A Quantitative Method to Assess Focal Acetabular Overcoverage Resulting From Pincer Deformity Using CT Data

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Abstract

Background Current assessment techniques for focal acetabular overcoverage are neither consistent nor quantitatively accurate.

Questions/purposes We propose: (1) a method to precisely quantify the amount of focal acetabular overcoverage in a patient's pincer deformity based on CT data; (2) to evaluate the consistency of this method; and (3) to compare the method with conventional radiographic assessments.

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Methods We developed a method to assess focal acetabular overcoverage using points selected from CT scans along the acetabular rim after realigning the pelvis into a neutral position. Using four resampled and segmented pelvic CT scans of cadaveric specimens with virtually induced impingement, two observers independently tested the algorithm's consistency. Our algorithm assessed the amount of focal acetabular overcoverage using CT data and projected data from reconstructed radiographs.

Results (1) We successfully showed the feasibility of the software to produce consistent, quantitative measurements. (2) Testing showed the average difference between observers in aligning the pelvis was 0.42° , indicative of a consistent approach. (3) Differences between measurements on three-dimensional (3-D) CT and simulated radiographs were significant.

Conclusions The proposed method represents a new avenue in consistently quantifying focal acetabular overcoverage using CT models while correcting for pelvic tilt and rotation. Our analysis confirms AP hip radiograph simulations overestimate the amount of overhanging acetabular rim in a pincer deformity.

Clinical Relevance This technique has potential to improve preoperative diagnostic accuracy and enhance surgical planning for correction of a pincer deformity resulting from focal acetabular overcoverage.

Introduction

Femoroacetabular impingement (FAI) initially presents with sharp hip pain during movement coupled with limited ROM and often with slow development of groin pain in young, active adults, ultimately leading to hip osteoarthritis [7, 10]. A subtype of FAI, pincer impingement, is an

acetabular abnormality in which there is abnormal contact of the femoral head-neck junction with the acetabular rim. Various anatomic abnormalities are associated with pincer FAI such as a deep acetabular socket [2, 7], a retroverted acetabulum, or increased anterolateral cover of the femoral head [2, 11]. This work focuses on assessing focal acetabular overcoverage, which causes anterior FAI.

Orthopaedic surgeons use AP radiographs (either hip or pelvis), clinical evaluation, and MRI in the diagnosis of FAI. A common radiographic finding related to focal acetabular overcoverage is referred to as the crossover sign (figure-of-eight) and exists when the lateral projection of the anterior wall crosses the posterior wall of the acetabular rim [11]. However, the degree of pelvic tilt and rotation changes the amount (or apparent existence) of crossover in patients, making it difficult to quantify on AP radiographs alone [9, 12, 17, 20, 22]. Moreover, the xray beam divergence in AP pelvis radiographs produces an overestimation of acetabular version by 4° [9]. Furthermore, defining the anterior and posterior rims on AP radiographs can be difficult [12]. Several methods [3, 17, 23] have been proposed to eliminate the effect of pelvic tilt on the appearance of the crossover sign. Dandachli et al. [4] showed the crossover sign has a high predictive value, although a low specificity, for depicting acetabular version when compared with 3-D CT data.

Recommended treatment of focal acetabular overcoverage generally involves surgically shaving bone from the acetabulum to restore impingement-free ROM [7, 10] for patients with sufficient posterior coverage. However, for patients with deficient posterior coverage, an acetabular reorientation procedure can help to correct both abnormalities [18]. The amount of bone requiring resection of an overhanging acetabular rim is difficult to quantify on radiographic projections. Inadequate resection will allow impingement to persist, whereas excessive resection can lead to biomechanical instability and even subluxation of the hip. Orthopaedic surgeons currently rely on their experience and subjective observations made from radiographs, clinical evaluation, and MRI to preoperatively estimate the amount of bone to resect. Siebenrock et al. [17] suggested a technique for preoperative analysis and planning that uses the ratio of the distance measured on an AP radiograph from the superolateral edge of the acetabulum to the point of crossover to the total diameter of the acetabulum. However, such measurements on plain radiographs are subject to projectional distortions and positioning variability. Dandachli et al. [4, 5] used CT data to analyze acetabular version and the validity of the crossover sign; however, to our knowledge, no algorithm has been reported to explicitly and accurately measure crossover from 3-D data and define the region of overhanging bone in a pincer-type deformity.

