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Original Article

Investigation of Cup Placement Position in Total Hip Arthroplasty with Cup-side Implant Placement in Computed Tomography Horizontal Sections

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The position attained in total hip arthroplasty (THA) is ideally in the center of the horizontal plane of the acetabulum. However, central placement is not always possible. We hypothesized that differences in approach result in individual differences in cup positioning; thus, we investigated the cup positions of 217 hips that underwent THA. The acetabulum's anteroposterior diameter was measured, and the cups placed within 2 mm of the line perpendicular to the center as a central placement (central). Of the 217 hips, 68, 114, and 35 hips were anterior, central, and posterior, respectively. In 21 hips, anteroposterior deviation was noted. Among patients operated using the anterolateral approach, 48, 93, and 30 hips were anterior, central, and posterior, respectively. Among those operated using the posterolateral approach, 16, 20, and 4 hips were anterior, central, and posterior, respectively. The cup position shifted either anteriorly or posteriorly to the acetabulum in approximately half of all hips operated using both approaches and tended to shift anteriorly in the hips operated using the posterolateral approach. During THA surgery, it is important to operate with awareness of the center of the acetabulum.

Key words: total hip arthroplasty, cup horizontal position, total hip arthroplasty approach, navigation system, computed tomography

Investigations of accurate cup placement in total hip arthroplasty (THA) have described cup angles, including the abduction and anterior-facing cup angles [1-3]. The cup angle is important due to its potential negative effects that can be either short-term, such as dislocation and impingement, or long-term, including implant failure due to wear [4-6]. Iliopsoas-muscle impingement is a significant postoperative complication, and Chalmers *et al*. describe an anterior component protrusion of ≥8 mm as an indicator that revision of the cup is recommended [7]. Some cases have even required cup revision due to iliopsoas-muscle impingement [8,9]. Additionally, a case with a hematoma caused by impingement of the iliopsoas muscle after THA surgery has been reported [10], which also emphasizes that the position of the cup is clinically very important.

Sakemi *et al*. stated that the range of motion becomes smaller when the cup is placed posteriorly from the center of the hip joint. It has been suggested that posterior placement of the cup may be a clinical problem [11]. Therefore, it is desirable to avoid anterior and posterior cup placement as much as possible, and it is very important to investigate the factors allowing accurate cup placement by verifying the accuracy of the placement by performing computed tomography (CT). However, because few medical centers perform routine

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CT examinations after THA (due to the radiation exposure), the cup placement in horizontal sections has not been reported to date according to our search of the relevant literature.

At our department, all patients who undergo a THA are examined using contrast-enhanced CT at 1 week postoperatively to check for postoperative complications, such as deep vein thrombosis and asymptomatic pulmonary embolism. We used these patients' images in the present study to assess the cup positions. Majority of the THAs conducted at our department are performed via lateral approaches, including the anterolateral (AL) approach and the posterolateral (PL) approach.

We hypothesized that (*i*) the cup tends to be placed anteriorly because the operator sees cups inserted by the AL approach from an anterior view, and (*ii*) cups inserted using a posterior approach tend to be placed posteriorly. Ideally, a navigation system must be used for accurate cup placement. However, we found no studies that evaluated the cup position in THA on the horizontal plane with the use of a navigation system. We speculated that CT-based navigation would enable accurate cup positioning on the horizontal plane because such a navigation method allows three-dimensional (3D) visualization of the cup position. We believe that the central position on the horizontal plane of the acetabulum is ideal for THA cup positioning. Our study's second hypothesis is that cup positions are also affected by the use of navigation systems. We conducted the present study to assess the post-THA cup position on the horizontal plane and determine whether different approaches and/or the use of a navigation system result in different cup positions in post-THA hips.

