Morphological Analysis of True Acetabulum in Hip Dysplasia (Crowe Classes I-IV) Via 3-D Implantation Simulation

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Background: The purpose of this study was to investigate the 3-dimensional (3D) morphological features of the true acetabulum in patients with developmental dysplasia of the hip (DDH).

Methods: Seventy-nine hips—53 in patients with developmental dysplasia of the hip (DDH) and 36 normal hips—were included in the present study. According to the Crowe classification, 26 hips were graded as Class I, 31 were Class II or III, and 22 were Class IV. The anterior pelvic plane was defined to standardize the measurements in the study. A selected virtual cup component was implanted into the true acetabulum of a 3D pelvic model of each hip. The acetabular anteversion angle, effective center-edge (CE) angle, effective Sharp angle, and thickness of the medial wall were measured to provide morphological indices of the true acetabulum. Acetabular sector angles and the component coverage ratio were measured to provide coverage indices.

Results: The acetabular anteversion angle increased with the severity of the DDH. Crowe-II/III hips had the smallest effective CE angle and the largest effective Sharp angle. The mean medial wall thickness was greatest in the Crowe-II/III hips (8.72 mm; 95% confidence interval [CI] = 7.52 to 9.92 mm), intermediate in the Crowe-I hips (7.17 mm; 95% CI = 6.24 to 8.11 mm), and smallest in the Crowe-IV hips (6.05 mm; 95% CI = 4.78 to 7.32 mm). The integrated coverage ratio of the Crowe-II/III hips was significantly less than that of the Crowe-I and IV hips.

Conclusions: The morphological features of the true acetabulum in patients with DDH can be evaluated comprehensively by using 3D implantation simulation. Segmental bone deficiency was prevalent in the dysplastic hips, especially those in the Crowe-II/III group. Both the severity and the individual morphology of the acetabular dysplasia should be carefully considered in preoperative planning.

Developmental dysplasia of the hip (DDH), which is characterized by a spectrum of pathological abnormalities, has been commonly considered to be a major cause of premature osteoarthritis. Historically, the morphological deformities were described in terms of decreased acetabular coverage of the femoral head, dysplastic deficiency of the true acetabular rim, and excessive anteversion of both the acetabulum and the femur. Total hip arthroplasty is considered to be an effective and standard treatment for patients with end-stage hip diseases. However, because of the anatomic abnormalities involved, hip dysplasia presents many technical challenges to orthopaedic surgeons. For mechanical reasons, most surgeons favor placing the acetabular component at the level of the true acetabulum to maintain hip abduction strength and to equalize limb lengths. Thus, the morphological features and bone density of the true acetabulum are of major concern during the operation. Although many studies have focused on femoral morphology in hip dysplasia, few have addressed the bone density of the true acetabulum as a function of the severity of the hip dysplasia.

Compared with conventional 2-dimensional (2D) radiographs, 3-dimensional (3D) images are more effective in detecting the morphological features and in assessing the bone density of the true acetabulum. In a 3D imaging environment,
migration, rotation, and segmentation of the models can visually facilitate preoperative planning\textsuperscript{10}. Furthermore, several studies\textsuperscript{11-14} have revealed that 3D simulation of implantation not only can offer accurate predictions of component sizing and positioning, but also can present anatomic information that is useful for acetabular reconstruction.

<table>
<thead>
<tr>
<th>TABLE I Demographic Data</th>
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<tr>
<td>Hips (no.)</td>
</tr>
<tr>
<td>Normal</td>
</tr>
<tr>
<td>DDH</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>II/III</td>
</tr>
<tr>
<td>IV</td>
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*The values are expressed as the mean and the standard deviation, with the 95% confidence interval in parentheses. BMI = body mass index.

\textsuperscript{9}Note: \textsuperscript{9}The values are expressed as the mean and the standard deviation, with the 95% confidence interval in parentheses. BMI = body mass index.