As a result of the difficulties in defining pelvic tilt and acetabular overcoverage, little is known about the natural history or overdiagnosis of pincer impingement. Consistent quantitative representation of overcoverage is missing, affecting treatment and patient comparison. The objectives of this study are to (1) introduce an approach that uses 3-D CT data to accurately assess the amount of focal acetabular overcoverage in a pincer deformity by quantifying the length and width of the overhanging region; (2) preliminarily evaluate the interobserver consistency of the approach; and (3) compare the method with conventional radiographic assessments.

Materials and Methods

We developed a method to assess acetabular overcoverage resulting from pincer deformity that relies on CT scans of the patient's hip region. From the scans, we segmented the acetabular lunate to define the anterior and posterior rims of the acetabular wall. We used the segmented acetabular wall and digitally reconstructed radiographs (DRRs) of the CT scans to place the pelvis in a neutral position and identify the amount of focal acetabular overcoverage.

To define the acetabulum lunate, we used the method of Armiger et al. [1]. In this method, a small cubic subvolume around the joint (72 mm per side) was created from the CT data and sampled circumferentially at 7.5°-intervals about the mediolateral axis of the hip. The lateral and medial edges of the acetabular rim were selected sequentially on each oblique slice; these points then were connected using a third-order polynomial spline to define a continuous outline of the acetabulum lunate. Interpolation over fixed intervals of the radius of curvature of the hip between the medial and lateral rims generated a triangular mesh representation of the acetabulum (Fig. 1). The manual segmentation was completed using software developed in MATLAB® (The MathWorks, Inc, Natick, MA, USA).

We defined the inclination of the pelvis according to the method of Tannast et al. [23]. For consistency, neutral position for each pelvis was defined at an angle of 60° between the sacral promontory and the pubic symphysis. This is a simple computation because we used the volumetric model of the pelvis to simulate radiographs from the lateral view, thereby observing the symphysis and promontory. The position of the pelvis also was corrected for rotation by minimizing the distances of the sacrococcygeal joint and pubic symphysis to the midsagittal plane.

A DRR is an xray imaging simulation based on volumetric data obtained from a CT study. The DRR paradigm uses line integrals of the intensity values through the volumetric data to construct an xray projection. This can be achieved through ray casting (eg, [6]), projecting tetrahedra

Fig. 1A–B Simulated xray projections of the computed crossover points for the same subject at (A) neutral pelvic tilt and (B) 22° of pelvic tilt are shown. The midacetabular axis is the cyan line connecting the superolateral point to the midpoint of the most inferior points on the anterior and posterior rims. The acetabular lunate is outlined in blue. The red crosses indicate the position of the superolateral point, crossover point, and the point of greatest width. The simulated projections are centered through the center of the femoral head and have been translated and magnified for improved observation

(eg, [13]), or several other means. Using specific parameters of focal length, detector dimensions, and field of view, DRRs sufficiently represent xray projections and have been used for numerous different procedures, including 2-D/3-D registration and radiotherapy [8, 13–15].

We used the method developed by Sadowsky et al. [13] to generate DRRs from the tetrahedral mesh. In this method, tetrahedra from the segmented pelvis volume acquired from CT data were projected onto the image plane, divided into fragments, and interpolated. Line integrals of the fragments are computed and summed, generating a geometrically correct perspective xray projection view. The DRRs were constructed with a focal length of 120 cm and a 30 cm × 30-cm detector plate. These parameters were chosen to most closely conform to the appearance of a standard AP hip radiograph with an emitter to film distance of 120 cm and the beam centered through the center of the femoral head.

Given the acetabulum lunate points as segmented from the CT data, the most superolateral point at the edge of the weightbearing zone was determined. Combining this point with the midpoint of the most inferior points on the anterior and posterior acetabular rims creates a line we termed the midacetabular axis (the cyan line in Fig. 1). Extending the midacetabular axis anteriorly and posteriorly creates a plane (the midacetabular plane). We defined crossover to occur when the anterior rim crossed the midacetabular plane. This does not exactly correspond with the previous definition of crossover, the point where the anterior wall crosses the posterior wall in a 2-D AP view, but this method was used to facilitate computational analysis and define crossover in 3-D from the CT scans.

Our technique identified intersections between the midacetabular plane and the acetabulum lunate. If more

than one intersection were present, the crossover point selected was the first (most superior) intersection along the midacetabular plane. (As noted in the Discussion, this can cause an identifiable mismeasurement.) The section between the crossover point and the superolateral point defined the portion of the posterior wall in crossover, which represented the true amount of focal acetabular overcoverage.

