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CLINICAL RESEARCH

Pelvic Deformity Influences Acetabular Version and Coverage in Hip Dysplasia

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Abstract

Background Although a wide variety of acetabular deformities in developmental dysplasia of the hip (DDH) have been reported, the morphologic features of the entire pelvis in DDH are not well characterized and their correlation with acetabular deformity is unknown.

Questions/purposes We determined whether there was a rotational deformity of the entire innominate bone, and if so, whether it related to acetabular version and coverage.

Patients and Methods We examined the morphologic features of the pelvis using CT for 50 patients with DDH (82 hips). Forty normal hips were used as controls. The innominate rotation angle was determined at three levels in the axial plane. The acetabular sector angle served as an indicator of acetabular coverage of the femoral head. We evaluated the association between innominate rotation angles and acetabular version and coverage.

Results We observed greater internal rotation of the innominate bone in patients with DDH than in the control subjects. Internal rotation of the innominate bone was associated with increased acetabular anteversion angle and acetabular inclination angle. In hips with acetabular retroversion (nine of 82 hips; 11.0 %), the entire innominate bone was externally rotated, compared with hips with acetabular anteversion. Internal rotation of the innominate bone also was associated with decreased anterior and superior acetabular coverage.

Conclusion Our observations suggest structural abnormalities exist throughout the pelvis in DDH, and the morphologic abnormalities of the acetabulum are not caused solely by local dysplasia around the hip, but are influenced by the morphologic features of the entire pelvis.

Level of Evidence Level IV, prognostic study. See Guidelines for Authors for a complete description of levels of evidence.

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Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.
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Introduction

DDH has been associated with numerous morphologic abnormalities when dysplastic lesions persist until bone maturity. These include insufficient acetabular coverage of the femoral head, shallow acetabular concavity, excessive femoral anteversion, coxa valga, and shortened femoral neck [8, 15, 25, 31]. It is believed these morphologic abnormalities lead to a decreased load-transferring articular area, abnormal stress distribution on the articular cartilage, and elevated joint contact pressure [4, 13]. Owing to this abnormal stress concentration, labral disorders and cartilage degeneration occur at an early age, followed by premature osteoarthritis (OA) [19, 27, 35].

Although the morphologic features of the hip in DDH have been described in detail, a limited number of studies have examined the morphologic features of the entire pelvis in DDH [21, 32]; however, the pathogenesis of these morphologic alterations remains unclear. Some authors have proposed growth disturbances affect not only the acetabulum, but also the entire innominate bone [1, 20]. It is unclear whether these pelvic abnormalities relate to morphologic aberrations of the hip. To better understand the pathogenesis of DDH, it is important to know whether and how the entire pelvis is affected. Additionally, this knowledge could be useful when considering the corrective maneuver to optimize the acetabular position during periacetabular osteotomy (PAO), such as those proposed by Ganz et al. [10]. Previous studies using CT revealed a substantial amount of individual variety of acetabular version, deficiency type, and degree of acetabular dysplasia [14, 25]. Thus, it is important to evaluate acetabular deformity three-dimensionally, and customize the correction in accordance with variations in the quantity and location of acetabular deficiencies [34].

We focused on rotational alignment of the innominate bone in the axial plane, and questioned whether (1) rotational deformity of the innominate bone exists with DDH, (2) the innominate rotation angles correlate with acetabular version and coverage, and (3) the innominate rotation angles correlate with the deficient portion of the acetabulum.

Patients and Methods

We reviewed standard AP radiographs of the pelvis [5, 29] and pelvic CT scans of 143 hips in 84 patients with DDH, obtained during preoperative examinations for corrective osteotomies between July 2004 and February 2008. DDH was defined as a lateral center-edge angle of Wiberg [35] less than 20°, based on measurements using AP radiographs of the pelvis. Twenty-seven hips were scored as Grade 2 or worse according to the Tönnis grading system [33] or had visible osteophyte formation and were excluded as their measurements could not be verified as accurate. We excluded six patients (12 hips) with prior surgery and seven (12 hips) with severe morphologic abnormalities of the femoral head. To eliminate the effect of morphologic differences between genders, we included only female subjects in this study (10 hips of seven male patients were excluded). This left 50 patients (82 hips). Forty-one patients had bilateral involvement, and nine had unilateral involvement. In nine patients with bilateral involvement, the contralateral hip was excluded from this study owing to a severe femoral head deformity in two patients, Tönnis Grade 2 in two patients, and history of surgery in five patients. The average age of the patients at examination was 40.0 years (range, 17–60 years) and all patients were skeletally mature. All hips were classified as Type I, according to the classification system of Crowe et al. [6]. Ten patients had a history of nonoperative treatment for congenital dislocation of the hip (CDH).

