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Evaluation of the Accuracy of Computed Tomography–Based Navigation for Femoral Stem Orientation and Leg Length Discrepancy

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Abstract: Although there is a great deal in the literature about the clinical accuracy of computed tomography (CT)–based navigation systems for acetabular cup orientation and leg length discrepancy in total hip arthroplasty, there is little analysis of femoral stem orientation. Thirty total hip arthroplasties in which CT-based navigation system had been used had their anteversion, valgus angle of stem, and leg length discrepancy measured on postoperative CT data. Differences in postoperative measurements from intraoperative records were −0.6° ± 4.8° (range, −11° to 10°) for stem anteversion, −0.2° ± 1.8° (range, −4° to 3°) for valgus angle of stem, and 1.3 ± 4.1 mm (range, −6 to 10 mm) for leg length. Although this system may need further improvement for stem orientation, it was helpful for intraoperative leg length adjustment. **Keywords:** total hip arthroplasty, femoral stem, accuracy, leg length, CT-based navigation.

Component malpositioning and postoperative leg length discrepancy (LLD) are the most common technical problems associated with total hip arthroplasty (THA) [1]. To prevent cup malpositioning that might lead to dislocation of the hip joint and/or early wear of the polyethylene liner, the so-called safe zone was suggested by Lewinnek et al [2]. In the last decade, not only cup orientation, but stem alignment also came to be regarded as an essential factor to acquire the optimal range of motion and to reduce the rate of dislocation and mechanical problems related to impingement. [3-6].

As for the LLD, although it was common among the healthy population to have discrepancies as high as 2 cm and still be asymptomatic, discrepancy after THA may lead to more patient complaints [7], for example, back pain, gait disorders, and general dissatisfaction [8,9]. In some literature, it was reported that reduction of LLD contributed to a better functional outcome [10,11].

Because navigation systems were supposed to offer the potential to implant components in an optimal orientation, there have been many reports about the accuracy of implant orientation of navigated THAs [12-17]. Dorr et al [14] evaluated stem anteversion with an imageless navigation system; they reported 10.9° ± 9.0° of navigation measurement and 10.6° ± 8.0° of postoperative measurement. As for the evaluation of LLD with computed tomography (CT)–based navigation system, the difference between intraoperative and postoperative leg length was reported to be −0.5 ± 1.77 mm (−5 to 3.9 mm) by Ecker et al [1] and Murphy and Ecker [15]. Although most of the rest of the literature mentioned cup orientation and/or LLD [1,12-17], we could not find any clinical literature that examined the orientation of the cup and stem and leg length in the same study. Because LLD is a result of both cup and stem positioning, alignment of the stem is as important as that of the cup. So the purpose of this study was to examine the accuracy of the femoral stem orientation and the LLD under the precise use of CT-based navigation in clinical use.

Materials and Methods

From July 2007 to May 2008, 54 THAs with cementless stems (CentPillar, Stryker, Mahwah, NJ) were performed with the use of CT-based navigation system (Stryker CT-Hip System V1.0, Stryker-Leibinger, Freiberg, Germany) in our hospital. All preoperative planning and postoperative measurements were

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completed on this planning module. As preparation for planning, the CT was taken from pelvis to knee joint and transferred into the planning module. Twenty reference points (bilateral anterior superior iliac spines, bilateral pubic tubercles, the most distal point of bilateral ischium, mid pubic symphysis and sacral mid plane for pelvic frame and femoral head, piriformis fossa, the most posterior point of the proximal femur, bilateral posterior condyles, and knee center for femoral frame) were taken, and segmentation of pelvis and femur was performed semiautomatically. Size and orientation of the stem were decided. As the first step, stem anteversion and valgus angle were adjusted to match the anatomical neck anteversion and shaft axis; and then the size of femoral stem was decided to fit both medial canal and lateral flare and to fill the canal of the proximal femur as much as possible. Afterward, cup orientation was adjusted according to the stem anteversion angle to acquire the best range of motion. Leg length was planned to get minimum LLD by adjusting the stem size, head offset, and cup position.

