Acta Med. Okayama, 2017
Vol. 71, No. 4, pp. 279-289

Acta Medica
Okayama

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*Original Article*

# An Analysis of the Characteristics and Improved Use of Newly Developed CT-based Navigation System in Total Hip Arthroplasty

**Yosuke Fujii[a], Kazuo Fujiwara[b]*, Tomonori Tetsunaga[a], Takamasa Miyake[a],
Kazuki Yamada[a], Hirosuke Endo[a], Nobuhiro Abe[c], Naohiko Sugita[d],
Mamoru Mitsuishi[d], Takayuki Inoue[e], Yoshio Nakashima[e], and Toshifumi Ozaki[a]**

*Departments of [a]Orthopaedic Surgery, and [b]Intelligent Orthopaedic System Development,
Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama 700-8558, Japan,
[c]Department of Orthopaedic Surgery, Kawasaki Medical school, Okayama 700-8505, Japan,
[d]Department of Mechanical Engineering, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan,
[e]TEIJIN NAKASHIMA MEDICAL CO., LTD., Okayama 709-0625, Japan*

**We developed a surface matching-type computed tomography (CT)-based navigation system for total hip arthroplasty (the N-navi; TEIJIN NAKASHIMA MEDICAL, Okayama, Japan). In the registration step, surface matching was performed with digitizing points on the pelvic bone surface after coarse paired matching. In the present study, we made model bones from the CT data of patients whose acetabular shapes had various deformities. We measured the distances and angles after surface matching from the fiducial points and evaluated the ability to correct surface-matching registration on each pelvic form, using several areas and numbers of points. When the surface-matching points were taken on the superior area of the acetabulum, the correction was easy for the external direction, but it was difficult to correct for the anterior and proximal directions. The correction was difficult for external and proximal directions on the posterior area. Each area of surface-matching points has particular directions that are easily corrected and other directions that are difficult to correct. The shape of the pelvis also affected the correction ability. Our present findings suggest that checking the position after coarse paired matching and choosing the surface-matching area and points that are optimal to correct will improve the accuracy of total hip arthroplasty and reduce surgical times.**

**Key words:** total hip arthroplasty, CT-based navigation system, surface matching

Computer navigation has been developed and used to aid the placement and improve the positioning of the acetabular component in total hip arthroplasty (THA). Improving the accuracy of setting an implant reduces complications related to arthroplasty [1-3]. Nowadays, various types of computer navigation systems have been developed for orthopedic surgery including imageless-type, fluoroscopy-based, and computed tomography (CT)-based navigation systems. The usefulness of each navigation system has been reported [4-13]. However, the internal structure and the programming of each navigation system have been matters of secrecy limited to each system's developer, and we therefore limited the present study to an analysis of the accuracy of established registration points.

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Received December 12, 2016; accepted March 3, 2017.
*Corresponding author. Phone: +81-86-235-7273; Fax: +81-86-223-9727
E-mail: fujiwara@md.okayama-u.ac.jp (K. Fujiwara)

Conflict of Interest Disclosures: K. Fujiwara is a member of an endowed department (Department of Intelligent Orthopaedic System Development, Okayama University Graduate School of Medicine, Dentistry, and Pharmaceutical Sciences) sponsored by TEIJIN NAKASHIMA MEDICAL Co., Ltd.

Many reports have been written about the accuracy of the angles and the positioning of implants using existing navigation systems. We further developed an existing CT-based navigation system currently used in total knee arthroplasty (N-navi; TEIJIN NAKASHIMA MEDICAL, Okayama, Japan), and we have reported its accuracy [14]. We customized the N-navi system into a surface matching-type CT-based navigation system for hip surgery. We were able to adjust the number of surface-matching points and evaluate the direction and distance from the fiducial point after the registration. We considered the influence that the choice of surface-matching points had on registration accuracy, and we investigated the choice of better locations to obtain more accurate measurements and reduce the number of registration points.

We conducted the present study to (1) assess the characteristics of surface matching-type registration around the acetabulum, and (2) describe how to use the surface matching-type CT-based navigation system more effectively in THA.

## Material and Methods

This was a single-center, retrospective, observational study that was approved by the Ethics Committee of our institute (No. 2127). Informed consent was obtained by the method of opt-out.

Between January 2014 and June 2014, three primary cementless THAs were performed in three female patients, average age 69 years (54-87 years). One patient showed Crowe 1 deformity on both sides of the acetabulum, one patient showed Crowe 2 deformity on both sides of the acetabulum, and one patient showed Crowe 4 deformity on both sides of the acetabulum. Preoperatively, transverse CT images of these patients were obtained using a helical CT scanner (Discovery CT750 HD, GE Medical Systems, Milwaukee, WI, USA). The slice thickness was 2 mm, and the pitch was 2 mm. Using these CT data, we created pelvic bone models of these patients laminated from a 16-μm pitch on a 3D printer (Objet350 CONNEX3, Stratasys, Eden Prairie, MN, USA), and these 6 pelvic models were used for this study.

