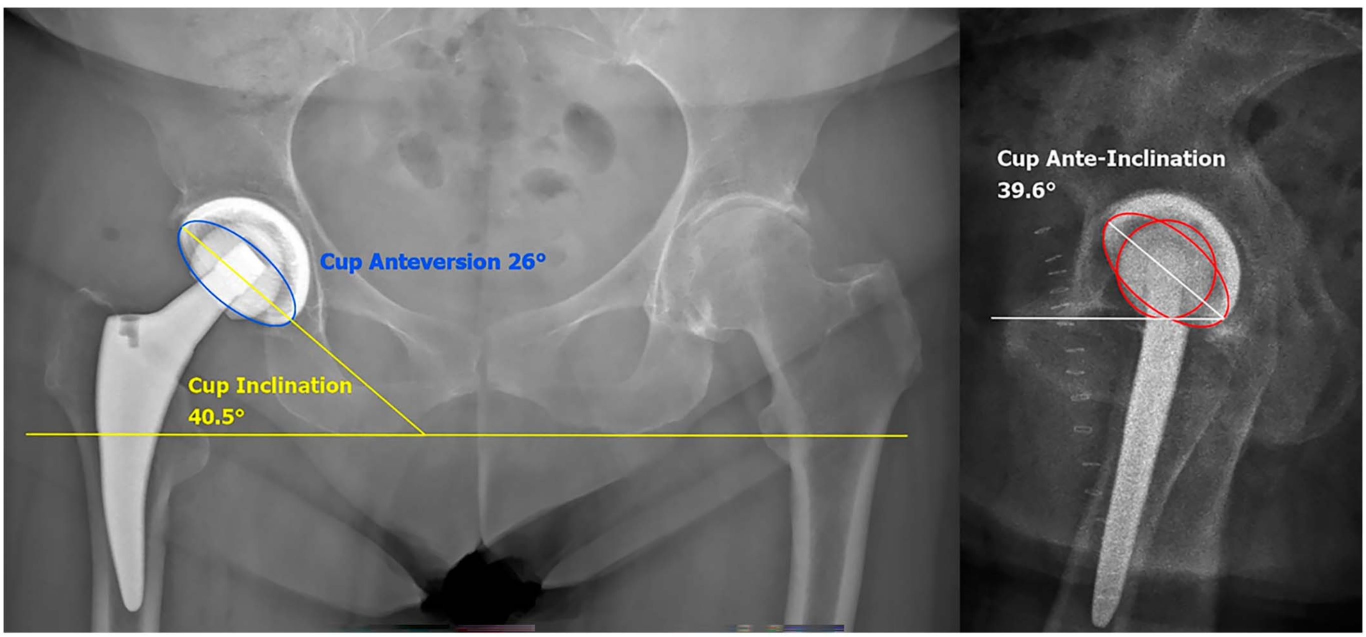

Fig. 2

Radiographic measurements of cup inclination and anteversion in the coronal plane (left) and AI in the sagittal plane (right).

in the coronal plane (RI and RA) on anteroposterior radiographs of the pelvis in both the supine and standing positions, and for AI in the sagittal plane on lateral standing radiographs (Fig. 2). Three previously published target cup orientations in the coronal plane were analyzed: inclination and anteversion of 30° to 50° and 5° to 25° (the Lewinnek safe zone), 30° to 45° and 5° to 25° (the Callanan safe zone), and 30° to 50° and 10° to 30° (the Grammatopoulos safe zone) on supine radiographs[2,6,15]. Validated software programs were used for radiographic measurements in the coronal plane (EBRA; University of Innsbruck) and the sagittal plane (Surgimap; Nemaris). The pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL), and pelvic-femoral angle (PFA) were also measured for each patient. This allowed for the calculation of the CSI (CSI = PFA + AI) and the determination of whether the standing CSI was within the previously defined target of 205° to 245°[4,7]. The measurements on lateral radiographs visualizing the region from the lumbar spine to the proximal femur were performed on the basis of the following definitions. PI is the angle between a line perpendicular to the sacral plate at its midpoint and a line connecting the same point to the midpoint of the axis between both centers of the femoral heads. PT is the angle between a line running from the sacral end plate midpoint to the midpoint between the femoral heads and the vertical axis. SS is the angle between the tangent line to the superior end plate of S1 and a horizontal line. LL is the angle between the line tangent to the superior end plate of L1 and the line tangent to the superior end plate of S1. AI is the angle between a horizontal line and the sagittal orientation of the acetabular component[9].

