Is Anterior Rotation of the Acetabulum Necessary to Normalize Joint Contact Pressure in Periacetabular Osteotomy? A Finite-element Analysis Study

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Is Anterior Rotation of the Acetabulum Necessary to Normalize Joint Contact Pressure in Periacetabular Osteotomy? A Finite-element Analysis Study

Running Title: Anterior Acetabular Rotation in PAO

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Abstract

Background Inappropriate sagittal plane correction can result in an increased risk of osteoarthritis progression after periacetabular osteotomy (PAO). Individual and postural variations in sagittal pelvic tilt, along with acetabular deformity, affect joint contact mechanics in dysplastic hips and may impact the direction and degree of acetabular correction. Finite-element analyses that account for physiologic pelvic tilt may provide valuable insight into the effect of PAO on the contact mechanics of dysplastic hips, which may lead to improved acetabular correction during PAO.

Questions/purposes We performed virtual PAO using finite-element models with reference to the standing pelvic position to clarify (1) whether lateral rotation of the acetabulum normalizes the joint contact pressure, (2) risk factors for abnormal contact pressure after lateral rotation of the acetabulum, and (3) whether additional anterior rotation of the acetabulum further reduces contact pressure.

Methods Between 2016 to 2020, 85 patients (92 hips) underwent PAO to treat hip dysplasia. Eighty-two patients with hip dysplasia (lateral center-edge angle < 20°) were included. Patients with advanced osteoarthritis, femoral head deformity, prior hip or supine surgery, or poor-quality imaging were excluded. Thirty-eight patients (38 hips) were eligible to this study. All patients were female, with a mean age of 39 ± 10 years. Thirty-three female volunteers without a history of hip disease were reviewed for controls. Individual with a lateral center-edge angle < 25° or poor-quality imaging were excluded. Sixteen individuals (16 hips) with a mean age of 36 ± 7

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years were eligible as controls. Using CT images, we developed patient-specific 3D surface hip models with the standing pelvic position as a reference. The loading scenario was based on the single-leg stance. Four patterns of virtual PAO were performed on the models. First, the acetabular fragment was rotated laterally in the coronal plane so that the lateral center-edge angle was 30°, then anterior rotation in the sagittal plane was added by 0°, 5°, 10°, and 15°. We developed finite-element models for each acetabular position and performed a nonlinear contact analysis to calculate the joint contact pressure of the acetabular cartilage. The normal range of the maximum joint contact pressure was calculated to be < 4.1 MPa using a receiver operating characteristic curve. A paired t-test or Wilcoxon's signed-rank test with Bonferroni's correction was used to compare joint contact pressure among acetabular positions. We evaluated the association of joint contact pressure with the patient-specific sagittal pelvic tilt and acetabular version and coverage using Pearson's or Spearman's correlation coefficient. An exploratory univariate logistic regression analysis was performed to identify which of the preoperative factors (CT measurement parameters and sagittal pelvic tilt) were associated with abnormal contact pressure after lateral rotation of the acetabulum. Variables with p values < 0.05 (anterior center-edge angle and sagittal pelvic tilt) were included in a multivariable model to identify the independent influence of each factor.

Results Lateral rotation of the acetabulum decreased the median maximum contact pressure compared with that before virtual PAO (3.7 MPa [2.2 to 6.7] versus 7.2 MPa [4.1 to 14]; difference of medians 3.5 MPa; $p < 0.001$). The resulting maximum contact pressures were within the normal range (< 4.1 MPa) in 63% of the hips (24 of 38 hips). The maximum contact

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pressure after lateral acetabular rotation was negatively correlated with the standing pelvic tilt (anterior pelvic plane angle) ($\rho = -0.52$; $p < 0.001$) and anterior center-edge angle ($\rho = -0.47$; $p = 0.003$). After controlling for confounding variables such as lateral center-edge angle and sagittal pelvic tilt, we found that a decreased preoperative anterior center-edge angle (per 1°; odds ratio 1.14; 95% CI, 1.01 to 1.28; $p = 0.01$) was independently associated with elevated contact pressure ($\geq$ 4.1 MPa) after lateral rotation; a preoperative anterior center-edge angle $< 32°$ in the standing pelvic position was associated with elevated contact pressure (sensitivity 57%, specificity 96%, area under the curve 0.77). Additional anterior rotation further decreased the joint contact pressure; the maximum contact pressures were within the normal range in 74% (28 of 38 hips), 76% (29 of 38 hips), and 84% (32 of 38 hips) of the hips when the acetabulum was rotated anteriorly by 5°, 10°, and 15°, respectively.

