Comparison of Acetabular Measurements Between 2 Validated Software Programs Used in Hip Preservation Surgery

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Background: Validated software tools (Clinical Graphics [CG] and Hip^{2}Norm) permit measurement of the percentage of femoral head coverage (%FHC), which aids in morphological classification and prediction of outcome after hip preservation surgery.

Purpose: (1) To assess whether acetabular parameter measurements determined from 2 commonly used software systems are comparable. (2) To determine which parameters influence the correlation or differences between software outputs and measurements.

Study Design: Cohort study (diagnosis); Level of evidence, 2.

Methods: The study included 69 patients (90 hips) who underwent periacetabular osteotomy and had comprehensive preoperative imaging available. Lateral center-edge angle (LCEA), acetabular index (AI), and %FHC were determined using 3-dimensional computed tomography (CT) measurements by CG and Hip^{2}Norm software. Images of 18 pelvises were segmented to determine spinopelvic parameters and subtended acetabular angles. Between-group measurements were compared using correlation coefficients and Bland-Altman analyses. The difference in the outputs of the 2 programs was defined as delta (Δ). Radiographic parameters were tested to assess whether they were responsible for differences in %FHC between software programs.

Results: Strong correlations between LCEA ($\rho = 0.862$) and AI ($\rho = 0.825$) measurements were seen between the Hip^{2}Norm and CG programs. However, weak correlation was seen in the estimate of %FHC ($\rho = 0.358$), with the presence of a systematic error. Hip^{2}Norm consistently produced lower anterior, posterior, and total %FHC values than CG. The %FHC determined by CG, but not Hip^{2}Norm, correlated with acetabular subtended angles ($P < .05$). Pelvic tilt measured on CT did not correlate with pelvic tilt estimated by Hip^{2}Norm ($P = .56$), and ΔPelvicTilt strongly correlated with the difference in %FHC by the 2 software programs ($\rho = 0.63$; $P = .005$), pelvic incidence ($\rho = 0.73$; $P < .001$), and pelvic tilt ($\rho = -0.91$; $P < .001$) as per CT.

Conclusion: The correlation of %FHC between Hip^{2}Norm and CG was weak ($\rho = 0.358$). The difference in measurements of %FHC correlated with ΔPelvicTilt. The %FHC determined by CG strongly correlated with the segmented acetabular subtended angles and thus more likely reflected true values. Hip preservation surgeons should be aware of these measurement differences because %FHC is important in the diagnosis and prognosis of acetabular dysplasia.

Keywords: hip; acetabular dysplasia; femoral head coverage

Acetabular dysplasia[28] encompasses a wide spectrum of acetabular morphology, which can vary widely in orientation and shape.[18,19,33] The percentage of femoral head coverage (%FHC), defined as the percentage of the femoral head surface covered by the acetabulum, is of importance as portrayed by extremes such as dysplasia and coxa profunda with pincer-type femoroacetabular impingement.[38] The degree of FHC is associated with the natural history of hip dysplasia even though femoral version also plays a fundamental role.[3,42] Murphy et al[22] observed that the degree of undercoverage directly influenced hip function, whereas Wyles et al[45] showed that the degree of coverage influenced the rate of development of radiographic osteoarthritic changes. Moreover, a strong correlation exists between FHC and postoperative outcomes after hip preservation surgery for both dysplasia and femoroacetabular impingement.[1,6,11,43] Ibrahim et al[13,14] demonstrated that anterior femoral coverage influenced postoperative patient-reported outcomes in patients undergoing surgery for femoroacetabular impingement, and further reported that FHC correlated with patient-reported outcomes after periacetabular osteotomy.

The degree of acetabular dysplasia and coverage can be estimated by several radiographic parameters based on 2-dimensional (2D) assessments on radiographs,[36] such as

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the lateral center-edge angle (LCEA), acetabular index (AI), extrusion index,[36] anterior and posterior wall indices,[30] and femoral-epiphyseal acetabular roof index.[44] Validated software tools that use either projected 2D appearance (eg, Hip^{2}Norm; University of Bern, Switzerland)[4,14,36,39,40,46] or 3-dimensional (3D) image data (eg, Clinical Graphics [CG]; Zimmer Biomet)[2,8,9,15,20] have been developed to calculate %FHC and are widely used for diagnostic and research purposes. Use of these software tools has demonstrated a good correlation between LCEA and %FHC.[4,8,9,17,21,27] However, few data exist regarding whether these tools provide similar outputs for a given case.

The primary purpose of this study was to compare the outputs produced by 2 commonly used, validated, software tools that measure and quantify acetabular morphology. In doing so, we aimed to (1) determine whether the degree of coverage correlates with radiographic parameters, (2) assess the extent of agreement of %FHC between 2 validated measurement tools (a 2D tool and a 3D tool), and (3) test which anatomic factors influence the correlation or differences between the 2 measurement methods.

METHODS

Study Design

This was a retrospective radiologic study of a consecutive surgical cohort from an academic tertiary referral center. The study received institutional review board approval.