Statistical Analysis

The data were normally distributed, and the values are therefore given as the mean and the standard deviation. Pearson correlation coefficients were calculated for continuous data.

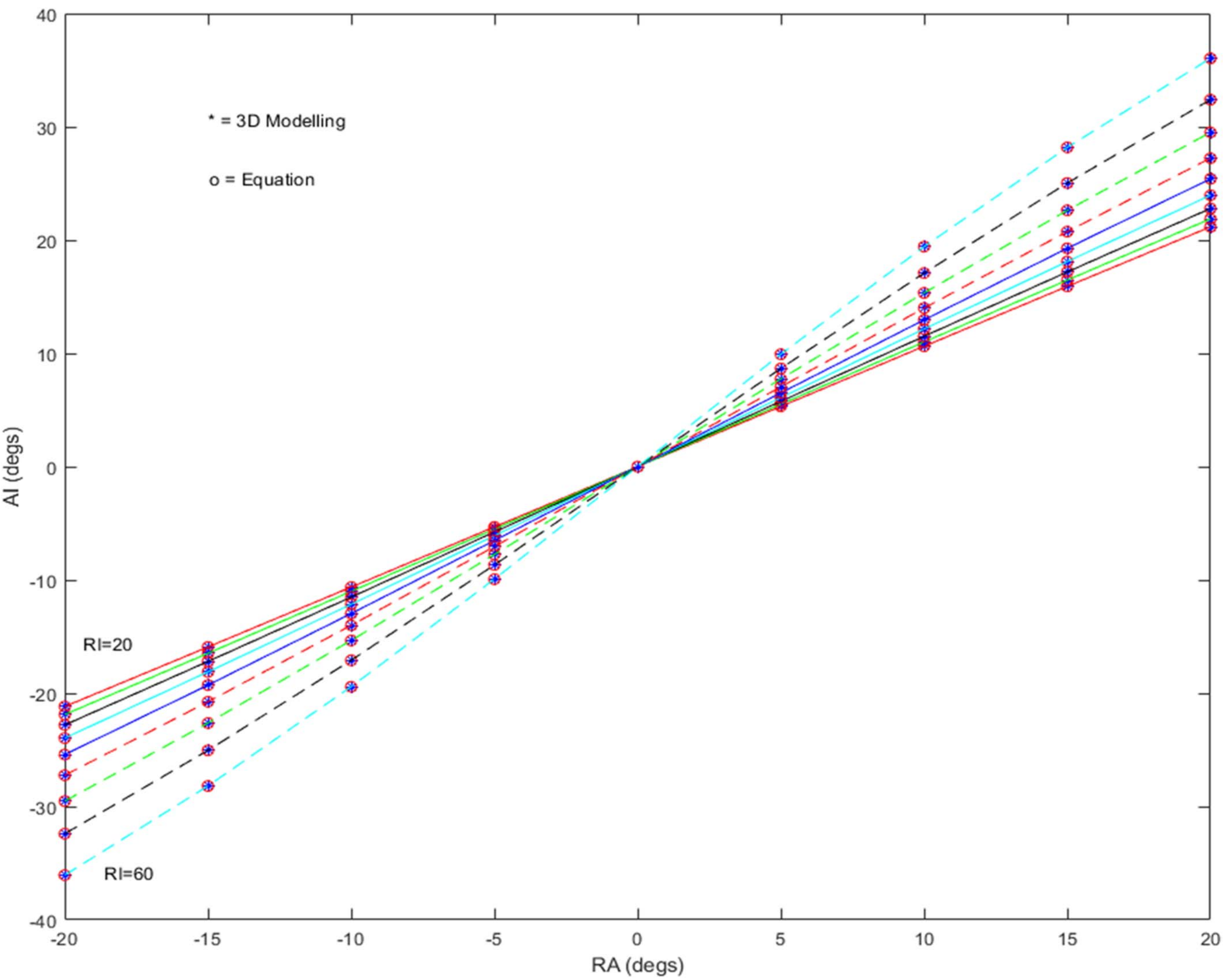

Fig. 3