Conclusion Via virtual PAO, normal joint contact pressure was achieved in 63% of patients by normalizing the lateral acetabular coverage. However, lateral acetabular rotation was insufficient to normalize the joint contact pressure in patients with more posteriorly tilted pelvises and anterior acetabular deficiency. In patients with a preoperative anterior center-edge angle $< 32°$ in the standing pelvic position, additional anterior rotation is expected to be a useful guide to normalize the joint contact pressure.

Clinical Relevance This virtual PAO study suggests that biomechanics-based planning for PAO should incorporate not only the morphology of the hip but also the physiologic pelvic tilt in the weightbearing position in order to customize acetabular reorientation for each patient.

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Introduction

Periacetabular osteotomies (PAO) are performed in young adults with symptomatic hip dysplasia to delay or prevent the development of hip osteoarthritis [5, 55]. PAO improves acetabular coverage of the femoral head and reduces abnormal joint contact pressure through multiplanar acetabular correction [1, 16, 17, 25, 29]. Although favorable intermediate- to long-term outcomes of PAO have been reported, previous studies have shown that inadequate acetabular correction is a risk factor for an inferior outcome, along with advanced age, Tönnis grade ≥ 2, and joint incongruity [26, 33, 48, 50, 53]. Considering substantial individual variations in acetabular version and deficiency types, acetabular correction must be customized for each patient, rather than applying uniform correction [10, 11, 34, 57].

Although the lateral center-edge angle and Tönnis angle are the most common parameters used to assess appropriate acetabular correction, a recent study [53] revealed that the anterior center-edge angle has a greater impact on improving the natural history after PAO. Hip dysplasia typically manifests with anterolateral acetabular deficiency [10, 11], in which shearing stress and contact stress are concentrated on the anterolateral acetabular rim [13, 22]. Therefore, adequate sagittal plane correction of the anterior undercoverage is crucial for successful hip preservation [15, 20, 40]. However, care should be taken not to overcorrect the sagittal plane because excessive anterior coverage can result in iatrogenic femoroacetabular impingement [26, 33], and anterior rotation of the acetabulum should be reserved for patients with residual anterior undercoverage after lateral acetabular rotation [20]. Currently, the characteristics of patients who

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undergo combined sagittal and coronal plane correction are unknown, and to our knowledge, no appropriate algorithm has been established for effectively combining sagittal and coronal acetabular correction to optimize the joint contact mechanics.

Individual-specific finite-element modeling has been shown to be potentially useful for ensuring the appropriate acetabular correction during the preoperative planning of PAO [28, 57]. However, in these previous studies, acetabular correction was performed only in the coronal plane, and the effect of sagittal plane correction on the joint contact mechanics was not evaluated. Although there are a few studies that have considered sagittal plane correction [27, 36, 56], these studies involved finite-element analyses of dysplastic hips using the supine position or the standardized pelvic position that was based on the anterior pelvic plane's coordinate system. Recent studies have revealed that the sagittal pelvic tilt varies widely among candidates for hip preservation surgery and suggested that assessments in the standard pelvic position may overlook changes in acetabular coverage and joint contact stress in the weightbearing position [22, 41, 44]. Finite-element analyses that incorporate the physiologic pelvic tilt may provide additional insight into the effect of acetabular correction in the sagittal and coronal planes on the contact mechanics of dysplastic hips, which can lead to improved acetabular reorientation during PAO.