Cohort

The study included 353 consecutive patients with periacetabular osteotomies performed by a single surgeon (J.D.W.) at a single institution between January 2014 and September 2017. The indications for surgery were symptomatic hip dysplasia that had failed nonsurgical treatment with a center-edge angle of Wiberg <25° (LCEA), AI >10°, and a congruent hip joint.[5,16] Patients were considered for surgery if their Tönnis grade[41] was ≤1.

Exclusion criteria were previous pelvic or hip surgery or aspherical femoral head (2 patients) or inadequate preoperative computed tomography (CT) imaging (not including all of the pelvis from the iliac crest to the lesser trochanter) and/or plain radiographs (244 hips). A total of 19 hips included in the study were the nonoperated contralateral hip, having a radiographic diagnosis of hip dysplasia as described earlier but currently under active surveillance and consideration for a future periacetabular osteotomy (Figure 1).

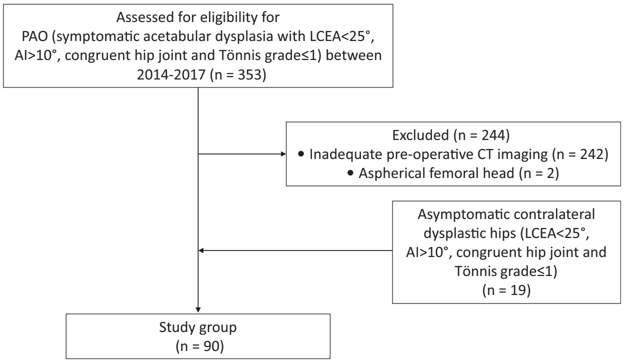

Figure 1. Flowchart of the hips in the study. Per the Clinical Graphics program, preoperative computed tomography (CT) imaging was considered adequate if it included the pelvis from the anterior-superior iliac spine to the lesser trochanter and had a maximum slice depth of 1 mm. AI, acetabular index; LCEA, lateral center-edge angle; PAO, periacetabular osteotomy.

Radiologic Assessments Performed

Two validated software tools that are commonly used in hip preservation surgery were included in this study: Hip^{2}Norm[46] and CG.[8]

Hip^{2}Norm. This software uses the shadow-casting method.[7] A supine anteroposterior pelvic radiograph is loaded into the program, and then several landmarks are interactively digitized, including the inferior margins of the teardrops as a horizontal reference, the anterior and posterior acetabular rim, the middle of the sacrococcygeal joint, and the upper border of the symphysis. In addition, the center and the radius of the femoral head and acetabulum are obtained by fitting a circle to 3 specific points drawn by the user. With the help of these landmarks, the center of the acetabulum can be determined, and all relevant acetabular parameters can be calculated without further manual definition or calculation of points. For the femur, 3 arbitrarily chosen points on the spherical part of the femoral head can be digitized.

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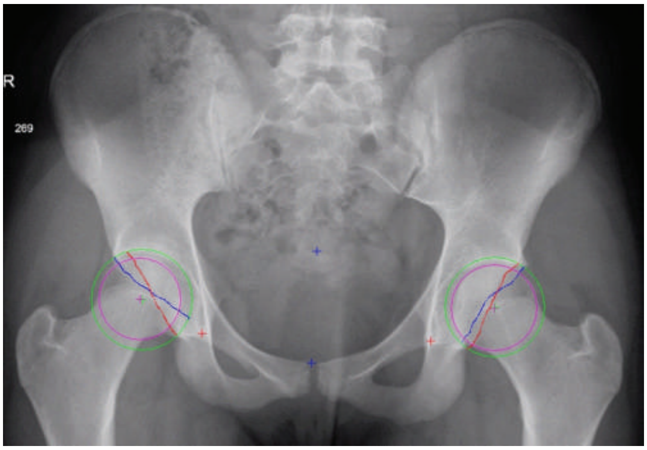

Figure 2. Illustration of Hip^{2}Norm. Red crosses represent the inferior margins of the teardrops as a horizontal reference. Blue crosses represent the middle of the sacrococcygeal joint and the upper border of the symphysis. The blue and red lines represent, respectively, the anterior and posterior wall of the acetabulum. The green and pink crosses represent, respectively, the center of the acetabulum and the femoral head. The green and pink circles represent, respectively, the radius of the acetabulum and the femoral head.

Thereafter, all of the radiographic landmark shadows are cast back toward the source of the beam to determine the relative position of the objects. Finally, a hip joint model is reconstructed from a simulated 2D craniocaudal image. The software projects the acetabular rim back to a neutral orientation, which is defined by 3 commutative rotations: pelvic tilt around the transverse axis, pelvic rotation around the longitudinal axis, and pelvic obliqueness around the sagittal axis.[37]

Errors in pelvic obliqueness are taken into consideration with the interteardrop line. Errors in pelvic rotation are estimated with the horizontal distance between the middle of the sacrococcygeal joint and the pelvic symphysis. A neutral, zero, pelvic tilt is defined with a pelvic inclination angle of 60° (the angle between a horizontal line and a line connecting the symphysis with the sacral promontory). If no additional lateral pelvic radiograph is available, the individual pelvic tilt is estimated with the vertical distance between the sacrococcygeal joint and the middle of the symphysis and is then related to mean values based on a normal population (31.5 mm for men and 47 mm for women).[29]

The output of the software includes LCEA, AI, anterior center-edge angle, acetabulum center margin angle, anterior wall index, posterior wall index, and the percentages of anterior, posterior, and total FHC (%AFHC, %PFHC, and %FHC, respectively). Measurements of all cases were performed by 2 observers: a hip preservation fellow (D.F.) and an orthopaedic resident (F.H.) with wide experience using this software (Figure 2).