Materials and Methods

Patients. A total of 217 hips of 209 patients (187 women, 30 men) who underwent their first THA at our department from August 2019 to August 2020 were included in the study. The patients' mean age at the time of surgery was 66 (range: 39-87) years. The primary hip disorders were coxarthrosis (n = 200), femoral head osteonecrosis (n = 9), trauma (n = 6), and rheumatoid arthritis (RA) (n = 2). None of the patients underwent one-stage bilateral THA. Among the included patients, the THA was performed via the AL approach in 171 hips, the posterolateral approach was used in 40 hips, and the Hardinge approach was used in 6 hips. All of the patients underwent contrast-enhanced CT at 1 week post-THA.

Methods. The cup position was observed on the contrast-enhanced CT image taken routinely at our department during the first post-THA week. Contrast-enhanced CT at the level from the patients' torso to the feet was used to check for deep vein thrombosis and pulmonary embolism and for the postoperative assessment of the hip joint. Contrast-enhanced CT was not used for patients with decreased renal function (an estimated glomerular filtration rate < 45 mL/min/1.73 m^2), those with a history of asthma, and those with allergies to contrast agents who were evaluated instead by non-enhanced CT and echography of the lower extremities.

The cup position was assessed with reference to the functional pelvic plane (FPP), and the central level of the THA head was identified on the scout view. The cup position was investigated from the horizontal plane on CT at that position. First, the center was identified using the anteroposterior diameter of the cup. The plane parallel to the cup's diameter was defined as the cup plane (Fig. 1).

Next, the centers of the head and cup were identified from the horizontal section of the CT image. The center of the cup (C) and the center of the head coincided because the head was structurally placed in the cup's medial depression. The anteroposterior diameter of the bone tissue was measured on a line parallel to the cup cross-section to identify the center of the anterior and posterior walls of the bone tissue (L).

The ideal cup placement position was in the center of the bone tissue. At the target cup location, the C and the L coincide. Cases with a gap > 2 mm were identified and evaluated (Fig. 2A-D).

Subsequently, the acetabular width parallel to the cup plane was checked to identify the center of the acetabular width. The distance between the two points from which the center was identified was measured; ≥ 2-mm displacement was identified and assessed. The hips with ≥ 2-mm anterior displacement were defined as anterior placement (anterior), those with ≥ 2-mm posterior displacement as posterior placement (posterior), and those with < 2-mm displacement as central placement (central). When the cup position was evaluated at the level of the femoral head center, the cups with ≥ 1-mm deviation from the acetabular anteroposterior width were defined as a case with deviation, and the

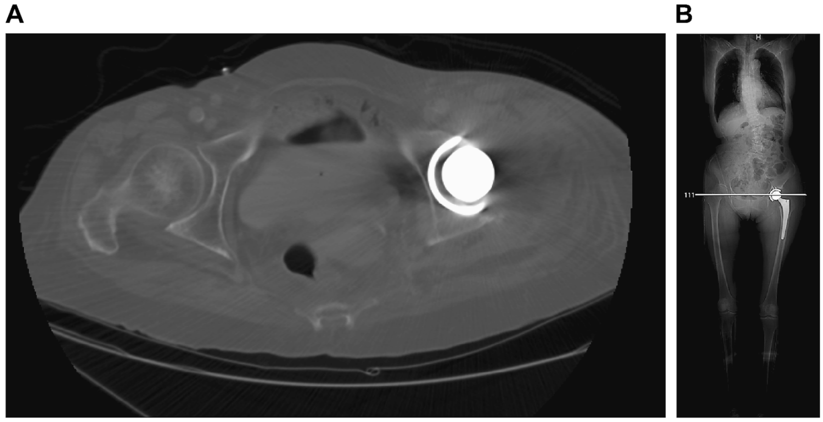

Fig. 1 A, Computed tomography (CT) horizontal-section functional pelvic plane criteria; B, CT scouter used to identify the center of the femoral head.

