

Can the Acetabular Position be Derived from a Pelvic Frame of Reference?

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Abstract Acetabular center positioning has an effect on hip function. However, reported clinical and plain radiographic methods are inaccurate and unreliable for ascertaining acetabular implant location. In an exploratory study we asked whether the normal acetabular position can be derived from simple radiographically measurable pelvic dimensions. We analyzed computed tomographic scans of 37 normal hips using a pelvic frame of reference centered on the ipsilateral anterior-superior iliac spine. We defined the x-, y-, and z-coordinates of the hip center (C_x, C_y, C_z) as a percentage of the corresponding pelvic dimensions (D_x, D_y, D_z). C_x/D_x averaged 9%, C_y/D_y 34%, and C_z/D_z 37%. These ratios had narrow distributions with small confidence intervals. Interobserver agreement tests showed a mean intraclass correlation coefficient of 0.95. We observed gender differences in the ratios of as much as 4%, which correspond to differences of as much as 9 mm in the hip center position. The ratios provide a simple and reliable way of deriving the normal position of the hip center from the pelvic dimensions alone. This gives the surgeon a simple way of planning where the hip center should be and may be

particularly helpful in revision hip arthroplasty or in cases involving extensive osteophytes, dysplasia, or protrusio.

Introduction

Positioning of the acetabular center in the pelvis influences function of the hip. The joint contact forces about a reconstructed hip are greater when the hip center is located superiorly, laterally, and posteriorly compared with the original location [18]. Moreover, the force- and moment-generating capacities of the hip muscles are sensitive to the location of the hip center [2, 10–12]. A 2-cm superior displacement, for instance, decreases abduction force by 44% and moment by 49%, whereas a 2-cm medial displacement decreases adduction force by 26% and moment by 40% [10]. Anteroposterior (AP) displacement, which is invisible on AP radiographs, alters the moment-generating capacity of the flexors and extensors considerably [10]. Optimal placement of the acetabulum is also crucial to avoid impingement, accelerated wear, and loosening in a reconstructed hip [9, 22, 28].

One report suggests differences in the width of the true pelvis between males and females account for different joint contact forces in male and female joints [19]. Gender differences also exist in pelvic height, abductor force, and joint contact forces [15]. These difference may be related to the particular position of the acetabulum in the pelvis in males and females.

Unlike acetabular angular orientation, few studies describe accurate methods of defining the acetabular center position in three-dimensional (3-D) space [3, 14, 20]. Predictive methods involve localizing the center in relation to palpable bony landmarks with the position calculated using pelvic dimensions [1, 20, 26]. The pelvic dimensions

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used in these studies did not take into account the full extent of each dimension. Moreover, errors of as much as 23 mm were observed when applying these methods on dry cadaveric pelvis [26]. These noninvasive methods rely on accurate palpation of bony landmarks and the distance between them, which is frequently difficult to measure in the clinical setting.

The alternative functional method involves determination of the center of rotation by fitting a sphere to paths followed by a femur-fixed point as motion occurs about the hip [6, 21, 27]. These methods can be associated with substantial errors. Although functional methods result in hip center location errors less than 26 mm, much larger errors of as much as 70 mm result when data collected during commonly performed hip motions are used [24]. This appears related to inability to move the hip in certain planes, especially the sagittal plane [24].

Radiographic methods of defining the hip center traditionally have relied on 2-D plain radiography [13, 23, 25]. One such method used Koehler's line and a line joining the two teardrops on plain AP radiographs [13]. In another study, the intersection between Koehler's line and a line between the upper rims of the two obturator foramina was used as a reference point. The x- and y-coordinates of the hip center then were related to pelvic height [5]. Although these 2-D methods are good at gross positioning the hip center, they lack the accuracy needed for acetabular reconstruction because they are associated with projectional errors.

Given the need for an accurate and reproducible method of determining the optimal position of the hip center during hip reconstruction, we addressed the following questions: (1) Can the normal position of the acetabulum be derived from simple radiographically measured pelvic dimensions?; (2) Will the method relating the acetabular position to these pelvic dimensions be reliable?; and (3) Will there be gender differences in the relationship between the acetabular position and the pelvic dimensions?

