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Does Acetabular Coverage Vary Between the Supine and Standing Positions in Patients with Hip Dysplasia?

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Abstract

Background Although variation in physiologic pelvic tilt may affect acetabular version and coverage, postural change in pelvic tilt in patients with hip dysplasia who are candidates for hip preservation surgery has not been well characterized, and its clinical importance is unknown.

Questions/purposes The aim of this study was to determine (1) postural changes in sagittal pelvic tilt between the supine and standing positions; (2) postural changes in the acetabular orientation and coverage of the femoral head between the supine and standing positions; and (3) patient demographic and morphologic factors associated with sagittal pelvic tilt.

Methods Between 2009 and 2016, 102 patients underwent pelvic osteotomy to treat hip dysplasia. All patients had supine and standing AP pelvic radiographs and pelvic CT images taken during their preoperative examination. Ninety-five patients with hip dysplasia (lateral center-edge angle < 20°) younger than 60 years old were included. Patients with advanced osteoarthritis, other hip disease, prior hip or spine surgery, femoral head deformity, or inadequate imaging were excluded. Sixty-five patients (64%) were eligible for participation in this retrospective study. Two board-certified orthopaedic surgeons (TT and MF) investigated sagittal pelvic tilt, spinopelvic parameters, and acetabular version and coverage using pelvic radiographs and CT images. Intra- and interobserver reliabilities, evaluated using the intraclass correlation coefficient (0.90 to 0.98, 0.93 to 0.99, and 0.87 to 0.96, respectively), were excellent. Demographic data (age, gender, and BMI) were collected by medical record review. Sagittal pelvic tilt was quantified as the angle formed by the anterior pelvic plane and a z-axis (anterior pelvic plane angle). Using a 2D-3D matching technique, we measured the change in sagittal pelvic tilt, acetabular version, and three-dimensional coverage between the supine and standing positions. We correlated sagittal pelvic tilt with demographic and CT measurement parameters using Pearson's or Spearman's correlation coefficients.

Results Although functional pelvic tilt varied widely among individuals, the pelvis of patients with hip dysplasia tilted posteriorly from the supine to the standing position (mean APP angle 8° ± 6° versus 2° ± 7°; mean difference -6°; 95% CI, -7° to -5°; range -17° to 4.1°; $p < 0.001$; paired t-test).The pelvis tilted more than 5° posteriorly from the

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Each author certifies that his institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.
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supine to the standing position in 39 patients (60%), and the change was greater than 10° in 12 (18%). In the latter subgroup of patients, the mean acetabular anteversion angle increased (22° ± 5° versus 27° ±5°; mean difference 5°; 95% CI, 4°-6°; p < 0.001) and the mean anterosuperior acetabular sector angle notably deceased from the supine to the standing position (91° ± 11° versus 77° ± 14°; mean difference -14°; 95% CI, -17° to -11°; p < 0.001; paired t-test). Postural change in pelvic tilt was not associated with any of the studied demographic or morphologic parameters, including patient age, gender, BMI, and acetabular version and coverage.

Conclusions On average, the pelvis tilted posteriorly from the supine to the standing position in patients with hip dysplasia, resulting in increased acetabular version and decreased anterosuperior acetabular coverage in the standing position. Thus, assessment with a supine AP pelvic radiograph may overlook changes in acetabular version and coverage in weightbearing positions. We recommend assessing postural change in sagittal pelvic tilt when diagnosing hip dysplasia and planning hip preservation surgery. Further studies are needed to determine how postural changes in sagittal pelvic tilt affect the biomechanical environment of the hip and the clinical results of acetabular reorientation osteotomy.

Level of Evidence Level IV, diagnostic study.

Introduction

Hip dysplasia is a common and can predispose patients to having osteoarthritis [14]. It is characterized by reduced acetabular coverage of the femoral head, shallow acetabular concavity, and joint instability [10, 29]. These deformities lead to abnormal distribution of stress on the articular cartilage, elevated joint contact pressure, and shearing stress on the anterosuperior acetabular rim complex, resulting in early hip joint degeneration [9, 16]. Reorientation osteotomies have been developed to manage such deformities to delay or prevent the development of osteoarthritis [13, 30]. The result of these osteotomies may be affected by various factors including insufficient correction, which could lead to an unfavorable patient outcome [15, 36]. Previous studies revealed substantial individual variety in acetabular version, deficiency type, and degree of acetabular dysplasia [10, 29]. Therefore, a three-dimensional (3-D) evaluation of acetabular deformities is helpful for customizing the correction procedure according to variation in the quantity and location of acetabular deficiencies [41].

Previous studies performed 3-D evaluations of the morphology of the hip using CT, with reference to standardized pelvic positions such as the anterior pelvic plane (APP) coordinate system to minimize measurement error [10, 20, 29]. However, given the individual and postural variation in physiologic pelvic tilt and its effect on acetabular orientation [17, 19, 33, 40], the reference position of the pelvis for morphologic analysis remains controversial. Additionally, for radiographic assessment, neutral pelvic positioning while planning periacetabular osteotomy has been recommended to avoid misinterpreting acetabular deformities [18, 34, 38].

Standardizing the pelvic position may be advantageous for anatomic and epidemiologic studies. However, recent studies suggested that radiographs taken in the supine position may not show the functional position of the acetabulum in relation to the femur, and a weightbearing radiograph may be more appropriate for assessing hip deformities [17, 33, 40]. An abnormal mechanical environment in dysplastic hips, such as shearing stress forces and overload on the anterosuperior acetabulum, becomes a problem when the patient's hip is in a weightbearing position rather than in the supine position. Therefore, we assume that characterizing the postural change in pelvic tilt and acetabular orientation may yield valuable functional information and help surgeons to diagnose hip conditions and plan for hip preservation surgery by improving acetabular reorientation and the biomechanical environment of the hip joint. Currently, little is known about postural change in pelvic tilt and its effect on acetabular orientation and 3-D coverage of the femoral head in patients with hip dysplasia who are candidates for hip preservation surgery.