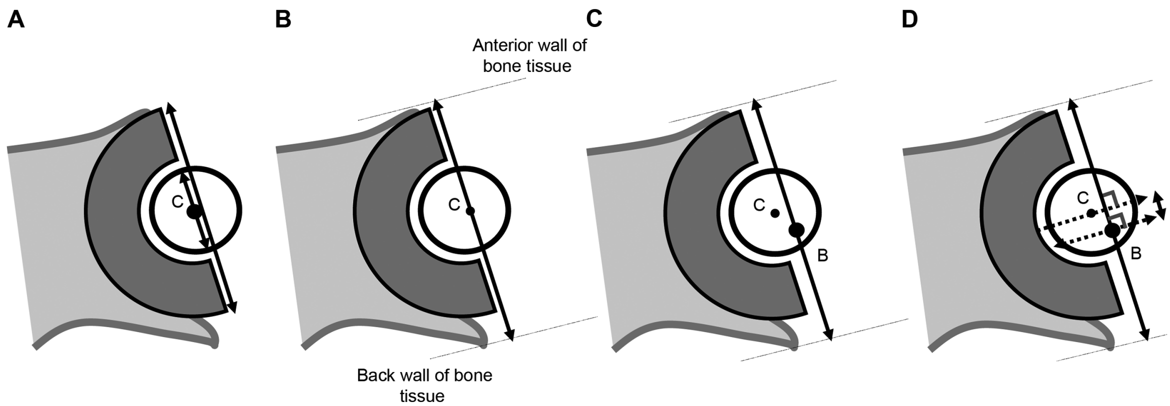

Fig. 2 How to decide where to place the cup. A, The center of the head and the center of the cup coincide, indicating the center of the cup (C). Extract the maximum diameter level; B, Measure the anteroposterior and posterior diameters of the bone tissue on a line parallel to the horizontal section of the cup. Define the center of this bony tissue as B. This is the reference center, and the cup is placed at this target; C, Investigate the distance between C and the center of the anterior and posterior walls of the bone tissue (L), the difference in centers, and whether the direction is forward or backward; D, In this patient's case, C is forward with respect to the center of L.

percentage of these was calculated. For example, the cases with central deviation were defined as a central placement with deviation.

When a cup installation was placed in the acetabulum, deviation anteriorly and posteriorly was defined as a deviated case (Fig. 3). The SQRUM AG/HA® Cup (Kyocera Medical Corp., Osaka, Japan) was used in 117 hips. The G7 OsseoTi® (Zimmer Biomet, Warsaw, IN, USA) was used in 48 hips. The R3 Cup® (Smith & Nephew, London, UK) was used in 28 hips. The Pinnacle Cup® (DePuy Synthes, West Chester, PA, USA) was used in 16 hips. The Escalade Cup® (Ortho Development Corp., Draper, UT) was used in seven hips. The GS Cup® (Teijin Nakashima, Okayama, Japan) was used in one hip. All cups were fixed with the aim of press-fit fixation with 2-mm under-reaming.

Furthermore, we examined whether the cup position differed based on the approach, and evaluated the cases for which a navigation system was used to determine whether the use of a navigation system resulted in any differences in the cup position. At our hospital, navigation is used whenever possible, depending on the