Materials and Methods

We analyzed CT scans of 37 pelvis (19 female, 18 male). Twenty-nine of these scans were performed before this study to investigate unilateral hip pain in patients who had normal contralateral hips. The other eight scans were performed previously to postoperatively evaluate surgical fixation of unilateral acetabular fractures; the parts of the pelvis used for the analysis, including the studied hips, were normal. Given this was an exploratory study, we did not perform a power analysis for sample size. The patients had a mean age of 59 years (standard deviation, 20 years); and they had varying shapes, sizes, and ethnicity typical of

a large cosmopolitan city. A Siemens Sensation 64 scanner (Siemens Medical Solutions, Erlangen, Germany) was used to obtain the 1-mm slices. The protocol used covered an area from the top of the iliac wings proximally to just below the lesser trochanters distally with an average of 250 slices per scan.

To analyze the CT scans, we used computer software that was validated previously by correlation with dry bone measurements [7, 16]. We chose the anterior pelvic plane, defined by the two anterior-superior iliac spines (ASIS) and the pubic tubercles [8, 17], as the basis of the coordinate system with the origin set at the ipsilateral ASIS. The x-axis pointed horizontally from left to right, the y-axis vertically upward, and the z-axis posterior to anterior. The femoral head center represented the hip center and we measured its coordinates (C_x, C_y, C_z) (Figs. 1, 2).

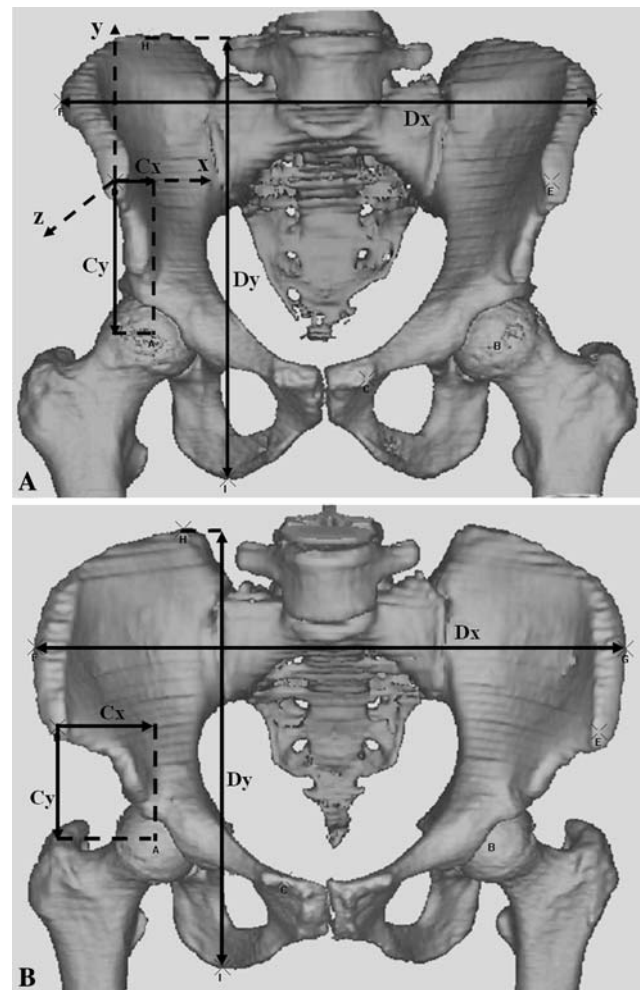


Fig. 1A–B Anteroposterior 3-D views show the x- and y-coordinates of the hip center (C_x, C_y) related to their corresponding horizontal (D_x) and vertical (D_y) dimensions of the pelvis for the right hip in (A) a male and (B) a female pelvis.

