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

北村,健二

https://hdl.handle.net/2324/4784460

# 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

Kenji Kitamura MD, Masanori Fujii MD, PhD, Miho Iwamoto MD, PhD, Satoshi Ikemura MD, PhD, Satoshi Hamai MD, PhD, Goro Motomura MD, PhD, Yasuharu Nakashima, MD, PhD

K. Kitamura, M. Fujii, M. Iwamoto, S. Ikemura, S. Hamai, G. Motomura, Y. Nakashima Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University, Fukuoka, Japan

This work was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (No. JP18K09109, JP21K09281). Each author certifies that neither he, nor any member of his immediate family, has funding or commercial associations (consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article.

All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research*<sup>®</sup> editors and board members are on file with the publication and can be viewed on request.

Ethical approval for this study was obtained from the Graduate School of Medical Sciences, Kyushu University (approval number 30-137).

M. Fujii Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University 3-1-1 Maidashi. Higashi-ku Fukuoka 812-8582, Japan Email: m-fujii@ortho.med.kyushu-u.ac.jp

#### 1 Abstract

2 *Background* Inappropriate sagittal plane correction can result in an increased risk of 3 osteoarthritis progression after periacetabular osteotomy (PAO). Individual and postural 4 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 5 6 analyses that account for physiologic pelvic tilt may provide valuable insight into the effect of 7 PAO on the contact mechanics of dysplastic hips, which may lead to improved acetabular 8 correction during PAO. 9 Questions/purposes We performed virtual PAO using finite-element models with reference to the 10 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 11 acetabulum, and (3) whether additional anterior rotation of the acetabulum further reduces 12 13 contact pressure. Methods Between 2016 to 2020, 85 patients (92 hips) underwent PAO to treat hip dysplasia. 14 15 Eighty-two patients with hip dysplasia (lateral center-edge angle  $< 20^{\circ}$ ) were included. Patients with advanced osteoarthritis, femoral head deformity, prior hip or supine surgery, or poor-quality 16 17 imaging were excluded. Thirty-eight patients (38 hips) were eligible to this study. All patients were female, with a mean age of  $39 \pm 10$  years. Thirty-three female volunteers without a history 18 19 of hip disease were reviewed for controls. Individual with a lateral center-edge angle  $< 25^{\circ}$  or 20 poor-quality imaging were excluded. Sixteen individuals (16 hips) with a mean age of  $36 \pm 7$ 

21 years were eligible as controls. Using CT images, we developed patient-specific 3D surface hip 22 models with the standing pelvic position as a reference. The loading scenario was based on the 23 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 24 25 was 30°, then anterior rotation in the sagittal plane was added by  $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$ . We developed finite-element models for each acetabular position and performed a nonlinear contact 26 27 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 28 29 characteristic curve. A paired t-test or Wilcoxon's signed-rank test with Bonferroni's correction 30 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 31 32 version and coverage using Pearson's or Spearman's correlation coefficient. An exploratory 33 univariate logistic regression analysis was performed to identify which of the preoperative factors (CT measurement parameters and sagittal pelvic tilt) were associated with abnormal 34 contact pressure after lateral rotation of the acetabulum. Variables with p values < 0.05 (anterior 35 36 center-edge angle and sagittal pelvic tilt) were included in a multivariable model to identify the 37 independent influence of each factor.

38 *Results* Lateral rotation of the acetabulum decreased the median maximum contact pressure

- 39 compared with that before virtual PAO (3.7 MPa [2.2 to 6.7] versus 7.2 MPa [4.1 to 14];
- 40 difference of medians 3.5 MPa; p < 0.001). The resulting maximum contact pressures were

41 within the normal range (< 4.1 MPa) in 63% of the hips (24 of 38 hips). The maximum contact AU: Please do not delete query boxes or remove line numbers; ensure you address each query in the query box. You may modify text within selected text or outside the selected text (as appropriate) without deleting the query.</p>

42 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 = 43 0.003). After controlling for confounding variables such as lateral center-edge angle and sagittal 44 pelvic tilt, we found that a decreased preoperative anterior center-edge angle (per 1°; odds ratio 45 46 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  $< 32^{\circ}$  in the 47 standing pelvic position was associated with elevated contact pressure (sensitivity 57%, 48 49 specificity 96%, area under the curve 0.77). Additional anterior rotation further decreased the 50 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 51 rotated anteriorly by 5°, 10°, and 15°, respectively. 52 Conclusion Via virtual PAO, normal joint contact pressure was achieved in 63% of patients by 53 normalizing the lateral acetabular coverage. However, lateral acetabular rotation was insufficient 54 to normalize the joint contact pressure in patients with more posteriorly tilted pelvises and 55

anterior acetabular deficiency. In patients with a preoperative anterior center-edge angle  $< 32^{\circ}$  in the standing pelvic position, additional anterior rotation is expected to be a useful guide to

58 normalize the joint contact pressure.

