Dynamic hip kinematics before and after periacetabular osteotomy in patients with dysplasia

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A B S T R A C T
Background: We prospectively analyzed the hip kinematics in patients with developmental dysplasia of the hip (DDH) before and after periacetabular osteotomy (PAO) and in healthy subjects while squatting to determine the influence of coverage of the femoral head on hip kinematics.

Methods: 14 hips in 14 patients with DDH and 10 hips in 10 volunteers were included. Continuous radiographs while squatting and computed tomography images were obtained to assess the in vivo kinematics of the hip and the rim-neck distance using density-based 3D-to-2D model-to-image registration techniques.

Results: The maximum hip flexion angles were 100.4° and 94.9° before and after PAO (p = 0.0863), respectively. The maximum hip flexion angles after PAO did not significantly differ from those of normal hips (102.2°; p = 0.2552). The hip abduction angles at maximum hip flexion were 31.7° and 26.2° before and after PAO (p = 0.1256), respectively. The rim-neck distance decreased from averaged 12.2 mm – 8.9 mm (p = 0.0044) after PAO. The lateral center edge angle (LCEA) and anterior center edge angle (ACEA) significantly improved 14.7°–42.4° and 50.4°–54.0° after PAO (p < 0.0001, p = 0.0347), respectively; in particular, the ACEA after PAO did not significantly differ from that in the normal hips (p = 0.1917). The ACEA was not correlated with hip flexion, or the rim-neck distance (p = 0.9601, 0.8764). The LCEA was also not correlated with hip abduction (p = 0.1683).

Conclusion: Patients after PAO showed no significant difference in maximum hip flexion while squatting compared to before PAO and normal hips. Horizontalized weight-bearing acetabulum with normalized ACEA could be adequate correction of the acetabular fragment to restore hip RoM without conoxial that induce the inability to perform squats after PAO.

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1. Introduction

Developmental dysplasia of the hip (DDH) is a common cause of secondary osteoarthritis (OA) [1]. Periacetabular osteotomy (PAO), including transposition osteotomy of the acetabulum [2–6], is an effective treatment for DDH. There are several variations in surgical technique [2,7–12]. PAO can improve the acetabular coverage of the femoral head and restore joint congruity and stability. Previous studies have shown satisfactory intermediate to long-term outcomes of PAO with excellent deformity correction, pain relief, and restored function [8,10,13]. We also previously reported the survival rate in cases with total hip arthroplasty (THA) conversion or progress to the end stages of OA as 94% and 88% at 10 and 15 years after PAO [4].

Several recent reports have described the occurrence of secondary femoroacetabular impingement (FAI) after PAO [14–16]. This condition can result from the overcorrection of the acetabulum...
and native cam type deformity of the proximal femur. Several computed tomography (CT) based simulation studies have also shown that hip flexion, abduction, and internal rotation decreased after PAO [17–19]. In particular, the anterior center-edge angle (ACEA) was found to have a negative correlation with flexion and internal rotation even in cases where the coverage of the femoral head was appropriate [17]. However, these simulation studies were performed in vitro, and they only considered the influence of bone morphology. Further in vivo analysis during daily activities such as deep hip flexion is needed to understand the dynamic kinematics in DDH and the influence of the coverage of the femoral head.

In this study, we aimed to evaluate (1) the kinematics of the hips between healthy subjects, patients before PAO, and after PAO, while squatting, using density-based 3D-to-2D model-to-image registration techniques [20–23]. We verified the hip kinematics, including maximum hip flexion, adduction/abduction, internal/external rotation, and distance between the acetabular rim and femoral neck at maximum hip flexion (rim-neck distance) [22,23], and then evaluated (2) whether the anterior and/or lateral coverage of the femoral head was significantly related to the hip range of motion (RoM) and rim-neck distance while squatting. We hypothesized that the amount of anterior and lateral acetabular coverage could significantly influence hip RoM while squatting.

