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■ **HIP**

Digitalized analyses of intraoperative acetabular component position using image-matching technique in total hip arthroplasty

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Aims

Appropriate acetabular component placement has been proposed for prevention of postoperative dislocation in total hip arthroplasty (THA). Manual placements often cause outliers in spite of attempts to insert the component within the intended safe zone; therefore, some surgeons routinely evaluate intraoperative pelvic radiographs to exclude excessive acetabular component malposition. However, their evaluation is often ambiguous in case of the tilted or rotated pelvic position. The purpose of this study was to develop the computational analysis to digitalize the acetabular component orientation regardless of the pelvic tilt or rotation.

Methods

Intraoperative pelvic radiographs of 50 patients who underwent THA were collected retrospectively. The 3D pelvic bone model and the acetabular component were image-matched to the intraoperative pelvic radiograph. The radiological anteversion (RA) and radiological inclination (RI) of the acetabular component were calculated and those measurement errors from the postoperative CT data were compared relative to those of the 2D measurements. In addition, the intra- and interobserver differences of the image-matching analysis were evaluated.

Results

Mean measurement errors of the image-matching analyses were significantly small (2.5° (SD 1.4°) and 0.1° (SD 0.9°) in the RA and RI, respectively) relative to those of the 2D measurements. Intra- and interobserver differences were similarly small from the clinical perspective.

Conclusion

We have developed a computational analysis of acetabular component orientation using an image-matching technique with small measurement errors compared to visual evaluations regardless of the pelvic tilt or rotation.

Article focus

■ It is often difficult to evaluate the acetabular component position in the intraoperative pelvic radiograph in case of the tilted or rotated pelvic position.
■ To develop the computational analysis to digitalize the acetabular component orientation regardless of the pelvic tilt or rotation.

Key messages

■ We have developed a computational analysis of acetabular component orientation using an image-matching technique.
■ Measurement errors were small compared to visual evaluations regardless of the pelvic tilt or rotation.

Strengths and limitations

■ Our method can help the surgeon to confirm the acetabular component

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orientation regardless of the pelvic tilt or rotation during surgery.
- Preoperative CT scan data are necessary, although CT-based 3D planning can help more precise placement of total hip arthroplasty (THA) components.

Introduction

Total hip arthroplasty (THA) has been a successful surgical procedure for hip disorders. One of the keys for implant longevity is to avoid dislocation and many surgeons make best efforts to prevent it (surgical approaches,[1] appropriate soft tissue balance,[2] and implant positions[3]). Optimal implant positions are also described as important factors for postoperative range of motion, implant stability such as polyethylene wear and osteolysis, impingement avoidance, and decrement of shearing force.[4-7]

Lewinnek et al[8] proposed "a safe zone" of component placement with a mean radiological inclination angle (RI) of 40° (SD 10°) and a mean radiological anteversion angle (RA) of 15° (SD 10°) for prevention of postoperative dislocation 40 years ago. However, many articles have recently demonstrated little significance of the Lewinnek safe zone[9-12] and suggested a new functional safe zone considering a combined anteversion technique[6,13,14] and spinopelvic movement.[15-17] This safe zone is often patient-specific and reported to be much narrower than previously believed,[18,19] therefore surgeons should place the acetabular component more correctly based on the individualized preoperative planning. However, manual placements often cause outlier in spite of attempts to insert the component within the intended safe zone.[20-22] Moreover, it is extremely difficult even for expert surgeons to place the acetabular component in the appropriate position in a freehand manner in cases of severe acetabular deformity caused by severe developmental dysplasia, hip arthrodesis, and others.[23-25]

Some surgeons take an intraoperative pelvic radiograph routinely after setting the acetabular component to confirm the placement.[26,27] The acetabular component is placed under the assumption that the pelvis is near the neutral position. However, the intraoperative pelvic position is often tilted or rotated relative to the aimed one,[28] and surgeons need to evaluate the component orientation relative to the tilted or rotated pelvic position visually. This visual evaluation has great ambiguity. It would be useful if surgeons could evaluate the component orientation digitally regardless of the pelvic tilt or rotation.

The purposes of this study were: 1) to develop a computational analysis to digitalize the acetabular component orientation from 2D radiographs using an existing image-matching technique; and 2) to evaluate its accuracy compared to the data from 3D analyses.

Methods

The study group was formed with 50 consecutive patients (50 hips) who underwent THA using one specific acetabular cementless component (AMS & PerFix HA;

Table I. Patient details.