We then developed our own CT-based, surface matching-type navigation computer system (Fig. 1). We used an iterative closest-point algorithm for the mathematical calculation [15], and an optical tracking unit which detected reflecting spherical markers by infrared camera. These reflecting spherical markers were set on

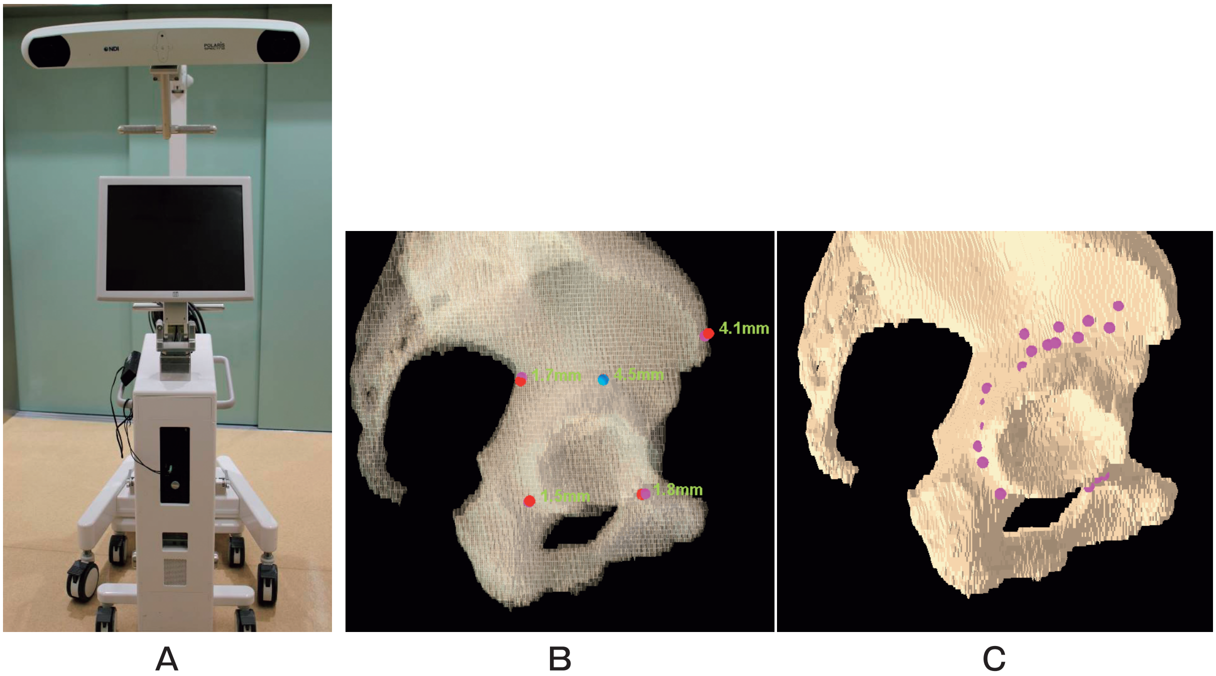

**Fig. 1** The whole view of our original navigation system (**A**). **B** was the screen performing point paired matching, and **C** was performing surface matching.

the pelvis, and rough paired-point registration was performed by digitizing 5 bony landmarks on the pelvis. Then, surface registration was performed by digitizing points on the pelvic bone surface around the acetabulum.

In this study, we evaluated the correction ability of the surface registration. The area around the acetabulum was divided into 4 areas of digitizing points: the superior, posterior, and postero-superior areas of the acetabulum, and the pubis. The numbers of surface registration points on the superior area were 20 points, 20 points on the posterior area, 10 points on the postero-superior area, and 3 points on the pubis area. As each operation approached, the areas were grouped into the superior area or the superior+postero-superior areas of the acetabulum and the pubis area (zone A), and the posterior area or the posterior+posterior-superior areas (zone B).

The anterior pelvic plane (APP) was used as a reference, and the coordinates were defined as follows: the x-axis for the external direction, the y-axis for the anterior direction, and the z-axis for the proximal direction (Fig. 2). In addition, three-dimensional coordinate axes were defined based on the rotation for each axis (x, y and z). We shifted the pelvis on each axis at 2-mm increments away from the fiducial point from −10 to 10 mm, and we shifted the angular variation from the fiducial point for each rotational axis in 2-degree increments from −10° to 10°.

Next, surface registration was performed using 10, 15, 20, and 30 points on zones A and B, and we calculated the distances and angles from each fiducial point to the point after the surface-matching registration (residual variation distance [RVD] and residual variation angle [RVA]). We repeated the registration process three times on each zone, using each of the four sets of surface points. We evaluated the RVD and RVA values using the absolute values of variation from the fiducial point which was within the correctable range in zones A and B. We also evaluated each pelvic shape (Crowe 1, 2, and 4) and observed how taking surface-matching points on the pubis influenced the variation correction.

We performed a statistical analysis of all significant variables to determine the differences in registration accuracy with an analysis of variance (ANOVA), followed by the Tukey test for multigroup comparisons.