2. Materials and methods

2.1. Subjects

From August 2012 to December 2015, a total of 32 hips of 29 patients underwent PAO for symptomatic DDH by the experienced hip surgeons, Y.N. and S.H. The indications for the osteotomy were radiological evidence of dysplasia with Wiberg’s lateral center-edge angle (CEA) of <20° [24], and hip pain that interfered with daily life. In this study, we could include 14 hips of 14 patients who agreed to participate in this study prior to surgery and met the following inclusion criteria: no neuromuscular disorders; no previous surgery of any abnormity in radiographic images of the hips. Among the 14 patients, 3 were male and 11 were female with an average age at surgery of 34.9 years (range, 13–57) and body mass index (BMI) of 23.5 kg/m² (range, 18.0–28.5). All dysplastic hips were categorized as Crowe 1 [25]. According to the category of dysplasia severity [26], 7 hips were classified as borderline-mild DDH (15° ≤ CEA < 25°), 4 hips were classified as moderate DDH (5° ≤ CEA < 15°), and 3 hips were classified as severe DDH (CEA < 5°). The healthy subjects included 6 males and 4 females, with an average age at surgery of 34.9 years (range, 13–57) and BMI of 23.5 kg/m² (range, 18.0–28.5). All dysplastic hips were categorized as Crowe 1 [25]. According to the category of dysplasia severity [26], 7 hips were classified as borderline-mild DDH (15° ≤ CEA < 25°), 4 hips were classified as moderate DDH (5° ≤ CEA < 15°), and 3 hips were classified as severe DDH (CEA < 5°). The healthy subjects included 6 males and 4 females, with an average age at surgery of 34.9 years (range, 13–57) and BMI of 23.5 kg/m² (range, 18.0–28.5). There were no significant differences in age, gender and BMI between cases with DDH and normal hips (p = 0.3651, p = 0.0529 and 0.1783 respectively). Informed consent was obtained from all the subjects prior to participation in the study, which was approved by the Institutional Review Board. Radiographic images of the patients with DDH were obtained before PAO and one year after PAO.

2.2. Surgical technique

The procedure has been previously described in detail [2–6]. In brief, the patient is placed in the lateral decubitus position. A lateral approach with and without transtrochanteric osteotomy was used in 3 and 11 cases, respectively. A spherical osteotomy is performed, starting 20 mm proximal to the superior acetabular edge and passing through the midpoint between the greater sciatic notch and the posterior edge of the acetabulum and the innominate sulcus of the ischium. Thereafter, a pubic osteotomy is performed lateral to the iliopectine tubercle. The acetabular fragment is rotated laterally to horizontalize weight-bearing acetabulum and improve anterior coverage, as well as medialization and distalization of the femoral head in case of subluxation. Although the majority of patients with DDH present with anterolateral acetabular deficiencies, previous studies have shown the acetabular version and the quantity and location of acetabular deficiencies can vary among individuals [9,27–30]. Therefore, anterior rotation of the acetabular fragment can exacerbate posterior acetabular coverage and therefore should be avoided in patients with insufficient posterior acetabular coverage [30–32]. We preoperatively evaluated the morphologic features of the hip of each patient three-dimensionally and customized the correction in accordance with the individual variation [29–31,33]. During procedure, we judged the amount of lateral rotation and anteverision of the fragment by reference to the 2.0 mm K-wire inserted in the fragment before correction, with intraoperative radiograph. Active range of hip exercises and partial weight-bearing on two crutches were initiated one and two weeks after the surgery, respectively. Weight-bearing was gradually increased during postoperative rehabilitation, based on the extent of pain in the patients, whereas full weight-bearing was permitted five to eight weeks after the operation. No patients claimed the symptom of coxalgia with deep hip flexion or impingement test that limited the ability to perform squats at recent follow-up visit.

2.3. Kinematic analysis

Continuous radiographic images of the subjects while squatting were recorded during dynamic movements using a flat-panel X-ray detector (Ultimax-I, Toshiba, Tochigi, Japan), with an image area of 420 mm × 420 mm, resolution of 0.274 mm × 0.274 mm/pixel, 0.02 s pulse width, 80 kV, and 360 mA [20–23]. The frame rate was set at 3.5 frames/s. Subjects were asked to squat with the feet at shoulder width and heels flat from flexed to extended standing positions, and were allowed to squat as they felt comfortable with the given instructions and to warm up sufficiently before data collection (Fig. 1). The 3D positions and orientations of the pelvis and femur while squatting were determined via density-based, 3D-to-2D model-to-image registration techniques with using image correlations (Fig. 2). A 3D digital image was constructed in a virtual 3D space using CT data, and the anatomical coordinate systems of the pelvis and femur were embedded in each density-based volumetric bone model. Thereafter, computer simulation of the radiographic process was conducted to generate virtual digitally reconstructed radiographs (DRRs). Correlations of the pixel values between the DRRs and real X-ray images were used to finetune the 3D model. In particular, multiple image windows that spanned the bone edge were defined for image-matching analysis [20–23].