Table 1. Demographic and radiologic parameters in DDH and control groups

Parameters	DDH	Control
Age* (years)	40.0 (37.36; 42.62)	66.1 (64.16; 67.99)
Body mass index* (kg/m^2)	22.7 (21.97; 23.46)	23.5 (22.36; 24.71)
Laterality (right:left) (number of hips)	39:43	21:19
Center-edge angle* (°)	11.3 (9.61; 13.02)	38.0 (36.18; 39.84)
Sharp angle* (°)	48.3 (47.44; 49.23)	36.5 (35.38; 37.68)
Acetabular roof obliquity* (°)	25.6 (23.96; 27.24)	1.2 (−0.37; 2.80)

* Values are presented as mean (95% CI).

The control group included 37 patients (40 hips) with OA of the knee who had no history of disease or articular symptoms in the hip, as indicated by a medical record search and radiographic examination. These subjects all were females with an average age of 66.1 years (range, 52–75 years). Although these two groups were similar in terms of the body mass index and laterality of the hips evaluated, the average age of the control group was greater than that of the DDH group (Table 1). Patients in the control group had no degenerative changes or other hip abnormalities. We examined AP pelvic radiographs and pelvic CT images obtained during planning for TKA using a CT-based navigation system [24]. This study was approved by the institutional review board of Kyushu University Hospital.

Pelvic CT was performed with the patients in a supine position, and images were obtained at 2-mm intervals from the anterior superior iliac spines (ASIS) to the inferior rim of the pelvis. For the control group, CT was performed with data obtained at 2-mm intervals from a 100-mm section of the femoral head, a 200-mm section of the knee, and 100-mm section of the distal part of the tibia. The CT images used for the control group included those of the ASIS and the pubic tubercles. After downloading data from the tomographs, in Digital Imaging and Communications in Medicine (DICOM; NEMA [National Electrical Manufacturers Association], Rosslyn, VA, USA) format, to a personal computer, we performed multiplanar reconstruction imaging using image processing and analysis software (3-D template; Japan Medical Materials, Osaka, Japan). To eliminate possible measurement errors, the pelvic position was corrected using digitally reconstructed radiograph images as follows. In the coronal plane, the pelvis was aligned horizontal to the line connecting the inferior aspects of the bilateral teardrops. In the axial plane, the pelvis was aligned vertical to the line connecting the pubic symphysis and the center of the sacrum. Pelvic inclination