All THAs were performed using the navigation system through the posterolateral approach, with patients in the lateral decubitus position. Before skin incision, a pelvic tracker was percutaneously fixed on an ipsilateral ilium by an external fixation device (Hoffman II, Stryker-Leibinger) through two 4-mm Apex pins (Fig. 1A). Following the dislocation of the hip joint, a femoral tracker was rigidly fixed on the greater trochanter by a triangular plate with three 2.0-mm screws (Fig. 1B).

Registration of the femur was completed by surface matching, digitizing 30 points on the femur with a pointer, and confirmed by touching femoral surface and characteristic points, that is, the tip of greater trochanter, smaller trochanter, and lateral epicondyle of the femur. A verification point of the femur, which was used to check intraoperative loosening of the femoral tracker fixation, was set on the greater trochanter (Fig. 2A). The femoral neck was then cut along the preoperative planned line that was shown on the navigation monitor. Registration of the pelvis was also done by surface matching, and a verification point of the pelvis was set on the posterosuperior portion of acetabular rim (Fig. 2B).

After reaming, implantation of the acetabular cup was done under the navigation system; final anteversion and inclination were recorded; and fixation of the pelvic tracker was checked by touching its verification point. Subsequently, femoral preparation was performed. At the end of rasping and implantation of the stem, anteversion, valgus angle, and leg lengthening were recorded. Afterward, the femoral tracker was checked for stability by touching its verification point. Leg length was finally adjusted by changing the neck length of the femoral head.

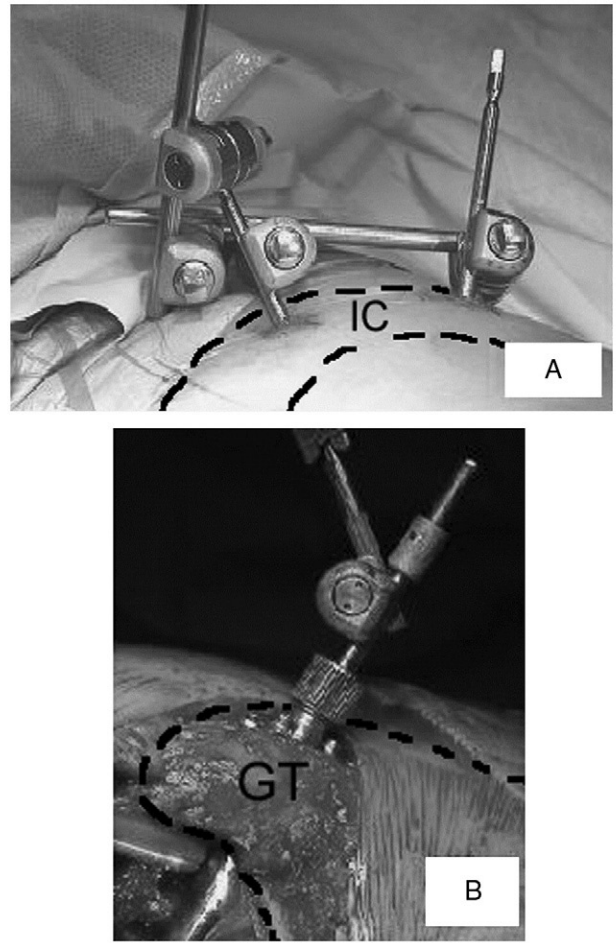

Fig. 1. A pelvic tracker was percutaneously fixed on an ipsilateral ilium (iliac crest, IC) by external fixation device through two 4-mm Apex pins (A). A femoral tracker was fixed at the lateral phase of the greater trochanter (GT) through the triangular plate (B).

Of all these patients, 24 hips in which stability of either the pelvic or femoral trackers could not be verified were excluded, even if the tracker seemed to be securely fixed and not displaced. Finally, 30 hips of 25 patients remained (Table 1).