Comparison of the AI_model and AI_eqn values for various combinations of RI (from 20° to 60°) and RA (from −20° to 20°).

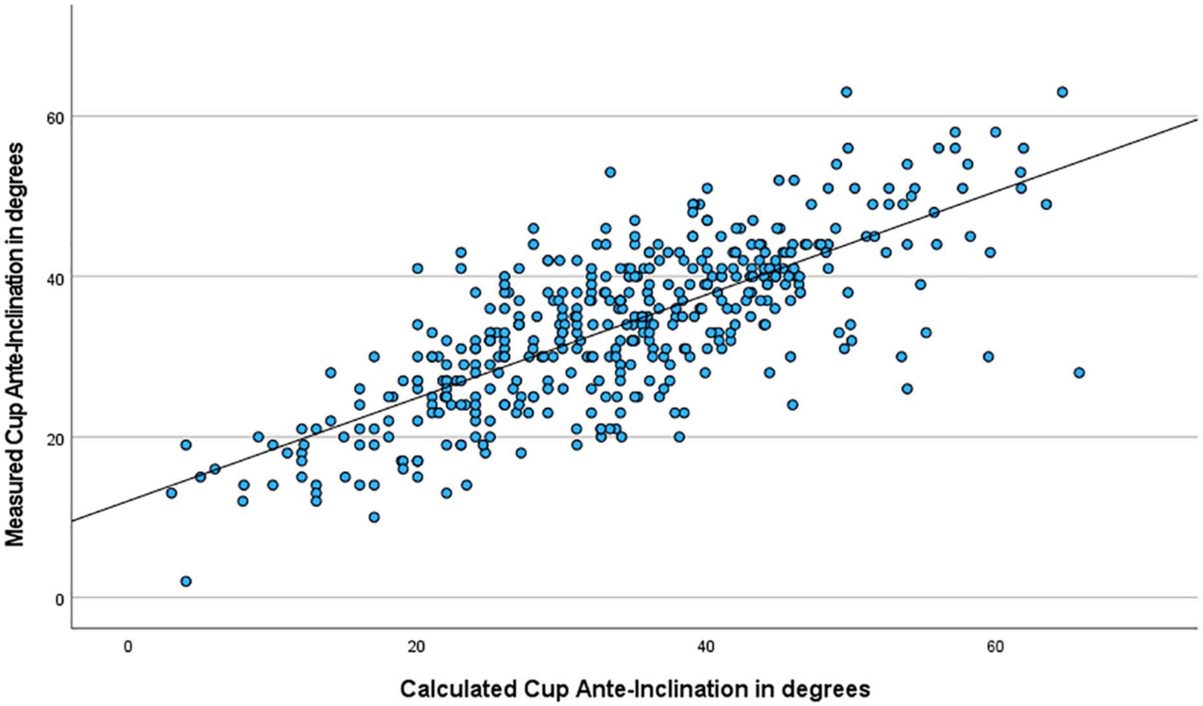

Fig. 4
Scatterplot illustrating the correlation between the measured and calculated AI.