59 *Clinical Relevance* This virtual PAO study suggests that biomechanics-based planning for PAO 60 should incorporate not only the morphology of the hip but also the physiologic pelvic tilt in the 61 weightbearing position in order to customize acetabular reorientation for each patient.

62

#### 63 Introduction

Periacetabular osteotomies (PAO) are performed in young adults with symptomatic hip dysplasia 64 65 to delay or prevent the development of hip osteoarthritis [5, 55]. PAO improves acetabular 66 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 67 68 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  $\geq 2$ , and joint 69 70 incongruity [26, 33, 48, 50, 53]. Considering substantial individual variations in acetabular 71 version and deficiency types, acetabular correction must be customized for each patient, rather than applying uniform correction [10, 11, 34, 57]. 72 73 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-7475 edge angle has a greater impact on improving the natural history after PAO. Hip dysplasia 76 typically manifests with anterolateral acetabular deficiency [10, 11], in which shearing stress and 77 contact stress are concentrated on the anterolateral acetabular rim [13, 22]. Therefore, adequate 78 sagittal plane correction of the anterior undercoverage is crucial for successful hip preservation 79 [15, 20, 40]. However, care should be taken not to overcorrect the sagittal plane because 80 excessive anterior coverage can result in iatrogenic femoroacetabular impingement [26, 33], and 81 anterior rotation of the acetabulum should be reserved for patients with residual anterior 82 undercoverage after lateral acetabular rotation [20]. Currently, the characteristics of patients who

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.

86 Individual-specific finite-element modeling has been shown to be potentially useful for ensuring 87 the appropriate acetabular correction during the preoperative planning of PAO [28, 57]. 88 However, in these previous studies, acetabular correction was performed only in the coronal 89 plane, and the effect of sagittal plane correction on the joint contact mechanics was not 90 evaluated. Although there are a few studies that have considered sagittal plane correction [27, 36, 91 56], these studies involved finite-element analyses of dysplastic hips using the supine position or 92 the standardized pelvic position that was based on the anterior pelvic plane's coordinate system. 93 Recent studies have revealed that the sagittal pelvic tilt varies widely among candidates for hip 94 preservation surgery and suggested that assessments in the standard pelvic position may overlook 95 changes in acetabular coverage and joint contact stress in the weightbearing position [22, 41, 44]. 96 Finite-element analyses that incorporate the physiologic pelvic tilt may provide additional insight 97 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. 98

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

## 103 contact pressure.

## 104 **Patients and Methods**

105 Patients

106 Between September 2016 and March 2020, 85 patients (92 hips) with symptomatic hip dysplasia 107 underwent transposition osteotomy of the acetabulum, one of the established PAOs to treat 108 symptomatic hip dysplasia, which is characterized by a lateral approach and spherical osteotomy 109 [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 110 by 82 patients [82 hips]) was the presence of hip dysplasia with a lateral center-edge angle  $< 20^{\circ}$ 111 on supine AP pelvic radiographs [51]. In patients with bilateral hip dysplasia, the operated-on 112 side was investigated. Patients were excluded if they had advanced osteoarthritis (Tönnis grade  $\geq$ 113 2 [42] (n = 13 patients), major femoral head deformity (n = 1), history of surgery on either hip 114 (n = 15), history of treatment for spinal disease (n = 1), or images with insufficient quality for 115 analysis (n = 14). Thus, 38 patients were eligible for this study. All patients were female and had 116 117 a mean age of 39 years  $\pm$  10 years (Table 1).

118 The AP pelvic radiographs and CT images of 33 female volunteers obtained for previous studies

119 were reviewed as the control group [12, 22]. No participants in the control group had a history of

120 diseases or articular symptoms in their hips, as determined by medical interviews and

121 radiographic examinations. All participants provided written informed consent to participate in

122 this study and were informed of radiation exposure. Seven patients with frank or borderline hip AU: Please do not delete query boxes or remove line numbers; ensure you address each query in the query box. You may modify text within selected text or outside the selected text (as appropriate) without deleting the query. 123dysplasia (lateral center-edge angle  $< 25^{\circ}$ ) and 10 without suitable images were excluded. Thus,12416 individuals (16 randomly selected hips) with a mean age of 36 years  $\pm$  7 years were included125as the control group (Table 1).