Preoperative diagnoses were osteoarthritis (28 hips), osteonecrosis (1 hip), and rheumatoid arthritis (1 hip). For evaluation of LLD, 14 hips were excluded. Simultaneous bilateral THA (6 patients, 11 hips) could not be evaluated. The other 3 hips were not planned with getting equal leg length in mind to avoid nerve palsy because preoperative LLD was too large (40, 32, and 32 mm). As a result, LLD was evaluated for the remaining 16 hips.

Stem orientation (anteversion and valgus angle), cup orientation (Murray anatomical anteversion and inclination angle [18]), and LLD were measured preoperatively, intraoperatively, and postoperatively. Preoperative parameters were acquired from preoperative planning. Intraoperative parameters were extracted from navigation records that were measured after each component

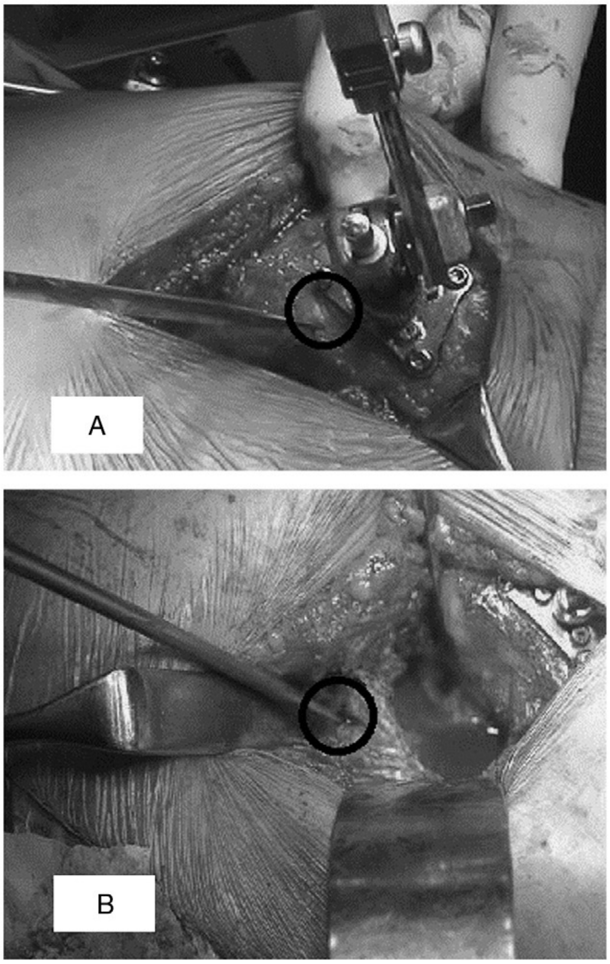

Fig. 2. Verification points for femoral (A) and pelvic tracker (B) were set on the greater trochanter and superior posterior wall of acetabular rim.

had been inserted. Postoperative parameters were measured on CT data that were taken 2 weeks postoperatively using a planning module of the same navigation system. After all the reference points on the preoperative plan were manually copied onto the postoperative CT, computer-aided design (CAD) models of the implants were superimposed on their images; and those parameters were measured (Fig. 3).

Difference between preoperative and postoperative CT data was defined as *clinical accuracy*. Difference between intraoperative and postoperative CT was defined as *measurement error*. For this measurement procedure, we also evaluated intraobserver and interobserver variability.

Statistically, a paired *t* test was adopted to compare the preoperative and intraoperative parameters with postoperative ones in the same joint. Differences of clinical accuracy and measurement error among 4 parameters were compared by the Friedman test, and post hoc comparison between parameters was subsequently performed according to the sign test.

Table 1. Demographic Data of the Study Group

Parameter	Results
Total no. of hips	30
Sex	
Female	19 (76%), 23 hips
Male	6 (24%), 7 hips
Height (m)	1.57 ± 0.07 (1.45-1.73)*
Weight (kg)	57.7 ± 9.4 (41.9-78)*
Body mass index (kg/m^2)	23.3 ± 3.2 (18.7-30)*
Age (y)	56.6 ± 7.8 (44-74)*
Side	
Left	12 (40.0%)
Right	18 (60.0%)
Diagnosis	
Osteoarthritis	28 (93.4%)
Rheumatoid arthritis	1 (3.3%)
Osteonecrosis	1 (3.3%)

* Mean ± SD (range).