## Results

The relationship RVD or RVA and the shifted variation from the fiducial point on zone A are shown in Fig. 3. For the x-axis, differences were significant between −10 mm and −8 mm error, and between −8 mm and −6 mm ($p < 0.05$). There was no significant difference between the groups of numbers of registration points. The averages of RVD were all small, in the range of −6 mm to 6 mm (Fig. 3A). For the y-axis, dif-

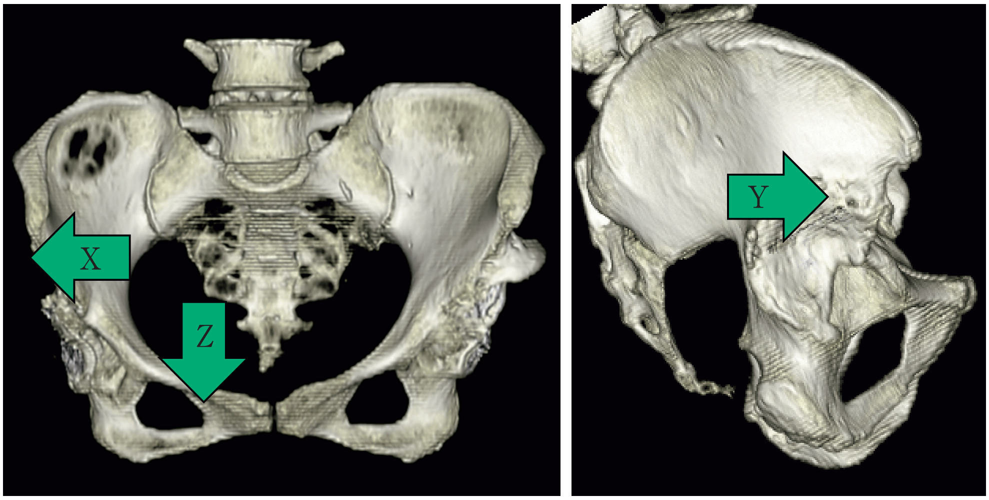

Fig. 2 The anterior pelvic plane (APP) was used as a reference, and the coordinates were defined as follows: x-axis for the external direction, y-axis for the anterior direction, and z-axis for the proximal direction. Three-dimensional coordinate axes were defined based on the rotation for each axis (x, y and z).

ferences were significant between −10 mm and −8 mm, −8 mm and −6 mm, −6 mm and −4 mm, −2 mm and 2 mm, 4 mm and 6 mm, and 8 mm and 10 mm ($p < 0.05$).

Neither reducing the shifted distance from the fiducial point nor increasing the number of surface-matching points produced convergence in the correction values. The RVD values on the y-axis were difficult to correct regardless of the number of registration points. That is, the differences were not significant between the groups of numbers of registration points (Fig. 3B). For the z-axis, the difference was significant between each of the groups ($p < 0.05$). As we took more numbers of surface-matching points, the correction distance converged nominally.

Improving accuracy on the y-axis was also difficult (Fig. 3C). For the rotational x-axis, it was possible to converge the RVA into a small range regardless of the amount of shifted angle and the number of surface-matching points (Fig. 3D). For the rotational y-axis, we found significant differences between −10° and −8°, −8° and −6°, and 6° and 10° ($p < 0.05$). The average of the RVA was favorable in the range of −6° to 4° (Fig. 3E).

For the rotational z-axis, the difference was significant between −10° and −6°, −8° and −4°, −6° and −4°, 6° and 8°, and 8° and 10° ($p < 0.05$). Correction was difficult even as the shifted angle decreased. Only the group of 30 surface-matching points showed good correction results in the range of −6° to 4° (Fig. 3F).

The RVD or RVA and the shifted variation from the fiducial point on zone B are shown in Fig. 4. For the x-axis, the difference was significant between −10 mm and −4 mm, −8 mm and −4 mm, 4 mm and 6 mm, 6 mm and 8 mm, and 6 mm and 10 mm ($p < 0.05$). The difference was not significant between the groups of numbers of registration points. The average of the RVD converged in the range of −4 mm to 4 mm (Fig. 4A). For the y-axis, the difference was significant between −10 mm and −8 mm, −8 mm and −4 mm, and 4 mm and 10 mm ($p < 0.05$). Here, the difference was significant between the groups of numbers of registration points, *i.e.*, 20 and 30 points (Fig. 4B).

For the z-axis, the difference was significant between each range ($p < 0.05$). As we used more numbers of surface-matching points, the RVD values converged marginally. The variation correction on the y-axis was also difficult (Fig. 4C). For the rotational x-axis, it was possible to converge the RVA in the lower range regardless of the shifted angle or the number of surface-matching points (Fig. 4D). For the rotational y-axis, the difference was significant between −10° and −8°, and 6° and 8° ($p < 0.05$). The RVA increased gradually as the shifted angle increased, but the numerical value was small (Fig. 4E). For the rotational z-axis, the difference was significant between all groups except −4° and −2° ($p < 0.05$). The influence of the number of registration points was small (Fig. 4F).