Variable	Data (n = 50)
Mean age, yrs (SD)	68.2 (11.3)
Sex, male:female, n	3:47
Side, right:left, n	27:23
Mean height, cm (SD)	150.8 (5.9)
Mean body weight, kg (SD)	53.0 (9.7)
Mean body mass index, kg/m² (SD)	23.2 (3.7)
Preoperative diagnosis, n	
Osteoarthritis	45
Rheumatoid arthritis	1
Osteonecrosis of the femoral head	3
Subchondral insufficiency fracture of the femoral head	1

Kyocera, Osaka, Japan) with osteoarthritis (OA), rheumatoid arthritis, osteonecrosis of the femoral head, and subchondral insufficiency fracture (SIF) of the femoral head (Table I). All patients were Japanese and provided informed consent. The local Institutional Review Board approved this study.

All THAs were performed in the lateral position through the posterolateral approach. The pelvis was fixed with bilateral anterior superior iliac spines (ASIS) and the sacrum. A preoperative pelvic radiograph was routinely taken just after setting the lateral position in our hospital. A portable radiograph device was set so that the irradiation origin was centered at the superior margin of the pubic symphysis. The film was held vertically and positioned at the back of the pelvis parallel to the trunk. The distance between the irradiation origin and the film was maintained consistently (180 cm). We adjusted the pelvic position carefully to match the aimed one by tilting or rotating an operating table.

The target angle of the acetabular component was generally set at an RA of 20° and an RI of 40° in our series. In some cases with larger or smaller femoral neck anteversion, RA was adjusted a little to keep combined anteversion.[6,13,14]

Definition of the 3D coordinate system in the pelvic model and acetabular component. Preoperative transverse CT scans (Revolution CT; GE Healthcare Japan, Tokyo, Japan) were taken at levels ranging from the whole pelvis to the knee joint at 1.25 mm intervals and 1.25 mm thickness with a field of view of 400 and pitch of 1.375 to make a preoperative 3D planning in all patients. CT images were acquired as Digital Imaging and Communications in Medicine format (DICOM) data from the CT system server, and DICOM datasets were imported into a 3D planning software (ZedHip; Lexi, Tokyo, Japan). 3D pelvic bone models were reconstructed and segmented with each femur in the software.

The anterior pelvic plane (APP) was defined as the plane including bilateral ASIS and the superior margin of the pubic symphysis (Figure 1a). The sagittal axis was corrected for the sagittal pelvic tilt in the supine position
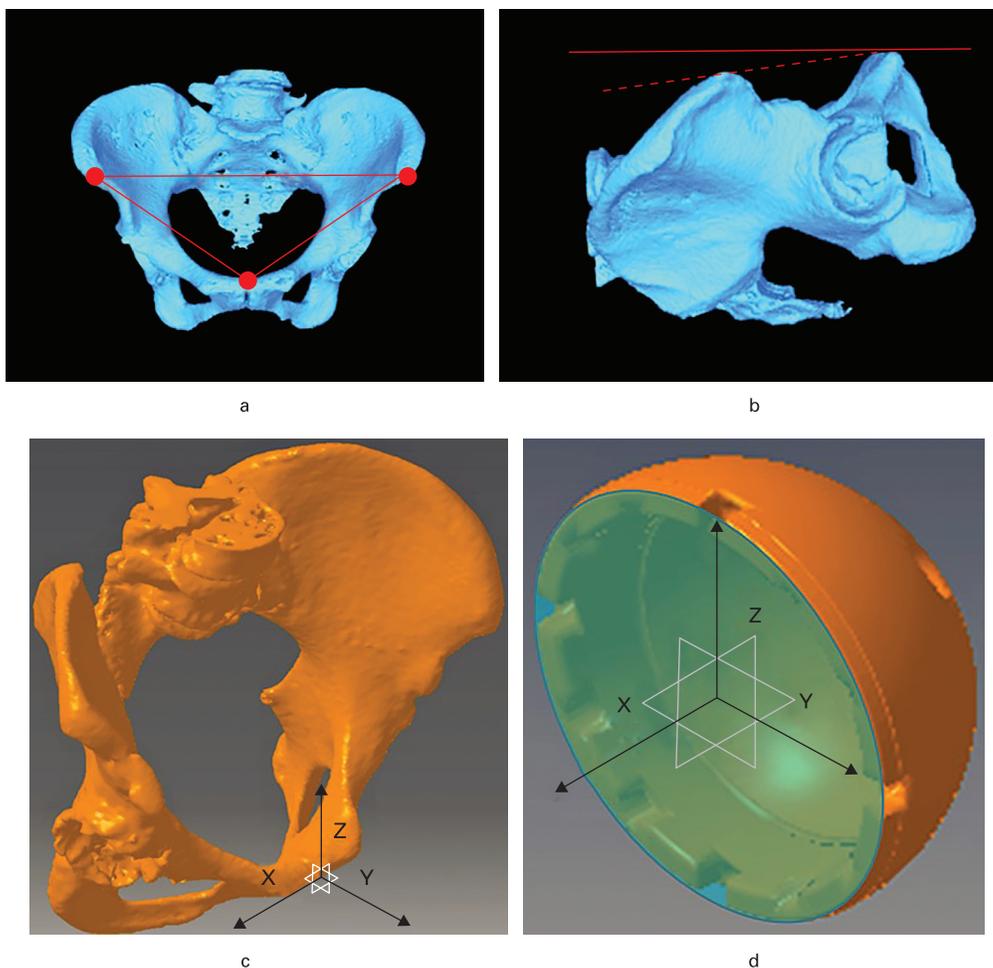
Fig. 1