The aim of this study was to determine (1) postural changes in sagittal pelvic tilt between the supine and standing positions; (2) postural changes in the acetabular orientation and coverage of the femoral head between the supine and standing positions; and (3) patient demographic and morphologic factors associated with sagittal pelvic tilt.

Patients and Methods

Patients

Our institutional review board approved this retrospective study. Between February 2009 and February 2016, 102 patients underwent pelvic osteotomy to treat hip dysplasia. During the study period, all patients had supine and standing AP pelvic radiographs and pelvic CT images taken during their preoperative examination. Two board-certified orthopaedic surgeons (TT and MF) retrospectively reviewed all pelvic radiographs and CT images. One of the observers (MF) was involved in the patients' care.

The inclusion criteria for this study were the presence of hip dysplasia, defined as a lateral center-edge angle [47] of less than 20° on AP pelvic radiographs, and age younger than 60 years (Fig. 1). Ninety-five patients met the

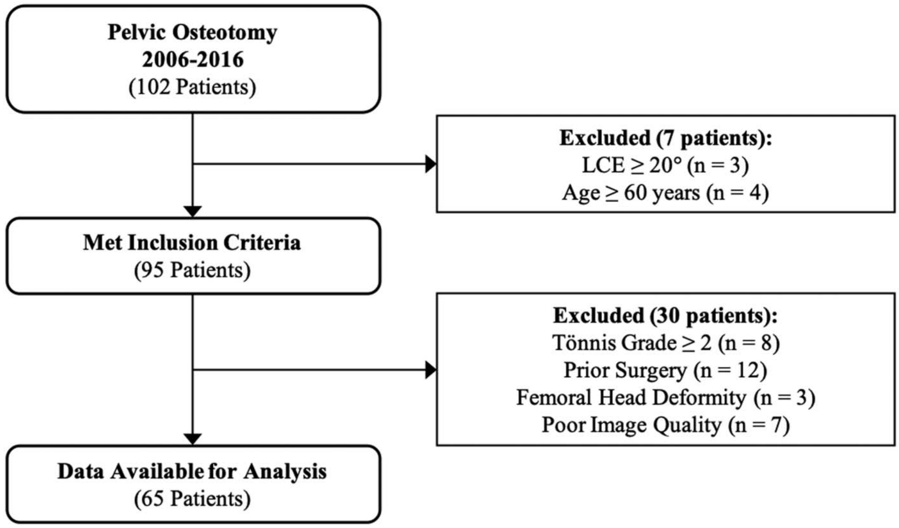

Fig. 1 A STROBE flow diagram of this study is shown. LCE = lateral center-edge angle.

inclusion criteria. The exclusion criteria were advanced osteoarthritis with a Tönnis grade of 2 or greater [39] in either hip, other hip disease, prior hip surgery of either hip, history of treatment of spinal disease, prior spinal surgery, morphologic abnormalities of the femoral head, or inadequate imaging. Eight patients who had hips with advanced osteoarthritis and 12 patients with prior hip or spinal surgery were excluded from this study. Three patients with a Legg-Calvé-Perthes disease-like deformity of the femoral head were also excluded. Seven patients were excluded because of poor-quality imaging.

According to the criteria, 65 of the 102 potential patients (64%) were eligible for participation in this study (Table 1). There were four men and 61 women, with a median age of 45 years (range 17 to 58 years). A morphologic evaluation was performed on the operated-on side (symptom-dominant side). There were 37 right hips and 28 left hips. Seventeen patients had unilateral hip dysplasia, 48 had bilateral hip dysplasia, and 20 had bilateral hip pain. The dysplasia of all hips was classified as Type I according to the classification system of Crowe et al. [5]. Medical records were retrospectively reviewed to collect demographic data including age, gender, and BMI (kg/m^2) at the time of examination.

CT Evaluations

Pelvic CT was performed with the patients in the supine position, and images were obtained from the superior rim to the distal femur at 1.0-mm intervals. After downloading data from these scans in Digital Imaging and Communications in Medicine format, we (TT and MF) performed the following measurements on the digitally reconstructed radiographs and multiplanar reconstruction images using image-processing software (3-D template; Kyocera Medical Corporation, Osaka, Japan). The x- and y-axes corresponded to the transverse and sagittal axes on the axial CT slice, and the z-axis corresponded to the longitudinal scanner axis. First, the pelvic position was standardized with reference to the APP coordinate system, defined by the bilateral anterosuperior iliac spines and the midpoint between the pelvic tubercles [25]. After matching the coordinate system of the APP with that of CT scanner, we re-created sagittal pelvic tilt on the pelvic radiographs in both the supine and standing positions on the coronal digitally reconstructed radiographs by matching the

Table 1. Patient demographic and radiographic data

Parameter	n = 65 patients (65 hips)
Age[a] (years)	45 (17-58)
Gender[b]	
Men	4 (6)
Women	61 (94)
BMI[a] (kg/m^2)	23 (17-34)
Laterality[b]	
Right hip	37 (57)
Left hip	28 (43)
Lateral center-edge angle[a] (°)	10 (-10 to 19)
Tönnis classification system[b]	
Grade 0	34 (52)
Grade 1	31 (48)

[a]Values are presented as the median (range);
[b]values are presented as a number (%).

vertical-to-horizontal ratio of the pelvic foramen (Fig. 2) [31, 37]. The following three pelvic positions were measured: the standardized position with reference to the APP, the supine position, and the standing position.