In this study, shifted distances of > 8 mm or angles > 8° from the fiducial point were difficult to correct, and thus we evaluated the RVD and RVA using the absolute values of shifted variation from the fiducial point of < 6 mm or < 6° in zone A. For the x-axis, the difference was significant between 2 mm and 4 mm, and between 4 mm and 6 mm ($p < 0.01$). The difference was not significant between the groups of numbers of registration points. Thirty points were necessary at > 6-mm distance when we aimed for convergence of under 2 mm.

For the y-axis, the difference was significant between 2 mm and 4 mm ($p < 0.01$). In addition, the difference was significant between the groups of numbers of registration points: 15 points and 20 points, and also 20 points and 30 points ($p < 0.01$). It was difficult to converge 4 mm of shift into 2 mm using 20 registration points. For the z-axis, the difference was significant between 2 mm and 4 mm and between 4 mm and 6 mm. The difference between 15 registration points and 20 registration points was also significant. It was difficult to converge 6 mm of shift into 2 mm using 30 registration points.

For the rotational x-axis, the correction was good regardless of the number of registration points or shifted distance. For the rotational y-axis, the difference was significant between 2° and 4° ($p < 0.01$). The difference was not significant between the groups of numbers of registration points. For the rotational z-axis, the difference was significant between 4° and 6° ($p < 0.01$). The difference was significant between 10 and 15 registration points, and between 20 and 30 registration points ($p < 0.01$).

Next, we compared the absolute values of shift variation from the fiducial point for < 6 mm or < 6° in zone B. For the x-axis, the difference was significant between 2 mm and 4 mm and between 4 mm and 6 mm ($p < 0.01$). The difference between 20 registration points