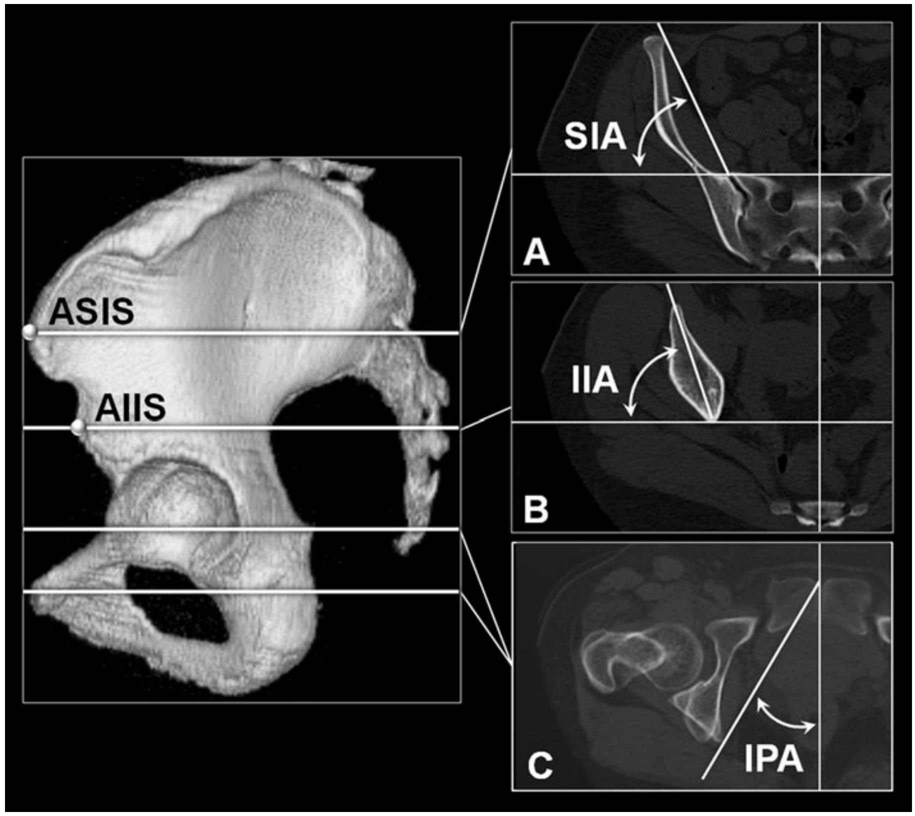

Fig. 1A–C Computer generated images show the innominate rotation angles. The reference point of the anterior superior iliac spine (ASIS) and the anterior inferior iliac spine (AIIS) were determined as the most anterior aspect of the iliac spines, respectively. The (**A**) superior iliac wing angle (SIA) is formed by the intersection of a line connecting the medial edge of the ASIS and the anterior margin of the sacroiliac joint, and a horizontal line on the axial plane. The (**B**) inferior iliac wing angle (IIA) is formed by a line connecting the anterior aspect of the AIIS and the posterior aspect of the ilium, and a horizontal line on the axial plane. The (**C**) ischiopubic angle (IPA) is a projection angle formed by the intersection of a line connecting the anterosuperior edge of the pubic symphysis and the ischial spine and a sagittal line on the axial plane for which we superimposed the sections that passed through the ischial spine and the pubic symphysis.

in the sagittal plane was aligned with the line connecting the ASIS and the pubic tubercle.

We defined three angles to evaluate rotational alignment of the innominate bone in the axial plane (Fig. 1). The opening angles of the ilium were measured at the level of the ASIS and the anterior inferior iliac spine (AIIS), and were named the superior iliac angle (SIA) and inferior iliac angle (IIA), respectively. The ischiopubic angle (IPA) was measured as a representative of the closing angle of the ischiopubic portion. Values greater than these three angles indicated increased internal rotation of the innominate bone.

We defined the acetabular anteversion angle (AcAV) in the axial plane passing through the femoral head center, as the angle created by the intersection of a line connecting the anterior and posterior edges of the acetabulum with a sagittal line (Fig. 2A). The acetabular inclination angle (AI) was determined in the coronal section that passed through the femoral head center, by connecting a line drawn between the superior and inferior edges of the acetabulum with a horizontal line (Fig. 2B). We measured the cranial anteversion angle (CA) on the axial section 5 mm distal to the acetabular roof to determine the presence of acetabular retroversion (Fig. 2C) [16]. We defined the acetabular retroversion group as consisting of hips with a negative CA value, and the acetabular anteversion group as containing hips with a positive value.

To determine acetabular coverage on the femoral head, we measured the acetabular sector angle (ASA) based on the method described by Anda et al. [2]. We used a horizontal line as the baseline of the measurement and determined the angle in anterior, superior, and posterior directions (Fig. 3). The values of the anterior and posterior ASA were used to classify the patients with DDH into four groups: anterior deficiency (anterior ASA $< 50°$ and posterior ASA $\geq 90°$), posterior deficiency (anterior ASA $\geq 50°$ and posterior ASA $< 90°$), global deficiency (anterior ASA $< 50°$ and posterior ASA $< 90°$) and mild deficiency (anterior ASA $\geq 50°$ and posterior ASA $\geq 90°$) [3, 14]. Using this criteria, 57.3% (47 hips) were diagnosed with anterior deficiency, 11% (nine hips) with posterior deficiency, 28% (23 hips) with global deficiency, and 3.7% (three hips) with mild deficiency.