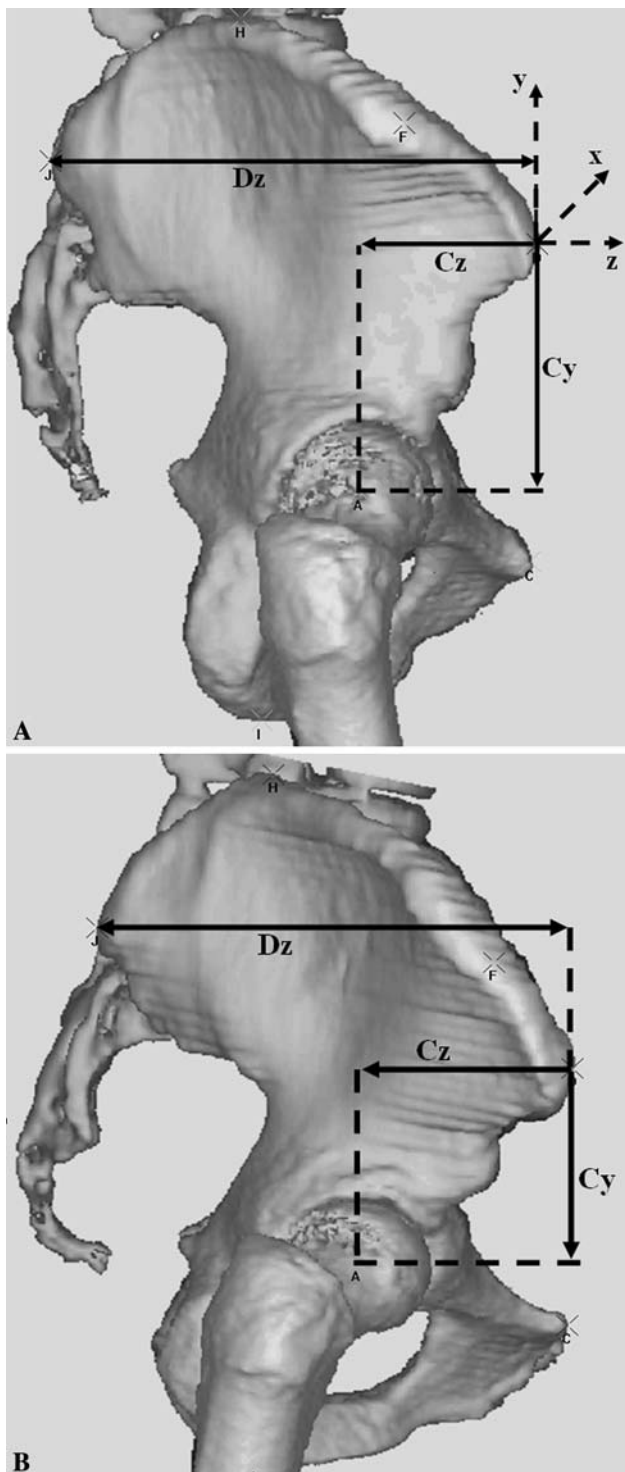


Fig. 2A–B Lateral 3-D views show the z-coordinate of the hip center (C_z) related to the AP dimension of the pelvis (D_z) for the right hip in (A) a male and (B) a female pelvis.

After aligning the pelvis with the anterior pelvic plane, we defined the pelvic horizontal dimension (D_x) as the distance between the most lateral points on the iliac crests, and its vertical dimension (D_y) was the distance between

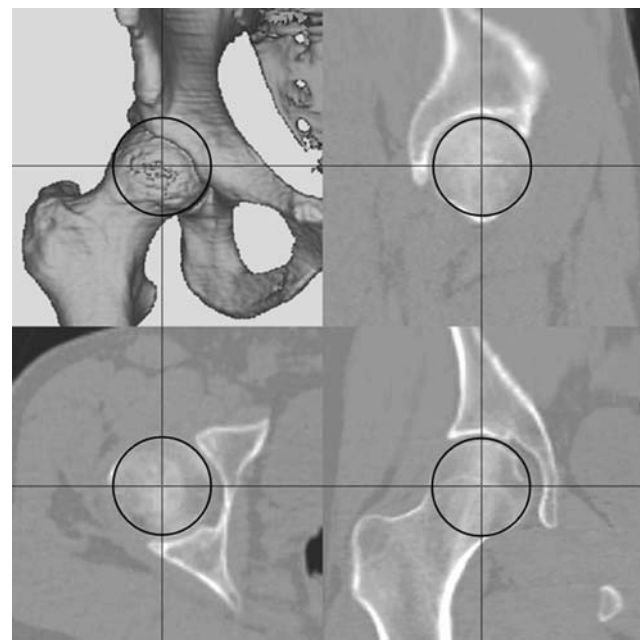


Fig. 3 The hip center is determined by using the coronal, sagittal, and axial views from the CT scan reconstruction.

the highest point on the iliac wing and the lowest point on the ischial tuberosity. The pelvic depth (D_z) was defined as the horizontal distance between the posterior-superior iliac spine and the ipsilateral ASIS (Figs. 1, 2).