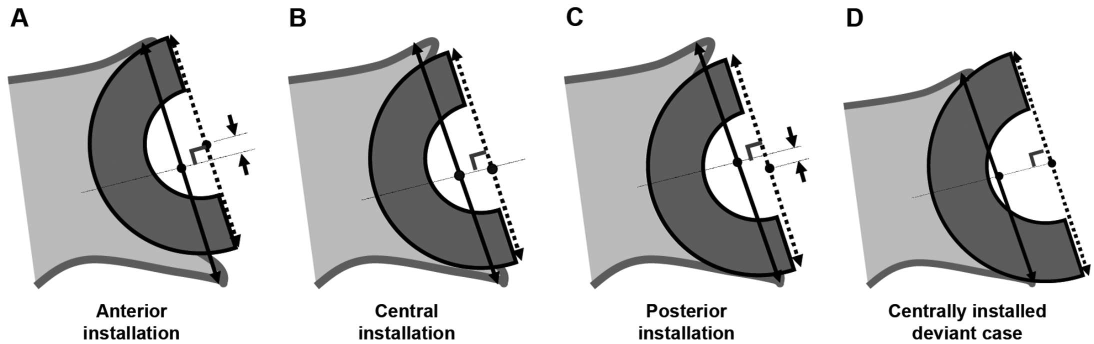

Fig. 3 Cup position classification. A, Anterior placement; B, Central placement; C, Central placement + deviation; D, Deviation both anteriorly and posteriorly was defined as a deviated case.

model of the cup used. The CT-free navigation systems Hip-Align (Zimmer Biomet) and NaviSwiss (Kyocera) have been used at our hospital, and a CT-based navigation system (BrainLab, Munich, Germany) has been used.

Of the 217 hips analyzed in this study, navigation systems were not used for 79 hips, CT-free navigation was used for 67 hips (Hip-Align, 18 hips; NaviSwiss, 49 hips), and the CT-based navigation system was used for 71 hips. The 200 hips with hip joint disease were assessed for hip subluxation or dislocation by the Crowe classification. 79 hips with femoral head osteonecrosis and eight hips with other diseases (trauma and RA) were also assessed. Two weeks after the THA surgeries, immediately before the patients were discharged home, the patients were administered a self-reporting numerical rating scale (NRS) to evaluate their pain as a clinical assessment.

Statistical analyses were performed using the software StatMate III (ATMS, Tokyo). All values are expressed as the mean ± standard deviation. The significance of differences in the data was evaluated with a 95% confidence interval, and the Kruskal–Wallis test was used for multiple comparisons between groups. P-values < 0.05 were considered significant. This study was approved by the Institutional Review Board of Kawasaki Medical School (Approval no. 3891-00). Written informed consent for the publication of their data was obtained from all of the patients.

Results

Of the 217 hips, the cup was placed anteriorly in 68 hips (31%), centrally in 114 hips (53%), and posteriorly in 35 hips (16%) (Fig. 4). Twenty-one hips had deviations (10%). The results based on the approach are as follows. Among the hips operated using the AL approach, the cup was placed anteriorly in 48 hips (28%), centrally in 93 hips (54%), and posteriorly in 30 hips (18%). Among the hips operated using the PL approach, the cup was placed anteriorly in 16 hips (40%), centrally in 20 hips (50%), and posteriorly in four hips (10%). Among the hips operated using the Hardinge approach, the cup was placed anteriorly in four hips (66%), centrally in one hip (17%), and posteriorly in one hip (17%).

Overall, anterior or posterior displacement was observed in half of the hips, with no significant differences between approaches (Table 1). Among the hips operated using CT-based navigation, the cup position was anterior in 19 (27%), central in 40 (56%), and posterior in 12 (17%). Among those operated using CT-free navigation, the cup position was anterior in 20 (30%), central in 36 (54%), and posterior in 11 (16%) hips (Table 2). Centrally positioned cups were observed in only approximately half of the patients, even those who were operated using a navigation system, and no significant differences were observed between CT-based or CT-free navigation, their models, or whether they were used at all.

Regarding differences in cup position between the cases of hip subluxation and dislocation, the Crowe class was 1 in 146 hips, 2 in 35 hips, 3 in 18 hips, and 4 in 1 hip, and their cup positions are listed in Table 3. No significant differences in the cup position were noted even in the severely dislocated hips with coxarthrosis; however, most of the 17 hips with RA or femoral head osteonecrosis were centrally positioned; *i.e.*,