Sagittal pelvic tilt in the supine and standing positions was quantified as the angle formed by the APP and the z-axis on the sagittal digitally reconstructed radiographs (APP angle) (Fig. 3) [7]. A positive APP angle indicated anterior tilting of the pelvis and a negative angle indicated posterior tilting of the pelvis. The postural change in pelvic tilt between the supine and standing positions was calculated by subtracting the APP angle in the supine position from that in the standing position. A negative value indicated posterior change in pelvic tilt between the supine and standing positions.

The following spinopelvic parameters were measured (Fig. 3) [22]. The spinopelvic tilt was the angle formed by a line connecting the midpoint of the sacral plate and the midpoint of the centers of the femoral heads (pelvic axis) and the z-axis. The sacral slope was the angle formed by the cranial sacral endplate tangent and the y-axis. Pelvic incidence was quantified as the angle formed by a line perpendicular to the superior plate of the first sacral vertebra at its midpoint and the pelvic axis.

The lateral center-edge angle, Tönnis angle [39], and acetabular wall index [35] were measured on the coronal digitally reconstructed radiographs. The acetabular anteversion and inclination angles were quantified at the transverse section through the femoral head's center and at the coronal section through the femoral head's center, respectively [10] (Fig. 4). The cranial acetabular version angle was quantified at the transverse section 5-mm distal to the acetabular roof, and we defined a hip with a negative angle as having acetabular retroversion [18]. The acetabular sector angle was measured as an indicator of radial acetabular coverage of the femoral head in five directions: anterior, anterosuperior, superior, posterosuperior, and posterior (Fig. 5) [2, 11]. The anterior and posterior acetabular sector angles were used to classify hips into four deficiency types: anterior deficiency (anterior acetabular sector angle < 50°, posterior acetabular sector angle ≥ 90°), global deficiency (anterior acetabular sector angle < 50°, posterior acetabular sector angle < 90°), mild deficiency (anterior acetabular sector angle ≥ 50°, posterior acetabular sector angle ≥ 90°), and posterior deficiency (anterior acetabular sector angle ≥ 50°, posterior acetabular sector angle < 90°) [4].

Using the data described above, we determined changes in sagittal pelvic tilt and spinopelvic parameter values between the supine and standing positions, changes in the acetabular version and coverage between the supine and standing positions, and the correlation between the APP angle and postural change and between patient demographic factors (age, gender, BMI, bilaterality, and Tönnis grade) and CT measurement values (spinopelvic parameters, acetabular anteversion angle, acetabular inclination angle, and acetabular sector angle) measured with reference to the APP coordinate system.

Statistical Analysis

Two board-certified orthopaedic surgeons (TT and MF) took all measurements. To test intraobserver reliability, we repeated the measurements in a blind test on 20 randomly selected hips more than 2 weeks later. A simple sampling technique through computer-generated random numbering was used to select the hips. Intraobserver reliabilities, evaluated using an intraclass coefficient, were excellent for both observers (range, 0.90 to 0.98 and 0.93 to 0.99). To test

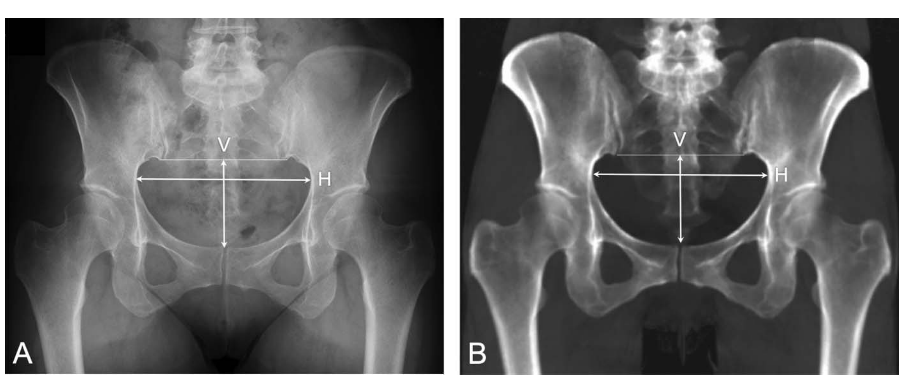

Fig. 2 **(A)** Our methods of matching sagittal pelvic tilt using radiographs and CT images are shown. On an AP pelvic radiograph, the vertical diameter of the pelvic foramen between the bilateral sacroiliac joint and pubic symphysis (V), divided by the maximum horizontal diameter of the pelvic foramen (H), was calculated. **(B)** On a digitally reconstructed radiograph generated from CT images, the pelvis was rotated sagittally until the ratio of the foramen (V/H) was consistent with that on the AP pelvic radiograph.

