Clinical accuracy and precision of hip resurfacing arthroplasty using computed tomography-based navigation

Running title: Navigated Hip Resurfacing Arthroplasty

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Abstract

Purpose To avoid malalignment of components during hip resurfacing arthroplasty (HRA), we used a computed tomography (CT)-based navigation system for guidance. This study aimed to evaluate the clinical accuracy and precision of HRA performed using the CT-based navigation systems.

Methods HRA was performed on 17 hips guided by the CT-based navigation systems. We measured cup alignment deviation, deviation of the stem position and alignment from the plan by image matching between preoperative and postoperative CT images.

Results Cup anteversion was within 5° of that in the plan in all cases. Cup inclination was within 5° of that in the plan in 82.4% and within 10° in all cases. The angular difference of the stem was within 5° in all cases, and the entry point of the stem was within 4 mm in all cases.

Conclusion The CT-based navigation system for HRA guided accurate component placement according to the plan.

Keywords Hip resurfacing arthroplasty; Computed tomography; Navigation; Computer-assisted orthopedic surgery; Accuracy

Introduction

Modern metal-on-metal hip resurfacing arthroplasty (HRA) is an alternative to total hip arthroplasty (THA) for highly active young patients with end-stage osteoarthritis [1]. Advantages of HRA are minimal bone resection, avoidance of stress shielding in the proximal femur, and a low dislocation rate. In addition, higher postoperative activity is enabled, and HRA allows easier revision surgery, if necessary [2-6]. HRA, however, requires high surgical skill, and the surgeon must have sufficient experience because malpositioning the acetabular and femoral components causes serious postoperative complications, including femoral neck fracture, femoral component loosening, and excessive wear of the bearing surface, which in turn causes an elevated metal ion concentration and ~~an~~ adverse reaction to metal debris (ARMD) [4,5,7].

Computer-assisted tools, including navigation, patient-specific guides and robotic systems, have been reported as useful for eliminating component malpositioning during HRA [4,8,9]. Among these aids, computed tomography (CT)-based computer-assisted systems are supposed to be more accurate than imageless navigation, and the size of the components needed can be determined preoperatively. CT-based preoperative planning is particular useful in complex, post-trauma deformity cases or those with osteonecrosis or developmental dysplasia of the hip [10,11]. Therefore, we introduced the use of CT-based navigation during HRA for more precise execution of an optimized plan. The purpose of the current study was to assess the clinical accuracy and precision of component placement during HRA using CT-based navigation systems.

Materials and methods

Patients

From January 2011 to January 2017, we performed HRA on 20 hips using two types of CT-based navigation. The objects of this study were 17 hips in 16 patients [12 male patients (13 hips) and 4 female patients (4 hips)] who had consented to undergo preoperative and postoperative CT scanning. The preoperative diagnoses were osteoarthritis in 14 hips and osteonecrosis of the femoral head in 3 hips.

A standard THA CT-based navigation system (CT-based Hip Navigation System; Stryker, Kalamazoo, MI, USA) was used for acetabular cup placement. A versatile CT-based navigation system (Orthomap 3D; Stryker, Kalamazoo, MI, USA) was used for guidewire insertion of the femoral component. ADEPT® Hip Resurfacing System (Finsbury Orthopaedics, Leatherhead, UK) was used in 9 hips and BHR System (Birmingham Hip Resurfacing System; Smith & Nephew, Memphis, TN, USA) in 8 hips. The mean follow-up period was 49.6 months (range 16–83 months).

Preoperative plan

For preoperative planning of the acetabular component, the targeted alignments were 40° in radiographic inclination and 15° in radiographic anteversion [1], relative to the functional pelvic coordinate system with patient-specific pelvic sagittal inclination in the supine position [10,12,13].

For preoperative planning of the femoral components, the alignment of the femoral component stem was set to be parallel with the medial cortex of the femoral neck in the coronal oblique view through the femoral neck axis and parallel to the femoral neck axis in the sagittal oblique view through the femoral stem axis (Fig. 1). The femoral component position was set so its distal edge of the articular surface came to the femoral head–neck junction.