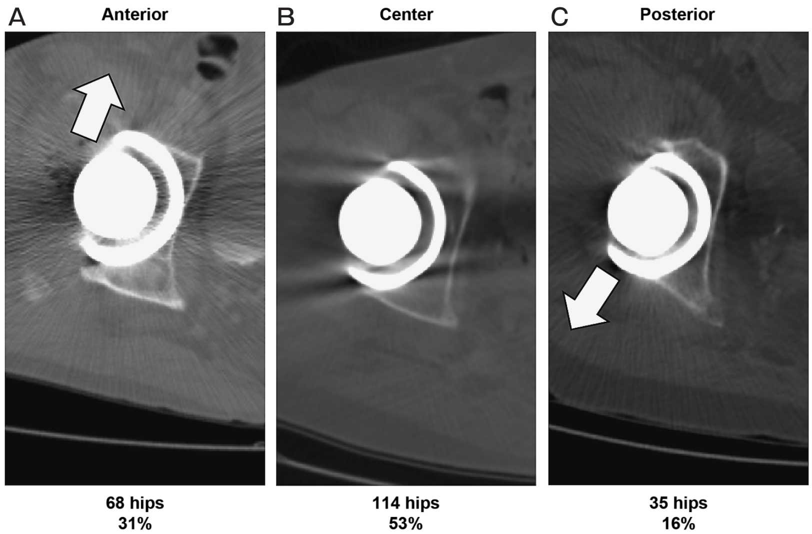

Fig. 4 The percentage of cup placement positions in all cases. A, 68 hips (31%) were placed anteriorly; B, 114 hips (53%) were placed centrally; C, 35 hips (16%) were placed posteriorly.

Table 1 Cup position by approach (n = 217)

–	Anterior	Central	Posterior
Anterior approaches	48 hips (28%)	93 hips (54%)	30 hips (18%)
Posterior approaches	16 hips (40%)	20 hips (50%)	4 hips (10%)
Other	4 hips (66%)	1 hip (17%)	1 hip (17%)

Kruskal-Wallis test: $p = 0.133$

Table 2 Differences in navigation use and cup position (n = 165)

–	Anterior	Central	Posterior
CT-based navigation	19 hips (27%)	40 hips (56%)	12 hips (17%)
CT-free navigation	20 hips (30%)	36 hips (54%)	11 hips (16%)
None	29 hips (37%)	38 hips (48%)	12 hips (15%)

Kruskal-Wallis test: $p = 0.931$

Table 3 Cup position in hip subluxation or dislocation

Crowe class	n = 217	Anterior	Central	Posterior	Deviated
1	146 hips	51 hips (35%)	72 hips (49%)	23 hips (16%)	15 hips (10%)
2	35 hips	10 hips (29%)	19 hips (54%)	6 hips (17%)	3 hips (9%)
3	18 hips	7 hips (37%)	8 hips (42%)	4 hips (21%)	2 hips (10%)
4	1 hip	–	–	–	–
Femoral head osteonecrosis	9 hips	0 (0%)	8 hips (89%)	1 hip (11%)	0 (0%)
Other	8 hips	0 (0%)	7 hips (88%)	1 hip (12%)	1 hip (12%)

Kruskal-Wallis test: $p = 0.877$ (for Crowe classes 1–4) the percentage of hips with centrally positioned cups was significantly higher than that of the hips with coxarthrosis ($p = 0.018$). The characteristics of the cases with deviations (n = 21) were as follows. The primary disease was osteoarthritis (OA) in 20 hips, and trauma in one hip; necrosis of the femoral head and RA were not observed.

The approach was AL for 16 hips (76%) and PL for 5 hips (24%). Navigation was used in 5 hips for CT-based navigation, 3 hips (14%) for CT-free navigation, and 13 hips (62%) for no navigation. The navigation system placed 16 hips (76%) in the front, 2 hips (10%) in the center, and 3 hips (14%) in the rear. The mean NRS score of the 217 hips at 2 weeks postoperatively was 1.3 ± 1.2. The mean NRS by cup position was 0.9 ± 0.8 for the anterior cups, 1.4 ± 1.4 for the central cups, and 1.5 ± 1.0 for the posterior cups. As in the case of the total sample, no significant differences in NRS by cup position were noted ($p = 0.981$).