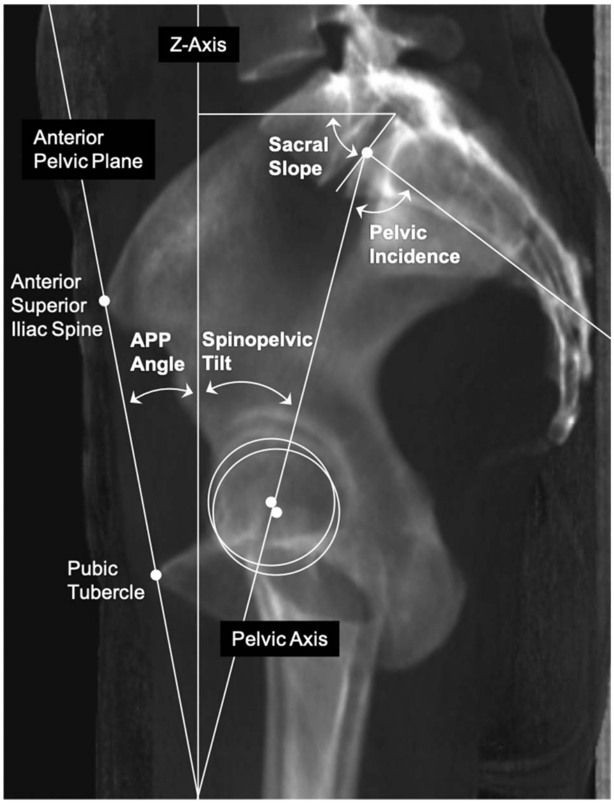

Fig. 3 Our methods of measuring sagittal pelvic tilt and spinopelvic parameters are shown. Sagittal pelvic tilt in the supine and standing positions was quantified as the angle formed by the APP and the z-axis (APP angle). The spinopelvic tilt was the angle formed by a line connecting the midpoint of the sacral plate and the midpoint of the centers of the femoral heads (pelvic axis) and the z-axis. The sacral slope was the angle formed by the cranial sacral endplate tangent and the y-axis. Pelvic incidence was quantified as the angle formed by a line perpendicular to the superior plate of the first sacral vertebra at its midpoint and the pelvic axis.

measurement reproducibility, two independent observers (TT and MF) performed measurements on 20 randomly selected hips in a blind test. Interobserver reliabilities evaluated using the intraclass correlation coefficient were excellent (range 0.87 to 0.96).

Paired t-tests or Wilcoxon signed-rank tests were used to compare continuous parameters for the supine and standing positions, depending on their distribution and homoscedasticity (Shapiro-Wilk's test and f-test). A chi-square test or Fisher's exact test was used to compare categorical parameters for the supine and standing positions, as appropriate. A t-test or Wilcoxon's rank sum test was used to compare the APP angles between two groups (men versus women, unilateral versus bilateral dysplasia, and Tönnis Grade 0 versus Grade 1), as appropriate. The significance level was set at $p < 0.05$ for all tests. Correlations of the APP angles with continuous parameters (age, BMI, and CT measurement parameters) were calculated using Pearson's correlation coefficients or Spearman's rank correlation coefficients, as appropriate. We characterized the correlation coefficient values as negligible (range 0.0 to 0.3), weak (range 0.3 to 0.5), moderate (range 0.5 to 0.7), good (range 0.7 to 0.9), or excellent (range 0.9 to 1.0). Statistical analyses were performed using JMP® Version 13.0 (SAS Institute Inc., Cary, NC, USA).

Results

Postural Change in Sagittal Pelvic Tilt

Although the APP angle in the supine and standing positions varied widely among individuals (Fig. 6), the pelvis of patients with hip dysplasia tilted posteriorly from the supine to the standing position (mean APP angle 8° ± 6° versus 2° ± 7°; mean difference -6°; 95% CI, -7° to -5°; $p < 0.001$) (Table 2). Larger APP angles in the supine position correlated with larger APP angles in the standing position ($r = 0.784$; $p < 0.001$). The change in the APP angle from the supine to the standing position ranged from -17° to 4°. Although the range of pelvic motion was less than 5° in 26 of the 65 patients in this study (40%), the APP angle changed by more than 5° posteriorly between the supine and standing positions in 39 patients (60%), and the posterior change was greater than 10° in 12 (18%) (Fig. 6). Spinopelvic tilt and sacral slope also changed between the supine and standing positions in a similar fashion as the APP angle, although the pelvic incidence was consistent (Table 2).

Postural Change in Acetabular Version and Coverage

Posterior change in pelvic tilt correlated with an increase in the acetabular anteversion angle ($r = -0.826$; $p < 0.001$), a decrease in the anterior acetabular sector angle ($r = 0.635$; $p < 0.001$) and anterosuperior acetabular sector angle ($r = 0.746$; $p < 0.001$), and an increase in the posterosuperior acetabular sector angle ($r = -0.357$; $p = 0.004$) and posterior acetabular sector angle ($r = -0.716$; $p < 0.001$) (Table 3). The acetabular anteversion angle was greater in the standing position than that in the supine position (23° ± 5° versus 21° ± 5°; mean difference 2°; 95% CI, 2° to 3°; $p < 0.001$), but the acetabular inclination angle did not differ between the two positions (Table 4). The prevalence of acetabular retroversion decreased from 23% in the supine position to 9% in the standing position (odds ratio, 0.339; 95% CI, 0.122 to 0.939; $p = 0.032$). Regarding acetabular coverage, the anterior, anterosuperior, and superior acetabular sector angles decreased, while the posterosuperior and posterior acetabular sector

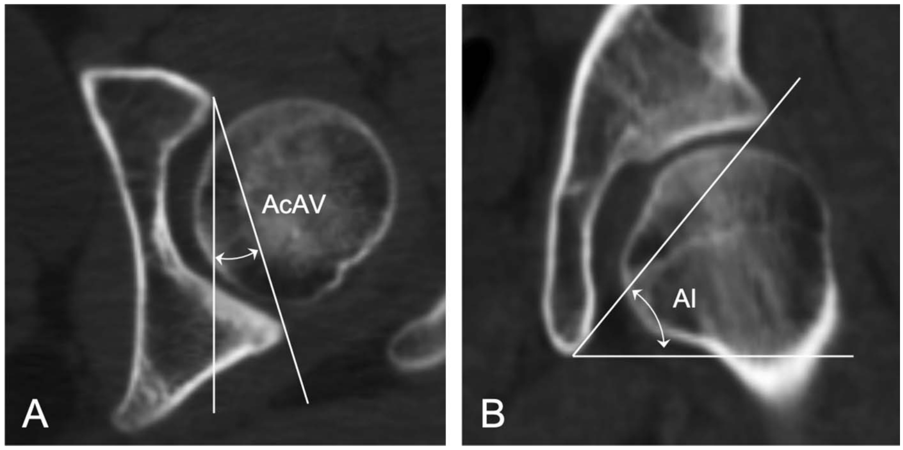

Fig. 4 **(A)** The acetabular anteversion angle was quantified as the angle formed by a line connecting the anterior and posterior edges of the acetabulum and the y-axis at the transverse section through the femoral head's center. **(B)** The acetabular inclination angle was quantified as the angle formed by a line connecting the superior and inferior edges of the acetabulum and the x-axis at the coronal section through the femoral head's center. AcAV = acetabular anteversion angle; AI = acetabular inclination.