Results

The preoperative planned position of the stem was 34.2° ± 12.4° of anteversion and 0.30°± 2.1° of valgus, and the position of the cup was 20.9° ± 4.5° of anteversion and 41.9° ± 1.1° of inclination. Intraoperative angles were 31.1° ± 11.7°, −0.1° ± 2.6°, 21.4° ± 5.9°, and 40.8° ± 2.0°, respectively. Because 93% of THAs were performed under the diagnosis of secondary osteoarthritis with dysplastic hip in this study, our planned angle (34.2°) was an average angle and not excessive [19,20]. Postoperative angles were 31.7° ± 11.7°, 0.1° ± 1.8°, 22.3° ± 7.7°, and 40.4° ± 3.5°, respectively (Table 2).

No statistical difference was found between intraoperative and postoperative stages for any of the parameters (paired *t* test). As for stem anteversion, there were differences between planned angle and intraoperative or postoperative angle ($P < .05$, paired *t* test). The clinical accuracy of the stem anteversion and valgus angle was −2.5° ± 6.1° and −0.2° ± 1.5°, and that of cup anteversion and inclination was 1.4° ± 5.6° and −1.5° ± 3.5°. There were differences between stem anteversion and cup anteversion ($P < .05$, sign test), between stem valgus angle and cup anteversion ($P < .05$, sign test), and between cup anteversion and inclination ($P < .01$, sign test) (Fig. 4).

For the clinical accuracy of the stem anteversion, 18 (60%) of 30 hips were included within 5°; and 28 (93%) of 30 hips were within 10° (Table 3).

The measurement error of each parameter was −0.6° ± 4.8°, −0.2° ± 1.8°, −0.8° ± 4.1°, and 0.4° ± 2.5°; and there were no statistical differences among these 4 groups ($P = .205$, Friedman test) (Fig. 5).

For the measurement error of the stem anteversion, 23 (77%) of 30 hips were included within 5°; and 29 (97%) of 30 hips were within 10° (Table 3).

The LLDs were 3.3 ± 3.0 mm on postoperative CTs and 4.6 ± 4.3 mm in the navigation records. The measurement error of the LLD was 1.3 ± 4.1 mm (Table 2). Intraobserver