**Fig. 1**
During implantation simulation, the 3D, coronal, sagittal, and transverse views were presented simultaneously in Mimics software. This facilitated the researcher’s adjustment of the acetabular component and evaluation of the surrounding bone mass, to reach an optimal match between the 2. R-ASIS and L-ASIS = right and left anterior superior iliac spines, PS = pubic tubercle, point O = rotation center of the virtual cup, and DPCN = distal part of cotyloid notch. **Fig. 1A** Anterior pelvic plane. **Fig. 1-B** Coronal image. **Fig. 1-C** Axial image. **Fig. 1-D** Sagittal image. **Fig. 1-E** Implantation simulation. **Fig. 1-F** 3D reconstructive image.
In this study, we present a novel, 3D implantation simulation method for evaluating the morphological features and the effective bone density in adults with DDH. The research questions were: (1) What are the morphological features of the true acetabulum in different categories of DDH? (2) What is the acetabular osseous deficiency pattern in different categories of DDH?

Materials and Methods

Study Subjects

We retrospectively reviewed the preoperative imaging data of 92 patients (137 hips) with adult DDH who were admitted to our institution from January 2010 to December 2014. Dysplastic hips were identified by the criterion of a lateral center-edge (CE) angle of <20° on standing anteroposterior pelvic radiographs. Of the 92 subjects, 19 (28 hips) with substandard scans, 14 (22 hips) who had undergone previous surgery, and 6 (8 hips) with Legg-Calvé-Perthes-like deformities were excluded. Thus, 79 dysplastic hips in 53 patients met the inclusion criteria and were retrospectively evaluated. Eighteen patients (36 hips) without hip disease or deformities who had undergone computed tomography (CT) angiography to diagnose vascular diseases were chosen as controls. According to the criteria of the Crowe classification system, 26 of the dysplastic hips were graded as Class I, 23 were Class II, 8 were Class III, and 22 were Class IV. Given the limited sample size and the similar morphological features of Classes II and III, these classes were combined (Crowe II/III), as had been done in previous studies. Demographic data for the subjects are shown in Table I.

CT Scanning and 3D Reconstruction

Pelvic CT was performed with a Toshiba Aquilion CT scanner (120 kVp, 320 mA, 512 x 512 matrix, and 0.5-mm slice thickness). The patients were placed in a supine position with the patellae facing the ceiling. Scanning was performed from the iliac crest to the distal third of the femur. All CT slices were saved in Digital Imaging and Communications in Medicine (DICOM) format and imported into Mimics 16.0 software (Materialise) for 3D reconstruction. Before measurement, the pelvic position was standardized with reference to the anterior pelvic plane, determined by the anterior superior iliac spines and the pubic tubercles (Fig. 1-A). Thus, the coronal, axial, and sagittal images in the following measurements were reoriented according to the anterior pelvic plane and the line between the iliac spines.

Simulating Implantation of the Prosthetic Acetabular Component

A set of hemispherical virtual acetabular components was created according to the sizes of dysplastic acetabula using 3-matic 9.0 software (Materialise). The outer diameters of the acetabular components ranged from 36 to 60 mm in 2-mm intervals, and all had a shell thickness of 4 mm. These 3D models were imported into Mimics software in STL (stereolithography) format. The simulated acetabular replacement was performed by placing the component in the true acetabulum (Fig. 1). The position of the cup was confined by the peripheral border of the true acetabulum such that so-called rim fit was achieved. The inferior edge of the virtual cup was placed at the level of the distal part of the cotyloid notch (the position of the transverse acetabular ligament). The cup size was chosen to best accommodate the anteroposterior...
diameter of the true acetabulum, which tended to utilize the osseous peak of the anterior and posterior bone columns in the axial section. The inner cortex of the medial acetabular wall was set as the medial limit for cup placement. The cup orientation was adjusted to restore the native acetabular anteversion and to achieve cup inclination of $40\degree \pm 10\degree$. In doing this, we strove to maximize the preservation of the native bone of the true acetabulum for morphological evaluation and simultaneously attain optimal osseous coverage.