We therefore performed virtual PAO using finite-element models with reference to the standing pelvic position to clarify (1) whether lateral rotation of the acetabulum normalizes the joint contact pressure, (2) risk factors for abnormal contact pressure after lateral rotation of the acetabulum, and (3) whether additional anterior rotation of the acetabulum further reduces

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contact pressure.

Patients and Methods

Patients

Between September 2016 and March 2020, 85 patients (92 hips) with symptomatic hip dysplasia underwent transposition osteotomy of the acetabulum, one of the established PAOs to treat symptomatic hip dysplasia, which is characterized by a lateral approach and spherical osteotomy [8, 9]. Supine and standing AP pelvic radiographs and pelvic CT images were obtained for each patient during a preoperative examination. The inclusion criterion for this study (which was met by 82 patients [82 hips]) was the presence of hip dysplasia with a lateral center-edge angle < 20° on supine AP pelvic radiographs [51]. In patients with bilateral hip dysplasia, the operated-on side was investigated. Patients were excluded if they had advanced osteoarthritis (Tönnis grade ≥ 2 [42]) (n = 13 patients), major femoral head deformity (n = 1), history of surgery on either hip (n = 15), history of treatment for spinal disease (n = 1), or images with insufficient quality for analysis (n = 14). Thus, 38 patients were eligible for this study. All patients were female and had a mean age of 39 years ± 10 years (Table 1).

The AP pelvic radiographs and CT images of 33 female volunteers obtained for previous studies were reviewed as the control group [12, 22]. No participants in the control group had a history of diseases or articular symptoms in their hips, as determined by medical interviews and radiographic examinations. All participants provided written informed consent to participate in this study and were informed of radiation exposure. Seven patients with frank or borderline hip

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dysplasia (lateral center-edge angle < 25°) and 10 without suitable images were excluded. Thus, 16 individuals (16 randomly selected hips) with a mean age of 36 years ± 7 years were included as the control group (Table 1).

CT Evaluations

Pelvic CT images were taken from the superior rim of the pelvis to the distal femur (matrix: 512 × 512, field of view: 261-670 mm, slice thickness: 1 mm or 2 mm), with the patient or volunteer in the supine position. We measured sagittal pelvic tilt with the participant in the standing position and the morphologic parameters using the 3D Template software (Kyocera Medical Corporation). The x and y axes corresponded to the transverse and sagittal axes on the axial CT slice, respectively, while the z axis corresponded to the longitudinal axis of the scanner. First, the coordinate system of the CT scanner was aligned with the anterior pelvic plane's coordinate system to standardize the position of the pelvis. Next, the sagittal pelvic tilt on the standing AP radiograph was reproduced on the digitally reconstructed radiographs by matching the vertical-to-horizontal ratio of the pelvic foramen. A previous study demonstrated that the correlation coefficient for the vertical-to-horizontal ratio between AP radiographs and the CT-based images in the same pelvic tilt was 0.99 ($p < 0.001$) [35]. Sagittal pelvic tilt was measured as the angle formed by the anterior pelvic plane and the z axis (anterior pelvic plane angle), with positive values representing anterior tilt of the pelvis [41]. Morphologic parameters were measured on CT images with the standing pelvic position as reference, including the anterior, lateral, and posterior center-edge angles, acetabular roof obliquity, acetabular anteversion angle, and

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acetabular inclination angle [32].

Virtual PAO and Finite-element Analysis

Mechanical Finder version 10 (Research Center for Computational Mechanics Inc.) was used to create 3D surface models of the hemipelvis, proximal femur, and articular cartilage in order to describe the bony shape and density distribution visible on CT images [22, 46]. The articular cartilage of the acetabulum and femoral head was modeled with a constant thickness (1.8 mm) as a homogeneous and isotropic material [28, 57]. Virtual PAO was performed to mimic transposition osteotomy of the acetabulum [8, 9]. In our experience, in the clinical setting, the radius of the osteotomy line is 40 mm in most female patients. The pubic osteotomy site was located on the iliopubic tubercle. Therefore, virtual PAO was performed on the pelvic models with a spherical osteotomy line (radius of 40 mm) centered on the femoral head (Fig. 1) [20]. The acetabular fragment was reoriented in four patterns with reference to the standing pelvic position. First, the acetabular fragment was rotated laterally in the coronal plane to achieve a lateral center-edge angle of 30° on a standing AP pelvic radiograph (Fig. 2A). Then, the acetabular fragment was rotated anteriorly in the sagittal plane at 0°, 5°, 10°, and 15° (Fig. 2B).