Clinical Graphics. In the CG program, only adequate CT scans were used, defined by inclusion of the pelvis from the anterior-superior iliac spine to the lesser trochanter and a maximum slice depth of 1 mm. Thereafter, a 3D reconstruction of the pelvis was rotated in the sagittal plane so that the anterior pelvic plane angle was zero (the anterior-superior iliac spine and pubic tubercles were in vertical alignment). The acetabular rim was then equated to a clockface, with 9-o'clock being the anterior acetabular margin at the level of the midpoint between the superior and inferior extent of the acetabulum. The LCEA was then obtained at 3 different positions, 11-, 12-, and 1-o'clock, whereas AI was obtained at the 12-o'clock reference point. In this study we used only the 12-o'clock LCEA.

To calculate %FHC, points were plotted along the acetabular rim, and a sphere of best fit was applied to the femoral head so that the femoral head center could be plotted. A craniocaudal projection was then generated such that the points of the acetabular margin were superimposed upon a circle depicting the femoral head formed by an upward projection of the femoral head from its equator. A topographical representation of the femoral head with the cover afforded by the superimposed acetabulum was generated, and FHC was presented as a percentage (Figure 3). Acetabular anteversion was determined by measuring the angle between the transverse axis and the acetabular axis as defined by Murray.[23]

Pelvic Segmentation

By segmenting the CT images of 18 patients' pelvises (18 hips; 20%), we were able to determine all of their acetabular and spinopelvic parameters (pelvic tilt, sacral slope, anterior pelvic plane angle, pelvic incidence, and pelvic inclination as per Hip^{2}Norm) and the subtended angles around the acetabular clockface. The protocol used for image acquisition has been previously described,[31,32] as has determination of the acetabular and spinopelvic parameters.[12] Subtended angles were determined around the weightbearing surface of the acetabular clockface beginning at the anterior to superior to posterior locations: 15°, 45°, 75°, 105°, 135°, and 165°.[9,12] The reference 0° orientation was defined by the anterior pelvic plane. The subtended angle was defined as the 3D angle between the hip joint center axis and a line connecting the hip joint center to the rim points and interpolated to each of these locations. Subtended angles are established surrogate markers of acetabular volume and FHC (Figure 4).

Analysis

First, we analyzed the correlation between %FHC and several radiographic parameters (LCEA, AI, extrusion index, anterior center-edge angle, acetabulum center margin angle, anterior wall index, and posterior wall index) using the 2 software programs. Next, we measured LCEA, AI, %FHC, %PFHC, and %AFHC using the 2 software programs, which allowed us to analyze their correlation and mean difference (Hip^{2}Norm - CG). A Bland-Altman analysis was performed to compare the agreement of the %FHC measurements between the 2 software programs. After this, we analyzed the correlation between the Δ%FHC and the following radiographic parameters provided by

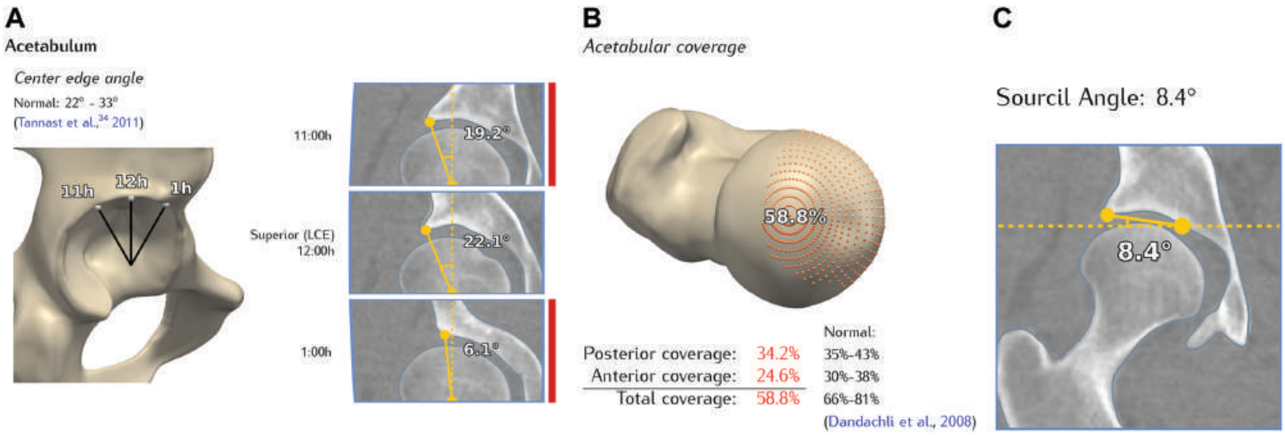

Figure 3. Illustration of clinical graphics: (A) lateral center-edge angle at 11-, 12-, and 1-o'clock (referred to as 12-o'clock in this article), (B) femoral head cover, and (C) acetabular index.