The points of the crossover section were used to automatically compute several 3-D measurements, including the acetabular length, crossover length, and crossover width (Fig. 2A). The triangular mesh of the acetabulum was separated into two pieces, the overhanging portion defined by the crossover section and the remainder. The surface area of the crossover section was the sum of the area of each triangular face in the overhanging bone.

To test our method, we obtained pelvis CT scans of four cadaver specimens (three males, aged 71, 90, and 93 years, and one female, aged 80 years) that included the pubic symphysis and sacral promontory. Only one specimen exhibited a positive radiographic crossover sign in the neutral (60° tilt) position. The scans were performed using an Aquilion 64 slice scanner (Toshiba, Tokyo, Japan) with 3-mm slice thickness and $0.6 \times 0.6\text{-mm}^2$ voxels. Using commercial image processing software (Amira®; Visage Imaging, Berlin, Germany), we converted the data to uniform slices of 1-mm thickness and segmented the pelvis to construct a volumetric model of a tetrahedral mesh.

Each pelvis was rotated through a series of varying tilt positions to virtually induce crossover and assess the effect of pelvic tilt on crossover. After placing the pelvis in a neutral tilt, the algorithm measured the crossover at 2°-intervals from -10° to 30° of tilt, giving 21 measurements per specimen and 84 measurements total to simulate

Fig. 2A–B The automated measurements made by the algorithm drawn in and labeled for **(A)** 3-D measurements made from CT data and **(B)** 2-D measurements made on the DRR (digitally reconstructed radiograph) are shown. The blue line in each figure is the segmented acetabular cup and the cyan line is the midacetabular axis. The distance between the superolateral point and the crossover point, as projected onto the coronal plane, defined the crossover length.

crossover anatomy. These 84 measurements are distinct and represent various crossover anatomies; only one measurement need be made per patient to define crossover at the neutral position. This simulation did not attempt to measure the same amount of crossover at each tilt iteration but simulated the crossover if a particular tilt angle was defined as the neutral axis.

When the algorithm identified crossover, the algorithm projected the crossover points onto a DRR of the pelvis at the particular tilt angle to generate the corresponding 2-D measurements (Fig. 2B). The projected points were accurately placed on the AP hip DRR, accounting for ‘camera’ effects, including magnification and distortion. Measurements similar to those in 3-D were made automatically; namely, we recorded the length and width of crossover and the length of the midacetabular axis (Fig. 1).

To test interobserver variability, two observers (RJM and TKS) independently examined the specimens. Each observer used the software to realign the pelvis and subsequently identify crossover. Both observers were familiar with the anatomic points described in this study, ie, the sacral promontory and pubic symphysis, to realign the pelvis into a neutral orientation.

Statistical analyses included performing paired t-tests to analyze the relationship between measuring mediums (CT and DRR) for the cases showing crossover. We used two sets of measurements to compare the imaging modalities: (1) the ratio between crossover length and acetabular length; and (2) the ratio between crossover width and acetabular length. The reported data use the average between the two observers’ measurements. To assess

The acetabular length is the length of the segment used to define the midacetabular axis. The crossover width is the maximum distance between the portion of acetabular rim in crossover and the midacetabular axis. The DRR is centered through the center of the femoral head. The images have been translated and magnified for improved observation. The definition of 3-D crossover here is a planar projection past the midacetabular axis

interobserver variability, we computed the intraclass correlation coefficient (ICC) between the observers. Additionally, we analyzed the relationship between pelvic tilt and the amount of crossover using Pearson’s correlation coefficient. We used crossover length and surface area as metrics for the amount of crossover. Again, these data were based on the average of the observers’ measurements. For our testing, we defined statistically significant differences to occur with a p value < 0.05. We used Microsoft Excel (Microsoft Corp, Redmond, WA, USA) and Matlab® (The MathWorks, Inc) to conduct the statistical analysis.

Results

Based on interobserver tests, our method produced consistent measurements of acetabular overcoverage with very strong agreement between observers (ICC = 0.98). The average difference in pelvic alignment was 0.42°. The difference between crossover length as computed on the CT images was 0.32 ± 3.7 mm with a median value of 0.25 mm and the difference between crossover width was 0.034 ± 1.4 mm. In the specimen exhibiting the largest difference (Subject 4) between observers, the initial pelvic alignment had a maximum difference of 1°, which exacerbated the differences between the observers, especially for simulated high pelvic tilt values (Table 1).