**Evaluations and Measurements**

In this protocol, the rotation center of the true acetabulum was determined by the central point of the component. The surface contact area between the cup and native bone was defined as the effective bone mass of the true acetabulum. In this context, effective bone mass corresponds to the bone that could be effectively utilized to support the implanted acetabular component.

We assessed the (1) morphology and bone distribution of the true acetabulum, (2) effective CE angle and effective Sharp angle (Fig. 2-A), (3) acetabular anteversion angle and minimum thickness of the medial acetabular wall (Fig. 2-B), (4) acetabular sector angles, and (5) component coverage ratio.

Using a method described previously, we established multiple sections to measure the acetabular sector angles in 5 directions. On the basis of the contact point between native bone and the component, anterior and posterior acetabular sector angles were measured in the axial plane (Fig. 2-B). In addition, acetabular sector angles in the $45\degree$ anterosuperior direction, superior direction, and $45\degree$ posterosuperior direction were measured in the corresponding plane (Figs. 2-C). The component coverage ratio was measured as follows. On the basis of the implantation simulation, an egg-shell cup with negligible thickness was developed to replace the implanted cup in the 3D environment. Utilizing the simulation function of Mimics, segmentations were performed according to the border between the covered and uncovered parts of the virtual cup (Fig. 2-D). The coverage was calculated as the ratio between the covered and total surface areas, which reflects the relative effective bone mass of the true acetabulum.

**Statistical Analysis**

To assess interobserver reliability, 2 experienced surgeons independently performed implantation simulation and corresponding measurements. To assess

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**TABLE II Size, Orientation, and Position of Acetabular Component**

<table>
<thead>
<tr>
<th>Acetabular Component*</th>
<th>Hips (no.)</th>
<th>Size (mm)</th>
<th>Inclination (°)</th>
<th>Anteversion (°)</th>
<th>BRCD† (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>36</td>
<td>52.67 ± 2.39 (51.86 to 53.48)</td>
<td>41.33 ± 3.71 (40.08 to 42.59)</td>
<td>18.45 ± 6.67 (16.19 to 20.70)</td>
<td>−0.61 ± 1.95 (−1.26 to 0.05)</td>
</tr>
<tr>
<td>DDH</td>
<td>79</td>
<td>45.22 ± 7.46 (43.54 to 46.89)†</td>
<td>45.05 ± 3.92 (44.17 to 45.93)†</td>
<td>25.31 ± 6.61 (23.83 to 26.79)†</td>
<td>1.18 ± 6.01 (−0.17 to 2.52)§</td>
</tr>
<tr>
<td>I</td>
<td>26</td>
<td>51.46 ± 5.92 (49.07 to 53.85)</td>
<td>46.12 ± 2.46 (45.13 to 47.12)†</td>
<td>21.90 ± 6.99 (19.08 to 24.73)§</td>
<td>0.68 ± 7.13 (−2.20 to 3.56)</td>
</tr>
<tr>
<td>II/III</td>
<td>31</td>
<td>44.84 ± 6.38 (42.50 to 47.18)†</td>
<td>45.07 ± 2.51 (44.16 to 45.99)†</td>
<td>25.42 ± 5.96 (23.23 to 27.60)†</td>
<td>0.24 ± 5.69 (−1.84 to 2.33)</td>
</tr>
<tr>
<td>IV</td>
<td>22</td>
<td>38.36 ± 3.00 (37.03 to 39.69)†</td>
<td>43.75 ± 6.13 (41.03 to 46.46)§</td>
<td>29.19 ± 4.83 (27.05 to 31.33)†</td>
<td>3.07 ± 4.71 (0.98 to 5.16)§</td>
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</table>

*The values are expressed as the mean and the standard deviation, with the 95% confidence interval in parentheses. †BRCD = bilateral rotation center difference, which is the height of the right rotation center minus the height of the left rotation center. §P < 0.01 compared with the control group. ¶P < 0.05 compared with the control group.
Results