126 CT Evaluations

127 Pelvic CT images were taken from the superior rim of the pelvis to the distal femur (matrix: 512 128  $\times$  512, field of view: 261-670 mm, slice thickness: 1 mm or 2 mm), with the patient or volunteer 129 in the supine position. We measured sagittal pelvic tilt with the participant in the standing 130 position and the morphologic parameters using the 3D Template software (Kyocera Medical 131 Corporation). The x and y axes corresponded to the transverse and sagittal axes on the axial CT 132 slice, respectively, while the z axis corresponded to the longitudinal axis of the scanner. First, the 133 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 134 135 radiograph was reproduced on the digitally reconstructed radiographs by matching the vertical-136 to-horizontal ratio of the pelvic foramen. A previous study demonstrated that the correlation 137 coefficient for the vertical-to-horizontal ratio between AP radiographs and the CT-based images 138 in the same pelvic tilt was 0.99 (p < 0.001) [35]. Sagittal pelvic tilt was measured as the angle 139 formed by the anterior pelvic plane and the z axis (anterior pelvic plane angle), with positive 140 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 141 142 posterior center-edge angles, acetabular roof obliquity, acetabular anteversion angle, and

### 143 acetabular inclination angle [32].

#### 144 Virtual PAO and Finite-element Analysis

145 Mechanical Finder version 10 (Research Center for Computational Mechanics Inc.) was used to 146 create 3D surface models of the hemipelvis, proximal femur, and articular cartilage in order to 147 describe the bony shape and density distribution visible on CT images [22, 46]. The articular 148 cartilage of the acetabulum and femoral head was modeled with a constant thickness (1.8 mm) as 149 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 150 151 radius of the osteotomy line is 40 mm in most female patients. The pubic osteotomy site was 152 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]. 153 The acetabular fragment was reoriented in four patterns with reference to the standing pelvic 154 155 position. First, the acetabular fragment was rotated laterally in the coronal plane to achieve a 156 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). 157 158 The 3D surface models of bone and articular cartilage were meshed using a previously described 159 method [22] (Fig. 3A). The mean numbers of finite elements and shell elements did not differ 160 between the models of before and after virtual PAO (1,359,085  $\pm$  128,332 versus 1,357,732  $\pm$ 161 128,988; p = 0.64 and  $64,853 \pm 5,459$  versus  $65,215 \pm 4,912$ ; p = 0.08, respectively). To allow 162 for bone heterogeneity, the distribution of bone mineral densities ( $\rho$  in g/cm<sup>3</sup>) was estimated AU: Please do not delete query boxes or remove line numbers; ensure you address each query in the query box. You may modify text within selected text or outside the selected text (as appropriate) without deleting the query.

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].

#### 168 Boundary and Loading Conditions

169 Nonlinear contact analyses were performed using the finite-element models of the dysplastic hips 170 before and after four patterns of virtual PAO and the control group to calculate the joint contact 171 area and joint contact pressure of the acetabular cartilage. In all analyses, load was applied with 172 the participant in the standing pelvic position. The finite-element model of the femur was 173 standardized with reference to the coordinate system described by the International Society of 174Biomechanics [52]. The definitions of tied-contact and sliding-contact constraints were set using 175 previously reported cartilage-to-bone and cartilage-to cartilage interfaces [4]. In the virtual PAO 176 models, the acetabular fragment was reconnected to the pelvis through tied contact to simulate 177complete bony union. The iliac crest and pubic region were completely fixed, while the distal 178 femur was restrained in the x and y directions and kept free only in the z direction. The loading 179 scenario was based on a single-leg stance, with the hip contact force acting on the nodes of the 180 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 181 182 contact force was set at 1158 N, and the components of the x, y, and z axes were set at 150 N, 71

183 N, and 1146 N, respectively. The loaded nodes were allowed to move only in the direction of the184 applied load.

185 Ethical Approval

186 The ethical review board at our institution approved this retrospective study (approval number 187 30-137). All participants in both groups provided written informed consent to participate in this 188 study and were informed of the radiation exposure required.

189 Statistical Analysis

A t-test or Wilcoxon's rank sum test was used to compare continuous parameters between the hip 190 191 dysplasia and control groups after we confirmed normal distribution and homoscedasticity 192 (Shapiro-Wilk W test and F test). The chi-square test was used to compare categorical parameters 193 between two groups, while the paired t-test or Wilcoxon's signed rank test with Bonferroni's 194 correction was used to compare continuous parameters before and after virtual PAO. The 195 Dunnett or Steel test with the normal hip as a control was used for multiple comparisons, as 196 appropriate. Statistical significance was set at p < 0.05. The correlation between two continuous 197 parameters was evaluated using Pearson's or Spearman's correlation coefficient, as appropriate. 198 The cutoff value of the normal maximum joint contact pressure was calculated to be 4.1 MPa 199 using a receiver operating characteristic curve (sensitivity 100%, specificity 94%, AUC 0.99). A 200 exploratory univariate logistic regression analysis was performed to screen for preoperative 201 factors associated with abnormal contact pressure after lateral rotation of the acetabulum among 202 morphological factors (anterior, lateral, and posterior center-edge angles, acetabular roof AU: Please do not delete query boxes or remove line numbers; ensure you address each query in the query box. You may modify text within selected text or outside the selected text (as appropriate) without deleting the query.

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</li>
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<sup>®</sup> version 15.0 (SAS Institute).