According to both observers, 54 of the 84 (64%) measurements exhibited crossover; that is, the anterior wall crossed the midacetabular axis. Differences between

Table 1. Height and width of crossover (in mm) measured by each observer on CT data

Tilt angle	Observer 1				Observer 2			
	Subject 1	Subject 2	Subject 3	Subject 4	Subject 1	Subject 2	Subject 3	Subject 4
Height								
−10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
−8	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0
−6	0.0	0.0	0.0	2.3	0.0	0.0	0.0	1.2
−4	0.0	0.0	0.0	3.2	0.0	0.0	0.0	2.3
−2	0.0	0.0	0.0	4.2	0.0	0.0	0.0	3.3
0	0.0	0.0	0.0	5.2	0.0	1.6	0.0	4.3
2	0.0	4.9	0.0	6.3	0.0	5.8	0.0	5.4
4	0.0	7.0	5.2	7.4	0.0	7.8	5.1	6.5
6	0.0	9.0	9.9	8.5	0.0	9.7	4.1	7.6
8	0.0	10.6	12.0	9.8	0.0	11.8	12.0	8.7
10	0.0	13.0	14.0	11.1	0.0	14.0	14.0	10.0
12	0.0	15.5	15.8	12.4	0.0	16.4	15.8	11.2
14	0.0	17.9	17.6	13.9	0.0	19.0	17.6	12.6
16	0.0	20.8	19.4	15.5	0.0	22.1	19.3	14.0
18	0.0	24.1	21.2	17.2	0.0	26.1	21.0	15.6
20	0.0	29.1	22.9	19.2	0.0	54.0	22.7	17.3
22	8.9	54.9	24.6	21.6	0.3	55.6	24.4	19.2
24	15.0	56.3	26.3	25.3	13.2	56.8	26.0	21.5
26	19.0	57.3	27.9	43.9	17.5	57.7	27.6	24.7
28	22.6	58.1	29.6	43.8	21.2	58.4	29.2	43.8
30	26.2	58.6	31.4	43.8	24.8	59.0	30.8	43.7
Width								
−10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
−8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
−6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1
−4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2
−2	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.4
0	0.0	0.0	0.0	0.7	0.0	0.1	0.0	0.5
2	0.0	0.2	0.0	0.9	0.0	0.3	0.0	0.7
4	0.0	0.4	0.1	1.0	0.0	0.6	0.1	0.8
6	0.0	0.7	0.5	1.2	0.0	0.9	0.5	1.0
8	0.0	1.0	0.9	1.4	0.0	1.2	0.9	1.2
10	0.0	1.3	1.3	1.6	0.0	1.5	1.3	1.4
12	0.0	1.6	1.7	1.8	0.0	1.8	1.7	1.5
14	0.0	2.0	2.1	2.0	0.0	2.1	2.1	1.7
16	0.0	2.3	2.5	2.2	0.0	2.5	2.5	1.9
18	0.0	2.6	3.0	2.4	0.0	2.8	2.9	2.1
20	0.0	3.0	3.4	2.6	0.0	3.2	3.3	2.3
22	0.0	3.4	3.8	2.8	0.0	3.6	3.7	2.6
24	0.3	3.7	4.3	3.0	0.2	4.0	4.1	2.8
26	0.6	4.1	4.7	3.3	0.5	4.4	4.6	3.0
28	1.0	4.5	5.2	3.5	0.9	4.8	5.0	3.2
30	1.4	5.0	5.6	3.8	1.2	5.2	5.4	3.5

measurements on CT and DRR for the ratio of crossover length to acetabular length (Fig. 3A) were statistically significant ($\bar{x}_{CT} = 0.238$, $\bar{x}_{DRR} = 0.265$, $p < 0.001$). Additionally, the differences between measurements on CT and DRR for the ratio of crossover width to crossover length (Fig. 3B) also were statistically significant ($\bar{x}_{CT} = 0.0242$, $\bar{x}_{DRR} = 0.0270$, $p < 0.001$). Both ratios, as measured on DRR, were consistently larger than those computed through the CT data.