Morphologic Analysis

The anatomy of the true acetabulum could be readily evaluated in this 3D environment. As a result of the overlap of the true and false acetabula, the Crowe-II/III hips tended to have a superior segmental deficiency of the acetabulum whereas, in the Crowe-I and IV hips, the rim of the acetabulum was relatively integrated. The bone mass of the anterior and posterior columns was relatively adequate in the Crowe-I and IV hips, whereas in the Crowe-I and IV hips, the rim of the acetabulum was relatively integrated. The bone mass of the anterior and posterior columns was relatively adequate in the Crowe-I and IV hips, whereas, in the Crowe-I and IV hips, the rim of the acetabulum was relatively integrated.

TABLE III Measurements of the Morphological Parameters

<table>
<thead>
<tr>
<th>No. of Hips</th>
<th>Acetabular Anteversion Angle* (°)</th>
<th>CE Angle* (°)</th>
<th>Sharp Angle* (°)</th>
<th>Medial Wall Thickness* (mm)</th>
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<tr>
<td>Normal</td>
<td>20.46 ± 7.68 (17.93 to 22.99)</td>
<td>46.10 ± 5.53 (44.22 to 47.97)</td>
<td>35.43 ± 4.07 (34.05 to 36.81)</td>
<td>3.58 ± 1.22 (3.16 to 3.99)</td>
</tr>
<tr>
<td>DDH</td>
<td>29.05 ± 8.10 (27.24 to 30.87)†</td>
<td>19.94 ± 13.93 (16.82 to 23.06)†</td>
<td>52.56 ± 8.17 (50.73 to 54.39)†</td>
<td>7.47 ± 3.05 (6.78 to 8.15)†</td>
</tr>
<tr>
<td>I</td>
<td>24.16 ± 8.08 (20.90 to 27.43)</td>
<td>21.41 ± 9.41 (17.61 to 25.22)†</td>
<td>51.52 ± 6.91 (48.73 to 54.32)†</td>
<td>7.17 ± 2.32 (6.24 to 8.11)†</td>
</tr>
<tr>
<td>II/III</td>
<td>30.15 ± 7.49 (27.40 to 32.90)†</td>
<td>10.22 ± 12.93 (5.48 to 14.97)†</td>
<td>57.97 ± 6.55 (55.56 to 60.37)†</td>
<td>8.72 ± 3.27 (7.52 to 9.92)†</td>
</tr>
<tr>
<td>IV</td>
<td>33.28 ± 5.98 (30.63 to 35.93)†</td>
<td>31.89 ± 9.21 (27.80 to 35.97)†</td>
<td>46.16 ± 6.49 (43.28 to 49.04)†</td>
<td>6.50 ± 2.87 (4.78 to 7.32)†</td>
</tr>
</tbody>
</table>

*The values are expressed as the mean and the standard deviation, with the 95% confidence interval in parentheses. †P < 0.01 compared with the control group.

Intraobserver reliability, both the implantation and the measurements were repeated by the same surgeon after 1 month. The intraclass correlation coefficient (ICC) was used to calculate interobserver and intraobserver effects. Furthermore, Bland-Altman analysis was performed to visually show the discrepancies between these repeated acetabular anteversion angle and acetabular thickness measurements. Kolmogorov-Smirnov tests were performed to determine the distributions of the data. For parametric data, when the variances in the groups were the same, 1-way ANOVA (analysis of variance) was used to compare the differences among groups, followed by the LSD (least significant difference) method for pairwise comparisons. For nonparametric data, or when the variances in the groups were different, Kruskal-Wallis ANOVA was performed, followed by the Dunn test for pairwise comparisons. All statistical analyses were performed using SPSS version-21.0 software (IBM), and a p value of <0.05 was considered to be significant.
Among the DDH groups, the effective CE angle was largest in the Crowe-IV hips and smallest in the Crowe-II/III hips. The Crowe-II/III hips had the largest effective Sharp angle. The normal hips had larger effective CE angles and smaller effective Sharp angles than the dysplastic hips. Medially, the acetabular wall was significantly thicker in the Crowe-II/III hips than in the other groups. The measurements and results of the statistical analyses are detailed in Table III and illustrated in Figure 4.