Measurements were repeated 2 weeks after the initial radiographic analysis for a randomly selected 10% of the THAs, by both reviewers in a blinded fashion, and average-measure correlation coefficients with a 2-way random-effects model for absolute agreement were calculated. These showed excellent intraobserver and interobserver reliabilities (range,

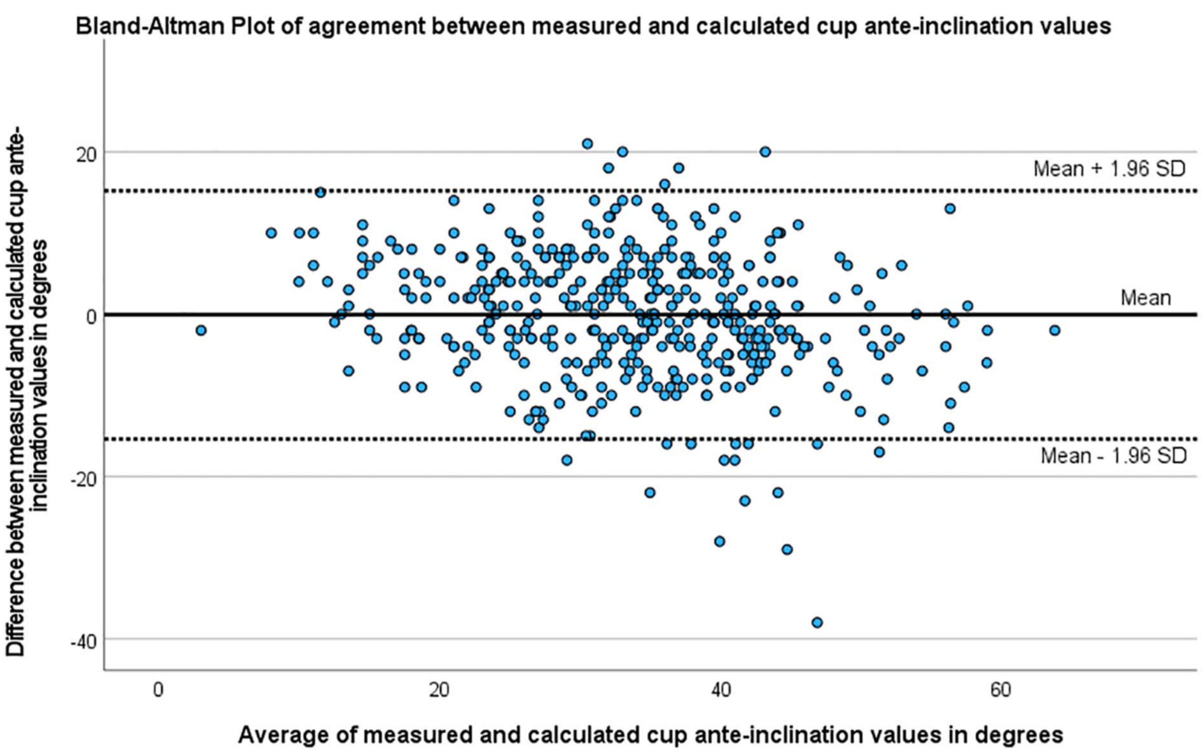

Fig. 5
Bland-Altman plot of agreement between measured and calculated AI, in degrees. SD = standard deviation.

0.925 [95% confidence interval (CI), 0.830 to 0.967] to 0.994 [95% CI, 0.983 to 0.998]). Chi-square tests were used for the analysis of categorical data. Sensitivity, specificity, and positive and negative predictive values for the ability of the coronal cup orientations to predict whether sagittal targets were achieved were determined from cross-tabulated data. The numerical difference between AI and operative anteversion values was determined. A logistic regression analysis was used for identifying factors associated with having satisfied the cup orientation target in the coronal plane but not having satisfied it in the sagittal plane (the dependent variable). We aimed to enter 7 independent variables (supine cup inclination, anteversion, standing LL, standing SS, PI, standing PT, and standing PFA). Based on a preliminary data analysis, we expected approximately 80 events and 360 non-events. Thus, we estimated that we would have sufficient power for entering 7 independent variables. The analysis was performed with a forced data entry method. Statistical analysis was performed using SPSS version 27 (IBM). Significance was set at $p < 0.05$.