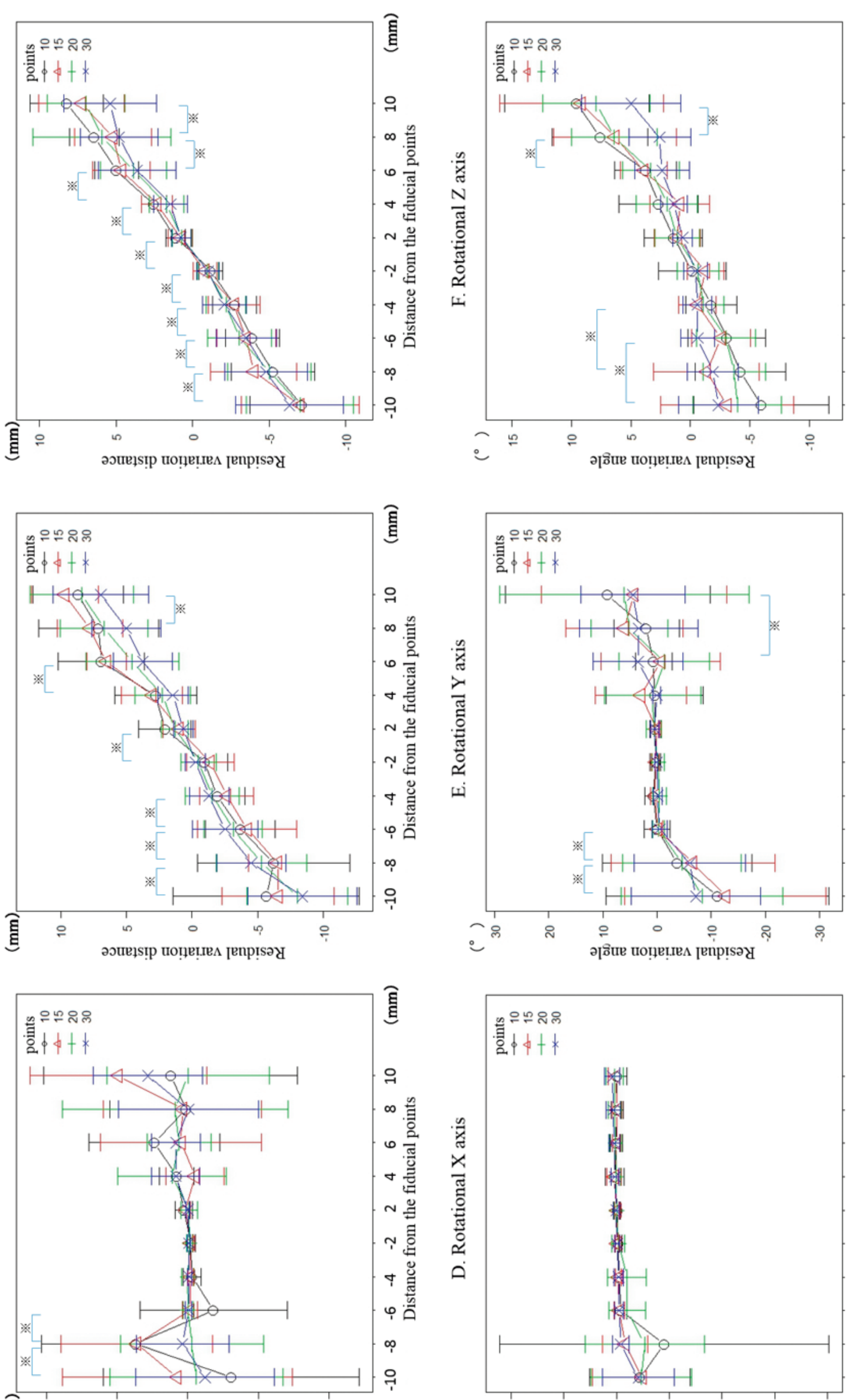

**Fig. 3** The shifted distances/angles and RVD/RVA in zone A. The x-axis represents the shifted distance and degrees from the fiducial point, and the y-axis is the distance and angle from the fiducial point to the point after the surface-matching registration (RVD/RVA). The shifts for **(A)** the x-axis, **(B)** the y-axis, **(C)** the z-axis, **(D)** the rotational x-axis, **(E)** the rotational y-axis, and **(F)** the rotational z-axis. The differences in registration accuracy were examined with an ANOVA, followed by a Tukey test multigroup comparison of all significant variables. (※) $p < 0.05$, (※※) $p < 0.01$.

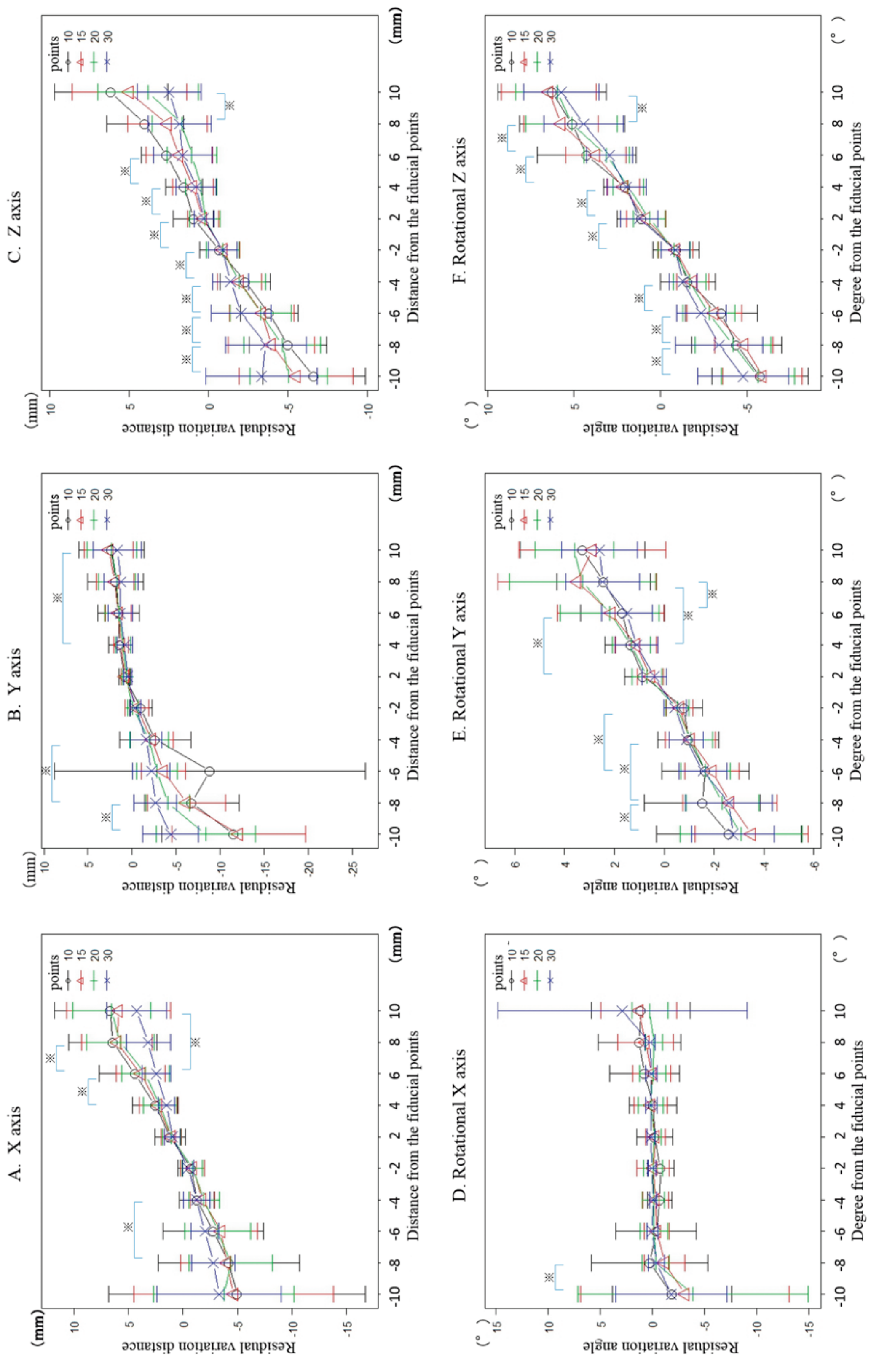

**Fig. 4** The shifted distances/angles and RVD/RVA in zone B.

and 30 registration points was also significant ($p < 0.01$). For the y-axis, the difference was significant between 2 mm and 4 mm ($p < 0.01$) as was the difference between 10 and 30 registration points ($p < 0.01$). It was not difficult to correct on the y-axis compared with in zone A, using 15 points that corrected 6 mm of shift into 2 mm.