Coordinate systems of the a) to c) pelvic bone and the d) acetabular component. a) The anterior pelvic plane (APP) including bilateral anterior superior iliac spines (ASIS) and the superior margin of the pubic symphysis (three points). b) The sagittal axis is corrected for the sagittal pelvic tilt in the supine position (solid line) from that of the APP (broken line), and this plane is defined as the functional pelvic plane (FPP). c) The FPP is defined as the XZ plane and the x-axis is parallel to the line connecting bilateral ASIS. d) The central axis perpendicular to the component opening plane (blue plane) is defined as the x-axis.

from that of the APP (Figure 1b), and this plane was defined as the functional pelvic plane (FPP).[29,30] The FPP was embedded into each pelvic bone model and the origin was defined as the superior margin of the pubic symphysis. The y-axis was defined as the axis perpendicular to the FPP. The x-axis was defined as the axis included in the FPP and parallel to the line connecting bilateral ASIS. The direction of each axis is described in Figure 1c.

In the acetabular component, the centre of the component opening plane was defined as the origin and the central axis of the acetabular component perpendicular to the component opening plane was defined as the x-axis (Figure 1d).

Analyses of acetabular component orientation in the intraoperative pelvic radiograph. An image-matching technique has been developed and used for the kinematic analysis of each joint.[31-36] The general methods are described below. Some objects were constructed as 3D models on the computer and image-matched to the edges of those objects in a 2D radiograph. The positions of each object were reconstructed three-dimensionally and the relative positional relationship of each object could be calculated.

An intraoperative pelvic radiograph including bilateral hips was routinely taken after setting the acetabular component and the femoral trial stem in our hospital. Intraoperative pelvic radiographs of all patients were collected retrospectively in this study. The 3D pelvic bone model and the acetabular component were image-matched to the intraoperative pelvic radiograph using the image-matching software (JointTrack; University of Florida, Gainesville, Florida, USA; Figures 2a to 2c). In the image-matching of the pelvic model, anatomical structures with distinctive shapes located around the centre of the radiograph (pubic symphysis, obturator foramina, pubis, ischium, and pelvic cavity) would help its precision. In the image-matching of the acetabular component, we fit the ellipse line made from the acetabular