An increase in pelvic tilt was correlated with the true 3-D length and width of crossover as measured from the CT data; as pelvic tilt increased, so did the length and width of crossover. This matches with the crossover and pelvic tilt correlation in 2-D radiographs reported by Siebenrock et al. [17] (which also was reconfirmed by our study). Additionally, the total amount of overhanging acetabular rim, as measured by surface area, increased with the pelvic tilt iterations. For all of the four subjects,

Fig. 3A–B The observer-averaged difference between ratios measured on DRR (digitally reconstructed radiographs) and CT images for varying angles of pelvic tilt are shown. A positive difference indicates the DRR ratio was higher and indicates overdiagnosis of impingement, which was the case in each measurement. Less crossover (corresponding to lower tilt angles) generally corresponded to a smaller difference between DRR and CT measurements. The differences between DRR and CT measurements for the ratio of (A) crossover length to acetabular length and (B) crossover width to acetabular length are shown. The outlier values in (B) (Subject 2 at 0° tilt and Subject 3 at 4° and 6° tilt) are the result of an initial mismeasurement of crossover

Table 2. Correlation between observer-averaged crossover metrics and pelvis tilt angle

Subject number	Average number of crossover measurements	Correlation between pelvic tilt and crossover length	Correlation between pelvic tilt and surface area
1	5.0	0.94	0.97
2	15.5	0.95	0.92
3	14.0	0.99	0.99
4	19.5	0.90	0.87

the linear correlation between tilt angle (which redefines the neutral axis of the pelvis in our simulation) and crossover was strong and significant ($p < 0.001$) using crossover length and surface area as metrics (Table 2).

Discussion

We present a new method using CT data to assess the amount of overhanging bone resulting from focal acetabular overcoverage. We assessed the interobserver variability of this method and performed comparisons with the conventional, radiograph-based technique using 21 distinct amounts of crossover per cadaver for four cadaveric specimens. Through our analysis, we showed this method to be observer-independent. This method achieved significantly different results from radiographic analysis because this method does not have the projectional distortions of xrays. Additionally, a CT technique allows assignment of physical dimensions to the crossover segment for the first time. In the future, this method could be used preoperatively to quantify the amount of bone to resect to correct a pincer deformity with focal acetabular overcoverage with sufficient posterior coverage. However, that assessment will be for future clinical studies.

During our study, we did not perform experimental evaluation of our measurements or evaluate the effects of FAI and associated crossover with hip pain, osteoarthritis, or other detrimental conditions. The focus of this technique is measuring focal acetabular overcoverage; we did not assess the acetabular coverage relative to the femoral head, although it may be clinically relevant, or take into account flexibility of lumbosacral spines. For example, a young woman with good flexibility and increased pelvic tilt could be managed with physical therapy rather than rim resection. Our goal was not to define every exception to the rule, but rather to take previously published norms for pelvic tilt and use them to define a method to quantify the amount of pincer deformity. Pincer impingement also may present with deficient posterior coverage; we believe that a similar CT-based algorithm can assess the posterior coverage and,

Fig. 4 Mismeasurement of crossover length is shown. This can occur at the onset of crossover where the first crossover point is recorded as the first portion of the posterior wall that crosses the midacetabular axis (the cyan line). The true crossover point actually is more inferior; thus, the length measurement from the superolateral point to the crossover point is incorrect. Also, the definition of crossover here is the point where the posterior wall crosses the midacetabular axis, not where it crosses the anterior wall.

combined, these two would effectively assess pincer impingement.

We occasionally encountered difficulty with our methodology when analyzing pelvises with minimal, clinically insignificant crossover. Subjects 2 and 3 had small gaps between the initial crossover and subsequent crossover measurements (Fig. 3B). Rarely, more than one intersection with the midacetabular plane occurred. When this happened, the software took the point closest to the superolateral point, which often is acceptable. Nonetheless, a particular acetabular segmentation (or anatomy) can exhibit unexpected crossover at small angles as a result of curves along the posterior rim that create the impression of the crossover point being more superior than it actually is (Fig. 4). This artifact occurs only in the initial observance of crossover and, at this point, the crossover measured is minimal and clinically insignificant. Therefore, we do not anticipate this artifact to be problematic in cases with clinically significant pincer impingement.

Several prior studies have reported on the difficulty and variability of predicting FAI based on AP radiographs [9, 12, 17, 20, 22] and this CT computational method might potentially reduce those errors. Using our methodology, it is possible not only to correct pelvic alignment, but also to simply define the acetabular rim. Additionally, this method does not have projectional distortions resulting from xray resulting in overestimation of the amount of crossover.