We determined the hip center by using the three orthogonal slices from the CT scan (Fig. 3). Its x-, y-, and z-coordinates were measured in relation to the reference coordinate system described previously. We measured the ratios of these coordinates to their corresponding pelvic dimensions (C_x/D_x , C_y/D_y , C_z/D_z) and expressed them as percentages.

In addition to the main investigator (WD), another investigator (AN) independently repeated the landmark acquisition and the measurements for all the scans to test the reliability of the method of determining the ratios. We assessed differences between the two observers using the intraclass correlation coefficients and plotting the Bland-Altman plots [4] for the individual ratios.

Confirmation of accuracy of the method was accomplished by digitizing the relevant landmarks on a rigidly clamped model pelvis using a Faro Titanium Arm (Faro Technologies, Lake Mary, FL). The hip center coordinates and the pelvic dimensions then were compared with those obtained from a CT scan of the model pelvis using the method described above.

To check for gender differences in C_x/D_x , C_y/D_y and C_z/D_z , we grouped the results according to gender. The investigators doing the measurements (WD, AN) had been blinded to the gender of the scans analyzed. Because the tests of normality showed normally distributed results for

both genders, and because the variances for the two groups were different, we used the Student's t-test assuming unequal variances to check for any differences between the genders.

Results

The CT method appeared valid: its accuracy and precision were good. The accuracy on the model pelvis was comparable to that obtained using the Faro digitizing arm, with the differences being within 1 mm. The precision, as tested by differences between measurements made by different observers (interobserver agreement), also was good (see below).

The normal 3-D position of the acetabulum could be derived from simple radiographically measured pelvic dimensions. We found the x-, y- and z-coordinates of the hip center (C_x , C_y , C_z) are related to their corresponding pelvic dimensions (D_x , D_y , D_z). If the pelvic dimensions are known, then the ratios C_x/D_x , C_y/D_y , and C_z/D_z can be used to derive the normal C_x , C_y and C_z . The mean C_x/D_x was 8.8%, the mean C_y/D_y was 33.8%, and the mean C_z/D_z was 37.3%. The distributions of these ratios were narrow and the confidence intervals were small (Table 1; Fig. 4).

The method by which the ratios were obtained was reliable. This was evident by the high intraclass correlation coefficients (0.98 for C_x/D_x , 0.94 for C_y/D_y and 0.96 for C_z/D_z) and the Bland-Altman plots (Table 2; Fig. 5). The mean differences between the observers' results were 0.1% (SD = 0.8) for C_x/D_x , 1.5% (SD = 1.9) for C_y/D_y , and 0.5% (SD = 1.6) for C_z/D_z .

We observed gender differences in the relationship between the acetabular position and the pelvic dimensions for all three ratios C_x/D_x , C_y/D_y , and C_z/D_z (Fig. 6). C_x/D_x was greater ($p = 0.04$) in males (9.9% versus 7.7%), C_y/D_y was greater ($p = 0.002$) in females (35.5% versus 31.7%),

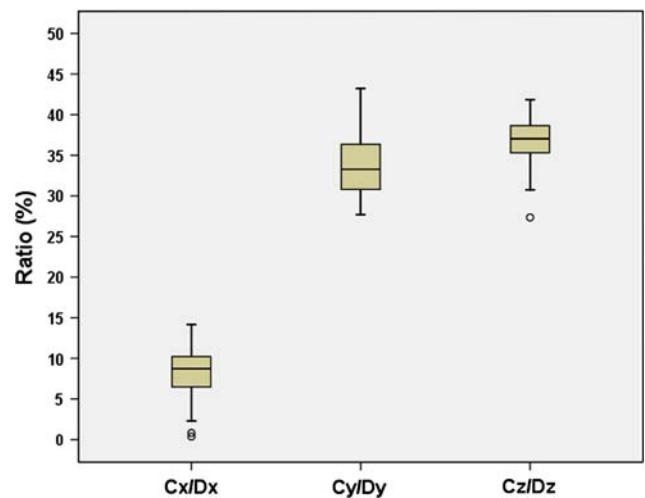


Fig. 4 The chart shows the distributions of the ratios C_x/D_x , C_y/D_y , and C_z/D_z .

and C_z/D_z was greater ($p = 0.03$) in males (38.5% versus 36.1%).