The upper left end point on the projection plane of a flat panel X-ray detector was defined as the world coordinate system origin. The mediolateral (ML: X) and superoinferior (Y) axis were horizontal and perpendicular to the floor; respectively. The anteroposterior (AP: Z) axis was formed from the cross product of the first two. Anatomical coordinate systems of the pelvis and femur were embedded in each density-based volumetric bone model. The coordinate system of the pelvis was based on the anatomical pelvic plane (APP). The mid-point of the bilateral anterior superior iliac spines was defined as the coordinate system origin for the pelvis. The ML (x) axis of the pelvis was defined by a line passing through
the bilateral anterior superior iliac spines. The proximal/distal (z) axis of the pelvis was defined by a line perpendicular to the x-axis in APP. The AP (y) axis was formed from the cross product of x-and z-axis. The centroid of the femoral head was calculated from the mean position of point clouds of the femoral head in the world coordinate systems, and was defined as the coordinate system origin for the femur. The ML (x) axis of the femur was defined by a line parallel to the trans-epicondylar axis (TEA) in the plane intersecting the origin. The proximal/distal (z) axis of the femur was defined by a line perpendicular to the x-axis in the plane intersecting the origin and the midpoint of TEA. The AP (y) axis was formed from the cross product of x-and z-axis. The relative positions and orientations of the pelvis (anterior/posterior tilt, upward/downward obliquity, contralateral/ipsilateral rotation) and femur (flexion/extension, adduction/abduction, internal/external rotation) with respect to the world coordinate systems were defined as the pelvic and femoral movements. We also defined the relative positions and orientations of the femur to the pelvis as hip movements (flexion/extension, adduction/abduction, internal/external rotation) [20–23].

The distance between the acetabular rim and the femoral neck at maximum hip flexion while squatting was calculated as the rim-neck distance [22,23]. First, pixels of the acetabular rim were plotted in the 3D bone models. Second, the femoral head was approximated as a sphere and was removed from the 3D femoral bone model. The distance between each pixels of the rim and the neck, which was identified by the 3D acetabular and femoral bone models, was calculated by using a computer-aided design software program (CATIA V5; Dassault Systemes, Velizy-Villacoublay, France), and the minimum distance was determined (Fig. 3).

2.4. Radiographic evaluation

AP pelvic radiographs were obtained in the supine position. In addition, each subject was scanned using CT (Aquilion, Toshiba, Tochigi, Japan) in the supine position with an image matrix of 512 × 512, pixel dimensions of 0.35 × 0.35, and a thickness of 1 mm spanning from the superior edge of the pelvis to below the knee joint. Multiplanar reconstruction of all images was performed using image analysis software (3D template; Japan Medical Materials, Osaka, Japan).

On the acetabular side, the sharp angle (SA), acetabular roof obliquity (ARO), and acetabular head index (AHI) were measured using pelvic radiographs. The lateral center-edge angle (LCEA) and ACEA were also measured on coronal and sagittal views of CT images through the femoral head center [34]. A functional pelvic plane in the supine position [35] was defined as the reference plane of the pelvic position. The ACEA, which was calculated based upon CT data in this study, has different meaning comparing with ACEA measured by false profile view radiograph.
On the femoral side, the neck-shaft angle (NSA) was measured using pelvic radiographs. The femoral neck anteversion angle (FNA) and α-angle were measured using CT images. A retrocondylar plane was defined as the reference plane of the femur position. To measure the α-angle, multiple radial planes through the femoral neck axes were reconstructed at 30° intervals. The locations were represented by the clock position; the superior aspect was considered as 0 o'clock and the anterior aspect was considered as 3 o'clock. The α-angles from 0 to 3 o'clock were measured because anterior FAI was generally observed from 0 to 3 o'clock. The intraobserver and interobserver correlation coefficients were found to be excellent for the CT measurements, as previously described.

2.5. Statistical analysis

Statistical analyses were performed using JMP software version 11.0 (SAS Institute, Cary, NC, USA). Paired t-test was used to compare continuous variables in DDH hips before and after PAO, and Student’s t-test was used to compare continuous variables of normal hips and that of DDH hips, whereas χ² statistics was used to compare categorical variables. Linear regression analyses were performed to assess whether the acetabular coverage of the femoral head was correlated with hip RoM and the rim-neck distance. A power analysis indicated that a sample size of 14 patients would provide 80% statistical power for detecting a 10° difference in absolute value of RoM between before and after PAO.
assumes a probability value of less than 0.05 and a standard deviation of 12°.

3. Results

3.1. Kinematics

In normal hips, the maximum hip flexion angles were 102.2° (SD, 14.3) (Fig. 4A). The femoral flexion angles and the pelvic tilt angles (posterior+, anterior−) at maximum hip flexion were 103.3° (SD 12.1) and 1.3° (SD 9.5), respectively (Fig. 4B and C). The hip abduction angles and internal rotation angles at maximum hip flexion were 35.2° (SD, 7.0) and 6.4° (SD, 12.0), respectively (Fig. 4D and E).