Results

Validation of the Equation by Modeling

The values of AI calculated from the simple equation (AI_eqn) were the same as those determined from the 3D modeling (AI_model) (Fig. 3).

TABLE II Radiographic Measurements of Spinopelvic and Cup Parameters*

Spinopelvic parameters	
LL standing, preoperatively	54 ± 13 (4 to 87)
LL standing, 1 year postoperatively	55 ± 13 (3 to 88)
SS standing, preoperatively	40 ± 10 (14 to 71)
SS standing, 1 year postoperatively	39 ± 10 (1 to 74)
PT standing, preoperatively	16 ± 9 (−16 to 40)
PT standing, 1 year postoperatively	17 ± 10 (−16 to 51)
PI standing, preoperatively	56 ± 12 (26 to 99)
PI standing, 1 year postoperatively	56 ± 13 (23 to 100)
PFA standing, preoperatively	187 ± 12 (144 to 222)
PFA standing, 1 year postoperatively	190 ± 13 (138 to 230)
CSI standing, 1 year postoperatively	225 ± 17 (178 to 291)
Cup orientation parameters	
Measured cup inclination, supine	41 ± 6 (18 to 63)
Measured cup anteversion, supine	25 ± 7 (4 to 51)
Measured cup inclination, standing	43 ± 7 (17 to 63)
Measured cup anteversion, standing	26 ± 9 (2 to 56)
Measured cup AI, standing	34 ± 10 (2 to 63)
Calculated cup AI	34 ± 12 (3 to 66)
Mean error between measured and calculated cup AI	0 ± 8 (−38 to 21)

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

TABLE III Cross-Tabulations for the 3 Zones of Optimal Coronal Orientation Versus the Optimal Sagittal Cup Orientation

Variable		Optimal Sagittal Cup Orientation (CSI, 205° to 245°) No	Yes	Total
Lewinnek optimal coronal cup orientation, supine (inclination and anteversion of 40° and 15° ± 10°); p = 0.236	No	56	153	209
	Yes	73	158	231
	Total	129	311	440
Callanan optimal coronal cup orientation, supine (inclination and anteversion of 30° to 45° and 15° ± 10°); p = 0.013	No	60	186	246
	Yes	69	125	194
	Total	129	311	440
Grammatopoulos optimal coronal cup orientation, supine (inclination and anteversion of 40° and 20° ± 10°); p = 0.986	No	32	78	110
	Yes	97	233	330
	Total	129	311	440

In Vivo Validation of the Equation in the Patient Cohort

The radiographic measurements showed a standing cup inclination of 43° ± 7°, anteversion of 26° ± 9°, and cup AI of 34° ± 10°. The calculated cup AI based on the measured cup inclination and anteversion values was 34° ± 12°. A strong correlation between measured and calculated AI was observed (Pearson $r = 0.75$; $p < 0.001$) (Fig. 4). The mean error between the measured and calculated cup AI values was 0° ± 8° (Fig. 5). The error was (weakly) positively correlated with measured AI (Pearson $r = 0.16$; $p < 0.001$) and (moderately) negatively correlated with anteversion (Pearson $r = -0.52$; $p < 0.001$).

Coronal and Sagittal Parameters

The cohort's cup and spinopelvic characteristics are detailed in Table II. The mean supine inclination was 41° ± 6° and the mean supine anteversion was 25° ± 7°. The cup RI increased by a mean of 2° ± 4° and the cup RA increased by an mean of 2° ± 7° between standing and supine positions. The mean standing PFA was 190° ± 13°, and the mean CSI was 225° ± 17°. Of the 440 cases, 194 (44%) to 330 (75%) were within the 3 supine coronal cup orientation targets tested, and 311 cases (71%) satisfied the standing sagittal orientation target. Overall, only 28% to 53% satisfied both coronal and sagittal cup orientation targets (Table III). Satisfying coronal RI and RA targets was associated with low sensitivity (25% to 47%) and moderate specificity (40% to 75%) for having achieved the optimal sagittal orientation (Table IV).