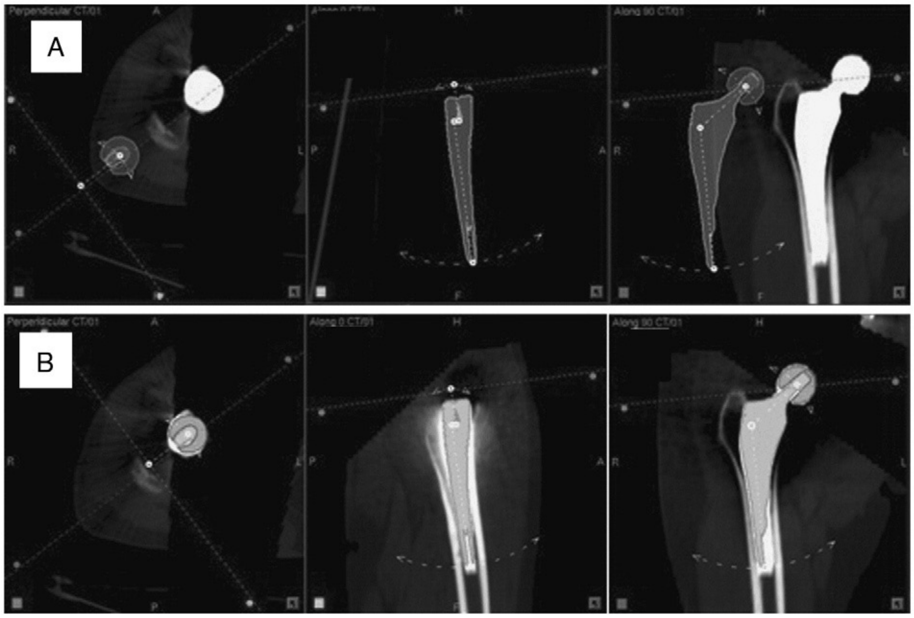

Fig. 3. Measurement of postoperative parameters. Postoperative CT was taken into the planning module and was reconstructed to axial, frontal, and sagittal planes. The CAD model of the femoral implant was going to be superimposed (A). The CAD was superimposed on the implant image, and its parameters were measured (B). Cup orientation was also measured in the same way.

and interobserver variabilities were 0.90° ± 0.66° and 1.7° ± 0.72° for stem anteversion, 0.20° ± 0.29° and 0.0° ± 0.10° for stem valgus angle, and 0.50 ± 0.34 and 1.1 ± 0.67 mm for LLD. Pearson correlation coefficients were 0.97, 0.96, 0.92, 0.87, 0.99, and 0.94, respectively. These data showed that this measurement method was highly reproducible.

Discussion

In addition to cup orientation, stem orientation was also taken into consideration as an essential factor in acquiring the optimal range of motion and joint stability in THA. Widmer and Zurfluh [3] suggested that acetabular cups should be oriented between 40° and 45° of radiographic inclination and between 20° and 28° of radiographic cup anteversion, and should be combined with stem anteversion so that the sum of cup anteversion plus 0.7 times the stem anteversion equals 37°. Yoshimine [4] proposed that the optimum values of combined cup and neck anteversion can be estimated by the following formula: (cup abduction angle) + (cup anteversion angle) + 0.77(neck anteversion angle) = 84.3°. Therefore, it is important to examined both cup and stem alignment.

There was no literature about the accuracy of femoral stem orientation in the clinical use of the CT-based navigation system. As for laboratory studies, Zheng et al [21] evaluated the stem orientation and leg length with a hybrid CT-free navigation system. In their study, compared with CT-based measurement, clinical accuracy of 1.0° ± 0.5°, 0.6° ± 0.5°, and 0.7 ± 0.6 mm was found for stem anteversion, stem valgus angle, and change in leg length, respectively. As for clinical use, Dorr et al [14] evaluated stem anteversion using imageless navigation. They reported 10.9° ± 9.0° of navigation measurement and 10.6° ± 8.0° of

Table 2. Results of Stem and Cup Orientation and LLD

		Preoperative Planning (*P*)	Navigation Record (*N*)	Postoperative CT (*C*)	Clinical Accuracy (*C* − *P*)	Measurement Error (*N* − *C*)
Stem	Anteversion	34.2 °± 12.4°	31.1° ± 11.7°	31.7° ± 11.7°	−2.5° ± 6.1°	−0.6° ± 4.8°
	(range)	(13° to 56°)	(2° to 58°)	(3° to 50°)	(−14° to 9°)	(−11° to 10°)
	Valgus	0.3° ± 2.1°	−0.1° ± 2.6°	0.1° ± 1.8°	−0.2° ± 1.5°	−0.2° ± 1.8°
		(−3° to 4°)	(−5° to 6°)	(−3° to 4°)	(−4° to 2°)	(−4° to 3°)
Cup	Anteversion	20.9° ± 4.5°	21.4° ± 5.9°	22.3° ± 7.7°	1.4° ± 5.6°	−0.8° ± 4.1°
		(11° to 28°)	(10° to 29°)	(3° to 32°)	(−13° to 9°)	(−6° to 8°)
	Inclination	41.9° ± 1.1°	40.8° ± 2.0°	40.4° ± 3.5°	−1.5° ± 3.5°	0.4° ± 2.5°
		(40° to 44°)	(36° to 45°)	(34° to 48°)	(−7° to 6°)	(−6° to 5°)
LLD (n = 16)		−0.1 ± 2.2	4.6 ± 4.3	3.3 ± 3.0	−3.4 ± 2.4	1.3 ± 4.1
		(−4 to 5) mm	(−1 to 14) mm	(−2 to 10) mm	(0 to 7) mm	(−6 to 10) mm