209 Results

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

The mean contact area was smaller ( $500 \pm 134 \text{ mm}^2$  versus  $919 \pm 121 \text{ mm}^2$ ; mean difference 420 211  $mm^2$  [95% CI 342 to 497]; p < 0.001) and the median maximum contact pressure was higher (7.2 212 213 MPa [4.1 to 14] versus 3.5 MPa [2.2 to 4.4]; difference of medians 3.7 MPa; p < 0.001) in 214 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 215 contact area increased ( $898 \pm 164 \text{ mm2}$  versus  $500 \pm 134 \text{ mm}^2$ ; mean difference  $398 \text{ mm}^2$  [95%216 217 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 218 preoperative value, resulting in no difference in the mean contact area ( $898 \pm 164 \text{ mm}^2$  versus 219  $919 \pm 121 \text{ mm}^2$ ; mean difference  $21 \text{ mm}^2$  [95% CI -70 to 113]; p = 0.64) or median maximum 220 221 contact pressure (3.7 MPa [2.2 to 6.7] versus 3.5 MPa [2.2 to 4.4]; difference of medians 0.2 222 MPa; p = 0.37) between patients with hip dysplasia and control participants (Table 2). Based on AU: Please do not delete query boxes or remove line numbers; ensure you address each query in the query box. You may modify text within selected text or outside the selected text (as

appropriate) without deleting the query.

223 the cutoff value of the normal maximum contact pressure (4.1MPa), 63% of the hips (24 of 38 224 hips) achieved the normal range of maximum contact pressure after virtual PAO (Table 2). CT 225 parameters improved after virtual PAO (to a lateral center-edge angle of 30°) except the posterior 226 center-edge angle and acetabular anteversion (Table 3). However, the anterior center-edge angle  $(47^{\circ} \pm 6^{\circ} \text{ versus } 52^{\circ} \pm 8^{\circ}; \text{ mean difference } 6^{\circ} [95\% \text{ CI } 2^{\circ} \text{ to } 10^{\circ}]; \text{ } \text{p} = 0.03)$  and posterior center-227 edge angle ( $94^\circ \pm 9^\circ$  versus  $106^\circ \pm 9^\circ$ ; mean difference  $12^\circ$  [95% CI  $7^\circ$  to  $17^\circ$ ]; p < 0.001) were 228 still lower and the acetabular anteversion angle was higher (29° [18° to 57°] versus 20° [10° to 229 26°]; difference of medians 9°; p < 0.001) in dysplastic hips after virtual PAO than in the control 230 231 hips (Table 3).

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

233 Before virtual PAO, the maximum contact pressure was negatively correlated with the anterior 234 and lateral center-edge angles and the standing anterior pelvic plane angle, and positively 235 correlated with acetabular roof obliquity and the acetabular inclination angle (Table 4). When the 236acetabular fragment was rotated laterally to a lateral center-edge angle of 30°, the maximum 237 contact pressure was negatively correlated with the anterior center-edge angle and standing 238 anterior pelvic plane angle (Table 4). After controlling for potential confounding variables such 239 as lateral center-edge angle and sagittal pelvic tilt, we found that a decreased preoperative 240 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 ( $\geq 4.1$  MPa) after virtual PAO (Table 241 242 5). The receiver operating characteristic curve analysis determined that a preoperative anterior

243 center-edge angle  $< 32^{\circ}$  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).

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

247 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

249 pressure at 10° and 15° of anterior rotation was lower than that at 0° of anterior rotation (that is,

250 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

252 10° of anterior rotation, and 84% (32 of 38 hips) at 15° of anterior rotation (Table 2). Among the

253 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.

## 257 Discussion

258 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
 AU: Please do not delete query boxes or remove line numbers; ensure you address each query in the query box. You may modify text within selected text or outside the selected text (as appropriate) without deleting the query.

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 centeredge angle <  $32^{\circ}$  in the standing pelvic position. In such cases, additional anterior rotation was effective to normalize the joint contact pressure.

270 Limitations

271 This study has several limitations. First, certain restrictions were introduced in the specification 272of loading and boundary conditions. In this study, only one loading condition (a single-leg 273 stance) was investigated; other conditions corresponding to daily activities and the gait cycle 274were not evaluated. Previous mathematical modeling studies reported that contact stress 275distribution in dysplastic hips changes during the gait cycle, and even during stair walking in 276 cases with a large acetabular anteversion [6, 18]. However, a recent study found that acetabular 277 coverage measured in the standing position is a suitable surrogate for coverage measured during 278 gait [45]; therefore, we posit that our observation of the single-leg stance scenario represents the 279 loading conditions during walking [7]. Future finite-element analysis studies are needed to 280 validate our findings with other activities. Moreover, although a constant joint resultant force 281 was adopted for all subjects in the present study, the individual variety in hip joint geometry and 282 changes in pelvic morphology and lateral-medial movement of the femoral head after PAO may

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.