Surgical technique

All HRAs were performed by surgeons with experience of more than 100 THAs using standard CT-based navigation, via the posterolateral approach, and with the patient in the lateral position. A pelvic navigation tracker with light-emitting diodes was fixed on the ipsilateral iliac crest. Surface registration of the computer pelvis model and real bone was completed by taking 30 points on the surface of the ilium and ischium [14]. We performed line-to-line reaming or 1-mm under-reaming with a navigated acetabular reamer according to the stiffness of the acetabular bone. Finally, the acetabular cup was implanted, aiming for 40° radiographic inclination and 15° radiographic anteversion as viewed on the navigation monitor.

On the femoral side, a tracker with light-emitting diodes was secured to the lateral aspect of the greater trochanter. Surface registration of the femur was then performed by taking 30 points on the surface of the proximal femur [14]. A guidewire was inserted into the femoral head using a navigated drilling sleeve (Fig. 2) [15]. The femur was cylindrically reamed and shaped around the guidewire. After this femoral head preparation, all fragile tissues, including cysts, areas of granulation, and necrotic bones, were removed. Anchoring holes were made over the normal bone in the dome and chamfer areas. Finally, the femoral component was fixed to the femoral head with cement (Surgical Simplex; Stryker, Kalamazoo, MI, USA). During insertion of the femoral component, bone marrow fluid was suctioned via a cannula placed in the lesser trochanter to prevent elevation of the intraosseous pressure and mixture of blood with cement [16].

Analysis

Using postoperative CT images, we measured cup inclination and anteversion, the deviation of cup alignment from that of the plan, the stem–shaft angle (SSA), stem inclination and version relative to the femoral neck axis, deviation of the stem entry point and deviation of alignment from the plan. We also looked for the presence of femoral neck notching.

The planning module of the standard THA navigation system was used for measuring cup alignment. The reference pelvic coordinate system of postoperative CT was matched with that of preoperative CT using the landmark-based matching method previously reported [12,17,18]. Cup inclination and anteversion were measured by overlapping the cup model on the implanted cup on the postoperative CT data (Fig. 3) [13]. Any deviations in cup inclination and anteversion from the target were calculated.

The planning module of the versatile CT-based navigation system was used to measure femoral component alignment. The femoral neck coordinate system was created on preoperative CT images as follows. The center of the femoral head was defined by fitting a sphere to the normal subchondral bone of the femoral head. The center of the femoral neck was defined by fitting a sphere to the anteroposterior and superoinferior inner cortexes of the femoral neck at its isthmus. The femoral neck axis was defined as the line passing through the centers of the femoral head and neck. The plane consisting of the femoral neck axis and the center of the femoral medullary canal 15 cm distal from the tip of the greater trochanter represented the oblique coronal plane of the femoral neck (Fig. 4A). The plane perpendicular to the oblique coronal plane through the neck axis represented the oblique sagittal plane of the femoral neck (Fig. 4B) [19]. The reference femoral coordinate system of the postoperative CT data was matched with that of the preoperative CT data using the volume registration method previously reported [20].

The proximal femoral bone axis was defined as the line between the center of the canal at the lesser trochanter and the center of the femoral medullary canal 15 cm distal from the tip of the greater trochanter [19]. The neck–shaft angle (NSA) was defined as the projected angle between the femoral neck axis and the proximal femoral bone axis in the oblique coronal plane. The stem–shaft angle (SSA) was defined as the projected angle between the stem–shaft axis and the proximal femoral bone axis in the oblique coronal plane. Stem inclination was calculated by subtracting NSA from SSA. We defined the femoral components as valgus or varus when SSA was 5° greater or less than NSA [19].

The stem version was defined as the projected angle between the femoral component axis and the femoral neck axis in the oblique sagittal plane. The angular difference between the preoperative plan and the stem alignment was measured by projecting the stem axis and the neck axis in both the oblique coronal and oblique sagittal planes, respectively (Fig. 5). The deviation between the planned and actual inserted stem entry point was measured with the original coordinate system of versatile CT-based navigation. The presence of femoral neck notching was sought along the femoral neck axis in the radial reconstructed view.

Results

The mean cup anteversion was 16.1° ± 2.8°, and the mean cup inclination was 37.7° ± 3.0°. The mean deviation of cup anteversion was 1.1° ± 2.8°, and that of cup inclination was −2.3° ± 3.0°. The cup anteversion was within 5° of that in the plan in all cases. The cup inclination was within 5° of that in the plan in 14 of 17 cases (82.4%), and it was within 10° in all cases.