All measurements using CT images were performed by one observer (MF) and were repeated in a blinded manner during the course of two sessions at least 1 month apart. Intraobserver reliabilities, evaluated with the use of the intraclass correlation coefficient (ICC), were excellent (range, 0.98–0.99). Two observers (MF and TS) independently made CT measurements on the scan of 30 randomly selected hips, and the ICC ranged from 0.88 to 0.96. Using the data obtained via CT measurements, we conducted the following analyses: (1) comparison of measurements between DDH and control groups, (2) correlation

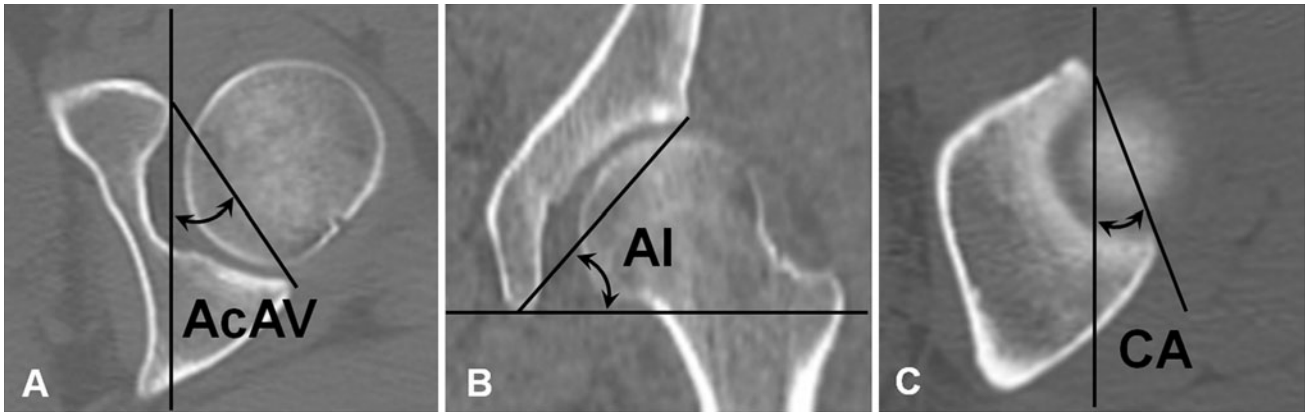

Fig. 2A–C The (**A**) acetabular anteversion angle (AcAV) was determined in the axial plane passing through the femoral head center as the angle formed by the intersection of a line connecting the anterior and posterior edges of the acetabulum and a sagittal line. The (**B**) acetabular inclination angle (AI) was determined in the coronal plane passing through the femoral head center as the angle formed by a line connecting the superior and inferior edges of the acetabulum and a horizontal line. The (**C**) cranial anteversion angle (CA) is formed by the intersection of a line connecting the anterior and posterior edges of the acetabulum and a sagittal line in the axial plane 5 mm distal to the acetabular roof.

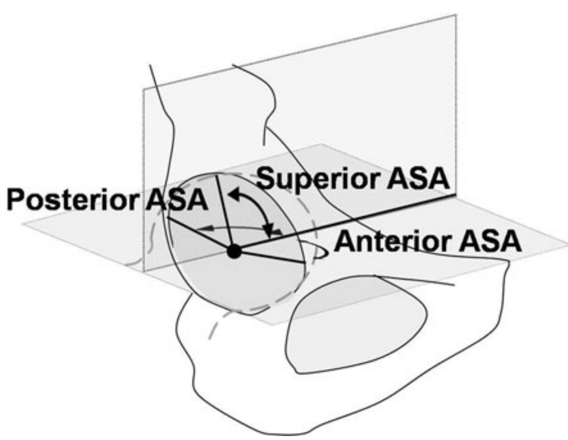

Fig. 3 The acetabular sector angle (ASA) is formed by the intersection of a line connecting the femoral head center and the acetabular edge with a horizontal line. The acetabular sector angle was measured in anterior, superior, and posterior directions.

of rotational alignment of the innominate bone with the acetabular opening angle, presence of acetabular retroversion and acetabular coverage of the femoral head, and (3) correlation between rotational alignment of the innominate bone and the deficient portion of the acetabulum.