The 3D surface models of bone and articular cartilage were meshed using a previously described method [22] (Fig. 3A). The mean numbers of finite elements and shell elements did not differ between the models of before and after virtual PAO (1,359,085 ± 128,332 versus 1,357,732 ± 128,988; $p = 0.64$ and 64,853 ± 5,459 versus 65,215 ± 4,912; $p = 0.08$, respectively). To allow for bone heterogeneity, the distribution of bone mineral densities (ρ in g/cm^3) was estimated

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from the Hounsfield units of each image by assuming a linear relationship between the values of these units and bone mineral density [22, 31, 46]. Next, the elastic modulus of the finite-element model was evaluated using the average bone mineral density value of the element, as described by Keyak et al. [21]. Poisson's ratio of the bone was set at 0.3. The elastic modulus and Poisson's ratio of the articular cartilage were set at 15 MPa and 0.45 MPa, respectively [28, 57].

Boundary and Loading Conditions

Nonlinear contact analyses were performed using the finite-element models of the dysplastic hips before and after four patterns of virtual PAO and the control group to calculate the joint contact area and joint contact pressure of the acetabular cartilage. In all analyses, load was applied with the participant in the standing pelvic position. The finite-element model of the femur was standardized with reference to the coordinate system described by the International Society of Biomechanics [52]. The definitions of tied-contact and sliding-contact constraints were set using previously reported cartilage-to-bone and cartilage-to cartilage interfaces [4]. In the virtual PAO models, the acetabular fragment was reconnected to the pelvis through tied contact to simulate complete bony union. The iliac crest and pubic region were completely fixed, while the distal femur was restrained in the x and y directions and kept free only in the z direction. The loading scenario was based on a single-leg stance, with the hip contact force acting on the nodes of the femoral head’s center (Fig. 3B) [3]. A consistent weight of 500 N was defined for all patients in order to avoid the scaling effect of weight on the absolute contact pressure values. The total joint contact force was set at 1158 N, and the components of the x, y, and z axes were set at 150 N, 71

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N, and 1146 N, respectively. The loaded nodes were allowed to move only in the direction of the applied load.

Ethical Approval

The ethical review board at our institution approved this retrospective study (approval number 30-137). All participants in both groups provided written informed consent to participate in this study and were informed of the radiation exposure required.

Statistical Analysis

A t-test or Wilcoxon's rank sum test was used to compare continuous parameters between the hip dysplasia and control groups after we confirmed normal distribution and homoscedasticity (Shapiro-Wilk W test and F test). The chi-square test was used to compare categorical parameters between two groups, while the paired t-test or Wilcoxon's signed rank test with Bonferroni's correction was used to compare continuous parameters before and after virtual PAO. The Dunnett or Steel test with the normal hip as a control was used for multiple comparisons, as appropriate. Statistical significance was set at $p < 0.05$. The correlation between two continuous parameters was evaluated using Pearson's or Spearman's correlation coefficient, as appropriate. The cutoff value of the normal maximum joint contact pressure was calculated to be 4.1 MPa using a receiver operating characteristic curve (sensitivity 100%, specificity 94%, AUC 0.99). A exploratory univariate logistic regression analysis was performed to screen for preoperative factors associated with abnormal contact pressure after lateral rotation of the acetabulum among morphological factors (anterior, lateral, and posterior center-edge angles, acetabular roof

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obliquity, acetabular anteversion angle, and acetabular inclination angle) and sagittal pelvic tilt (anterior pelvic plane angle). Variables with p values < 0.05 (anterior center-edge angle and sagittal pelvic tilt) were included in a multivariable model to identify the independent influence of each factor. Receiver operating characteristic curves were plotted to calculate the sensitivity, specificity, and cutoff value of the independent factor. Statistical analyses were performed using JMP® version 15.0 (SAS Institute).