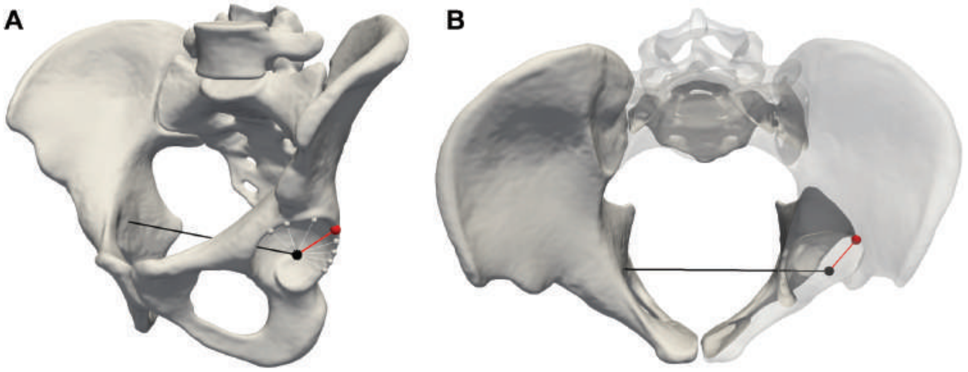

Figure 4. Calculation of the subtended angles from lines connecting the hip joint center and rim points. (A) Oblique lateral image, where the red line joins the hip joint center to the rim point and the black line joins the hip joint centers. The angle represents the subtended angle. (B) Oblique axial image, demonstrating the subtended angle as a nominal 2-dimensional angle.

Hip^{2}Norm (LCEA, AI, acetabulum center margin angle, anterior center-edge angle, sharp angle, extrusion and retroversion indexes) to find out where this difference originated, if present. Thereafter, using the CT pelvic segmentation method, we tested for correlation between the %FHC of each software program and the subtended angles. Finally, we measured the pelvic tilt as per Hip^{2}Norm calculations (ie, Measured Pelvic Tilt = 60° – Pelvic Inclination) and analyzed its correlation with the estimated pelvic tilt as measured by Hip^{2}Norm. The difference between measured and estimated pelvic tilt (ΔPelvicTilt) was tested for correlation with the pelvic tilt and pelvic incidence as measured on CT.

Statistical Analysis

Linear regression was used to determine correlation between measurements. The strength of the correlation was assessed with the Spearman rho (ρ) correlation coefficient, which was interpreted as follows: very weak if ρ = 0 to 0.19, weak if 0.20 to 0.39, moderate if 0.40 to 0.59, strong if 0.60 to 0.79, and very strong if 0.80 to 1.00.[25] Bland-Altman plots were used for correlation of %FHC between the 2 software programs to allow identification of any systematic difference between the measurements (ie, fixed bias) or possible outliers. The mean difference was the estimated bias, and the standard deviation of the difference indicated the random fluctuations around this mean. Statistical significance was set at $P < .05$. All analyses were performed using IBM SPSS (Statistical Product and Service Solutions) software for Windows (Version 27).

RESULTS

The study included 90 hips (17 male and 73 female) in 69 patients. The mean ± SD age for the group was 28.4 ± 7.6 years (range, 16-52 years).

Excellent inter- and intraobserver reliabilities were achieved for LCEA, 0.98 (intraclass correlation coefficient [ICC] 95%, 0.98-1) and 0.96 (ICC 95%, 0.94-0.98), respectively; AI, 0.94 (ICC 95%, 0.67-0.99) and 0.95 (ICC 95%,

TABLE 1

Correlation Analysis Between %FHC and Several Radiographic Parameters for the 2 Software Programs[a]

	%FHC as per Hip^{2}Norm		%FHC as per Clinical Graphics	
	ρ	*P* Value	ρ	*P* Value
Lateral center-edge angle	0.38	<.001	0.96	<.001
Acetabular index	−0.28	.007	−0.88	<.001
Anterior center-edge angle	0.31	.003	—	—
Acetabulum center margin	0.29	.006	—	—
Extrusion index	−0.43	<.001	—	—
Anterior wall index	0.26	.014	—	—
Posterior wall index	0.48	<.001	—	—

[a] %FHC, percentage of femoral head coverage. –, not applicable.

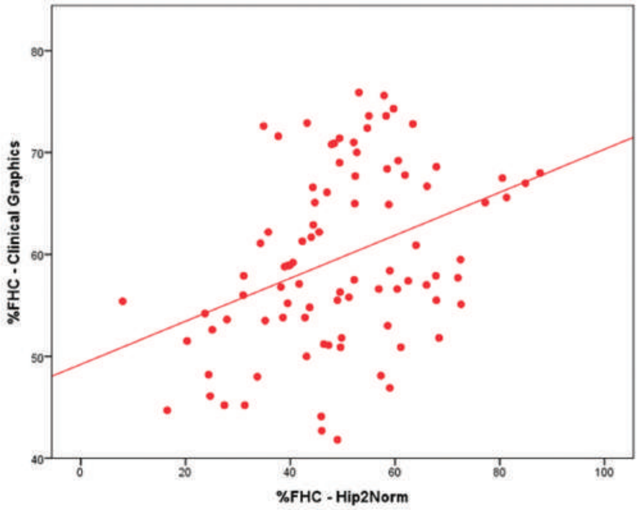

Figure 5. Scatterplot of the percentage of femoral head coverage (%FHC) measured by Hip^{2}Norm and Clinical Graphics.