Discussion

The position of the hip center is crucial for optimal functioning of the hip musculature [2, 10–12], for reducing joint contact forces [18], and for avoiding accelerated wear, impingement, and loosening [9, 22, 28]. Its accurate determination is a major variable over which the surgeon has some control in reconstructive surgery around the hip. We therefore asked three questions: (1) Can the normal position of the acetabulum be derived from simple radiographically measured pelvic dimensions?; (2) Will the method relating the acetabular position to these pelvic dimensions be reliable?; and (3) Will there be gender differences in the relationship between the acetabular position and the pelvic dimensions?

The major limitation of this study was size: we had only 37 hips. This sample was the basis for answering our primary research question. Ideally, a larger sample of normal hips would allow more detailed analysis. Subgroups that are age- and gender-matched then could be compared with greater statistical power. We had hips from only 19 females and 18 males to answer a secondary question regarding gender differences. For an α of 0.05, the power β was 0.50. The error in the measurement software used depended on the scans' resolution and the presence of artifacts. The scans were 1 mm thick, with an average of 250 slices per scan. Nevertheless, the computer software was confirmed previously on dry bones using similar scanning protocols [7, 16]. We used an indirect measure, namely interobserver agreement, to test the reliability of the method used for

Table 1. Descriptive statistics for ratios of hip center coordinates and pelvic dimensions

Statistic	Ratio (%)		
	C_x/D_x	C_y/D_y	C_z/D_z
Mean	8.8	33.8	37.3
SD	3.4	3.7	3.3
Minimum	0.4	27.7	27.4
Maximum	14.2	43.2	45.4
Range	13.8	15.5	18.0
95% CI	± 1.1	± 1.4	± 1.1

C_x , C_y , $C_z = x$ -, y - and z -coordinates of the hip center; D_x , D_y , $D_z = x$ -, y - and z -dimensions of the pelvis; SD = standard deviation; CI = confidence interval.

Table 2. Reliability results showing intraclass correlation coefficients for C_x/D_x , C_y/D_y and C_z/D_z

Ratio	Intraclass correlation coefficient
C_x/D_x	0.98
C_y/D_y	0.94
C_z/D_z	0.96

$C_x, C_y, C_z = x-, y-$ and $z-$ coordinates of the hip center; $D_x, D_y, D_z = x-, y-$ and $z-$ dimensions of the pelvis.