Discussion

In addition to patients with severe dislocation corresponding to Crowe class 3 or 4 [12], we aim to place press-fit cups into the true acetabulum in patients who undergo THA at our department if sufficient coverage can be achieved. However, in cases in which sufficient coverage is impossible, it is positioned superiorly until sufficient coverage and a press-fit can be achieved. The cup position should therefore be planned in a manner ensuring that a cup-center-edge angle > 0° is achieved and initial fixation of the acetabular component and biological fixation is obtained, thereby resulting in sufficient bone coverage [13].

In practice, we encounter cases wherein the anterior wall is missing on the horizontal plane view even if apparent sufficient bone coverage is viewed on anterior–posterior radiographs, and in other cases in which a press-fit cannot be achieved because of an absent posterior wall. For both of these types of cases, 3D templates are used to prepare preoperative plans that are used as the reference for positioning. The cup position is determined by the reaming orientation. In particular, it cannot be controlled at the stage of cup placement. In other words, errors in cup position are due to incorrect reaming orientation, which can be associated with two factors. First, differences in the cup position can be associated with how the position of the acetabular fossa appears slightly more anterior on FPP. Shimodaira *et al.* reported that the acetabular fossa is positioned slightly anteriorly [14], suggesting that the cup can be turned slightly more anterior than the reaming orientation (Fig. 5). Furthermore, patients with severe OA changes and larger anterior iliac spines are particularly prone to errors in central positioning. Although not evaluated within the scope of this study, patients with well-built anterior and posterior iliac bone spurs are likely to be more susceptible to erroneous cup positioning. Second, incorrect reaming orientation could be the result of differences in approaches. We hypothesized that anterior observation is easy; posterior observation may be difficult when the operative field is viewed from the front. Conversely, posterior observation is easier whereas anterior observation is more difficult from a posterior

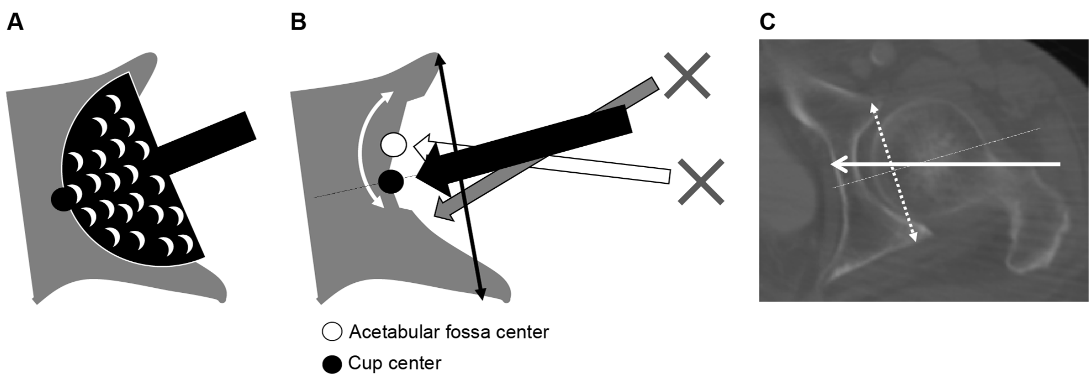

Fig. 5 Hypothesized cup position. A, The cup position is determined during reaming; B, The centers of the acetabular fossa and cup. The *black arrow* is the correct reaming direction toward the acetabular fossa center. *White arrows:* forward reaming. *Gray arrow:* backward reaming; C, Positioned slightly anteriorly. The direction of the arrow is the exact direction of reaming.

view, which may predispose operators to place the cup in a position that is more accessible to them. However, our present analyses revealed that the cup was positioned centrally in approximately half of all cases, and our analysis of the cup position based on approach identified no difference between the anterior and posterior approaches, where the cups were positioned in the center in approximately half of the hips. The case of deviation is an error in the anterior–posterior diameter of the acetabulum.