Results

Does Lateral Rotation of the Acetabulum Normalize the Joint Contact Pressure?

The mean contact area was smaller (500 ± 134 mm^2 versus 919 ± 121 mm^2; mean difference 420 mm^2 [95% CI 342 to 497]; p < 0.001) and the median maximum contact pressure was higher (7.2 MPa [4.1 to 14] versus 3.5 MPa [2.2 to 4.4]; difference of medians 3.7 MPa; p < 0.001) in dysplastic hips than in controls (Fig. 3). When the acetabulum was rotated laterally to a lateral center-edge angle of 30° (median lateral rotation angle, 18.4° [range 12.6°-36.5°]), the mean contact area increased (898 ± 164 mm2 versus 500 ± 134 mm^2; mean difference 398 mm^2 [95% CI 350 to 447]; p < 0.001) and the median maximum contact pressure decreased (3.7 MPa [2.2 to 6.7] versus 7.2 MPa [4.1 to 14]; difference of medians 3.5 MPa; p < 0.001) compared with the preoperative value, resulting in no difference in the mean contact area (898 ± 164 mm^2 versus 919 ± 121 mm^2; mean difference 21 mm^2 [95% CI -70 to 113]; p = 0.64) or median maximum contact pressure (3.7 MPa [2.2 to 6.7] versus 3.5 MPa [2.2 to 4.4]; difference of medians 0.2 MPa; p = 0.37) between patients with hip dysplasia and control participants (Table 2). Based on

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the cutoff value of the normal maximum contact pressure (4.1MPa), 63% of the hips (24 of 38 hips) achieved the normal range of maximum contact pressure after virtual PAO (Table 2). CT parameters improved after virtual PAO (to a lateral center-edge angle of 30°) except the posterior center-edge angle and acetabular anteversion (Table 3). However, the anterior center-edge angle (47° ± 6° versus 52° ± 8°; mean difference 6° [95% CI 2° to 10°]; $p = 0.03$) and posterior center-edge angle (94° ± 9° versus 106° ± 9°; mean difference 12° [95% CI 7° to 17°]; $p < 0.001$) were still lower and the acetabular anteversion angle was higher (29° [18° to 57°] versus 20° [10° to 26°]; difference of medians 9°; $p < 0.001$) in dysplastic hips after virtual PAO than in the control hips (Table 3).

Risk Factors for Abnormal Contact Pressure after Lateral Rotation of the Acetabulum

Before virtual PAO, the maximum contact pressure was negatively correlated with the anterior and lateral center-edge angles and the standing anterior pelvic plane angle, and positively correlated with acetabular roof obliquity and the acetabular inclination angle (Table 4). When the acetabular fragment was rotated laterally to a lateral center-edge angle of 30°, the maximum contact pressure was negatively correlated with the anterior center-edge angle and standing anterior pelvic plane angle (Table 4). After controlling for potential confounding variables such as lateral center-edge angle and sagittal pelvic tilt, we found that a decreased preoperative anterior center-edge angle (per 1°; odds ratio 1.14; 95% CI, 1.01 to 1.28; $p = 0.01$) was independently associated with abnormal contact pressure (≥ 4.1 MPa) after virtual PAO (Table 5). The receiver operating characteristic curve analysis determined that a preoperative anterior

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center-edge angle < 32° in the standing pelvic position was associated with abnormal contact pressure after virtual PAO (sensitivity 57%, specificity 96%, area under the curve 0.77) (Fig. 4).

Does Additional Anterior Rotation of the Acetabular Fragment Further Reduce Joint Contact Pressure?