$$RA = \sin^{-1}\left(\frac{b}{a}\right)$$
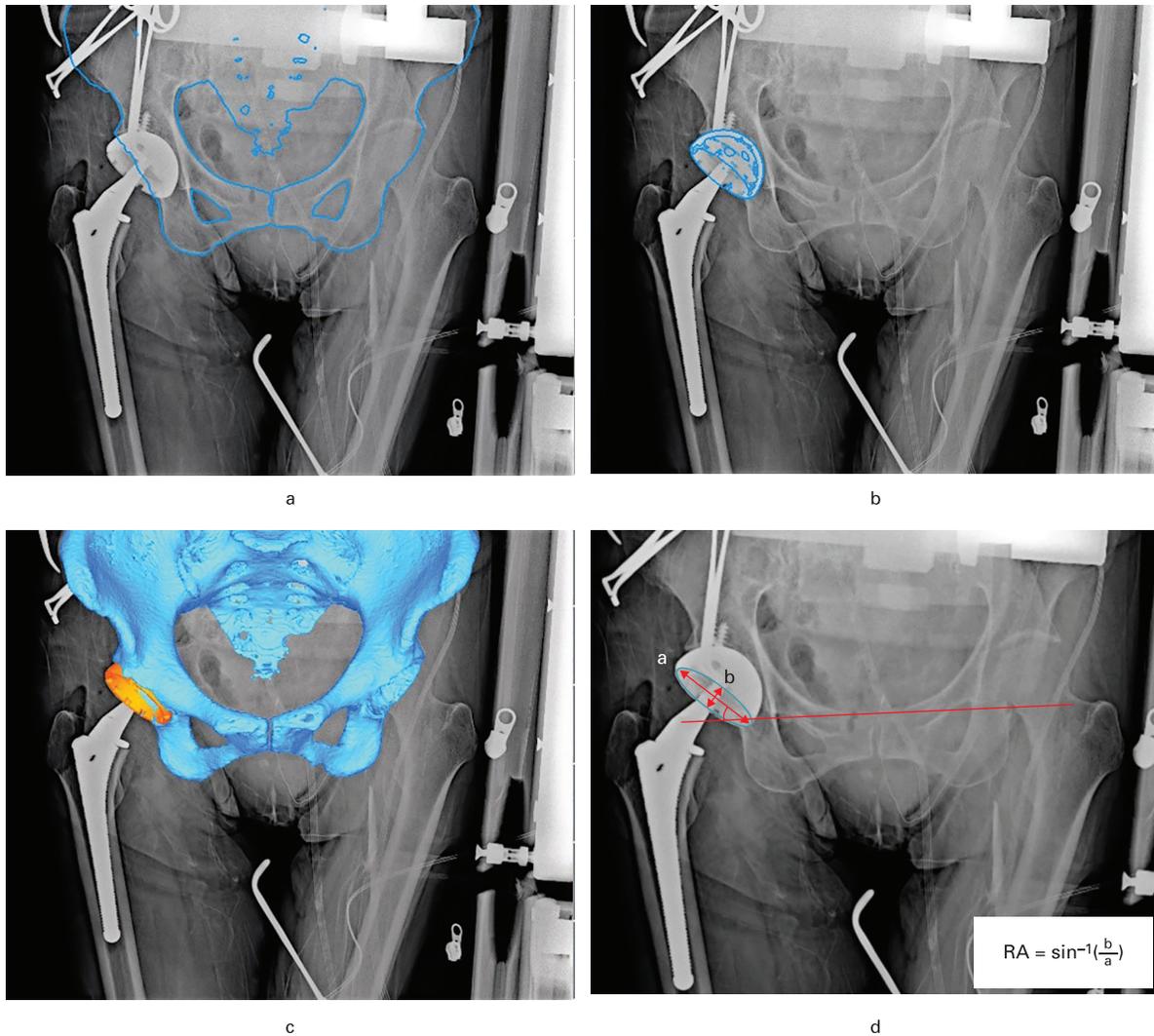
Fig. 2

a) The edge of the 3D pelvic bone model is image-matched to the perioperative pelvic radiograph using the image-matching software (JointTrack; University of Florida, Gainesville, Florida, USA). b) The edge of the 3D acetabular component is image-matched. c) 3D view of the pelvic bone model and the acetabular component. d) The radiological anteversion angle (RA) was calculated with the formula reported by Lewinnek et al,[8] and the radiological inclination angle (RI) was measured as the angle between the line connecting both tear drops (solid line) and the long axis of the acetabular component (red arrow indicating "a").

component edge very carefully. The pelvic tilt and rotation on the coronal, sagittal, and axial planes and the RA and RI of the acetabular component relative to the FPP were calculated from the image-matching data using the program as described in the Supplementary Material (i.e. image-matched RA and RI).

Then, the RA and RI were measured two-dimensionally with the same radiographs. The RA was calculated with the formula reported by Lewinnek et al[8] and the RI was measured as the angle between the line connecting both tear drops and the long axis of the acetabular component (Figure 2d).