289 Second, we did not model patient-specific cartilage or the labrum because they were not clearly 290 identifiable on plain CT images. Previous studies demonstrated the similarity of peak contact 291 pressures between constant-thickness cartilage models and patient-specific cartilage models [28] 292 and the validity of finite-element models without a labrum [2, 24]. However, the labrum may 293 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 294unclear whether the anterior rotation performed in this study would lead to an increase in 295 296 iatrogenic impingement. In order to optimize the joint contact mechanics while avoiding impingement following PAO, future studies should simulate impingement and evaluate the 297 298 balance between acetabular coverage and hip range of motion. Fourth, we did not evaluate 299 asphericity of the femoral head [39, 49] or incongruity between the acetabulum and femoral head 300 [19], which are common findings in dysplastic hips that may contribute to the joint contact 301 pressure's distribution after PAO. Further studies are required to evaluate the impact of these 302 factors on the optimal acetabular reorientation during PAO.

303 We further acknowledge that 55% of patients (47 of 85 patients) were not eligible for this study 304 and only female patients met the criteria, which could have resulted in a selection bias. The 305 demographic and radiographic parameters of the excluded patients did not differ from those of 306 the included patients, suggesting that the risk of a potential bias was low. However, further 307 research is needed to address the impact of differences in hip morphology between sexes on the 308 generalizability of our observations. Additionally, although the hip dysplasia and control groups 309 were comparable in age and BMI, the age of the control subjects was relatively young (mean, 36 310  $\pm$  7 years) to define a biomechanically healthy hip joint, and only hips that are asymptomatic in 311 the old age are ideal as normal hips [30]. However, we confirmed that control subjects had no 312 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 313 314 studies [47]; thus, we deemed them suitable as control subjects for this study. Lastly, the study 315 population consisted of non-obese patients with a mean BMI of  $22 \pm 3$ . However, we defined a 316 consistent body weight for all participants in order to avoid the scaling effect of body weight on 317 the absolute value of contact pressure and to focus on the effect of individual differences in 318 morphology and physiological pelvic tilt on contact pressure. Therefore, we believe that our 319 observations are not influenced by the patient's BMI.

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

321 Consistent with previous studies [20, 37], the current study showed that lateral rotation of the 322 acetabulum is effective in correcting anterior and lateral coverage. Iwamoto et al. [20] reported

323 that 79% of hips achieved normal anterior coverage after lateral rotation to a lateral center-edge 324 angle of 30°, whereas 19% had residual anterior undercoverage and 2% had anterior 325 overcoverage. Previous studies [28, 57] that used independent-specific finite-element models 326 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 327 328 in this study decreased 0.5-fold after median lateral rotation of 18.6°, and the resulting maximum 329 contact pressure was within the normal range in 63% of hips (24 of 38 hips). Therefore, because 330 lateral rotation of the acetabulum can normalize the anterior and lateral acetabular coverage and 331 joint contact pressure in a substantial number of patients, anterior acetabular rotation does not 332 appear to be necessary in all patients in terms of preventing anterior femoroacetabular

impingement after PAO.

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

335 We observed that lateral rotation of the acetabulum failed to normalize the joint contact pressure 336 in 37% (14/38 hips). Elevated joint contact pressure after lateral acetabular rotation was 337 associated with posterior pelvic tilt and a decreased anterior center-edge angle in the standing 338 position. Previous studies reported that posterior pelvic tilt while weightbearing decreased 339 anterior-to-superior acetabular coverage of the femoral head and increased joint contact pressure 340 [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 341 342 variations in physiologic pelvic tilt while weightbearing on acetabular reorientation to optimize

the mechanical environment in the hip. A previous study using CT-based simulated PAO revealed that a preoperative anterior center-edge angle  $< 37^{\circ}$  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  $< 32^{\circ}$  in the standing pelvic position, additional acetabular correction in the sagittal plane was necessary to normalize the joint contact pressure.

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

351 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 352 anterior rotation [9, 43]. Although there have been several finite-element analysis studies 353 considering multiplanar correction including the coronal and sagittal planes [27, 36, 56], no 354 appropriate algorithm has been established for effectively combining sagittal and coronal 355 356 acetabular correction to optimize the joint contact mechanics. A previous study using theoretical 357 models demonstrated that anterolateral rotation of the acetabular fragment was more effective in 358 reducing contact pressure than lateral rotation alone [15]. Similarly, in our study, we observed 359 that the mean contact area further increased, and the median maximum contact pressure further 360 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 361 362 appropriate to achieve sufficient anterior coverage while retaining posterior coverage.

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.

369 Conclusion

370 Using virtual PAO, we demonstrated that normal joint contact pressure was achieved in 63% (24 371 of 38 hips) of patients after normalizing lateral acetabular coverage, suggesting that anterior 372 acetabular rotation may not always be necessary, especially when iatrogenic femoroacetabular 373 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 374 acetabular deficiency. In patients with a preoperative anterior center-edge angle  $< 32^{\circ}$  in the 375 376 standing pelvic position, additional anterior acetabular rotation is expected to be a useful guide to 377 normalize the joint contact pressure. The results of this virtual PAO study suggest that future 378 biomechanics-based planning for PAO should incorporate not only the morphology of the hip but 379 also physiologic pelvic tilt while weightbearing to customize acetabular reorientation for 380 individual patients.