The mean contact area increased and the median maximum contact pressure decreased with additional anterior rotation of the acetabular fragment (Fig. 5). The median maximum contact pressure at 10° and 15° of anterior rotation was lower than that at 0° of anterior rotation (that is, lateral rotation alone) (Table 2). As a result, the maximum contact pressures were within the normal range in 74% (28 of 38 hips) of the hips at 5° of anterior rotation, 76% (29 of 38 hips) at 10° of anterior rotation, and 84% (32 of 38 hips) at 15° of anterior rotation (Table 2). Among the four patterns of virtual PAO, the number of hips with the lowest maximum contact pressure was highest at 15° of anterior rotation (53%; 20 of 38 hips), followed by 31% (12 of 38 hips) at 10° of anterior rotation, 16% (six of 38 hips) at 5° of anterior rotation, and no hips without anterior rotation.

Discussion

Inappropriate sagittal plane correction results in an increased risk of osteoarthritis progression following PAO [26, 40, 53]. Individual variations in sagittal pelvic tilt, along with acetabular deformity, affect the acetabular coverage and joint contact mechanics in dysplastic hips [22, 41, 44] and may have an impact on the direction and degree of acetabular correction in patients who undergo PAO. Therefore, we performed finite-element analyses that considered physiologic

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pelvic tilt to determine the effect of acetabular correction in the sagittal and coronal planes in virtual PAO. We found that normal joint contact pressure was achieved in 63% of hips (24 of 38 hips) by normalizing the lateral acetabular coverage. However, lateral acetabular rotation was insufficient to normalize the joint contact pressure in patients with more posteriorly tilted pelvises and anterior acetabular deficiency, especially those with a preoperative anterior center-edge angle < 32° in the standing pelvic position. In such cases, additional anterior rotation was effective to normalize the joint contact pressure.

Limitations

This study has several limitations. First, certain restrictions were introduced in the specification of loading and boundary conditions. In this study, only one loading condition (a single-leg stance) was investigated; other conditions corresponding to daily activities and the gait cycle were not evaluated. Previous mathematical modeling studies reported that contact stress distribution in dysplastic hips changes during the gait cycle, and even during stair walking in cases with a large acetabular anteversion [6, 18]. However, a recent study found that acetabular coverage measured in the standing position is a suitable surrogate for coverage measured during gait [45]; therefore, we posit that our observation of the single-leg stance scenario represents the loading conditions during walking [7]. Future finite-element analysis studies are needed to validate our findings with other activities. Moreover, although a constant joint resultant force was adopted for all subjects in the present study, the individual variety in hip joint geometry and changes in pelvic morphology and lateral-medial movement of the femoral head after PAO may

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alter muscle forces and joint reaction forces and affect the contact stress distribution in the hip joint [16, 25, 38]. The loading conditions applied in this study were derived from in vivo data from patients who underwent total hip arthroplasty [3] and are considered to approximate the actual loading conditions in the native hip joint. However, further studies are needed to elucidate how changes in the joint reaction force after PAO may affect the accuracy of the calculation of the joint contact pressure.

Second, we did not model patient-specific cartilage or the labrum because they were not clearly identifiable on plain CT images. Previous studies demonstrated the similarity of peak contact pressures between constant-thickness cartilage models and patient-specific cartilage models [28] and the validity of finite-element models without a labrum [2, 24]. However, the labrum may play a larger role in load transfer and joint stability [14], and further studies are required to determine the effect of the absence of the labrum. Third, we did not model impingement and it is unclear whether the anterior rotation performed in this study would lead to an increase in iatrogenic impingement. In order to optimize the joint contact mechanics while avoiding impingement following PAO, future studies should simulate impingement and evaluate the balance between acetabular coverage and hip range of motion. Fourth, we did not evaluate asphericity of the femoral head [39, 49] or incongruity between the acetabulum and femoral head [19], which are common findings in dysplastic hips that may contribute to the joint contact pressure's distribution after PAO. Further studies are required to evaluate the impact of these factors on the optimal acetabular reorientation during PAO.