angles increased from the supine to the standing position (Table 4). However, the overall magnitude of the observed differences was small, reflecting considerable variation in the range of pelvic motion among patients. The change in the acetabular sector angle was the largest in the anterosuperior direction (88° ± 9° in the supine position versus 83° ± 11° in the standing position; mean difference -6°; 95% CI, -7° to -4°; $p < 0.001$). The prevalence of anterior deficiency increased from 31% in the supine position to 60% in the standing position ($p = 0.005$). Regarding the radiographic parameters, the lateral center-edge angle and anterior wall index decreased, and the Tönnis angle and posterior wall index increased from the supine to the standing position (Table 4). These postural changes in acetabular version and coverage were noticeable in a subgroup of patients whose posterior change in the APP angle was greater than 10° (Table 5). In this subgroup of patients, the mean increase in the acetabular anteversion angle in the standing position was 5° (95% CI, 4° to 6°; $p < 0.001$). The change in the acetabular sector angle was the largest in the anterosuperior direction, with a mean value of -14° (95% CI, -17° to -11°; $p < 0.001$). The prevalence of anterior deficiency increased from 17% in the supine position to 75% in the standing position ($p = 0.033$).

Factors Associated with Sagittal Pelvic Tilt

The APP angle of patients with bilateral hip dysplasia was greater than that of patients with unilateral hip dysplasia in both the supine (9° ± 5° versus 4° ± 6°; mean difference 5°; 95% CI, 2° to 8°; $p < 0.001$) and standing positions (4° ± 7° versus -4° ± 6°; mean difference 7°; 95% CI, 4° to 11°; $p < 0.001$) (Table 6). Among the pelvic parameters, spinopelvic tilt correlated positively with the APP angle in both the supine ($r = 0.570$; $p < 0.001$) and standing positions ($r = 0.499$; $p < 0.001$). The acetabular anteversion and inclination angles were positively correlated with the APP angle in both the supine and standing positions (Table 6). Regarding acetabular coverage, the anterior, anterosuperior, and superior acetabular sector angles were negatively correlated with the APP angle in both the supine and standing positions (Table 6). Postural change in the APP angle did not have a correlation with patient demographic data or CT measurement parameters (Table 6).

Discussion

Background and Rationale

Substantial individual and postural variation in physiologic pelvic tilt may affect acetabular orientation [17, 19, 33, 40]. Considering the abnormal mechanical environment of dysplastic hips, assessment in the supine or standardized pelvic position may not show the functional orientation of the acetabulum to the femur, and a weightbearing position may be more appropriate for assessing hip deformities and planning acetabular reorientation [17, 33, 40]. To date, postural change in sagittal pelvic tilt in patients with hip dysplasia has not been well characterized, and its effect on acetabular version and coverage of the femoral head is unclear. In this study, we found that the pelvis of patients with hip dysplasia tilted posteriorly from the supine to the standing position by an average of 6°, and that the change was greater than 10° in

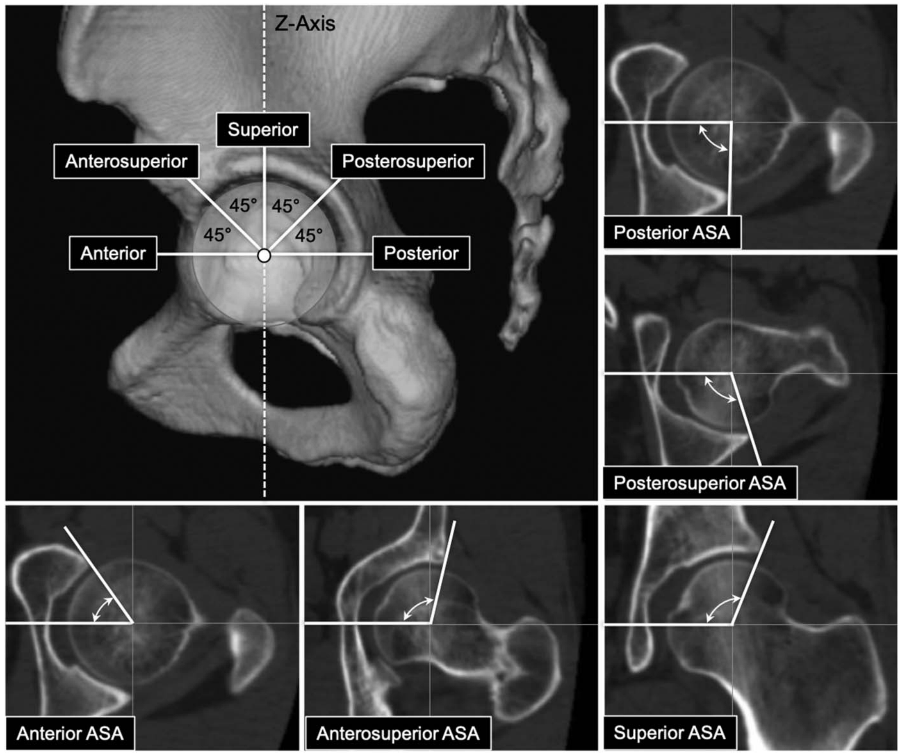

Fig. 5 This figure shows our methods of measuring the acetabular sector angle in five radial directions. The acetabular sector angle was defined as an angle formed by a line connecting the acetabular edge and femoral head's center and the x-axis passing through the femoral head's center. Anterior and posterior acetabular sector angles were measured in the axial plane passing the femoral head's center. Acetabular sector angles were also measured at 45° in the anterosuperior direction and in the superior direction, and at 45° in the posterosuperior direction. ASA = acetabular sector angle.