## Acknowledgments

We thank Mitsugu Todo PhD (Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan), Takeshi Utsunomiya MD, Kyohei Shiomoto MD, Ryosuke Yamaguchi MD, Taishi Sato MD, Shinya Kawahara MD (Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University, Fukuoka, Japan) for their invaluable advice for this study.

## References

1. Abraham CL, Knight SJ, Peters CL, Weiss JA, Anderson AE. Patient-specific chondrolabral contact mechanics in patients with acetabular dysplasia following treatment with peri-acetabular osteotomy. *Osteoarthritis Cartilage*. 2017;25:676–684.

 Anderson AE, Ellis BJ, Maas SA, Peters CL, Weiss JA. Validation of Finite Element Predictions of Cartilage Contact Pressure in the Human Hip Joint. *J. Biomech. Eng.* 2008;130:051008.

3. Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda GN. Hip contact forces and gait patterns from routine activities. *J Biomech*. 2001;34:859–871.

4. Caligaris M, Ateshian GA. Effects of sustained interstitial fluid pressurization under migrating contact area, and boundary lubrication by synovial fluid, on cartilage friction. *Osteoarthritis Cartilage*. 2008;16:1220–1227.

5. Clohisy JC, Schutz AL, St John L, Schoenecker PL, Wright RW. Periacetabular osteotomy: a systematic literature review. *Clin Orthop Relat Res*. 2009;467:2041–2052.

6. Daniel M, Iglič A, Kralj-Iglič V. Hip contact stress during normal and staircase walking: the influence of acetabular anteversion angle and lateral coverage of the acetabulum. *J Appl Biomech*. 2008;24:88–93.

7. Debevec H, Pedersen DR, Iglič A, Daniel M. One-legged stance as a representative static body position for calculation of hip contact stress distribution in clinical studies. *J Appl Biomech*.

2010;26:522-525.

Fujii M, Nakashima Y, Kitamura K, Motomura G, Hamai S, Ikemura S, Noguchi Y.
 Preoperative rather than Postoperative Intra-articular Cartilage Degeneration Affects Long-term
 Survivorship of Periacetabular Osteotomy. *Arthroscopy*. 2021 in press.

9. Fujii M, Nakashima Y, Noguchi Y, Yamamoto T, Mawatari T, Motomura G, Iwamoto Y. Effect of intra-articular lesions on the outcome of periacetabular osteotomy in patients with symptomatic hip dysplasia. *J Bone Joint Surg Br*. 2011;93:1449–1456.

10. Fujii M, Nakashima Y, Sato T, Akiyama M, Iwamoto Y. Pelvic deformity influences acetabular version and coverage in hip dysplasia. *Clin Orthop Relat Res*. 2011;469:1735–1742.

11. Ganz R, Leunig M. Morphological variations of residual hip dysplasia in the adult. *Hip Int*. 2007;17:22–28.

12. Hara D, Nakashima Y, Hamai S, Higaki H, Ikebe S, Shimoto T, Hirata M, Kanazawa M, Kohno Y, Iwamoto Y. Kinematic analysis of healthy hips during weight-bearing activities by 3D-to-2D model-to-image registration technique. *Biomed Res Int.* 2014;2014:457573–8.

13. Henak CR, Abraham CL, Anderson AE, Maas SA, Ellis BJ, Peters CL, Weiss JA. Patientspecific analysis of cartilage and labrum mechanics in human hips with acetabular dysplasia. *Osteoarthritis Cartilage*. 2014;22:210–217.

14. Henak CR, Ellis BJ, Harris MD, Anderson AE, Peters CL, Weiss JA. Role of the acetabular labrum in load support across the hip joint. *J Biomech*. 2011;44:2201–2206.

15. Hipp JA, Sugano N, Millis MB, Murphy SB. Planning acetabular redirection osteotomies based on joint contact pressures. *Clin Orthop Relat Res*. 1999;364:134–143.

16. Iglic A, Iglic VK, Antolic V, Srakar F, Stanic U. Effect of the periacetabular osteotomy on the stress on the human hip joint articular surface. *IEEE Trans Rehabil Eng.* 1993;1:207–212.

17. Ike H, Inaba Y, Kobayashi N, Yukizawa Y, Hirata Y, Tomioka M, Saito T. Effects of rotational acetabular osteotomy on the mechanical stress within the hip joint in patients with developmental dysplasia of the hip: a subject-specific finite element analysis. *Bone Joint J*. 2015;97:492–497.

18. Ipavec M, Brand RA, Pedersen DR, Mavcic B, Kralj-Iglic V, Iglic A. Mathematical modelling of stress in the hip during gait. *J Biomech*. 1999;32:1229–1235.