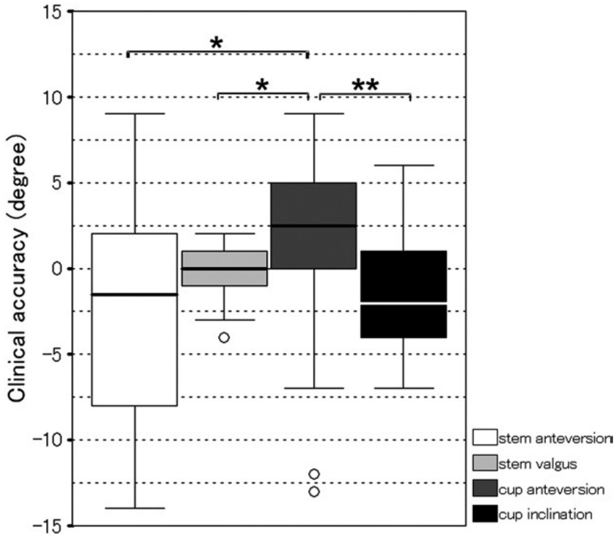

Fig. 4. Boxes show the clinical accuracy of the anteversion and valgus angle of the stem, and the anteversion and inclination of the cup. Box length represents the interquartile range (first to third quartiles). The line in the center of the boxes represents the median value. Data represented by "o" are outliers (greater than 1.5 to 3.0 times the interquartile range over the third quartile) ($P < .05$, $P < .01$).

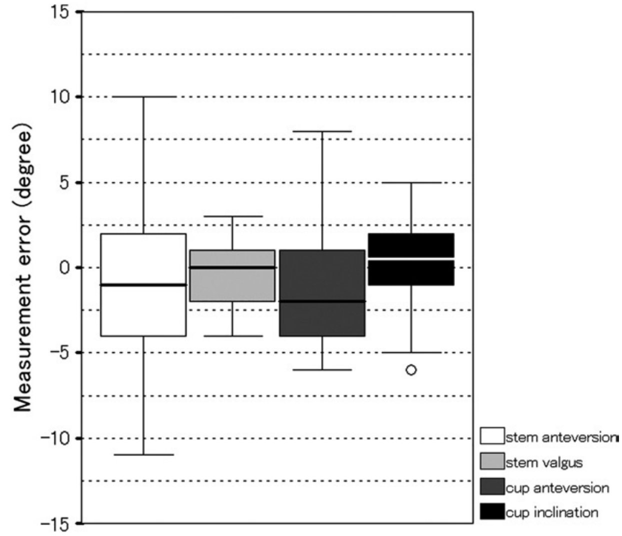

Fig. 5. Boxes show the measurement error of the anteversion and valgus angle of the stem, and the anteversion and inclination of the cup. Box length represents the interquartile range (first to third quartiles). The line in the center of the boxes represents the median value. Data represented by "o" are outliers (greater than 1.5 to 3.0 times the interquartile range over the third quartile).

postoperative measurement. However, they did not express measurement error as mean ± standard deviation. Clinical accuracy was not discussed either.

In the present study, clinical accuracy of stem anteversion was −2.5° ± 6.1° and that of the stem valgus angle was −0.2° ± 1.5°. Measurement error was −0.6° ± 4.8° and −0.2° ± 1.8°, respectively. As for clinical accuracy, although there were statistical differences between stem anteversion and cup anteversion ($P < .05$, sign test) and between cup anteversion and inclination ($P < .01$, sign test), these were reasonable results. It was difficult to implant all components as perfectly as planned even though THA was performed under navigation; orientation of acetabular cup could easily deviate a few degrees during impaction because of its hemispherical shape, whereas femoral stem implantation was strongly restricted by intramedullary shape. On the other hand, measurement error of femoral stem orientation did not differ from that of the cup (sign test, $P = .57$). As for the measurement error of cup orientation, Ybinger et al [12] reported 3.5° ± 4.4°