The chi square test and Wilcoxon rank sum test were used to compare the categorical and continuous parameters between the two groups, respectively; the Tukey-Kramer HSD test was used for multiple comparisons. Correlations between two continuous parameters were evaluated using Pearson's correlation coefficient. Statistical analyses were performed using JMP software (Version 7.0; SAS Institute, NC, USA).

Table 2. CT measurement values in DDH and control groups

Parameters	DDH*	Control*	p Value
Innominate rotation angles			
SIA	57.0° (6.1°)	48.4° (5.8°)	$p < 0.0001$
IIA	72.0° (4.3°)	67.3° (5.0°)	$p < 0.0001$
IPA	30.6° (2.7°)	27.5° (2.4°)	$p < 0.0001$
Acetabular opening angles			
AcAV	25.1° (5.7°)	18.6° (6.6°)	$p < 0.0001$
AI	48.8° (3.8°)	36.7° (3.6°)	$p < 0.0001$
CA	9.6° (7.6°)	11.6° (10.5°)	$p = 0.2239$
Acetabular coverage			
Anterior ASA	41.5° (7.6°)	63.4° (8.9°)	$p < 0.0001$
Superior ASA	101.2° (6.8°)	129.1° (6.4°)	$p < 0.0001$
Posterior ASA	91.3° (7.2°)	101.4° (8.7°)	$p < 0.0001$

* Values are presented as mean (SD). SIA = superior iliac angle; IIA = inferior iliac angle; IPA = ischiopubic angle; AcAV = acetabular anteversion angle; AI = acetabular inclination angle; CA = cranial anteversion angle; ASA = acetabular sector angle.

Results

The rotational angles of the innominate bone were increased in patients with DDH compared with those of the control subjects at all three levels (Table 2). These observations indicate that in DDH the innominate bone was internally rotated at the level of the ilium through the ischiopubis. When the IPA measurement value was subtracted from the SIA, the resulting value was larger ($p < 0.001$) in the DDH group than in the control group (26.4° versus 20.9°, respectively), whereas the value obtained after subtracting the IPA from the IIA were

Table 3. Correlation between subgroups

Group	Parameters	Superior iliac angle*	Inferior iliac angle*	Ischiopubic angle*
DDH	AcAV	0.5620 ($p < 0.0001$)	0.7084 ($p < 0.0001$)	0.6666 ($p < 0.0001$)
	AI	0.3599 ($p = 0.0009$)	0.4370 ($p < 0.0001$)	0.2940 ($p = 0.0073$)
	Anterior ASA	−0.4377 ($p < 0.0001$)	−0.5884 ($p < 0.0001$)	−0.6376 ($p < 0.0001$)
	Superior ASA	−0.3431 ($p = 0.0016$)	−0.3864 ($p = 0.0003$)	−0.3432 ($p = 0.0016$)
	Posterior ASA	0.3540 ($p = 0.0011$)	0.4589 ($p < 0.0001$)	0.3124 ($p = 0.0043$)
Control	AcAV	0.7190 ($p < 0.0001$)	0.6843 ($p = < 0.0001$)	0.7281 ($p = < 0.0001$)
	AI	0.3325 ($p = 0.0361$)	0.4389 ($p = 0.0046$)	0.3538 ($p = 0.0251$)
	Anterior ASA	−0.4808 ($p = 0.0017$)	−0.5066 ($p = 0.0009$)	−0.5581 ($p = 0.0002$)
	Superior ASA	−0.4301 ($p = 0.0056$)	−0.3851 ($p = 0.0141$)	−0.3427 ($p = 0.0304$)
	Posterior ASA	0.5289 ($p = 0.0005$)	0.6452 ($p = < 0.0001$)	0.4642 ($p = 0.0026$)

* Values are presented as correlation coefficients (p value); AcAV = acetabular anteversion angle; AI = acetabular inclination angle; ASA = acetabular sector angle.

similar ($p = 0.085$) between groups (41.3° versus 39.8°, respectively). Therefore, the ilium was more internally rotated at the cranial level of the AIIS relative to the ischiopubis in the DDH group than in the control group. We observed no correlation between the innominate rotation angles and age. The AcAV and AI were increased in the DDH group compared with the control group (Table 2); however, the CA did not differ between the two groups. The ASA was decreased in patients with DDH at all directions compared with control subjects (Table 2).