In hips with DDH, the maximum hip flexion angles were 100.4° (SD, 18.6) before PAO and 94.9° (SD, 14.0) after PAO (Fig. 4A). The femoral flexion angles at maximum hip flexion were 98.7° (SD, 12.7) before PAO and 97.8° (SD, 9.0) after PAO (Fig. 4B). The pelvic tilt angles (posterior+, anterior−) at maximum hip flexion were 0.4° (SD, 13.5) before PAO and 3.2° (SD, 12.9) after PAO (Fig. 4C). There was no significant difference in maximum hip flexion angles, femoral flexion angles, and pelvic tilt angles at maximum hip flexion before and after PAO (p = 0.0863, 0.1228 and 0.4257, respectively). The hip abduction angles at maximum hip flexion were 31.7° (SD, 12.0) before PAO and 26.2° (SD, 6.3) after PAO (Fig. 4D). The hip internal rotation angles at maximum hip flexion were 3.4° (SD, 11.3) before PAO and 2.8° (SD, 10.8) after PAO (Fig. 4E). There was no significant difference in the hip abduction and hip internal rotation angles at maximum hip flexion before and after PAO (p = 0.1256 and 0.7901). The maximum hip flexion angles, pelvic tilt angles, femoral flexion angles, and hip internal rotation angles at maximum hip flexion after PAO did not significantly differ from those of normal hips (p = 0.2552, 0.7129, 0.2298, and 0.4705, respectively). However, the hip abduction angles at maximum hip flexion after PAO were significantly smaller than those of normal hips (p = 0.0047). When assessing the correlation of acetabular coverage and hip RoM, we found that the ACEA was not significantly correlated with the maximum hip flexion angles.
(p = 0.9601, r = 0.01), pelvic tilt angles (p = 0.2838, r = 0.18), or hip internal rotation angles (p = 0.7350, r = 0.06) at maximum hip flexion (Fig. 5A, B, C). Moreover, the LCEA was not significantly correlated with the hip abduction angles at maximum hip flexion (p = 0.1683, r = 0.23) (Fig. 5D). The FNA was not correlated with the hip flexion (p = 0.5453, r = 0.23), hip internal rotation (p = 0.5011, r = -0.11) and hip abduction at maximum hip flexion (p = 0.4732, r = 0.12).

3.2. Minimum rim-neck distance

The mean minimum rim-neck distance was 11.3 mm (SD, 5.2) in normal hips, and was 12.2 mm (SD 6.1) before PAO and 8.9 mm (SD 4.6) after PAO in DDH hips. The rim-neck distance was significantly decreased after PAO (p = 0.0044). There was no significant correlation between the ACEA and the rim-neck distance (p = 0.8764, r = 0.03) (Fig. 5E).

3.3. Radiographic evaluation

The LCEA, ACEA, SA, ARO, and AHI in DDH hips improved significantly after PAO (p = 0.0347 for ACEA and p < 0.0001 for the other parameters). The LCEA and AHI after PAO were significantly larger than those of normal hips (p < 0.0001). Moreover, the SA and ARO after PAO were significantly smaller than those of normal hips (p = 0.0003 and p = 0.0109). However, there were no significant differences between the ACEA after PAO and that of normal hips (p = 0.1917). In all patients with DDH, the ACEA after PAO did not exceed the range of that of normal hips. NSA and FNA were not significantly different between normal hips and DDH hips (p = 0.9521 and 0.4258). At any aspect, there was no significant difference in the α-angle between normal hips and DDH hips (p = 0.1840 at 0°, p = 0.0660 at 1°, p = 0.1146 at 2° and p = 0.4012 at 3°; Table 1).

4. Discussion

In the present in vivo study, we examined the dynamic kinematics of DDH and normal hips while squatting, and assessed the effect of acetabular coverage on hip kinematics. The acetabular coverage of the femoral head improved after PAO, whereas the ACEA after PAO and that of normal hips did not significantly differ. There was no significant difference in maximum hip flexion angles while squatting between before and after PAO, or between patients after PAO and normal hips. Although range of flexion could vary depending on adduction/abduction and internal/external rotation angles, there was no significant difference in the hip abduction and internal rotation angles at maximum hip flexion before and after PAO. The ACEA was not significantly correlated with the hip flexion angles, pelvic tilt, hip internal rotation angles, or the rim-neck distance. The LCEA was also

Fig. 5. No significant correlation between the maximum hip flexion angles and the anterior center edge angle (ACEA) is noted (p = 0.9601; A). No significant correlation between the pelvic tilt (p = 0.2838; B), or internal rotation (p = 0.7350; C) angles at maximum hip flexion and the ACEA is noted. No significant correlation between the hip abduction angles at maximum hip flexion and the LCEA is noted (p = 0.2083; D). No significant correlation between the rim-neck distance and the ACEA is noted (p = 0.8764; E). The ACEA and LCEA were calculated based upon a functional pelvic plane of CT data [34,41].
not significantly correlated with the hip abduction angles. The correction of acetabular coverage through PAO restored hip RoM without coxalgia that induce the inability to perform squats.