18% of patients. Posterior change in pelvic tilt from the supine to standing positions was associated with an increase in acetabular anteversion and a decrease in anterior-to-anterosuperior acetabular coverage of the femoral head.

Limitations

This study has several limitations. First, we did not evaluate spinal factors influencing sagittal pelvic tilt. Posterior pelvic tilt in the standing position has been reported to be associated with lumber degeneration, as found in degenerative disc diseases, degenerative spondylolisthesis, and vertebral compressive fractures in elderly patients with advanced osteoarthritis [37]. Although we excluded patients who were treated for spinal disease and those with prior spinal surgery to minimize the effect of spinal factors, a further investigation is needed to address the effect of spinal factors on our observations. Second, the study participants were symptomatic and underwent

Table 2. Comparisons of pelvic parameters between the supine and standing positions

Parameter[a]	Supine	Standing	Mean difference (95% CI)	p value[b]
APP angle (°)	8 ± 6	2 ± 7	-6 (-7 to -5)	< 0.001
Spinopelvic tilt (°)	9 ± 5	15 ± 7	6 (5-7)	< 0.001
Sacral slope (°)	42 ± 8	36 ± 9	-6 (-7 to -5)	< 0.001
Pelvic incidence (°)	51 ± 9	51 ± 9	0 (-0.1 to 0.1)	0.467

[a]Values are presented as the mean ± SD;
[b]paired t-test.

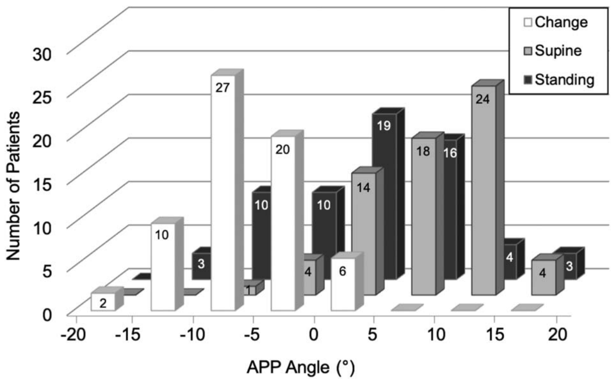

Fig. 6 This figure shows the distributions of the APP angles in the supine and standing positions and postural change in the APP angle.

surgery, and 74% of them had bilateral hip dysplasia. Therefore, this group consisted of patients with more severe dysplasia. Our observation may apply only to people with severely dysplastic hips. Although a morphologic evaluation was performed on the operated-on side, similar results, including asymptomatic, mild dysplasia, were found in the contralateral hips. Thus, we assume that the study result applies to hip dysplasia of varying severity. Third, the study cohort was limited to Japanese patients, most of whom were women. Previous studies have demonstrated similarities between the spinopelvic parameters of white and Japanese patients, as well as between genders [21, 26], and we believe that our observations would remain unaffected by racial and gender differences. However, differences in hip morphology between races [48] and between genders [8] have been reported, and further research is warranted to address the impact of racial and gender differences on the generalizability of our observations. Lastly, exposure to radiation is a disadvantage of using a CT-based assessment. Further efforts are needed to minimize the dose of irradiation used or to develop assessment methods based on other modalities such as MRI.

Table 3. Correlations between change in the APP angle and change in acetabular parameters

Parameter	Change in APP angle
Change in acetabular version	
Anteversion	-0.826 (< 0.001)
Inclination	-0.142 (0.260)
Change in acetabular sector angle	
Anterior	0.635 (< 0.001)
Anterosuperior	0.746 (< 0.001)
Superior	0.171 (0.174)
Posterosuperior	-0.357 (0.004)
Posterior	-0.716 (< 0.001)

Values are presented as a correlation coefficient (p value).

Postural Change in Sagittal Pelvic Tilt

In this study, although the APP angle in both the supine and standing positions varied widely among individuals, the pelvis of patients with hip dysplasia tilted posteriorly from the supine position to the standing position. Similar to our observation, one small study [40] found that the pelvis tilted posteriorly from the supine to the weightbearing position in patients with hip dysplasia; however, the degree of the change in pelvic tilt was not directly measured. Another study [43] found that the pelvis tilted posteriorly from the supine (mean APP angle 6.2°) to the standing position (mean APP angle 0.5°) and that the mean change in the APP angle was -5.5° in 273 patients with advanced osteoarthritis secondary to hip dysplasia. These postural changes in pelvic tilt are not unique to hip dysplasia. Several studies have documented wide variation in pelvic tilt among participants and have shown that the pelvis tilts posteriorly by 4° to 5° from the supine to the standing position in normal people [6, 19, 24]. Others suggest that positioning has little or no effect on pelvic tilt [3, 27]. Anterior pelvic inclination was proposed as a feature of hip dysplasia in two studies [12, 32]. Okuda et al. [32] reported that patients with hip dysplasia tended to have a greater sacral slope angle than did healthy volunteers; however, the mean value (41.2°) was within the normal range [23, 26, 28, 45]. Although our study had no control participants, the mean values of spinopelvic parameters in the study cohort were within the reported normal range [23, 26, 28, 45]. In view of the substantial variation in physiologic pelvic tilt of normal people, that is, variation in the mean APP angle from -4° to 6.8° in the supine position and from -8° to 6.7° in the standing position in previous studies [6, 23, 24, 27, 46], we cannot conclude that patients with hip dysplasia have a distinctive pattern of pelvic tilt compared with normal people.