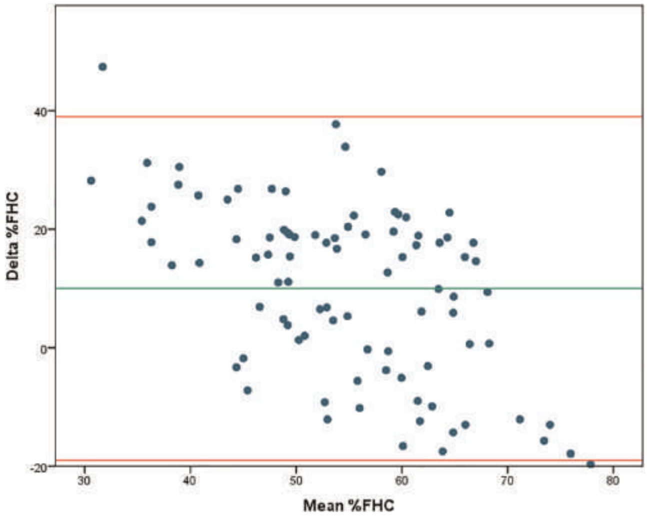

Figure 6. Bland-Altman analysis plot of difference in percentage of femoral head coverage (%FHC) between Hip^{2}Norm and Clinical Graphics.

0.93-0.97); and %FHC, 0.96 (ICC 95%, 0.79-0.99) and 0.97 (ICC 95%, 0.94-1).

Correlation Between Radiographic Parameters and %FHC

The correlations between %FHC and several radiographic parameters are detailed in Table 1.

Correlation Between Software Measurements

LCEA and AI. Hip^{2}Norm- and CG-derived LCEAs were 20.7° ± 12° (range, −5.5° to 50.4°) and 19.4° ± 10.3° (range, −2.8° to 38.8°), respectively, with a mean difference of 1.3° ± 5.8° (range, −18.7° to 15.7°) and a very strong correlation between Hip^{2}Norm and CG for LCEA (ρ = 0.862; *P* < .001). Hip^{2}Norm- and CG-derived AIs were 9.1° ± 8.8° (range, −10° to 31°) and 10.9° ± 9.8° (range, −7.1° to 32.9°), respectively, with a mean difference of −1.8° ± 5.2° (range, −20.6° to 13.2°) and a strong correlation between Hip^{2}Norm and CG for AI (ρ = 0.825; *P* < .001).

Femoral Head Coverage. Hip^{2}Norm- and CG-derived %FHC values were 49.5% ± 15.5% (range, 8% to 87.7%) and 59.7% ± 8.8% (range, 41.8% to 75.9%), respectively, with a mean difference of −10.1% ± 14.7% (range, −47.4% to 19.7%). There was a weak correlation between Hip^{2}Norm and CG for %FHC (ρ = 0.358) (Figure 5).

The Bland-Altman plot (Figure 6) comparing the measure of %FHC of the 2 methods exhibited a proportional bias of 10.1 and limits of agreement from −18.7 to 38.9%.

By further analyzing the %FHC, we determined that the difference stemmed from underestimation of both %AFHC (−6.6% ± 7.6%) and %PFHC (−5.3% ± 8.1%) with Hip^{2}Norm compared with CG (Table 2). The degree of %FHC underestimation, relative to CG, was proportionally greater for the %AFHC. Mean values, differences, and correlations between the 2 software programs are detailed in Table 2.

Segmentation Correlations

The %FHC determined by CG was significantly correlated with subtended angles at 45°, 75°, and 105°, whereas

TABLE 2
Mean Values, Differences, and Correlations of LCEA, AI, %FHC, %AFHC, and %PFHC of the 2 Software Programs[a]

	Hip^{2}Norm	CG	Mean Difference	Degree of Difference Relative to CG[b]	ρ	*P* Value (for ρ)
LCEA	20.7° ± 12°	19.4° ± 10.3°	1.3° ± 5.8°	6.7%	0.862	<.001
AI	9.1° ± 8.8°	10.9° ± 9.8°	−1.8° ± 5.2°	16.5%	0.825	<.001
%FHC	49.6% ± 15.5%	59.7% ± 8.8%	−10.1% ± 14.7%	16.9%	0.358	<.001
%AFHC	20.7% ± 9.7%	27.3% ± 5.7%	−6.6% ± 7.6%	24.2%	0.617	<.001
%PFHC	27.0% ± 8.7%	32.4% ± 4.1%	−5.3% ± 8.1%	16.3%	0.341	<.001

[a] AI, acetabular index; CG, Clinical Graphics; LCEA, lateral center-edge angle; %AFHC, percentage of anterior femoral head coverage; %FHC, percentage of total femoral head coverage; %PFHC, percentage of posterior femoral head coverage.