For the z-axis, the difference was significant between 2 mm and 4 mm and between 4 mm and 6 mm ($p < 0.01$) The difference between 10 registration points and 20 registration points was also significant ($p < 0.01$). It was not difficult to converge the 4 mm of shift into 2 mm. For the rotational x-axis, the difference was not significant between the amounts of shifted angle. The difference was significant between 10 and 15 registration points, and between 20 and 30 registration points ($p < 0.01$). Even 6 degrees of shift could be corrected to under 2° by using 15 or more points.

For the rotational y-axis, the difference was significant between 2° and 4° and between 4° and 6° ($p < 0.01$). However, the difference between the groups of the number of registration points was not significant. The variation correction was straightforward at even 6° of shifted angle. For the rotational z-axis, the difference was significant between 2° and 4° and between 4° and 6° ($p < 0.01$). The difference was not significant between the groups of numbers of registration points. It was difficult to converge ≥6° of shifted angle, and thus reducing the shifted angle to under 4° was necessary.

We next evaluated the influence pelvic deformity had on registration. The graph in Fig. 5 shows the deformity of the pelvis and the RVD or RVA for the x-, z-, and rotational z-axis on zone A, and the x-, z-, and rotational z-axis on zone B, which was difficult to correct using 20 surface-matching points. On zone A, for the y-axis, the difference was significant between Crowe 1 and 2 deformity ($p < 0.01$) (Fig. 5A). In this study, the patient with a Crowe 2 pelvis had dysplasia of the hip. Its shape at the superior of the acetabulum was very flat. For the z-axis, the difference was not significant between the different pelvic shapes, however the Crowe 4 pelvis did tend to correct better than other shapes (Fig. 5B).

For the rotational z-axis, the difference was not significant between the shapes of the pelvises (Fig. 5C). On zone B, for the x-axis, the difference was not significant between the shapes of the pelvises, but the Crowe 1 pelvis did tend to correct better than the other shapes (Fig. 5D). For the z-axis, however, the shifted distance was difficult to correct for Crowe 1 (Fig. 5E). For the rotational z-axis, the shifted angle was difficult to correct for Crowe 1 (Fig. 5F).

We also conducted an evaluation using the points on the pubis in zone A. Fig. 6 provides the graphs for the y-, z- and rotational z-axes using 20 registration points without the pubis on zone A, compared with 17 registration points on zone A with three points on the pubis. For the y-axis, the difference was significant depending on the area of the registration points, and 20 points without the pubis was better than with the pubis (Fig. 6A). For the z-axis, the difference was not significant, but including the pubic points tended to provide better correction than without the pubis (Fig. 6B). For the rotational z-axis, the difference was significant, and 20 registration points with the pubis was better than that without the pubis (Fig. 6C).

## Discussion

As noted in the Introduction, various types of navigation systems have been used for total hip arthroplasty. Few studies have investigated methods of improving the accuracy of navigation systems. Sugano *et al.* [16] reported that the slice thickness and the reconstruction pitch affected the accuracy of registration. As the sampling area was expanded, the accuracy increased slightly. However, when the whole area was used for registration, the accuracy did not increase. It has been suggested that an optimal area for registration exists, and that it may be affected by the pelvic shape. We therefore evaluated the influence of the surface-matching area location and the number of points for each shape of pelvis. In addition, our existing CT-based navigation system showed only residual and angle data, and previous reports used this for evaluating registration accuracy. In the present study however, we evaluated the accuracy by also using three-dimensional and rotational coordinates.

For our study, the surface-matching area was divided into 2 zones around the acetabulum as operations approached, because it makes no sense to evaluate the accuracy with surface-matching points without completing the surgical procedure itself. This system is intended to be used not only in THA but also in osteotomy, so we chose only surface-matching points around the acetabulum. Our findings demonstrated that on zone A, it was easy to correct the error for the x-axis,