Acetabular Coverage Angles and Component Coverage Ratio

Compared with the control group, segmental defects of the dysplastic acetabulum were mainly located anterosuperiorly, superiorly, and posterosuperiorly in the Crowe-I and Crowe-II/III hips versus anterosuperiorly and superiorly in the Crowe-IV hips. Interestingly, the posterior acetabular sector angle was larger in the DDH groups than in the control group. Furthermore, the component coverage ratio of the hips in the DDH groups was significantly smaller than that in the control group.

The acetabular sector angles decreased in the anterior direction and increased in the posterior direction as the severity of the DDH increased. Notably, both the acetabular coverage angles and the acetabular coverage ratio in the Crowe-II/III hips revealed significant segmental deficiency in the superior and posterosuperior directions as compared with the other DDH groups (Fig. 5).

Reproducibility

The intraobserver reliabilities, evaluated with 1-way random effects model ICCs, were in the excellent range (0.83 to 0.96). The interobserver ICCs ranged from 0.86 to 0.95 for the morphological indices and from 0.77 to 0.88 for the coverage indices. Bland-Altman analysis also showed good agreement between the observers for the measurements of the acetabular anteverision angle and medial thickness (Fig. 6).

Discussion

When performing a primary total hip arthroplasty for a patient with DDH, the acetabular reconstruction especially presents considerable technical challenges for orthopaedic surgeons. Although several studies have assessed acetabular parameters on 2D and 3D images, the evaluation and measurements have mostly been confined to Crowe-I hips and to the corresponding plane through the center of femoral head. However, accurate morphological characteristics of the true acetabulum cannot be obtained through a dislocated rotation center, even in moderately dysplastic Crowe-I hips. Van Bosse et al. revealed that the dysplastic acetabulum is not hemispherical, but rather elongated and shallow. For that reason, not all of the native bone in the true acetabulum can be effectively utilized in total hip arthroplasty. Authors of several previous studies have reported that 3D simulation not only can provide high-resolution visualization of morphological changes in skeletal disorders, but also can predict the postoperative rotation center and the orientation of the prosthesis with high validity and accuracy. Hence, it is appropriate to apply 3D implantation simulation to accurately define the location and effective bone mass of the true acetabulum. We believe that this is the first report to present a systematic quantitative 3D morphological analysis of the true acetabulum in every Crowe type of DDH.

The acetabular anteverision angle is a crucial parameter of the acetabulum that can dramatically influence the orientation, initial stability, and durability of the implanted prosthesis. Our data suggested a progressive increase in acetabular anteverision with increased severity of hip dysplasia, which conflicts with the conclusion of previous studies that there is no significant difference in anteverision between dysplastic and normal hips.

The results in the normal and Crowe-I groups in the present study were quite consistent with previously reported measurements. In addition, the relatively wide variance of acetabular anteverision in patients with hip dysplasia indicates that cautious individualized preoperative planning is necessary before total hip arthroplasty.
hip arthroplasty, especially in seriously deformed hips. The abnormally distributed bone at the posterior rim of the true acetabulum contributes to the larger anteversion in high dislocated hips. Fuji et al. suggested that a growth disturbance of the anterior ramus of the lunate surface might cause an anteriously oriented acetabular notch and thus the resultant posterior rotation of the acetabulum seen in DDH. That deformity was also observed in our study and may contribute to another potential explanation for excessive anteversion in hip dysplasia.

Without a virtually implanted component, it would be impossible to measure the effective CE angle and effective Sharp angle—which reflect the superolateral acetabular osseous coverage and the acetabular inclination—in Crowe-II/III and IV hips. In the Crowe-II/III hips, engagement of the dislocated femoral head with the superior edge of the true acetabulum resulted in the smallest effective CE angle and largest effective Sharp angle. In the Crowe-I and IV groups, however, inclination was reduced so the matching component could engage with a relatively intact acetabular rim. Kim et al. arrived at similar conclusions when they analyzed the cup-CE angle postoperatively according to the original lateral edge of the anatomic acetabulum in 83 hips with DDH.