We found positive correlations between acetabular opening angles and innominate rotation angles in both groups (Table 3). Acetabular retroversion was recognized in 11.0% (nine of 82 hips) in the DDH group and 10% (four of 40 hips) in the control group; the prevalence was similar ($p = 0.870$) between the two. When the innominate rotation angles were compared between the acetabular anteversion and retroversion groups, hips with acetabular retroversion had decreased rotation angles relative to hips with acetabular anteversion (Table 4).

As for acetabular coverage on the femoral head, the innominate rotation angles were negatively correlated with the anterior and superior ASA, and positively correlated with the posterior ASA in both groups (Table 3). This suggests hips with an internally rotated innominate bone have decreased acetabular coverage of the anterior and superior portions and increased acetabular coverage of the posterior portion. When the DDH group was subdivided into four groups based on defect location, hips with posterior deficiencies had decreased innominate rotation angles than the other groups, with the exception of an insignificant difference in the IPA between the mild deficiency and posterior deficiency groups (Table 5). Regarding the relationship between acetabular retroversion and acetabular coverage, 33.3% (three of nine hips) of the retroversion group were included in the global deficiency group whereas 66.7% (six of nine hips) were included in the posterior deficiency group.

Table 4. Comparison of the innominate rotation angles

Group	Parameters	*Anteversion group	*Retroversion group	p Value
DDH	SIA	58.3° (4.7°)	46.9° (7.1°)	$p < 0.0001$
	IIA	72.8° (3.3°)	64.9° (5°)	$p = 0.0001$
	IPA	31° (2.3°)	27.3° (3.4°)	$p = 0.0003$
Control	SIA	49.5° (4.6°)	38.5° (4.9°)	$p = 0.0045$
	IIA	68.1° (4.5°)	60° (2.4°)	$p = 0.0048$
	IPA	27.8° (2.3°)	24.5° (0.5°)	$p = 0.0089$

* Values are presented as mean (SD). SIA = superior iliac angle; IIA = inferior iliac angle; IPA = ischiopubic angle.

Discussion

Although the morphologic features of the hip in DDH have been well described, the morphologic features of the entire pelvis in DDH are not well characterized and their association with morphologic features of the acetabulum is unclear. We focused on rotational alignment of the innominate bone in the axial plane, and questioned whether (1) the rotational deformity of the innominate bone existed in DDH, (2) the innominate rotation angles correlated with the acetabular version and coverage, and (3) the innominate rotation angles correlated with the deficient portion of the acetabulum.

There were several limitations in this study. First, subjects in the control group were older than patients in the DDH group. However, none of the control subjects had a history of hip disease and none had osteoarthritic findings

Table 5. Comparison of the CT measurement values between the types of DDH

Angle	Anterior deficiency	Posterior deficiency	Global deficiency	Mild deficiency
Superior iliac angle	58.4° (4.4°)	49.3° (8.2°)*	56.8° (6.3°)	60.1° (5.0°)
Inferior iliac angle	73.2° (3.3°)	66.1° (4.6°)*	71.4° (3.9°)	73.8° (4.8°)
Ischiopubic angle	31.0° (2.6°)	27.0° (3.2°)†	31.4° (1.7°)	29.5° (1.0°)
Acetabular anteversion angle	28.1° (3.6°)	14.4° (5.4°)*	23.3° (3.1°)‡	23.3° (3.9°)
Acetabular inclination angle	49.1° (3.8°)	45.9° (2.6°)	49.6° (3.7°)	45.6° (2.7°)
Cranial anteversion angle	13.2° (6.7°)	−2.0° (6.1°)*	6.5° (5.3°)‡	11.6° (3.1°)

Values are presented as means; * significant differences compared with the other group at the 0.05 level; †significant differences compared with anterior and global dysplasia group at the 0.05 level; ‡significant differences compared with anterior dysplasia group at the 0.05 level.