[b] Calculated as mean difference divided by mean CG value.

TABLE 3
Correlation of %FHC as Per Software and Subtended Angles Around the Acetabular Clockface[a]

	%FHC by Hip^{2}Norm		%FHC by Clinical Graphics	
SA	ρ	*P* Value	ρ	*P* Value
SA at 15°	0.055	.881	0.212	.556
SA at 45°	0.013	.958	0.536	**.022**
SA at 75°	−0.054	.850	0.625	**.013**
SA at 105°	−0.169	.516	0.498	**.042**
SA at 135°	−0.064	.808	0.471	.057
SA at 165°	−0.007	.980	0.493	.062

[a] Boldface *P* values indicate statistical significance. %FHC, percentage of femoral head coverage; SA, subtended angle.

%FHC determined by Hip^{2}Norm was not correlated with any subtended angles (Table 3).

There was no correlation between measured (6.1° ± 5.1) and estimated (9.6° ± 2.3) pelvic tilt (ρ = 0.14; *P* = .56), as evident in Figure 7.

We found a strong correlation between ΔPelvicTilt and the difference in %FHC (ρ = 0.63; *P* = .005) (Figure 8A) and pelvic incidence (ρ = 0.73; $P < .001$) (Figure 8B) and between ΔPelvicTilt and measured pelvic tilt (ρ = −0.91; $P < .001$) (Figure 8C). We noted a weak correlation between acetabular version at the equator measured with CG and the difference in %FHC (ρ = −0.24; *P* = .02).

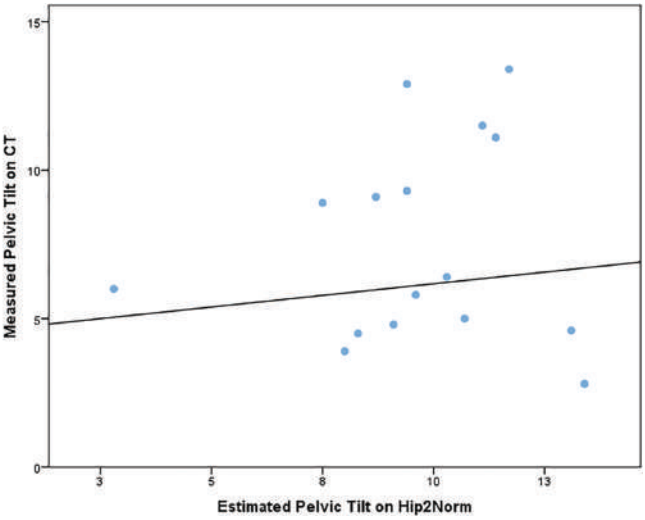

Figure 7. Scatterplot of the correlation of pelvic tilt as estimated by Hip^{2}Norm and measured on computed tomography (CT).

DISCUSSION

The main finding of our study is that there is a weak correlation in the measurement of FHC between Hip^{2}Norm and CG. The %FHC has been shown to be an important predictor for the development of osteoarthritis[22] and the outcome after hip preservation surgery.[13,14] Although %FHC has been associated with certain radiographic features (particularly LCEA), the absolute value cannot be directly determined from a single measurement, and different software programs[10,17,24,26,46] have been developed and described for its measurement. To date, however, agreement between the calculation of %FHC provided by different software programs has not been tested. By comparing the assessments of 90 hips, we were able to show that although excellent correlation in radiographic parameters exists between Hip^{2}Norm and CG, the agreement of %FHC was weak. This is important because the findings presented by different studies, especially those