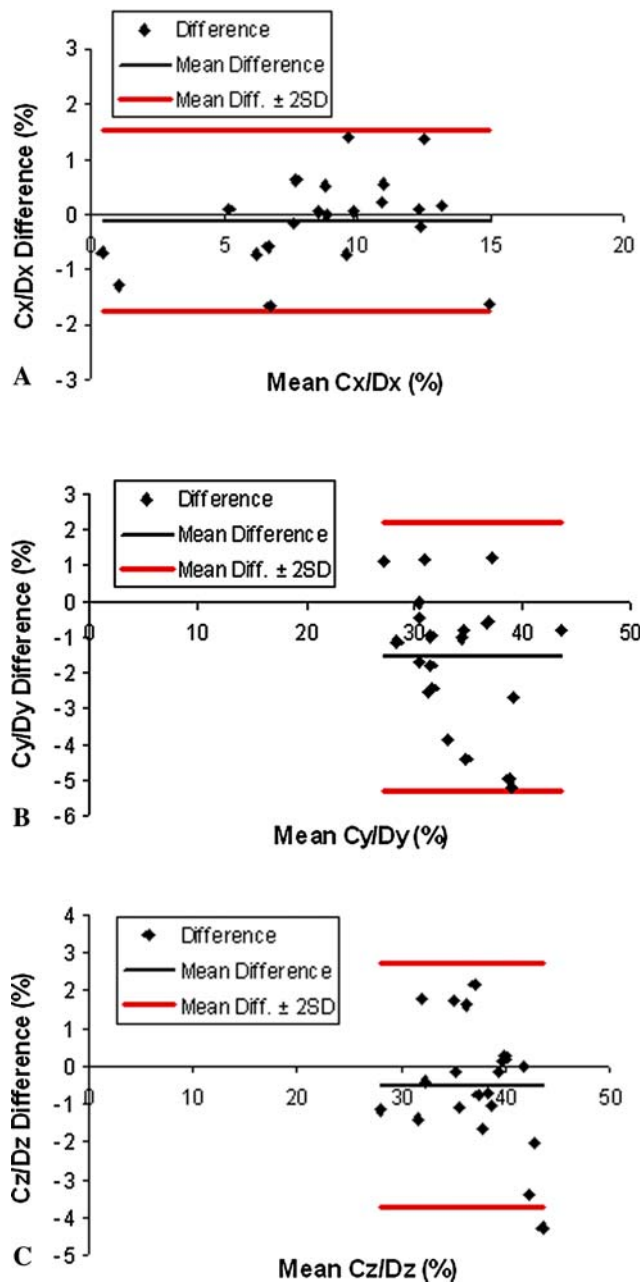


Fig. 5 A–C Bland-Altman plots for (A) C_x/D_x , (B) C_y/D_y , and (C) C_z/D_z show the interobserver difference in the measurements as a function of the mean. Results within ± 2 standard deviations (SDs) suggest a reproducible method [4].

measuring the hip center’s coordinates and pelvic dimensions. The data showed good interobserver reliability. This can be seen by the high intraclass correlation coefficients for all the ratios. The Bland-Altman plots suggest almost 100% of the results were within ± 2 standard deviations (Fig. 5). The mean differences between the two observers’ measurements of C_x/D_x , C_y/D_y , and C_z/D_z were small: the mean differences were 0.1% (SD = 0.8) for C_x/D_x , 1.5% (SD = 1.9) for C_y/D_y , and 0.5% (SD = 1.6) for C_z/D_z . Another limitation of the study relates to the CT scans analyzed. The hips contralateral to the studied hips had either early hip disease or operatively fixed acetabular fractures. However, the studied hips and the parts of the pelvis used for measuring their dimensions were normal.

We found a fairly constant relationship among the $x-$ (horizontal), $y-$ (vertical), and $z-$ (AP) coordinates of the hip center and their corresponding pelvic dimensions. The ratios of these parameters give gender-specific values, which provide a way of deriving the normal 3-D position of a patient’s hip center from that individual patient’s pelvic dimensions. The ratios have potential applications for the practicing surgeon. They provide a simple way of deriving the 3-D position of the hip center from the patient’s pelvic anatomy. The surgeon can use standardized plain radiographs, or CT in complex cases, to measure the horizontal (D_x), vertical (D_y), and AP (D_z) dimensions (Figs. 1, 2) of the pelvis. These dimensions, together with the normal ratios reported in this study, then can be used to derive and

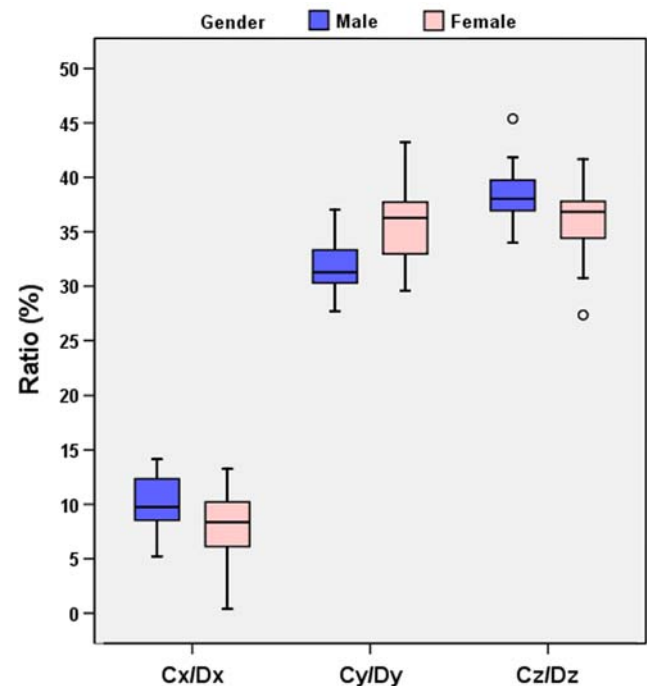


Fig. 6 The chart shows the gender differences in the ratios C_x/D_x , C_y/D_y , and C_z/D_z .