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We further acknowledge that 55% of patients (47 of 85 patients) were not eligible for this study and only female patients met the criteria, which could have resulted in a selection bias. The demographic and radiographic parameters of the excluded patients did not differ from those of the included patients, suggesting that the risk of a potential bias was low. However, further research is needed to address the impact of differences in hip morphology between sexes on the generalizability of our observations. Additionally, although the hip dysplasia and control groups were comparable in age and BMI, the age of the control subjects was relatively young (mean, 36 ± 7 years) to define a biomechanically healthy hip joint, and only hips that are asymptomatic in the old age are ideal as normal hips [30]. However, we confirmed that control subjects had no history of hip disease, osteoarthritis, or morphology abnormalities, and their maximum contact pressures were comparable to the normal range reported in previous finite element analysis studies [47]; thus, we deemed them suitable as control subjects for this study. Lastly, the study population consisted of non-obese patients with a mean BMI of 22 ± 3. However, we defined a consistent body weight for all participants in order to avoid the scaling effect of body weight on the absolute value of contact pressure and to focus on the effect of individual differences in morphology and physiological pelvic tilt on contact pressure. Therefore, we believe that our observations are not influenced by the patient's BMI.

Does Lateral Rotation of the Acetabulum Normalize the Joint Contact Pressure?

Consistent with previous studies [20, 37], the current study showed that lateral rotation of the acetabulum is effective in correcting anterior and lateral coverage. Iwamoto et al. [20] reported

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that 79% of hips achieved normal anterior coverage after lateral rotation to a lateral center-edge angle of 30°, whereas 19% had residual anterior undercoverage and 2% had anterior overcoverage. Previous studies [28, 57] that used independent-specific finite-element models reported that the maximum contact pressure decreased 0.75-fold to 0.96-fold after mean lateral acetabular rotation of 7° to 10°. Similar to these reports, the median maximum contact pressure in this study decreased 0.5-fold after median lateral rotation of 18.6°, and the resulting maximum contact pressure was within the normal range in 63% of hips (24 of 38 hips). Therefore, because lateral rotation of the acetabulum can normalize the anterior and lateral acetabular coverage and joint contact pressure in a substantial number of patients, anterior acetabular rotation does not appear to be necessary in all patients in terms of preventing anterior femoroacetabular impingement after PAO.

Risk Factors for Abnormal Contact Pressure after Lateral Rotation of the Acetabulum

We observed that lateral rotation of the acetabulum failed to normalize the joint contact pressure in 37% (14/38 hips). Elevated joint contact pressure after lateral acetabular rotation was associated with posterior pelvic tilt and a decreased anterior center-edge angle in the standing position. Previous studies reported that posterior pelvic tilt while weightbearing decreased anterior-to-superior acetabular coverage of the femoral head and increased joint contact pressure [22, 41]. Therefore, the results of our study suggest that future morphology-based and biomechanics-based planning studies for PAO should consider the impact of individual variations in physiologic pelvic tilt while weightbearing on acetabular reorientation to optimize

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the mechanical environment in the hip. A previous study using CT-based simulated PAO revealed that a preoperative anterior center-edge angle < 37° was associate with residual anterior deficiency after lateral rotation of the acetabulum [20]. In this study, the anterior center-edge angle was also determined to be an independent factor for elevated contact pressure after lateral rotation. In a subgroup of patients with a preoperative anterior center-edge angle < 32° in the standing pelvic position, additional acetabular correction in the sagittal plane was necessary to normalize the joint contact pressure.

Does Additional Anterior Rotation of the Acetabular Fragment Reduce Joint Contact Pressure?

During the reorientation process of PAO, the first step is to achieve sufficient lateral coverage through coronal correction, and the second step is to achieve sufficient anterior coverage through anterior rotation [9, 43]. Although there have been several finite-element analysis studies considering multiplanar correction including the coronal and sagittal planes [27, 36, 56], no appropriate algorithm has been established for effectively combining sagittal and coronal acetabular correction to optimize the joint contact mechanics. A previous study using theoretical models demonstrated that anterolateral rotation of the acetabular fragment was more effective in reducing contact pressure than lateral rotation alone [15]. Similarly, in our study, we observed that the mean contact area further increased, and the median maximum contact pressure further decreased as the acetabular fragment was rotated anteriorly from 0° to 15° after lateral rotation. In a simulation study, Iwamoto et al. [20] reported that 10° to 15° of anterior rotation is appropriate to achieve sufficient anterior coverage while retaining posterior coverage.