Postural Change in Acetabular Version and Coverage

Although a number of studies have explored the relationship between pelvic tilt and acetabular orientation [3, 17, 33, 34], few referred to patients with hip dysplasia and early-stage osteoarthritis who were candidates for hip preservation surgery. Our results showed that the posterior change in pelvic tilt correlated with an increase in the acetabular anteversion angle and a decrease in anterior and anterosuperior coverage. The latter was clearly evident in 12 patients (18%) in whom the posterior change in the APP angle was more than 10°. The prevalence of acetabular retroversion decreased from the supine (23%) to the standing position (9.2%). Similarly, Troelsen et al. [40] reported that the prevalence of acetabular retroversion decreased from 35% in the supine position to 13% in the

Table 4. Comparisons of acetabular parameters between the supine and standing positions (n = 65 patients)

Parameter	Supine	Standing	Mean difference (95% CI) or median difference (95% CI)	p value
Radiographic parameter (°)[a]				
Lateral center-edge angle	11 (-8 to 19)	9 (-9 to 19)	-0.5 (-2 to 0)	< 0.001
Tönnis angle	20 (11-35)	22 (11-41)	0.4 (-0.5 to 2)	0.007
Anterior wall index	0.32 ± 0.13	0.25 ± 0.12	-0.07 (-0.09 to -0.05)	< 0.001
Posterior wall index	0.94 ± 0.16	1.01 ± 0.16	0.07 (0.05-0.09)	< 0.001
Acetabular version (°)[a]				< 0.001
Anteversion	21 ± 5	23 ± 5	2 (2-3)	< 0.001
Inclination	48 ± 3	48 (42-57)	0.1 (-0.6 to 0.6)	0.734
Acetabular retroversion[b]	15 (23)	6 (9)		0.032
Acetabular sector angle (°)[a]				
Anterior	49 (30-60)	45 ± 6	-2 (-4 to -0.4)	< 0.001
Anterosuperior	88 ± 9	83 ± 11	-6 (-7 to -4)	< 0.001
Superior	105 (80-113)	104 (77-113)	-0.6 (-2 to 0.5)	0.001
Posterosuperior	101 ± 6	103 ± 7	2 (2-3)	< 0.001
Posterior	90 (70-99)	91 ± 7	2 (0.8-4)	< 0.001
Deficiency type[b]				0.005
Anterior	20 (31)	39 (60)		
Global	15 (23)	13 (20)		
Mild	15 (23)	6 (9)		
Posterior	15 (23)	7 (11)		

[a]Values are presented as the mean ± SD or the median (range);
[b]values are presented as a number (%).

standing position, and they warned of the risk of overestimating acetabular retroversion as seen on radiographs taken in the supine position. No studies that we know of have correlated postural change in pelvic tilt with 3-D coverage of the femoral head in dysplastic hips. The current study showed that the decrease in acetabular coverage from the supine to the standing position was the largest in the anterosuperior direction. A possible explanation for this phenomenon is that posterior tilt of the pelvis shifts the psoas valley from the anterior to the anterosuperior area, resulting in less anterosuperior coverage [44]. In dysplastic hips, shear stress forces and overload concentrate on the anterosuperior acetabulum, and the intraarticular pathology generally originates from the anterosuperior labrochondral junction [9, 16]. Therefore, decreased coverage of this area can exacerbate joint degeneration in hips with dysplasia [1].

In view of these postural changes in acetabular version and coverage, standardized pelvic radiographs taken in the supine position [34] may not show the patient-specific functional orientation of the acetabulum, and radiographs taken during weightbearing may be more appropriate when assessing abnormalities associated with hip dysplasia [17, 33, 40]. Although neutral pelvic positioning has been recommended for the preoperative planning of reorientation osteotomy to avoid misinterpreting acetabular deformities [18, 34, 38], evaluation in the supine or standardized pelvic position overlooks a possible decrease in anterosuperior acetabular coverage caused by individual and postural variation in physiologic pelvic tilt. A recent study indicated that acetabular coverage in the standing position correlated with coverage measured during gait [42]. Thus, we assume that a morphologic evaluation of a weightbearing position may yield valuable functional information and help surgeons to diagnose the hip's condition and improve surgical reorientation and the biomechanical environment of the dysplastic hip. In patients with substantial posterior change in pelvic tilt in the standing position, anterior rotation of the acetabular fragment during osteotomy may be beneficial to correct the anterosuperior acetabular deficiency in the standing position [11].

Factors Associated with Sagittal Pelvic Tilt

Similar to previous reports in asymptomatic patients [26, 45], we observed no correlation between pelvic tilt and gender. Although we found no correlation between pelvic

Table 5. Comparisons of acetabular parameters between the supine and standing positions in patients whose posterior change in the APP angle was greater than 10° (n = 12 patients)