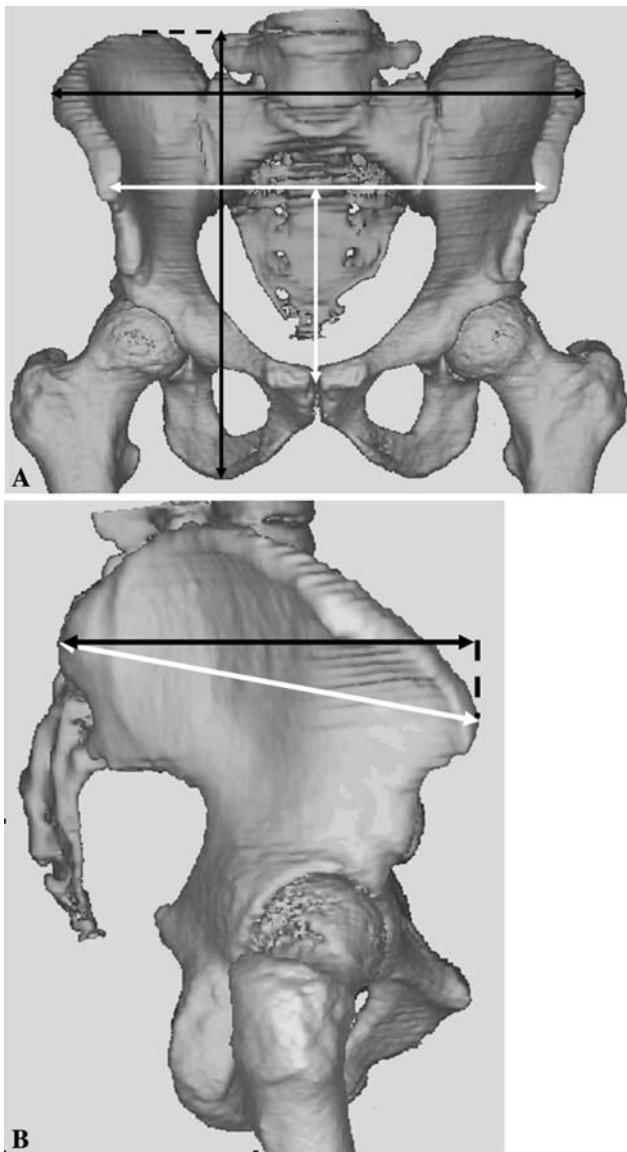


Fig. 7A–B (A) Anteroposterior and (B) lateral 3-D views of the pelvis show the difference in the definition of the horizontal, vertical, and AP dimensions of the pelvis, as defined by Seidel et al. [26] (white arrows) and by us (black arrows).

plan the optimal horizontal (C_x), vertical (C_y), and AP (C_z) position of the hip center in relation to the ASIS. With computer-assisted navigation, the derived values also can be achieved intraoperatively. It also is possible to

investigate a malfunctioning hip replacement by exposing and possibly blaming and addressing subtle malpositioning. This may be particularly useful when there are extensive osteophytes or in cases involving complex revision surgery, dysplasia, or protrusio.

There are two main studies in the literature relating the x-, y-, and z-coordinates of the hip center to pelvic dimensions [3, 26]. Both studies involved manual measurements on cadaveric pelvis with one relating the three coordinates to pelvic width only [3] and the other also relating them to their three corresponding pelvic dimensions [26]. It is difficult to make direct comparisons between our results and the results obtained in those studies because pelvic dimensions were defined differently (Fig. 7; Table 3). However, the data for the hip center coordinates alone suggest reasonable agreement (Table 4). Differences in the pelvic dimensions then can explain the differences in the ratios or scaled offsets. The difference in the x-coordinate (C_x) may be related to the way the hip center was identified. In the two published studies [3, 26], this was accomplished by manually estimating the center of the bony acetabular rim as opposed to 3-D CT measurement used in our study. Using the acetabular rim center as the hip center makes the assumption that the acetabulum is a hemisphere with a smooth rim.