19. Irie T, Orías AAE, Irie TY, Nho SJ, Takahashi D, Iwasaki N, Inoue N. Three-dimensional curvature mismatch of the acetabular radius to the femoral head radius is increased in borderline dysplastic hips. *PLoS ONE*. 2020;15:e0231001.

20. Iwamoto M, Fujii M, Komiyama K, Sakemi Y, Shiomoto K, Kitamura K, Yamaguchi R, Nakashima Y. Is lateral acetabular rotation sufficient to correct anterolateral deficiency in periacetabular reorientation osteotomy? A CT-Based simulation study. *J Orthop Sci.* 2020;25:1008–1014.

21. Keyak JH, Rossi SA, Jones KA, Skinner HB. Prediction of femoral fracture load using automated finite element modeling. *J Biomech*. 1998;31:125–133.

22. Kitamura K, Fujii M, Utsunomiya T, Iwamoto M, Ikemura S, Hamai S, Motomura G, Todo M, Nakashima Y. Effect of sagittal pelvic tilt on joint stress distribution in hip dysplasia: A finite element analysis. *Clin Biomech (Bristol, Avon)*. 2020;74:34–41.

23. Kiyama T, Naito M, Shiramizu K, Shinoda T. Postoperative acetabular retroversion causes posterior osteoarthritis of the hip. *Inter Orthop*. 2009;33:625–631.

24. Konrath GA, Hamel AJ, Olson SA, Bay B, Sharkey NA. The role of the acetabular labrum and the transverse acetabular ligament in load transmission in the hip. *J Bone Joint Surg Am*. 1998;80:1781–1788.

25. Kralj M, Mavčič B, Antolič V, Iglič A, Kralj-Iglič V. The Bernese periacetabular osteotomy:
clinical, radiographic and mechanical 7-15-year follow-up of 26 hips. *Acta Orthop.*2005;76:833–840.

26. Lerch TD, Steppacher SD, Liechti EF, Tannast M, Siebenrock KA. One-third of hips after periacetabular osteotomy survive 30 years with good clinical results, no progression of arthritis, or conversion to THA. *Clin Orthop Relat Res.* 2017;475:1154–1168.

27. Liu L, Ecker T, Xie L, Schumann S, Siebenrock K, Zheng G. Biomechanical validation of computer assisted planning of periacetabular osteotomy: A preliminary study based on finite element analysis. *Med Eng Phys.* 2015;37:1169–1173.

28. Liu L, Ecker TM, Schumann S, Siebenrock KA, Zheng G. Evaluation of constant thickness cartilage models vs. patient specific cartilage models for an optimized computer-assisted

planning of periacetabular osteotomy. PLoS ONE. 2016;11:e0146452.

29. Mavcic B, Pompe B, Antolic V, Daniel M, Iglic A, Kralj-Iglic V. Mathematical estimation of stress distribution in normal and dysplastic human hips. *J Orthop Res.* 2002;20:1025–1030.

30. Mavcic B, Slivnik T, Antolic V, Iglic A, Kralj-Iglic V. High contact hip stress is related to the development of hip pathology with increasing age. *Clin Biomech (Bristol Avon)*. 2004;19:939–943.

31. Miyamura S, Oka K, Abe S, Shigi A, Tanaka H, Sugamoto K, Yoshikawa H, Murase T. Altered bone density and stress distribution patterns in long-standing cubitus varus deformity and their effect during early osteoarthritis of the elbow. *Osteoarthritis Cartilage*. 2018;26:72–83.

32. Miyasaka D, Sakai Y, Ibuchi S, Suzuki H, Imai N, Endo N. Sex- and age-specific differences in femoral head coverage and acetabular morphology among healthy subjects-derivation of normal ranges and thresholds for abnormality. *Skeletal Radiol*. 2017;46:523–531.

33. Myers SR, Eijer H, Ganz R. Anterior femoroacetabular impingement after periacetabular osteotomy. *Clin Orthop Relat Res.* 1999;363:93–99.

34. Nepple JJ, Wells J, Ross JR, Bedi A, Schoenecker PL, Clohisy JC. Three patterns of acetabular deficiency are common in young adult patients with acetabular dysplasia. *Clin Orthop Relat Res*. 2017;475:1037–1044.

35. Nishihara S, Sugano N, Nishii T, Ohzono K, Yoshikawa H. Measurements of pelvic flexion angle using three-dimensional computed tomography. *Clin Orthop Relat Res.* 2003;411:140–151.

36. Park SJ, Lee SJ, Chen WM, Park JH, Cho YS, Shin T, Kwon SY. Computer-assisted optimization of the acetabular rotation in periacetabular osteotomy using patient's anatomy-specific finite element analysis. *Appl Bionics Biomech*. 2018;2018:9730525.

37. Rab GT. Lateral acetabular rotation improves anterior hip subluxation. *Clin Orthop Relat Res.* 2007;456:170–175.

Srakar F, Iglic A, Antolic V, Herman S. Computer simulation of periacetabular osteotomy.
 *Acta Orthop Scand.* 1992;63:411–412.