The clinically relevant factors associated with having satisfied the cup orientation target in the coronal plane given by the Lewinnek zone but not in the sagittal plane were low RI (39° ± 5° compared with 41° ± 6° for those that also satisfied the sagittal target; $p = 0.025$), low RA (21° ± 6° compared with 25° ± 7°; $p < 0.001$), and low standing PFA (177° ± 12°

TABLE IV Sensitivity, Specificity, and Positive and Negative Predictive Values for Predicting Optimal Sagittal Cup Orientation According to Each of the Coronal Supine Cup Orientation Zones Tested

Zone	Sensitivity	Specificity	Positive Predictive Value	Negative Predictive Value
Lewinnek	43.4%	50.8%	26.8%	68.4%
Callanan	46.5%	40.2%	24.4%	64.4%
Grammatopoulos	24.8%	74.9%	29.1%	70.6%

compared with 189° ± 11°; p = 0.002) (Table V). A diagram (Fig. 6) can be used for the determination of the desired radiographic cup inclination and anteversion in the coronal plane, based on cup AI (colored lines) in the sagittal plane, in degrees.

Discussion

Identifying the optimal cup orientation in THA is an important academic frontier[8,11,13,16]. There has been debate on the ideal cup orientation, as evident by the various approaches employed by navigation and robotic platforms[13]. Studies on the hip-spine interaction have highlighted the relevance of studying and incorporating the sagittal plane when determining optimal cup orientation[4,7]. However, this is different from traditional practice, which primarily focuses on the target cup orientation on anteroposterior pelvic radiographs. If a target cup orientation is to satisfy both coronal and sagittal targets, how the orientation in one plane relates to that in the other is crucial for preoperative planning and postoperative evaluation. In this study, we mathematically determined the simple equation linking cup AI, radiographic cup inclination, and radiographic cup anteversion. Furthermore, we validated this equation in both modeling and an in vivo setting. The modeling validation showed that the simple equation produced the same results as the 3D modeling, which is the basis for the rather more complex formulation presented by Tang et al.[13]. There was a very strong correlation between the in vivo measurements of AI and the values calculated from the simple equation, with a mean difference of 0° between the calculated value and the measured value. Cups that satisfy coronal orientation targets (e.g., the Lewinnek zone) do not necessarily satisfy sagittal orientation targets. This is primarily because the traditionally considered safe zones are associated with low anteversion and an associated low AI, increasing impingement risk[6,15]. The only coronal cup orientation zone associated with increased chances of optimal sagittal orientations was that of Grammatopoulos et al.[2]; this is likely because that orientation zone has greater anteversion (10° to 30°), which yielded higher AI values. The equation that we developed allowed for the development of nomograms to help surgeons to identify a cup orientation goal for each patient that satisfies both coronal and sagittal targets.

In the present study, we derived a simple equation describing the trigonometric relationship of cup inclination, anteversion, and AI. Cup AI is akin to operative anteversion as per Murray's definitions[12]. Having derived the trigonometric equation and validated it with a 3D model, it was important to determine its efficacy in clinical practice. Although the mean difference between the calculated and measured AI values was small (0°), the range was quite considerable (−38° to 21°). As the radiographs analyzed were derived from EOS radiographs, it is unlikely that the differences are due to the location of the x-ray beam relative to the pelvis. It is thus most likely that this difference reflects the measurement errors of cup orientation using the radiographic software.