in the hip on medical record review and plain radiographs. Additionally, there was no correlation between the innominate rotation angles and patient age. Thus, we considered them available as control subjects. Second, the study cohort was limited to Asian females with Crowe Type 1 hips, which may limit the generalizability of our findings to other populations. However, we believe this does not change the fact that rotational alignment of the innominate bone correlates with acetabular version and coverage. Third, the CT measurements in subjects with pelvic asymmetry could be inaccurate because the discrepancy between the sacral coordinate axis and the anterior pelvic plane makes it difficult to define the precise pelvic coordinate axis. Therefore, we used the line connecting the inferior aspects of the bilateral teardrops as the baseline of the coronal alignment, and the line connecting the pubic symphysis and the center of the sacrum as the baseline of sagittal pelvic alignment to eliminate the effect of the asymmetric shape of the iliac wing on measurements. Fourth, we did not examine femoral deformities or their potential associations with the pelvic deformity. The proximal femoral deformity could affect acetabular coverage on the femoral head, although the primal deformity in most patients with DDH is located on the acetabular side of the joint. Further investigations are needed to address the effect of the femoral deformity.

Although rotational alignment of the innominate bone ranged widely among individuals, the mean values showed greater internal rotation from the iliac wing through the ischiopubic level in the DDH group compared with the control group. We also observed internal rotation of the ilium at the cranial level of the AIIS relative to the ischiopubis as a variation of the pelvis in DDH. Kumeta et al. used CT measurement to show that the pelvis of patients with DDH were characterized by the "inward wing ilium" and lateralization of the femoral head [21]. Suzuki used three-dimensional MRI to evaluate 16 hips in eight infants with CDH and showed that the prime deformity of the pelvis was not just simple malrotation, but also increased medial twisting of the entire affected pelvic wing [32]. The pelvic alterations we observed were consistent with alterations reported in these studies, except we observed no medial twisting.

The morphologic relationship between the entire pelvis and the hip has not been investigated. We observed a correlation between rotational alignment of the innominate bone and acetabular version and coverage. In subjects with an internally rotated innominate bone, the acetabula tended to rotate anterosuperiorly, resulting in decreased anterosuperior coverage and increased posterior coverage. When we classified the patients with DDH into four subgroups, based on dysplastic portion, 85% (70 hips in 46 patients) were classified as having anterior or global deficiency. However, 11% (nine hips in eight patients) were classified as having posterior deficiency, and the innominate rotation of this group was more externally rotated than for other dysplasia types. We believe acetabular dysplasia is a prime cause of abnormal acetabular opening angle and insufficient acetabular coverage of the femoral head; however, our data suggest all morphologic features of the pelvis are contributing factors to abnormal acetabular morphologic features in DDH.

A high prevalence of acetabular retroversion in various hip diseases, including DDH, has been reported [9, 22]. Acetabular retroversion has been recognized as one of the causes of pincer impingement when excessive anterior acetabular coverage exists [8, 12, 28, 30]. This retroversion reportedly is caused by a prominence of the anterior acetabular wall, hypoplastic posterior acetabular wall, or malpositioning of the acetabulum [7, 12, 17]. We previously reported that acetabular retroversion in DDH results from relatively deficient posterior acetabular coverage and is associated with early pain onset [11]. Kalberer et al. suggested the high correlation between ischial spine prominence and crossover signs showed that acetabular retroversion is not only a periacetabular phenomenon, but also could represent malrotation of the inferior hemipelvis [17]. We found retroverted hips had externally rotated innominate bones from the level of the ilium to the ischiopubis when compared with anteverted hips in both groups. This indicates the morphologic features of the entire pelvis affect the occurrence of acetabular retroversion.

When planning PAO, it is important to customize the correction in accordance with individual variability in the quantity and location of acetabular deficiencies. Lateral rotation of the acetabular fragment is the most effective maneuver to enhance acetabular coverage of the femoral head. However, care should be taken for suboptimal correction of the acetabular version and coverage in the axial plane that also leads to an undesirable result of the osteotomy [18, 23, 26]. Our observations suggest a rotational maneuver in the axial plane is a rational procedure to enhance the acetabular position by balancing anterior and posterior coverage and versional status of the acetabulum during the osteotomy.

Our data show a principal pelvic deformity in DDH is an internally rotated innominate bone with an iliac wing that opens inwardly relative to the ischiopubis. The degree of rotation alignment of the innominate bone correlates with the acetabular opening angle and coverage of the femoral head. These observations suggest the structural abnormalities may exist throughout the pelvis in patients with DDH, and morphologic abnormalities of the acetabulum are not caused solely by local dysplasia around the hip, but are influenced by morphologic features of the entire pelvis.

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