The gender differences we observed in the ratios C_x/D_x , C_y/D_y , and C_z/D_z are in distinct contrast to the published studies [3, 26]. However, as has been discussed, we used the entire height and width of the pelvis, including the iliac blades and ischial tuberosities. This larger scale may have exposed the proportional differences between the genders.

One immediate application of our study relates to revision hip arthroplasty. An acetabular component that has been inserted high or migrated to a high position poses a particular problem for the surgeon. Currently no method exists to help the surgeon predict the correct height for the hip center nor establish whether it has been achieved. The additional help of a position in the x- and z-axes allows the revision to be planned with greater confidence. If height (y) and medial-lateral position (x) are considered important, then sufficient information for most cases will be available from a plain radiograph. An example is a male patient whose right hip replacement has an actual center (C_A) which is superior and medialized (Fig. 8). The actual

Table 3. Literature comparison of definitions of pelvic dimensions

Study	Pelvic width	Pelvic height	Pelvic depth
Seidel et al. [26]	Horizontal distance between ASISs	Perpendicular distance from pubic center to inter-ASIS line	Oblique distance between ASIS and PSIS
Current study	Horizontal distance between lateral edges of iliac wings	Vertical distance between top of iliac wing and bottom of ischial tuberosity	Direct horizontal distance between ASIS and PSIS

ASIS = anterior-superior iliac spine; PSIS = posterior-superior iliac spine.

Table 4. Literature comparison of means of the hip center coordinates, pelvic dimensions, and their ratios

Study	Hip center coordinate (mm)			Pelvic dimension (mm)			Ratio (%)		
	C_x	C_y	C_z	D_x	D_y	D_z	C_x/D_x	C_y/D_y	C_z/D_z
Seidel et al. [26]	34	71	57	238	90	164	14	79	34
Current study	24	72	55	275	214	147	9	34	37

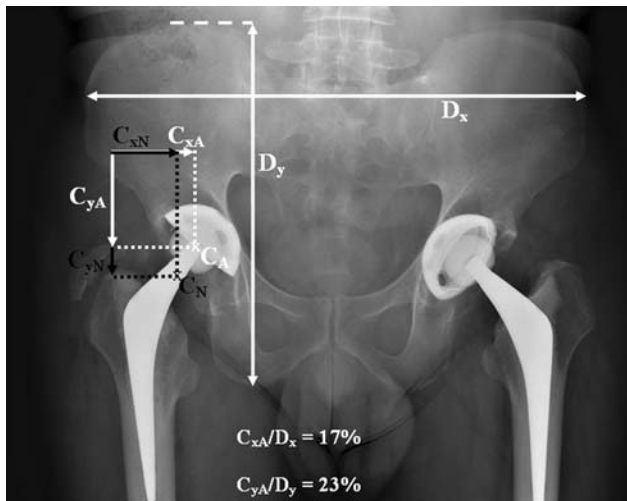


Fig. 8 An AP radiograph of the pelvis of a male patient shows a hip replacement with a superior and medialized hip center (C_A). The positions of the actual (C_A) and normal (C_N) hip centers are shown. The actual C_{xA}/D_x is high and the C_{yA}/D_y is low compared with the normal male C_x/D_x (9.9%) and C_y/D_y (31.7%). The latter were used to derive the normal position of the hip center (C_{xN} , C_{yN}). $C_x, C_y, C_z = x-, y-$ and z -coordinates of the hip center; $D_x, D_y, D_z = x-, y-$ and z -dimensions of the pelvis.

C_x/D_x is high (17%) and the actual C_y/D_y is low (23%) compared with that of a normal male C_x/D_x (9.9%) and C_y/D_y (31.7%). If this patient's pelvic width is 260 mm and his pelvic height is 220 mm, then the normal position of his hip center (C_N) can be planned using the normal male C_x/D_x and C_y/D_y as follows: the hip center's normal x -position (C_{xN}) is 26 mm ($[260 \times 9.9]/100$), and its normal y -position (C_{yN}) is 70 mm ($[220 \times 31.7]/100$) from the ASIS. We believe displacement of the hip center in the AP axis (z) may contribute to poor stability or function. Faced with a difficult revision, using this method to establish a normal hip center may be helpful to the surgeon.

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