RA and RI measurements using postoperative CT. A postoperative CT scan was performed at two weeks after surgery in all cases to determine the postoperative

component angle, and postoperative CT datasets were imported into a 3D planning software (3D Template; Kyocera). The preoperative FPP (reference pelvic plane during surgery) should be reproduced in RA and RI measurements. Therefore, the sagittal angle between the APP and FPP was measured in the preoperative CT data at first, then the preoperative FPP was reproduced in the postoperative CT data by adjusting the sagittal angle from the APP. The RA and RI of the acetabular component relative to the FPP were measured in the multiplanar reformat (MPR) images by two examiners (SK, T. Sato) (Figure 3), and their mean measurements of the RA and RI were adopted as the postoperative component angles (i.e. true RA and RI).
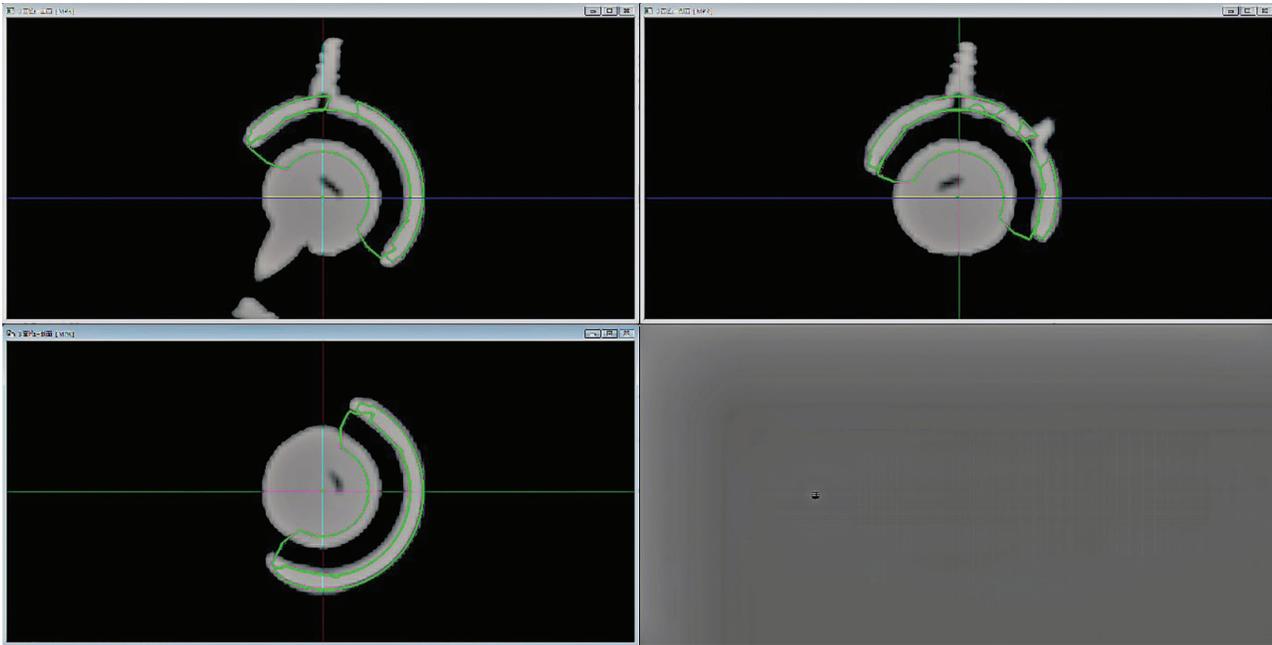
Fig. 3

The acetabular component is matched in the multiplanar reformat (MPR) images reconstructed from postoperative CT data, and the radiological anteversion angle (RA) and radiological inclination angle (RI) of the acetabular component relative to the functional pelvic plane (FPP) were measured.

RA and RI measurements from postoperative CT data were repeated twice at least one month apart for ten randomly extracted patients, and intra- and interobserver differences of those measurements were investigated. The intraclass correlation coefficient and the interclass correlation coefficient were all over 0.9, proving to be sufficiently reliable.

The RA and RI calculated from the image-matching analysis (image-matched RA and RI) and those measured two-dimensionally were compared with those measured from the postoperative CT (true RA and RI). The deviations were described as means and absolute values and compared with each other with a paired *t*-test. Significance was set at a p-value of < 0.05.

Intra- and inter-observer trials of the image-matching analysis. Image-matching analyses were repeated twice at least one month apart for ten randomly extracted patients, the first time by two surgeon examiners (SK and KK) and the second time by one surgeon examiner on the same ten patients (SK). Intra- and interobserver differences of the image-matched RA and RI were evaluated as the intraclass correlation coefficient and the interclass correlation coefficient, respectively.