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Unnecessary sagittal plane correction should be avoided, because it may result in posterior undercoverage or anterior overcoverage, leading to a worse prognosis [23, 26, 33, 53]. It should also be noted that the weightbearing acetabular cartilage area is limited in patients with severe dysplasia, making it difficult to achieve normal anterolateral coverage [54]. We simulated four patterns of acetabular reorientation in this study; however, the joint contact pressure could not be normalized in 8% (3 of 38 hips) with a severe form of anterior acetabular deficiency.

Conclusion

Using virtual PAO, we demonstrated that normal joint contact pressure was achieved in 63% (24 of 38 hips) of patients after normalizing lateral acetabular coverage, suggesting that anterior acetabular rotation may not always be necessary, especially when iatrogenic femoroacetabular impingement after PAO is a concern. Nevertheless, lateral acetabular rotation was insufficient to normalize the joint contact pressure in patients with more posteriorly tilted pelvises and anterior acetabular deficiency. In patients with a preoperative anterior center-edge angle < 32° in the standing pelvic position, additional anterior acetabular rotation is expected to be a useful guide to normalize the joint contact pressure. The results of this virtual PAO study suggest that future biomechanics-based planning for PAO should incorporate not only the morphology of the hip but also physiologic pelvic tilt while weightbearing to customize acetabular reorientation for individual patients.

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Legends

Fig. 1 This 3D surface model represents a dysplastic hip with a spherical osteotomy line (radius: 40 mm) centered on the femoral head center in the (A) AP and (B) lateral views.

Fig. 2 (A) The acetabular fragment was rotated laterally in the coronal plane to achieve a lateral center-edge angle of 30° to restore the normal lateral coverage of the femoral head. (B) After lateral rotation, the acetabular fragment was rotated anteriorly in the sagittal plane by 0°, 5°, 10°, and 15°.

Fig. 3 (A) This finite-element model represents the distribution of the elastic modulus (in MPa) in a dysplastic hip after virtual PAO. The meshed bone models were produced with a 2-mm tetrahedral element and a 0.4-mm triangular shell element on the surface. The meshed cartilage models of the acetabulum and femoral head were discretized using a locally refined 0.5-mm to 2.0-mm tetrahedral element in the weightbearing region of the acetabular cartilage. Three nodal shell elements, each with a thickness of 0.0005 mm, were placed on the surface of the acetabular cartilage to visualize the contact pressure on the acetabular cartilage. (B) The loading scenario was based on a single-leg stance, with the hip contact force acting on the nodal point at the center of the hip. During loading, the iliac crest and pubic area were completely fixed, and the distal femur was kept free only in the z direction while restrained in the x and y directions. Tied-contact and sliding-contact constraints were set on the cartilage-to-bone and cartilage-to-cartilage interfaces, respectively. The acetabular fragment was reconnected to the pelvis through a tied contact to simulate complete bony union. Frictional shear stress between the contacting articular

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surfaces was ignored.

Fig. 4 The receiver operating characteristic curve for abnormal maximum contact pressure after virtual PAO (to a lateral center-edge angle of 30°) is shown. Based on the curve, the cutoff value of the preoperative anterior center-edge in the standing pelvic position was 31.8° (sensitivity 57%, specificity 96%, area under the curve 0.77).

Fig. 5 This figure shows the distribution of joint contact pressures on the acetabular cartilage of the right hip in representative patients from the hip dysplasia group (lateral center-edge angle of 16°) before and after virtual PAO and the control group (lateral center-edge angle of 30°). Lateral rotation of the acetabular fragment decreased the joint contact pressure, and subsequent anterior rotation further decreased this pressure, as reflected in the color distribution.

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