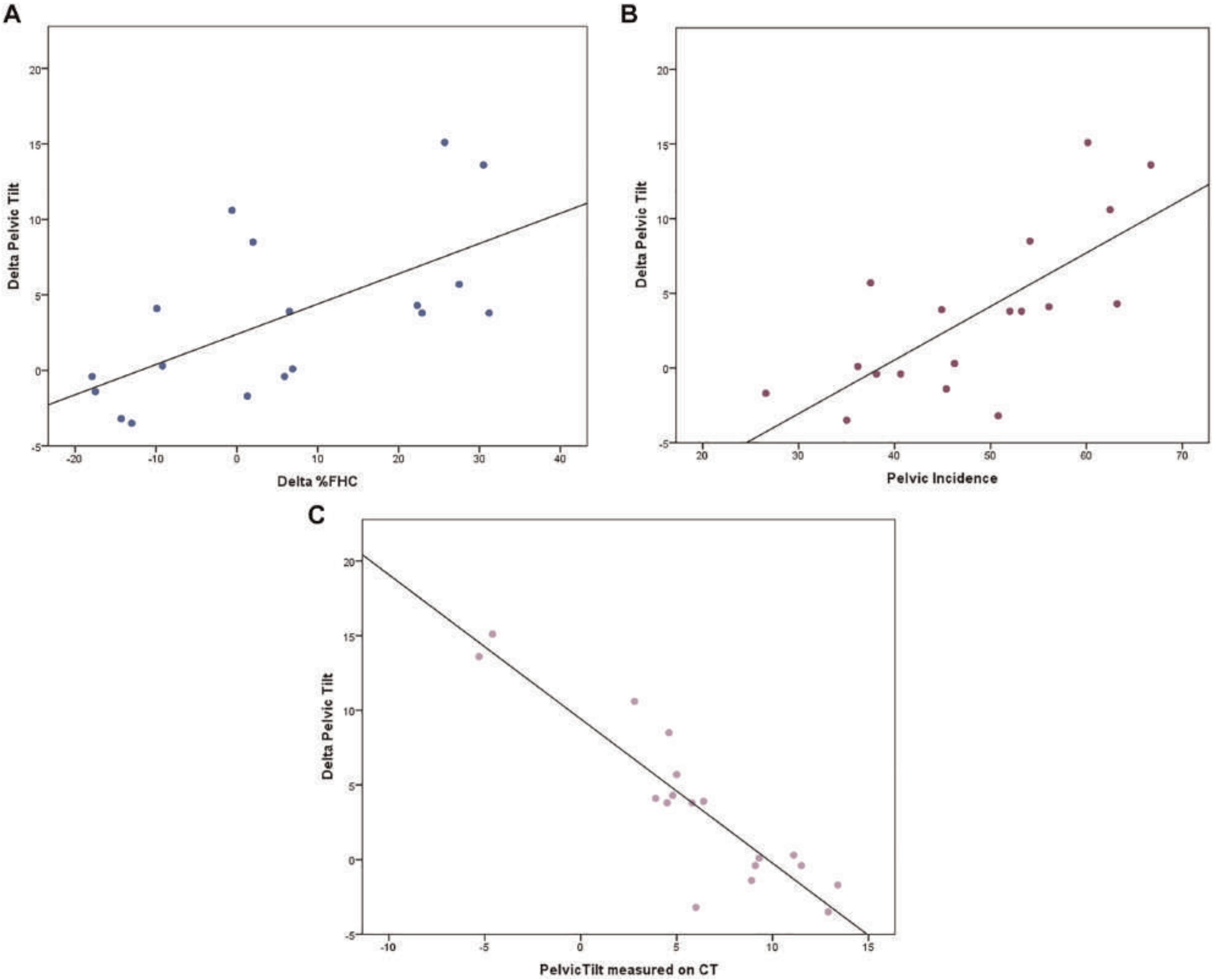

Figure 8. Scatterplot of the difference in pelvic tilt versus (A) the difference in percentage of femoral head coverage (%FHC) between Clinical Graphics and Hip^{2}Norm, (B) pelvic incidence, and (C) pelvic tilt as measured on computed tomography (CT).

describing thresholds, might not be directly interchangeable. The difference in %FHC was due to a difference in both %AFHC and %PFHC calculated by the 2 programs, although not proportionally. By analyzing in further detail 18 segmented pelvises, we were able to make important observations and identify parameters that contribute to this difference. The subtended angles measured had a strong correlation with %FHC as per CG but no correlation with %FHC as per Hip^{2}Norm. Furthermore, we found no agreement between the pelvic tilt angle estimated by Hip^{2}Norm and the pelvic tilt angle measured by CT. In fact, ΔPelvicTilt correlated with the difference in %FHC, illustrating its contribution in the differences. Given that Hip^{2}Norm corrects for pelvic tilt (in the absence of a lateral radiograph) in order to calculate %FHC, it is likely that this estimation, which can be erroneous given the varying pelvic incidence and actual pelvic tilt, leads to miscalculation of %FHC. However, in our study, no lateral radiograph was available for pelvic tilt assessment. It is likely that with these additional data, and therefore a different estimate of pelvic tilt, the results would have been different.

The first aim of this study was to analyze the correlation between %FHC and several radiographic parameters. Using the CT-based method, we observed a strong correlation between %FHC and both LCEA and AI, as previously reported. With the 2D-based method, a strong correlation was also observed with LCEA, AI, anterior center-edge angle, acetabulum center margin angle, extrusion index, and anterior and posterior wall indices. The strong correlation between 2D and 3D measurements of LCEA and AI provides evidence that both software tools are able to provide valuable information that can be measured relatively easily by the clinician. However, it appears that the calculation of %FHC showed weak correlation (ρ = 0.358), despite the strong correlation in LCEA (ρ = 0.862) and AI between these 2 software programs (*P* = .825). The proportional difference in %FHC points toward a systematic error