Learning curve. One young orthopaedic surgeon (KK) who was not familiar with THA and our image-matching procedures did the same analyses. The time for completion of the image-matching procedure of the acetabular component and the pelvic model was measured, and the differences between his measurements and component angles measured from postoperative CT (true RA and RI) were calculated.

Table II. Implantation angle of the acetabular component in each measurement and their measurement deviations.

Variable	RA	RI
Mean target angle, ° (SD)	21.4 (2.2)	40.0 (0.0)
Implantation angle measured from postoperative CT (true RA and RI) (A), ° (SD)	22.1 (4.4)	40.9 (3.5)
Implantation angle calculated by image-matching analyses (image-matched RA and RI) (B), ° (SD)	24.6 (4.5)	41.0 (3.5)
Implantation angle measured two-dimensionally (C), ° (SD)	18.0 (4.0)	40.9 (3.1)
B-A, ° (SD)	2.5 (1.4)	0.1 (0.9)
C-A, ° (SD)	-4.1 (4.0)	0.0 (2.2)
|B-A| (absolute value), ° (SD)	2.5 (1.4)*	0.1 (0.9)*
|C-A| (absolute value), ° (SD)	4.7 (3.2)*	1.8 (1.2)*

*p < 0.01, paired *t*-test.
RA, radiological anteversion angle; RI, radiological inclination angle.

Results

Our results showed clinically high accuracy of component implantation. Mean pelvic tilt and rotation on the coronal, sagittal, and axial planes in the intraoperative pelvic radiograph calculated from the image-matching data were 1.8° (SD 1.4°), 2.7° (SD 2.0°), and 2.6 (SD 1.8°), respectively. Mean measurement errors of the image-matching analyses compared to the data obtained from postoperative CT were within 3° in the RA and within 1° in the RI and significantly small relative to those of the 2D measurements (Table II).

Mean intra- and inter-observer differences of the image-matching analyses were 1.3° (SD 1.0°) and 1.5° (SD 1.1°) in the RA and 0.6° (SD 0.5°) and 0.9° (SD 0.5°)
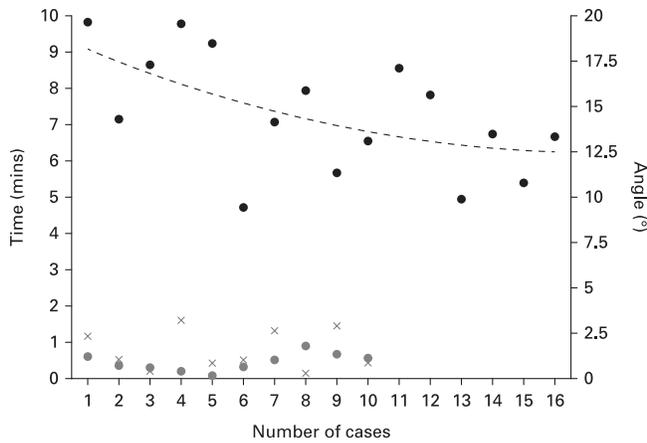
Fig. 4

The time for completion of the image-matching procedure of the acetabular component and the pelvic model performed by a young orthopaedic surgeon (KK) (time for each case: black point; approximate curve: black broken line) and his measurement differences compared to the data obtained from postoperative CT (radiological anteversion angle (RA): grey x-mark; radiological inclination angle (RI): grey point).

in the RI. The intraclass correlation coefficient and the interclass correlation coefficient were 0.90 and 0.89 in the RA and 0.93 and 0.91 in the RI.

The time for completion of the image-matching procedure of the acetabular component and the pelvic model performed by a young orthopaedic surgeon (KK) and his measurement differences compared to the data obtained from postoperative CT are shown in Figure 4.

Discussion

Intraoperative evaluation of the acetabular component position using pelvic radiographs is useful for the purpose of excluding excessive malposition.[37] However, even for expert surgeons visual evaluation has great ambiguity especially in the anteversion angle. A computational analysis to digitize the acetabular component orientation from 2D pelvic radiographs using an image-matching technique has been developed in this study.