This work reproduces the results of Siebenrock et al. [17] using 3-D CT data assessing how varying degrees of pelvis tilt affect the actual amount of the crossover sign. Our study differs from previous studies in that we use a different crossover metric and report measurements in physical dimensions using 3-D CT data rather than

a percentage of acetabular length. Tannast et al. [21] used CT data to validate an xray-based method to define coverage, but their technique only provides results in terms of percent cover. As such, their technique is unable to provide quantitative assessment of the actual amount of crossover. Other techniques do not provide accurate measurements of the length and width of crossover [3, 4, 23]. Our proposed technique provides consistent, quantitative measurement of the length and width of crossover, thereby defining the amount of overhanging acetabular rim.

The estimates of crossover using the DRR methodology, which simulates plain radiography, were consistently greater than those using CT in our study, highlighting the tendency of radiographic projection to overestimate the magnitude of deformity in this condition. Prior work has shown the xray beam divergence in AP radiographs of the pelvis to produce an overestimation of acetabular version by 4° [9]. However, our work also presents a case for overestimation in AP radiographs of the hip.

Based on the ICC, our method appears resistant to major differences between observers. The automaticity of this algorithm potentially explains the large SD between observers' measurements. Because the test algorithm steps by 2°, there occasionally exists a range of pelvic tilt over which the amount of crossover changes significantly. For example, in the fourth specimen, crossover jumps from half of the acetabular length to the entire acetabular length at approximately 26° of pelvic tilt. The difference in initial alignment specified by each observer can create an inflated difference in the crossover height measurement at a given tilt angle between the observers related to where the crossover actually is assessed. Over the entire set of measurements, there were only three of these outliers; each occurred at a pelvic tilt (of at least 20°) potentially modeling unrealistic crossover. Removing these outliers, the difference between observers becomes 0.46 ± 1.34 mm for length measurements of overcoverage. Because, in a clinical setting, this algorithm would only measure crossover at the neutral axis, this technique will be very consistent. Moreover, a power analysis shows that, for a SD of 1.34 mm and detectable difference of 1 mm, a power level of 0.8 requires a sample size of 59 (much smaller than our sample of 168).

Pelvic segmentation is an arduous, time-consuming process that generates a volumetric tetrahedral mesh. From this mesh, one can create DRRs defined in a known coordinate system to reduce the errors in presenting lateral and AP views. The presented methodology depends on these DRRs to define osseous landmarks and subsequently correct the pelvic orientation. The ability to identify the sacral promontory in a lateral view necessitates the need for a DRR. However, DRRs can be constructed through a process involving the summed attenuations of CT

slices [6, 16, 19]. Creating DRRs in this fashion removes the requirement for a tetrahedral mesh but reduces information from pelvic coordinate systems making it more difficult to correctly align the pelvis. Developing software that can use this DRR creation principle would be much quicker and more feasible for clinical applications because pelvic segmentation would not be required.

Treatment for pincer deformity is relatively new. To establish treatment norms, reliable definitions for the degree of deformity and reliable, reproducible targets for the degree of correction must be established. Radiographic parameters for normal morphologic features of the hip have long been established. The challenge comes in defining preoperatively how much acetabular bone should be removed to produce those radiographic parameters on the postoperative xray. We believe our method provides a valuable tool to accurately assign physical dimensions to the pincer deformity resulting from focal acetabular overcoverage while eliminating confounding factors of pelvic tilt, rotation, and radiographic projection. Future clinical investigations can further show the use of this method.