Parameter	Supine	Standing	Mean difference (95% CI)	p value
Radiographic parameter (°)[a]				
Lateral center-edge angle	15 ± 4	14 ± 4	-1 (-2 to 0)	0.035
Tönnis angle	16 ± 4	18 ± 4	2 (1-3)	0.001
Anterior wall index	0.33 ± 0.13	0.18 ± 0.10	-0.15 (-0.21 to -0.10)	< 0.001
Posterior wall index	0.99 ± 0.12	1.14 ± 0.10	0.15 (0.11-0.20)	< 0.001
Acetabular version (°)[a]				
Anteversion	22 ± 5	27 ± 4	5 (4-6)	< 0.001
Inclination	46 ± 3	46 ± 2	0.7 (-0.2 to 1)	0.106
Acetabular retroversion[b]	3 (25)	0 (0)		0.217
Acetabular sector angle (°)[a]				
Anterior	48 ± 8	44 ± 7	-5 (-6 to -3)	< 0.001
Anterosuperior	91 ± 11	77 ± 14	-14 (-17 to -11)	< 0.001
Superior	108 ± 5	106 ± 5	-1 (-2 to -0.5)	0.006
Posterosuperior	105 ± 7	108 ± 7	3 (2-4)	< 0.001
Posterior	91 ± 5	96 ± 5	5 (4-7)	< 0.001
Deficiency type[b]				0.033
Anterior	2 (17)	9 (75)		
Global	3 (25)	1 (8)		
Mild	5 (42)	2 (17)		
Posterior	2 (17)	0 (0)		

[a]Values are presented as the mean ± SD;
[b]values are presented as a number (%).

tilt and age, a large study [26] demonstrated that the pelvis tended to tilt slightly posteriorly with age in asymptomatic adults without spinal symptoms. Because our study cohort was small and we limited the study participants to patients under 60 years of age with hip dysplasia, we might have overlooked the association between pelvic tilt and age. Anterior rotation of the pelvis was associated with bilateral hip dysplasia, an increase in the acetabular anteversion and acetabular inclination angles, and a decrease in the anterior-to-superior acetabular sector angles, suggesting that anterior rotation of the pelvis compensated for acetabular deficiency in the anterior-to-superior acetabular region. These observations imply that patients with severe hip dysplasia tend to present with anterior rotation of the pelvis. Wassilew et al. [46] reported that the pelvis tilted more posteriorly in asymptomatic hips with acetabular retroversion than in those with anteversion. Consistent with our results, Zahn et al. [49] reported that anterior tilting of the pelvis positively correlated with the acetabular anteversion angle and inferred that pelvic tilt depends on acetabular orientation and compensates for an increased acetabular anteversion angle. Our results showed that postural change in pelvic tilt is unpredictable in terms of patient demographic and morphologic data. AP pelvic radiography while bearing weight is a convenient method to evaluate the individual patient's range and direction of pelvic rotation and should be added to the routine assessment of hip dysplasia.

Conclusions

The results of this study showed that the pelvis tilts posteriorly from the supine to the standing position in patients with hip dysplasia. Postural change in sagittal pelvic tilt varied among individuals, and this postural change in pelvic tilt was capable of altering acetabular version and coverage of the femoral head. The change in pelvic tilt was more than 10° in 18% of patients, and these patients showed a marked increase in acetabular anteversion and a decrease in anterosuperior acetabular coverage of the femoral head in a weightbearing position. In such cases, anterior rotation of the acetabular fragment may be beneficial for correcting anterosuperior acetabular deficiency during reorientation osteotomy. We recommend assessing postural change in sagittal pelvic when diagnosing hip dysplasia and during the planning of hip preservation surgery. Further studies are needed to determine how postural changes in acetabular version and coverage affect the biomechanical

Table 6. Correlation between APP angles and demographic and CT measurement parameters

Parameter	APP angle in the supine position	APP angle in the standing position	Postural change in the APP angle
Age[a]	-0.123 (0.330)	0.018 (0.886)	0.246 (0.049)
Gender[b]	Men, 5 (1-15) Women, 9 (-6 to 19) (p = 0.437)	Men, 3 (-4 to 12) Women, 2 (-14 to 19) (p = 0.662)	Men, -4 (-4 to 0) Women, -6 (-17 to 4) (p = 0.076)
BMI*	-0.009 (0.945)	-0.045 (0.726)	-0.066 (0.611)
Unilateral or bilateral dysplasia[b]	Unilateral, 4 ± 6 Bilateral, 9 ± 5 (p < 0.001)	Unilateral, -4 ± 6 Bilateral, 4 ± 7 (p < 0.001)	Unilateral, -8 ± 4 Bilateral, -6 ± 4 (p = 0.072)
Tönnis classification system[b]	Grade 0, 8 ± 6 Grade 1, 8 ± 6 (p = 0.957)	Grade 0, 1 ± 7 Grade 1, 2 ± 7 (p = 0.435)	Grade 0, -7 ± 5 Grade 1, -6 ± 4 (p = 0.232)
CT parameters with reference to the APP coordinate system[a]			
Supinopelvic tilt	0.570 (< 0.001)	0.499 (< 0.001)	0.092 (0.474)
Sacral slope	-0.275 (0.030)	-0.287 (0.023)	-0.120 (0.351)
Pelvic incidence	0.120 (0.359)	0.069 (0.593)	-0.039 (0.760)
Acetabular version			
Anteversion	0.471 (< 0.001)	0.337 (0.007)	-0.046 (0.721)
Inclination	0.389 (0.002)	0.468 (< 0.001)	0.267 (0.035)
Acetabular sector angle			
Anterior	-0.413 (< 0.001)	-0.341 (0.006)	-0.042 (0.741)
Anterosuperior	-0.499 (< 0.001)	-0.424 (< 0.001)	-0.055 (0.665)
Superior	-0.349 (0.004)	-0.454 (< 0.001)	-0.235 (0.059)
Posterosuperior	0.009 (0.945)	-0.096 (0.447)	-0.165 (0.188)
Posterior	0.319 (0.010)	0.143 (0.256)	-0.168 (0.180)

[a]Values are presented as correlation coefficients (p value);
[b]values are presented as the mean ± SD or the median (range) (p value).

environment of the hip and the clinical results of acetabular reorientation osteotomy.

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