The medial thickness of the true acetabulum provides important information about medial bone quality. The medial thickness was significantly larger in the dysplastic hips than in the normal hips. Liu et al. also observed more bone in the medial acetabular wall of Crowe-II/III hips than in Crowe-I hips (7.1 ± 3.1 versus 3.8 ± 2.1 mm). Moreover, our data revealed that the medial wall thickness was largest in Crowe-II/III hips, intermediate in Crowe-I hips, and smallest in Crowe-IV hips. According to Kanai et al., patients with DDH tend to develop a gait strategy characterized by leaning their trunk toward the affected side in order to reduce muscle load and hip joint stress. Thus, our hypothesis is that the laterally subluxated femoral heads in Crowe-I and II/III hips maintain contact with the bottom of the acetabulum, leading to the abnormal alignment and mechanical stress that induce medial hyperplasia. However, Crowe-IV hips lose articular contact at an early age, so the hyperplasia is less marked. The quantitative analysis in our study may have important clinical relevance for surgeons who perform acetabular reconstruction in dysplastic hips, especially when the technique of medialization is applied.

Our acetabular sector angle measurements indicate that the apparent osseous deficiency is mainly located anterosuperiorly, superiorly, and posterosuperiorly in Crowe-I and II/III hips, and anterosuperiorly and superiorly in Crowe-IV hips, as compared with the control group. The corresponding differences in coverage angles and in acetabular anteversion were consistent. The superior and posterosuperior as well as the anterior and anterosuperior osseous deficiency should be fully addressed, and there is a need for an individualized acetabular reconstruction strategy due to the wide variance of deficiency in hip dysplasia. The segmental deficiency in the Crowe-II/III hips was much more serious and more extensive in the superior and posterosuperior directions than it was in the other 2 groups of dysplastic hips. Hence, cautious preoperative planning is especially needed when performing reconstruction at the level of the true acetabulum in patients with this type of DDH. Xu et al. investigated the morphology and bone mass of 14 Crowe-II hips preoperatively and intraoperatively. Although no allograft or reinforcement ring was used for acetabular reconstruction, several components were placed at a high position because of the deficient coverage. Another follow-up study of 138 dysplastic hips treated with total hip arthroplasty without cement also showed that the proportion of acetabular reconstructions at a high position was much greater in Crowe-II/III hips than in the other groups. Similarly, Yang and Cui concluded that acetabular deficiency prevents anatomic cup placement in Crowe-II/III hips. Special techniques such as the use of a high hip center or bone graft may be necessary to address inadequate osseous coverage of the acetabular component. In Crowe-IV hips, placement in the anatomic hip center is often possible with the use of a small acetabular cup. Interestingly, our data revealed that posterosuperior and posterior coverage in the Crowe-IV group was relatively sufficient, supporting the conclusion by Xu et al. that bone availability in the posterosuperior aspect of the acetabulum can provide sufficient coverage for the cup component in high-riding Crowe-IV hips.

The limitations of our study should be noted. First, the sample size was relatively small, and the subjects with normal hips were older than those with DDH on average. Second, in the 3D implantation simulation, the acetabular cups were manually adjusted according to osseous references. Despite this, the statistical analysis indicated reliable reproducibility. Third, the size of the acetabular component that was chosen was determined by the bone condition of the true acetabulum, which in some instances might be beyond the range of on-the-shelf cup sizes. Furthermore, acetabular anteversion was analyzed with the anterior pelvic plane as the reference plane, without involving the pelvic tilt angle, which would influence the component’s functional acetabular anteversion intraoperatively. Since the actual weight-bearing area was difficult to define in the 3D environment, we chose to weight the uncovered portions equally when calculating the coverage parameter.

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References