The results were also similar for the THAs in which a navigation system was used. This suggests that the cup is reamed in a displaced orientation in approximately half the cases at the reaming stage, even when the central position is the goal. On CT-based navigation, the anteroposterior width can be visualized on screen at the stage of anteroposterior reaming, and the operator can then conduct reaming by considering the anteroposterior width as well. However, interestingly, the results were consistent with those achieved by CT-free navigation, which does not allow the confirmation of the anteroposterior width, suggesting that placement in the central position is difficult even with CT-based navigation.

The central cup position was achieved in only approximately half of the hips with both subluxation and dislocation, revealing that the dislocation severity did not affect the cup position. However, the cup position was central in 90% of the hips with RA without OA changes and femoral head osteonecrosis. It is possible that in hips without OA changes without iliac spine protrusion, the cup can be fitted relatively centrally, suggesting that the iliac spines may be the cause of the propensity to anteroposterior mispositioning on the horizontal plane. In our patients, 66% of the cases with deviations were those with anterior positions, and most of these were operated using an anterior approach. When a large cup size is selected, opening it anteriorly is easier than opening it posteriorly, and this might explain why these cups were more likely to be anteriorly positioned.

Decreased cup fixation is a potential concern in patients with anterior or posterior displacement. Lachiewicz *et al.* reported that anterior cup protrusion can cause a collision between the anterior rim of the cup and the iliopsoas muscle [15]. Cup impingement that can aggravate pain is a concern in patients with significant anterior displacement. Notably, the most important finding of our present analyses is that anteroposterior displacement occurred in approximately half of all of the cases, even in the patients with good press-fit and positioning identified on frontal radiographs. Central positioning remains difficult even by operating from different approaches or using navigation systems, and operators should attempt the surgery by cautiously taking the center of the acetabulum into consideration.

Although we observed no significant difference in the patients with an anteriorly positioned cup, the pain was indeed lesser in these patients, and this is attributed to musculotendinous preservation, which is possible by using anterior approaches. According to the findings of this study, the cup position was unlikely to be the cause of pain in the early postoperative period.

This study has several limitations to consider. First, the correlation between the extent of displacement and actual pain is unknown because the displacement could not be quantified. Significant anterior cup displacement causes impingement and can be a possible factor of worsened pain in the anterior tissues. Conversely, anteroposteriorly protruding iliac spines are likely to make the patient more susceptible to misestimation of the cup center. However, this can make it difficult to measure the anteroposterior diameter. The relationship between the degree of iliac spine formation and changes in the cup position is a topic for future studies. It has been reported that using robotic technology for THAs provides highly accurate cup placement [16,17]. Although we have not performed this type of robotic cup installation at our hospital, we consider it an interesting challenge. Central placement has been difficult even with CT-based navigation, but with advances in robotic technology, accurate placement can be expected in the future.

Although this is a study limitation, it is unclear whether the amount of displacement correlates with the patients' actual pain because we did not quantitatively evaluate this amount in this study. In cases where osteophytes protrude anteriorly and posteriorly, the cup center is misjudged, and measuring the anteroposterior diameter itself may be difficult. The degree of osteophyte formation and the change in the position of the osteophytes are issues for future studies. In the use of horizontal CT sections reflecting the cup placement, the goal is to achieve central placement. However, if initial fixation is not achieved, early postoperative dislocation may be a concern. The cup was placed centrally on the horizontal plane of the CT scan in half of the present cases, depending on the differences in approach. In ~50% of the cases, it was displaced posterior or anterior to the acetabulum; no differences by approach were noted. Even with a navigation system for cup installation, only about half of the cups were installed centrally. Particular attention should be paid to cases with many osteophytes. Surgical maneuvers on the acetabular side, including reaming, with awareness of the center of the acetabulum during surgery are necessary. The evaluation of cup placement in horizontal CT sections is very important for cup stability, and our present findings provide a valuable contribution to efforts to achieve the optimal cup placement position in THAs.

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