Having determined the coronal characteristics (cup inclination and anteversion) and sagittal characteristics (AI) of the whole cohort enabled us to determine how many satisfied both, 1, or none of the component orientation criteria

TABLE V Logistic Regression Analysis Investigating Factors Associated with Optimal Coronal (per the Lewinnek Zone) and Sagittal Orientation of the Cup*

Parameter	Regression Coefficient β	Standard Error	Odds Ratio (Exp (β))	95% CI of the Odds Ratio	P Value
Cup inclination, supine, in degrees	−0.059	0.026	0.943	0.895 to 0.992	0.025
Cup anteversion, supine, in degrees	−0.183	0.029	0.833	0.787 to 0.882	<0.001
LL standing, preoperatively, in degrees	−0.032	0.018	0.969	0.935 to 1.004	0.078
SS standing, preoperatively, in degrees	0.051	0.091	1.052	0.880 to 1.258	0.579
PI standing, preoperatively, in degrees	0.008	0.091	1.008	0.843 to 1.205	0.931
PT standing, preoperatively, in degrees	−0.034	0.088	0.967	0.813 to 1.149	0.700
PFA standing, preoperatively, in degrees	−0.049	0.016	0.952	0.922 to 0.982	0.002

*R^2 = 0.339.

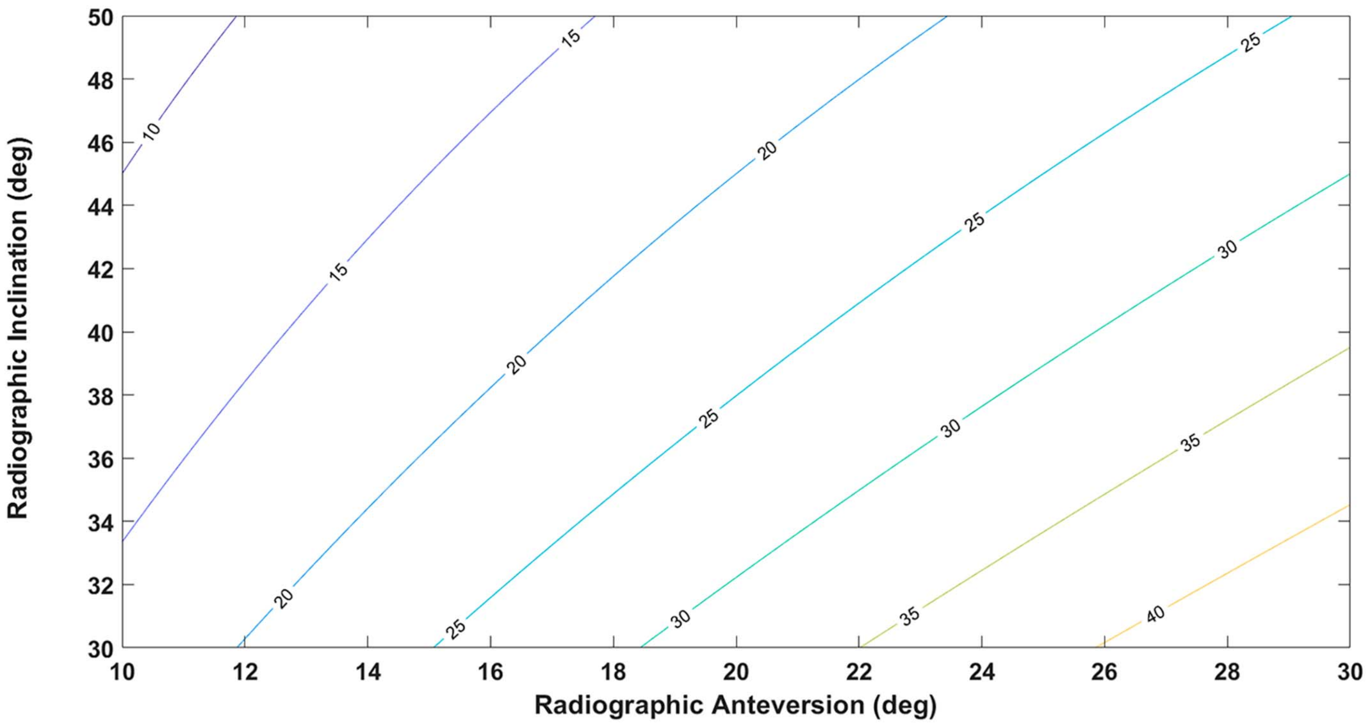

Fig. 6
Diagram for determination of the desired radiographic cup inclination and anteversion in the coronal plane, based on cup AI (colored lines) in the sagittal plane, in degrees.

previously described (Tables III and IV). On average, most patients satisfied the coronal targets (range, 44% to 75%) and the sagittal targets (71%). On average, however, only a minority (range, 28% to 53%) satisfied both. Furthermore, the sensitivity, specificity, and positive and negative predictive values were low for predicting a sagittally well-placed cup based on satisfying each of the previously described optimal zones. These observations are important and likely contribute to why dislocations are sometimes seen in patients with well-positioned cups (according to inclination and anteversion targets) and why patients with cup malorientation (according to the inclination and anteversion targets) do not necessarily show instability[5,15]. It is thus important to evaluate both planes, as each has been shown to be of importance for function and stability after THA; having optimal cup orientation in one plane does not necessarily equate to that cup being optimally placed in the other. Cases that would have been perceived to have optimally placed cups according to the coronal-plane safe zone, but were not optimal in the sagittal plane, had lower PFA and lower cup anteversion than cups that were considered optimally placed in both planes. The lower PFA would indicate that a greater AI is necessary to achieve the target. Thus, in patients with lower PFA, the cup should be impacted with greater anteversion, which would also mean a greater AI and a higher likelihood to be within the target CSI.