Mean measurement errors of the image-matching analyses compared to the actual acetabular component angles were within 3° in the RA and within 1° in the RI. The RA is generally evaluated with the ellipse made from the acetabular component edge and might be overestimated slightly during the manual line fitting. However, it would be extremely difficult to evaluate the RA visually within the error range of 2° to 3° much more in cases of pelvic tilt or rotation. Some papers defined RA calculation methods based on the ratios of the ellipse on an antero-posterior pelvic radiograph.[3,8,38,39] However, it is under the assumption that the pelvis keeps the neutral position. When we used the formula reported by Lewinnek et al,[8] measurement errors of the image-matching analyses were significantly small relative to those of the 2D measurements. In addition, intra- and interobserver differences were similarly small in our method. Therefore,

Table III. Accuracy of angular measurements in each method.[40-44]

Author	Navigation or method	Mean RA deviation, ° (SD)	Mean RI deviation, ° (SD)
Inaba et al[40]	CT-based	1.9 (1.9)	2.2 (2.1)
Kajino et al[41]	CT-based	2.9 (1.8)	1.5 (1.2)
Gurgel et al[42]	Image-free	5.5 (3.8)	3.0 (1.8)
Lass et al[43]	Image-free	6.5 (3.7)	3.2 (2.4)
Ybinger et al[44]	Image-free	6.5 (7.3)	3.5 (4.4)
This study	Image-matching	2.5 (1.4)	0.1 (0.9)

RA, radiological anteversion angle; RI, radiological inclination angle.

we believe our method can provide reliable and reproducible evaluations of the acetabular component orientation regardless of the pelvic tilt or rotation.

For clinical use in the future, another important question is whether any surgeons can use our method easily and speedily because they have to evaluate the acetabular component orientation intraoperatively. Measurement precisions of the RA and RI were stabilized in early series even for a young surgeon with the same as the results described above. The time required for analyses converged into six to seven minutes with experiences of approximately 15 cases; therefore our analysis would not extend the operation time so much.

Computer-assisted surgery (CAS) has been developed and clinically used for the last few decades. Computer-navigation systems are one of the major CAS items and much literature has described their accuracy in THA (Table III).[40-44] Our measurement reliabilities are comparable to those of CT-based computer navigations and superior to those of image-free computer navigations. Our method cannot assist the accuracy of the acetabular cup placement directly; however, it can help the surgeon to confirm the acetabular component orientation during surgery.

The current study has several limitations. First, preoperative CT scan data are necessary for reconstructing 3D pelvic bone models. However, they are originally taken to make a preoperative 3D planning in all patients regardless of this study. Several articles have demonstrated that preoperative planning with CT-based 3D templating achieved more precise placement of THA components,[45-47] and preoperative CT for THA was associated with a slight but justifiable increase of radiation exposure in comparison to conventional radiographs and low per-patient costs.[48] Second, plain pelvic radiographs were used during the image-matching procedure. Distortion-corrected radiographs such as radiographs taken with a flat panel device (FPD) should be used during the original image-matching procedure.[31-34] However, it is not realistic to use FPD during surgery and surgeons have no choice but to use a portable radiograph device. The measurement errors of the image-matching analyses described above include both observer error itself and radiological distortion. Nevertheless, our method demonstrated clinically small errors compared to visual evaluations despite using a distortion uncorrected

radiograph. In addition, interobserver differences were also small. Therefore, our method would be clinically relevant. Third, this is not a clinical study but a retrospective methodological study because the major objective was to develop the computational analysis to digitalize the acetabular component orientation from 2D radiographs using an image-matching technique. Therefore, it should be verified in the near future whether our method is useful during surgery. Fourth, patients implanted with one specific acetabular component were selected in our series because computer-aided design (CAD) data of the component were needed for image-matching. However, most acetabular components have hemispherical shapes and our method would be flexible to other implants. Last, our method in itself allows for measurement of version but does not specify whether the component is anteverted or retroverted. However, the trial liner in which some beads are embedded would show whether the component is anteverted or retroverted. We have not used these devices in our series, therefore they should be adopted in future studies.

In conclusion, we have developed a computational analysis of acetabular component orientation using an image-matching technique regardless of pelvic tilt or rotation with extremely small measurement errors compared to visual evaluations. The learning curve was relatively low even for young surgeons. A simple software should be developed so that surgeons can accomplish whole analysis procedures easily.

Supplementary material

Equations illustrating the calculation program of the radiological anteversion angle (RA) and radiological inclination angle (RI) of the acetabular component relative to the functional pelvic plane (FPP) from the image-matching data.

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