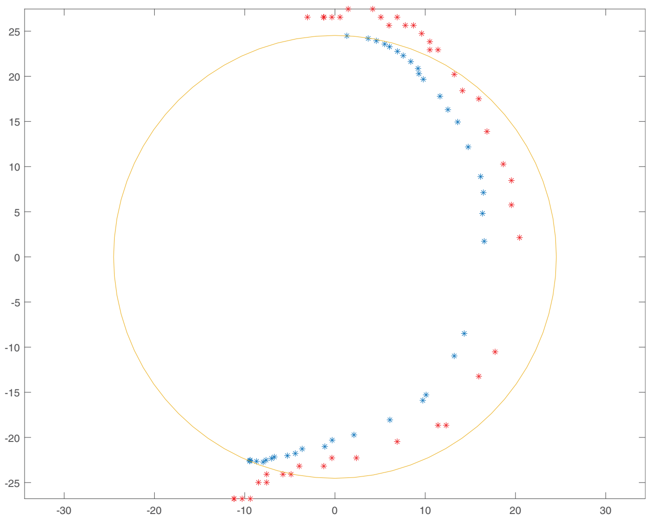

Figure 9. Two methods of calculating the percentage of femoral head coverage (%FHC) on a left hip (medial is on the left and anterior at the bottom): red dots are the actual rim projected onto the axial plane (Clinical Graphics method of %FHC calculation) and blue dots are projected toward the center of the femoral head and then flattened (Hip^{2}Norm method of %FHC calculation).

taking place in the calculations. To determine what contributes to this, we performed further analyses after segmenting 20% of the cohort.

When comparing the %FHC of the 2 programs with the subtended angles on CT measurements, we found an absence of correlation with the %FHC measured by Hip^{2}Norm, whereas the %FHC measured by CG was significantly correlated with 3 subtended angles. It would appear therefore that the calculation of coverage determined by CG is closer to the native acetabular anatomy. It thus appears that the assumptions used by Hip^{2}Norm to calculate pelvic tilt and define a neutral tilt led to a potentially erroneous calculation, which resulted in an error in the calculation of %FHC and particularly %PFHC.

Both software tools assume that the femoral head is spherical; thus, to minimize assessment bias, we excluded aspherical heads (without using a threshold to define it) from the study. Additionally, the 2 software programs use different methods to analyze pelvic tilt. If a lateral radiograph is available, Hip^{2}Norm defines a neutral pelvic tilt by an angle of 60° between a horizontal line and a line connecting the symphysis with the sacral promontory (named "pelvic inclination" by Hip^{2}Norm); without an available lateral pelvic radiograph, Hip^{2}Norm estimates pelvic tilt by the vertical distance between the sacrococcygeal joint and the middle of the symphysis, which is then related to mean values based on a normal population.[29] In contrast, CG defines a neutral pelvic tilt as a neutral anterior pelvic plane angle relative to the plane defined by CT (ie, horizontal). Because the method of defining neutral pelvic tilt was different between the 2 programs, we wanted to further analyze the calculation of pelvic tilt according to the method of Hip^{2}Norm. We found no agreement between measured (as per CT) and estimated pelvic tilt, with no correlation. In fact, the difference between measured and estimated pelvic tilt was dependent on an individual's pelvic incidence, which measures how anterior the hip is relative to the sacrum in the sagittal plane and pelvic tilt. Furthermore, the ΔPelvicTilt correlated with the difference in %FHC. Thus, the individual morphology and erroneous estimation of pelvic tilt would lead to the introduction of systematic bias in the calculation of %FHC measurement. Last, the 2 methods calculate the %FHC differently; in the CG method, the actual rim is projected onto the axial plane, whereas in the Hip^{2}Norm method, the rim is projected radially toward the center of the femoral head and then flattened. This difference in calculation method could also lead to numerical differences, as portrayed in Figure 9. Because Hip^{2}Norm evaluates a coronal projection and tries to fit a model to this, the accuracy can only be as good as the model. Any attempt to fit a 3D model to a 2D radiograph can have reasonable in-plane results, but more uncertain results out of the plane. The correlation between the difference in %FHC and acetabular version seems to support our hypothesis that %FHC is influenced by how each software program accounts for pelvic tilt, because %FHC is known to be strongly influenced by pelvic tilt.[9,35]

The comparison between 2D and 3D software was previously explored by Cheng et al.[4] Contrary to our study, those investigators reported a strong correlation of %FHC measurement between Hip^{2}Norm and a 3D software. Cheng et al measured %FHC with Hip^{2}Norm from digitally reconstructed radiographs with the anterior pelvic plane as a reference plane to control pelvic tilt. With this method, the pelvic tilt was the same for both software assessments. This difference in pelvic tilt management can explain the contradicting result with the present study.

The current study presents some limitations, the first being its retrospective nature. Further, we did not analyze demographic parameters such as height, weight, and body mass index on any of the correlations performed. Moreover, even though both programs automatically correct pelvic tilt and pelvic rotation, they still assume that the joint is spherical, which may not always be the case, especially for dysplastic hips. Although we excluded hips with grossly aspherical femoral heads, we did not quantify sphericity to define a threshold for inclusion. Finally, it is possible that the inclusion of dysplastic hips that had not undergone surgery led to selection bias.

CONCLUSION

A strong agreement in LCEA and AI was found between software programs used in hip preservation studies. However, the correlation of %FHC detected between Hip^{2}Norm and CG was weak ($\rho = 0.358$). Hip^{2}Norm consistently and proportionally underestimated both %AFHC and %PFHC. The difference in measurements of %FHC correlated with ΔPelvicTilt. Hip preservation surgeons should be aware of these measurement differences, given that %FHC is important in the diagnosis and prognosis of acetabular dysplasia.

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