The equations and nomograms provided allow surgeons to determine the optimal orientation within their desired range that satisfies all 3 parameters, to account for individual spinopelvic characteristics, and to potentially minimize the risk of dislocation after THA due to functional cup malorientation; however, further in vivo study is necessary. A standing CSI, which depends on PT and patient posture, between 205° and 245° is associated with a substantially reduced dislocation risk[11]. CSI is calculated as the sum of cup AI and hip flexion angle (CSI = AI + PFA), and the postoperative PFA is typically comparable with the preoperative value[4,8]. By determining the sagittal PFA preoperatively and assuming that this value is similar or only slightly larger postoperatively (by 3° on average), surgeons are able to determine the desired sagittal safe zone for cup AI preoperatively (maximum $AI_{standing} = 245° - PFA_{standing}$, and minimum $AI_{standing} = 205° - PFA_{standing}$)[11]. To achieve optimal sagittal cup orientation, surgeons need to know how AI values can be converted to the corresponding cup inclination and anteversion values, which is what this study provides.

This study had several limitations. First, it was a radiographic study, and we could therefore not determine the true risk of dislocation due to coronal or sagittal cup malpositioning. However, the aim of the present study was not to evaluate the effect of coronal or sagittal cup malpositioning on the risk of dislocation. Second, all assessments were performed with radiographs, instead of 3D axial imaging with computed tomographic (CT) scans. Although accuracy would have been superior with CT scans, their clinical applicability for postoperative assessment of THAs is limited. We thus elected to test and validate the use of the most common examination modalities used in clinical practice. Furthermore, the use of CT scans would have been associated with increased radiation risk.

In conclusion, this study provides a simple equation linking AI, inclination, and anteversion (tan[AI] = tan[RA]/cos[RI]) and validates its use in clinical practice through 3D modeling and in vivo assessments. Achieving optimal cup inclination and anteversion does not ensure optimal orientation in the sagittal plane. The equation and nomograms provided can be used to determine and visualize how the 2 planes used for evaluating cup orientation and the pertinent angles relate.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSOA/A653). ■

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