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References

1. Armiger RS, Armand M, Lepistö J, Minhas D, Tallroth K, Mears SC, Waites MD, Taylor RH. Evaluation of a computerized measurement technique for joint alignment before and during periacetabular osteotomy. *Comput Aided Surg*. 2007;12:215–224.
2. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. *J Bone Joint Surg Br*. 2005;87:1012–1018.
3. Clohisy JC, Carlisle JC, Beaulé PE, Kim YJ, Trousdale RT, Sierra RJ, Leunig M, Schoenecker PL, Millis MB. A systematic approach to the plain radiographic evaluation of the young adult hip. *J Bone Joint Surg Am*. 2008;90(suppl 4):47–66.
4. Dandachli W, Islam SU, Liu M, Richards R, Hall-Craggs M, Witt J. Three-dimensional CT analysis to determine acetabular retroversion and the implications for the management of femoroacetabular impingement. *J Bone Joint Surg Br*. 2009;91:1031–1036.
5. Dandachli W, Kannan V, Richards R, Shah Z, Hall-Craggs M, Witt J. Analysis of cover of the femoral head in normal and dysplastic hips: new CT-based technique. *J Bone Joint Surg Br*. 2008;90:1428–1434.
6. de Greef M, Crezee J, van Eijk JC, Pool R, Bel A. Accelerated ray tracing for radiotherapy dose calculations on a GPU. *Med Phys*. 2009;36:4095–4102.
7. Ganz R, Parvizi J, Beck M, Leunig M, Notzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. *Clin Orthop Relat Res*. 2003;417:112–120.
8. Goitein M, Abrams M, Rowell D, Pollari H, Wiles J. Multi-dimensional treatment planning: II. Beam's eye-view, back projection, and projection through CT sections. *Int J Radiat Oncol Biol Phys*. 1983;9:789–797.

9. Jamali AA, Mladenov K, Meyer DC, Martinez A, Beck M, Ganz R, Leunig M. Anteroposterior pelvic radiographs to assess acetabular retroversion: high validity of the 'crossover-sign.' *J Orthop Res.* 2007;25:758–765.
10. Philippon MJ, Stubbs AJ, Schenker ML, Maxwell RB, Ganz R, Leunig M. Arthroscopic management of femoroacetabular impingement: osteoplasty technique and literature review. *Am J Sports Med.* 2007;35:1571–1580.
11. Reynolds D, Lucas J, Klaue K. Retroversion of the acetabulum: a cause of hip pain. *J Bone Joint Surg Br.* 1999;81:281–288.
12. Richards PJ, Pattison JM, Belcher J, Decann RW, Anderson S, Wynn-Jones C. A new tilt on pelvic radiographs: a pilot study. *Skeletal Radiol.* 2009;38:113–122.
13. Sadowsky O, Cohen JD, Taylor RH. Projected tetrahedra revisited: a barycentric formulation applied to digital radiograph reconstruction using higher-order attenuation functions. *IEEE Trans Vis Comput Graph.* 2006;12:461–473.
14. Sherouse GW, Novins K, Chaney EL. Computation of digitally reconstructed radiographs for use in radiotherapy treatment design. *Int J Radiat Oncol Biol Phys.* 1990;18:651–658.
15. Shirley P, Tuchman A. A polygonal approximation to direct scalar volume rendering. *SIGGRAPH Comput Graph.* 1990;24:63–70.
16. Siddon RL. Fast calculation of the exact radiological path for a three-dimensional CT array. *Med Phys.* 1985;12:252–255.
17. Siebenrock KA, Kalbermatten DF, Ganz R. Effect of pelvic tilt on acetabular retroversion: a study of pelves from cadavers. *Clin Orthop Relat Res.* 2003;407:241–248.
18. Siebenrock KA, Schoeniger R, Ganz R. Anterior femoroacetabular impingement due to acetabular retroversion: treatment with periacetabular osteotomy. *J Bone Joint Surg Am.* 2003;85:278–286.
19. Spoerk J, Bergmann H, Wanschitz F, Dong S, Birkfellner W. Fast DRR splat rendering using common consumer graphics hardware. *Med Phys.* 2007;34:4302–4308.
20. Tannast M, Kubiak-Langer M, Langlotz F, Puls M, Murphy SB, Siebenrock KA. Noninvasive three-dimensional assessment of femoroacetabular impingement. *J Orthop Res.* 2007;25:122–131.
21. Tannast M, Mistry S, Steppacher SD, Reichenbach S, Langlotz F, Siebenrock KA, Zheng G. Radiographic analysis of femoroacetabular impingement with Hip2Norm: reliable and validated. *J Orthop Res.* 2008;9:1199–1205.
22. Tannast M, Murphy SB, Langlotz F, Anderson SE, Siebenrock KA. Estimation of pelvic tilt on anteroposterior X-rays: a comparison of six parameters. *Skeletal Radiol.* 2006;35:149–155.
23. Tannast M, Zheng G, Anderegg C, Burckhardt K, Langlotz F, Ganz R, Siebenrock KA. Tilt and rotation correction of acetabular version on pelvic radiographs. *Clin Orthop Relat Res.* 2005;438:182–190.