39. Steppacher SD, Tannast M, Werlen S, Siebenrock KA. Femoral morphology differs between deficient and excessive acetabular coverage. *Clin Orthop Relat Res*. 2008;466:782–790.

40. Stetzelberger VM, Leibold CS, Steppacher SD, Schwab JM, Siebenrock KA, Tannast M. The acetabular wall index is associated with long-term conversion to THA after PAO. *Clin Orthop Relat Res.* 2021;479:1052–1065.

41. Tachibana T, Fujii M, Kitamura K, Nakamura T, Nakashima Y. Does acetabular coverage vary between the supine and standing positions in patients with hip dysplasia? *Clin Orthop Relat Res*. 2019;477:2455–2466.

42. Tönnis D, Legal H. Congenital dysplasia and dislocation of the hip in children and adults. Springer-Verlag (Berlin and New York); 1987:165–171.

43. Troelsen A, Elmengaard B, Soballe K. A new minimally invasive transsartorial approach for periacetabular osteotomy. *J Bone Joint Surg Am*. 2008;90:493–498.

44. Troelsen A, Jacobsen S, Rømer L, Søballe K. Weightbearing anteroposterior pelvic radiographs are recommended in DDH assessment. *Clin Orthop Relat Res.* 2008;466:813–819.

45. Uemura K, Atkins PR, Maas SA, Peters CL, Anderson AE. Three-dimensional femoral head coverage in the standing position represents that measured in vivo during gait. *Clin Anat*. 2018;31:1177–1183.

46. Utsunomiya T, Motomura G, Ikemura S, Kubo Y, Sonoda K, Hatanaka H, Baba S, Kawano K, Yamamoto T, Nakashima Y. Effects of sclerotic changes on stress concentration in early-stage osteonecrosis: A patient-specific, 3D finite element analysis. *J Orthop Res.* 2018;36:3169–3177.

47. Vafaeian B, Zonoobi D, Mabee M, Hareendranathan AR, El-Rich M, Adeeb S, Jaremko JL. Finite element analysis of mechanical behavior of human dysplastic hip joints: a systematic review. *Osteoarthritis Cartilage*. 2017;25:438–447.

48. Wells J, Millis M, Kim Y-J, Bulat E, Miller P, Matheney T. Survivorship of the Bernese periacetabular osteotomy: What factors are associated with long-term failure? *Clin Orthop Relat Res*. 2017;475:396–405.

49. Wells J, Nepple JJ, Crook K, Ross JR, Bedi A, Schoenecker P, Clohisy JC. Femoral morphology in the dysplastic hip: Three-dimensional characterizations with CT. *Clin Orthop Relat Res*. 2017;475:1045–1054.

50. Wells J, Schoenecker P, Duncan S, Goss CW, Thomason K, Clohisy JC. Intermediate-term hip survivorship and patient-reported outcomes of periacetabular osteotomy: The Washington

university experience. J Bone Joint Surg Am. 2018;100:218-225.

51. Wiberg G. Studies on dysplastic acetabula and congenital subluxation of the hip joint: with special reference to the complication of osteo-arthritis. *Acta Chir Scand*; 1939:5–135.

52. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, Witte H, Schmid O, Stokes I, Standardization and Terminology Committee of the International Society of Biomechanics. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of Biomechanics. *J Biomech*. 2002;35:543–548.

53. Wyles CC, Vargas JS, Heidenreich MJ, Mara KC, Peters CL, Clohisy JC, Trousdale RT, Sierra RJ. Hitting the target: Natural history of the hip based on achieving an acetabular safe zone following periacetabular osteotomy. *J Bone Joint Surg*. 2020;102:1734–1740.

54. Xuyi W, Jianping P, Junfeng Z, Chao S, Yimin C, Xiaodong C. Application of threedimensional computerised tomography reconstruction and image processing technology in individual operation design of developmental dysplasia of the hip patients. *Inter Orthop*. 2016;40:255–265.

55. Yasunaga Y, Yamasaki T, Ochi M. Patient selection criteria for periacetabular osteotomy or rotational acetabular osteotomy. *Clin Orthop Relat Res*. 2012;470:3342–3354.

56. Zhao X, Chosa E, Totoribe K, Deng G. Effect of periacetabular osteotomy for acetabular dysplasia clarified by three-dimensional finite element analysis. *J Orthop Sci.* 2010;15:632–640.

57. Zou Z, Chávez-Arreola A, Mandal P, Board TN, Alonso-Rasgado T. Optimization of the position of the acetabulum in a ganz periacetabular osteotomy by finite element analysis. *J Orthop Res.* 2013;31:472–479.

## 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  $30^{\circ}$  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  $0^{\circ}$ ,  $5^{\circ}$ ,  $10^{\circ}$ , and  $15^{\circ}$ .

**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

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.