In CT based simulation studies, hip flexion, abduction and internal rotation decreased after PAO [17–19], even if the coverage of the femoral head after PAO was close to that of normal hips [34,35]. Furthermore, Iwai et al. [17], in their simulation study, reported that the ACEA after PAO could be adequate correction of the acetabular coverage of the femoral head after PAO induced anterior bony impingement and reduced hip flexion and internal rotation RoM. In the present in vivo study, the maximum hip flexion angles before and after PAO were 100.4° and 94.9° without significant difference with those of normal hips: 102.2°. Using an electromagnetic tracking system, Hemmerich et al. [38] reported that mean maximum hip flexion angles reached up to 95° on average for squatting, which is consistent with our results. In this study, the acetabular coverage increased, and the rim-neck distance decreased significantly after PAO. We have previously evaluated kinematics of pincer- and cam-type FAI before and after surgery using image-matching techniques [22,23]. Acetabuloplasty [22] and osteochondroplasty [23] improved the minimum rim-neck distance at maximum hip flexion while squatting from 1.8 to 7.3 mm and from 2.0 to 10.4 mm, respectively. In this study, the mean minimum rim-neck distance was 11.3 mm in normal hips, and was 12.2 mm before PAO and still 8.9 mm after PAO in DDH hips. Although the hip RoM decreased 5.5° and was 12.2 mm before PAO and still 8.9 mm after PAO in DDH hips. Horizontalized weight-bearing acetabulum with normalized ACEA after PAO could be adequate correction of the acetabular fragment to restore hip RoM without coxalgia that induce the inability to perform squats. Anterior and lateral overcorrection in the PAO may create secondary FAI with hip flexion disturbance during activities [15,42,43]. Findings in this study may be useful in the decision-making process of surgeons attempting to correct acetabular coverage during PAO.

**Conflict of interest**

None.

**Acknowledgement**

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**Table 1**

<table>
<thead>
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<th>Normal hips (n = 10)</th>
<th>DDH (n = 14)</th>
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<tbody>
<tr>
<td></td>
<td>Before PAO</td>
<td>After PAO</td>
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<tr>
<td>LCEA (°)</td>
<td>31.6 (SD 4.4)</td>
<td>14.7 (SD 5.0)</td>
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<td>AHI (%)</td>
<td>58.2 (SD 8.5)</td>
<td>50.4 (SD 4.5)</td>
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<tr>
<td>ARO (°)</td>
<td>40.3 (SD 4.0)</td>
<td>47.5 (SD 4.3)</td>
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<tr>
<td>NSA (°)</td>
<td>8.7 (SD 4.2)</td>
<td>15.5 (SD 7.1)</td>
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<tr>
<td>AHI (%)</td>
<td>82.0 (SD 4.9)</td>
<td>67.9 (SD 5.4)</td>
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<tr>
<td>FNA (%)</td>
<td>123.2 (SD 4.4)</td>
<td>133.0 (SD 5.6)</td>
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<tr>
<td>α angle 0° (°)</td>
<td>23.4 (SD 6.2)</td>
<td>26.9 (SD 11.7)</td>
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<tr>
<td>α angle 1° (°)</td>
<td>40.2 (SD 5.8)</td>
<td>37.1 (SD 4.9)</td>
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<tr>
<td>α angle 2° (°)</td>
<td>48.5 (SD 3.6)</td>
<td>43.7 (SD 5.8)</td>
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<tr>
<td>α angle 3° (°)</td>
<td>38.8 (SD 2.9)</td>
<td>14.7 (SD 5.0)</td>
</tr>
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Values are mean (SD: standard deviation).

\[ \begin{align*}
\text{a} & \quad p < 0.05 \text{ for the comparison of DDH before and after PAO.} \\
\text{b} & \quad p < 0.05 \text{ for the comparison of DDH before PAO and normal hips.} \\
\text{c} & \quad p < 0.05 \text{ for the comparison of DDH after PAO and normal hips.}
\end{align*} \]
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