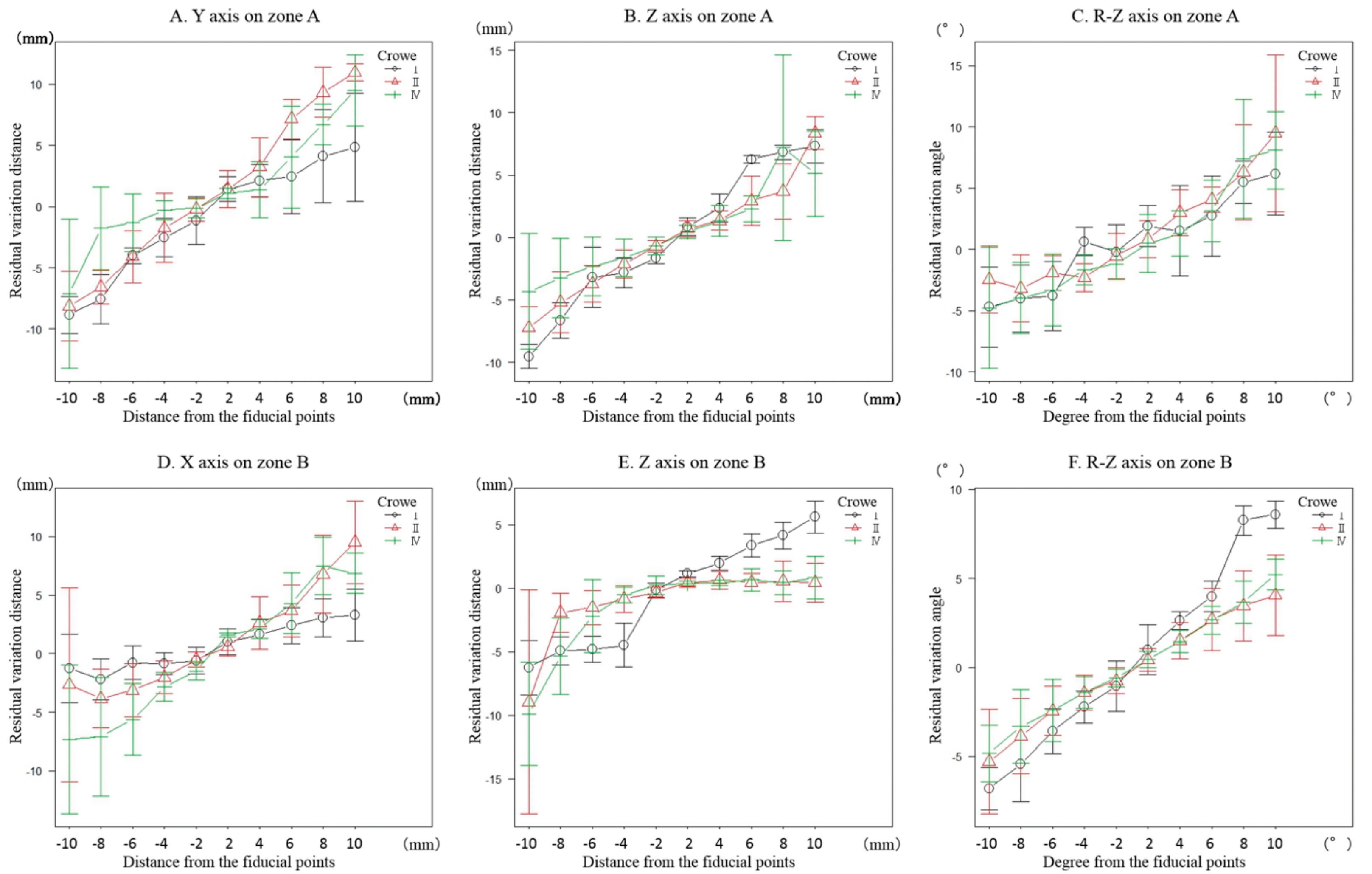

**Fig. 5** The results for the various pelvic deformities, including the RVD and RVA after correction using 20 surface-matching points for the x-, z-, and rotational z-axes on zone A, and the x-, z-, and rotational z-axes on zone B, all of which were difficult to correct.

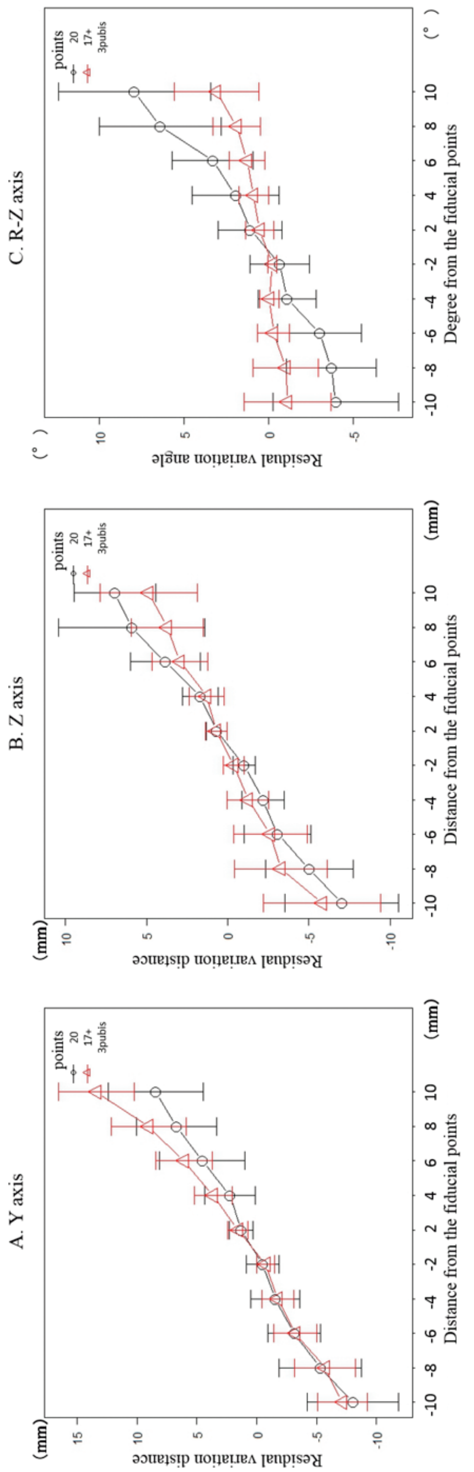

**Fig. 6** The RVD and RVA for the y-, z-, and rotational z-axes using 20 points without the pubis on zone A, and 17 points on zone A with three points on the pubis.