Table 3. Distribution of the Clinical Accuracy and Measurement Error of the Stem Anteversion

Range (°)			Clinical Accuracy (Hips)	Measurement Error (Hips)
	–	−11°	2 (7%)	1 (3%)
−10°	–	−6°	8 (26%)	3 (10%)
−5°	–	5°	18 (60%)	23 (77%)
6°	–	10°	2 (7%)	3 (10%)
11°	–		0 (0%)	0 (0%)

(range, 0.2°-12.7°) for inclination and 6.5° ± 7.3° (0.4°-13.4°) for anteversion. Langlotz et al [13] reported 1.6° ± 1.3° (−3° to 4°) and 2.3° ± 1.4° (−5° to 5°), respectively. Considering that these angles were radiographic angles [18], which were smaller than the anatomical angles, our results were comparable to theirs: 0.4° ± 2.5° (−6° to 5°) and −0.8° ± 4.1° (−6° to 8°), respectively. Therefore, it can be concluded that the measurement error of stem orientation was equal to that of the cup.

However, considering that the system accuracy of this navigation system originally targeted 1 mm and 1° [22], these results cannot be said to have been good enough; and improvements were needed. Several proposals were suggested. (1) Taking reference points from a broader area of the femur might improve the accuracy. Sugano et al [22] reported that taking reference points from the proximal femur to the medial and lateral aspects of the femoral condyles reduced the position and angle error compared with readings from only the proximal femur. So we started taking reference points of the distal diaphysis of the femur through pinhole incision on the lateral thigh, although we do not have the results yet. (2) There were some problems with the instruments. In addition to loose fixation between stem and stem holder, there was some interference between the greater trochanter and the stem holder. As a result, stem alignment of intraoperative navigation tended to be recorded in more varus than that of postoperative measurement. (3) There were differences between the planned angles and intraoperative or postoperative angles ($P < .05$, paired t test). Considering that intraoperative and postoperative angles were almost the same, there may be a room for improving the planning interface of the workstation for the stem.

Leg length discrepancies were evaluated among 16 joints that had been planned for differences of less than 10 mm. Intraoperative and postoperative LLD and measurement errors were 4.6 ± 4.3, 3.3 ± 3.0, and 1.3 ± 4.1 mm, respectively. There was no statistical difference between intraoperation and postoperation (P = .10). In previous reports of CT-based navigation, intraoperative and postoperative LLD and measurement errors were 6.6 ± 4.1 (−2 to 22), 6.1 ± 4.3 (−5 to 20), and −0.5 ± 1.77 (−5 to 3.9) mm [1,15]. Although these measurement errors were better than the results of the present study, our postoperative evaluation was based on CT scans that were not influenced by posture.

The range of the LLD where navigation system has not been used is well reported in the literature. Jasty et al [7] used special calipers before and after the insertion of the trial components and reported that the LLD was within 6 mm in 89% of their patients. Woolson et al [23] used a single method of leg length equalization by preoperative planning with overlay templates and reported that 90% of the patients had a postoperative LLD that was less than 1 cm and 86% had a leg length difference that was 6 mm or less. In the present study, the LLD was within 6 mm in 94% of patients (15 of 16 patients). On this point, CT-based navigation was reliable for leg length adjustment.

There were 2 limitations in this study. First, the number of the patients was small, especially the patients whose leg length could be evaluated. Further accumulation of cases will be needed. Second, errors may have been introduced in the reconstruction of the postoperative pelvic and femoral coordination systems. This is because all of the reference points were manually copied on to the postoperative CT by comparing screen shots of preoperative planning of the same joint. We examined the level of reproducibility of this measurement method between interobservers and intraobservers. However, an automatic method to copy the reference points may lead to a much more accurate evaluation of the implant orientation.

In conclusion, when using the CT-based navigation system properly, the measurement error of the stem alignment was equal to that of the cup orientation; and intraoperative leg length adjustment was a practical option.

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