but it was difficult for the y- and z-axes. On zone B, correction was difficult for the x- and z-axes. We speculate that the superior area around the acetabulum was orthogonal to the x-axis, and the posterior area was orthogonal to the y-axis, and thus the reconstruction of a three-dimensional image was easy in these directions for each zone.

In addition, the superior area is parallel to the y- and z-axes, and the posterior area is relatively parallel to the x- and z-axis. This was the reason why it was difficult to correct the shifted distance in these directions for each zone. In other words, when the area of the surface-matching points was orthogonal to the direction which should correct, the variation correction was good, but when the area was parallel, it was not. The correction ability in zone B was better than that in zone A, possibly because the postero-superior area was in a different direction to the posterior area.

Correcting the rotational angle was difficult for the rotational z-axes in both zones. We suspect that this is because the shape of the surface-matching area on both zones was similar to the rotational z-axis. Regarding the number of surface-matching points necessary to correct, the rough paired matching before surface matching should be considered. If there are few similarities, it is difficult to correct by solely increasing the number of surface-matching points. Even though we aimed to converge the variation from the fiducial point to under 2 mm or 2° in each direction as our final goal, we were only able to converge the variation to under 4 mm or 4° on coarse paired matching, using over 20 surface-matching points, though 30 points was recommended where possible in zone A.

On the other hand, to converge the variation from the fiducial point to under 6 mm and 6° on coarse paired matching, using 15 to 20 surface-matching points was recommended in zone B. It was difficult to improve correction in the direction that was difficult to correct using residual which was even very small on coarse paired matching. We therefore recommend checking the position on coarse paired matching, and then taking the surface-matching points which are optimal area to correction. However, in cases in which the shifted distance and angle are beyond the correctable range, on difficult directions especially, we should perform coarse paired matching once again and correct as possible.

Regarding the evaluation of the accuracy of the registration between pelvic deformities, Kajino *et al.* [17]

reported that there was no significance regarding the angle of the implant when using navigation systems between severe deformities and mild dysplasia of the pelvis. In the present study, for the correction of the shifted distance on the y-axis in zone A, it was more difficult on a flat-shaped surface-matching area. On a flat shape, and in hip dysplasia cases, care should be taken because the correction ability is decreased. The shape of the surface-matching area may have more significance than the pelvis shape. Moreover, Crowe 1 was difficult to correct in some directions on the posterior of the acetabulum. The more severe the deformity of the pelvis is, the easier it may be to correct.

Hananouchi *et al.* [18] found that the accuracy of the setting of the cup was not significantly different between the anterior approach and the posterior approach. The surface-matching points for the anterior approach are taken on the anterior of the acetabulum. We expected the correction ability to be increased to the same degree as the posterior approach. We used 'new' surface-matching points on the pubis and then evaluated the correction ability. On zone A, the correction ability was evaluated for the y-, z-, and rotational z-axis using 20 registration points on the superior of the acetabulum versus 17 registration points on the anterior of the acetabulum and 3 points on the pubis. For the y-axis, only the superior area of the acetabulum tended to improve, whereas the other axes improved on the superior area plus the pubis area. This was because the shape of the pubis area is parallel to the y-axis and relatively orthogonal to the z- and rotational z-axes.

Thus, adding points to the area orthogonal to the direction to be corrected was thought to improve the correction ability. For example, though it would add a new skin invasion to correct to z-axis, taking points on the iliac crest may increase the correction ability.

The limitations of the present study were the very small group and the evaluation of only the correction ability in a single shifted direction. We continue to use this navigation system in THA and we are further evaluating the correction for multiple shifted directions and angles.

How many and where to take surface-matching points around the acetabulum has been unclear, and our present findings resolve these problems. Each area of surface-matching points has directions that are easy to correct and directions that are difficult to correct. The shape of the pelvis also affects the correction ability. We recommend first checking the position after coarse paired matching, then choosing the surface-matching area and points that are optimal to correct. Our results showed how to use the surface matching-type CT-based navigation system more effectively in total hip arthroplasty. Surface registration has its own set of characteristics in correction, and understanding them will improve the accuracy of total hip arthroplasty and reduce surgical times.

Acknowledgments. We thank all of the orthopedic surgeons at Okayama University Hospital, Tokyo University, and Teijin Nakashima Medical Co. who participated in this study.

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