The mean stem inclination of the femoral component was 4.5° ± 3.0° relative to the neck axis, and the mean stem version was 7.2° ± 4.9°. There was no case of varus placement of the femoral component relative to the neck axis. There was no femoral neck notching. The mean angular differences between the femoral stem and the preoperatively planned alignment were 0.8° ± 1.9° on the oblique coronal plane and 0.3° ± 2.5° on the oblique sagittal plane. The angular difference in the stem was within 5° of that of the plan in all cases on both planes. The deviations between that of the plan and the actual inserted stem entry point were 4 mm on both the oblique coronal and oblique sagittal planes. During the follow-up period, no case exhibited femoral neck fracture, femoral component aseptic loosening, or ARMD (Table 1).

Discussion

HRA is a technically demanding procedure because malalignment of femoral components causes serious postoperative complications. To avoid malalignment, we introduced CT-based navigation systems to HRA. Although some clinical reports suggested that imageless navigation could improve the accuracy of femoral component placement during HRA [9,21,22] (Table 2), we found no clinical reports on the accuracy or precision of femoral component placement during HRA using the CT-based navigation system. The current study showed that this system enabled us to place the femoral components accurately and precisely according to the preoperative CT-based plans. There have been several reports of cup placement in THA or revision THA using navigation systems including CT-based navigation and imageless navigation [12,13,17,18,23-25]. Some studies have reported good accuracy of cup alignment during THA or revision THA using the same CT-based navigation of the current study [12,13,17,18] (Table 3). The current study showed that the CT-based navigation system could provide accurate, precise cup alignment during HRA that was as good as that achieved with standard THA.

It is necessary to match preoperative and postoperative CT data to assess the accuracy and precision of osteotomy or arthroplasty using CT-based navigation. In some study for osteotomy, the position of the pelvis on the preoperative and postoperative CT images was matched using volume matching method [26]. In our study for THA, the position of the pelvis on the preoperative and postoperative CT images was matched using a landmark-based matching method [12,17]. Kyo et al. compared the accuracy of the navigation evaluated using the landmark-based matching method versus that assessed using computational volume registration. They reported that the navigation accuracy of cup placement using a land-mark method was similar to that using a volume registration method [27]. Kyo et al. reported that the accuracy of the measurement of stem alignment during THA was worse using a landmark-based matching method than when using a volume matching method [27]. We used a volume matching method for the postoperative measurement of stem alignment and position.

It has been reported that acetabular orientation was critical during HRA to avoid excessive wear due to impingement or edge loading [15]. Steep cup alignment can increase the risk of edge loading and impingement, which could cause ARMD [15]. Grammatopoulos et al. recommended that radiographic orientation of the acetabular component should be 45° ± 10° in inclination and 20° ± 10° in anteversion to reduce the risk of a pseudotumor developing [15]. McMinn et al. recommended cup inclination of 40° to prevent edge loading [1]. Preoperatively, we planned for 40°cup inclination and 15°cup anteversion as the optimal alignment. Postoperatively, we achieved a mean cup inclination of 37.7° ± 3.0° and mean cup anteversion of 16.1° ± 2.8°. In 14 of 17 cases, the cup inclination was within 5° of the planned inclination. In the remaining 3 cases, it was in the range of 30°–35°. Hence, we avoided steep cup inclination, presumably decreasing the risk of ARMD. In fact, there were no cases of ARMD during the follow-up period (maximum 7.8 years). Cup anteversion was within 5° of the operative plan in all cases. We therefore believe that the acetabular cup could be placed with an acceptable range in all cases.

It has been reported that stem malpositioning causes femoral neck fracture and stem loosening [4,5,7]. Excessive valgus positioning and positional errors during guidewire insertion could cause notching of the superior portion of the femoral neck. In turn, notching could expose patients to the risk of femoral neck fracture [4,5]. In this study, the positional error of the guidewire was within 4 mm, and the alignment deviation from that of the plan was within 3° in the coronal oblique plan, resulting in no femoral neck notching.

It has also been reported that varus positioning could increase the risk of postoperative femoral neck fracture in the case of NSA <130° [7]. Varus placement of the femoral component causes early aseptic loosening [7]. The optimal range for stem alignment has not been clarified [7,28]. In the current study, we aimed for stem alignment that was parallel to the medial cortex in the oblique coronal plane and to the neck axis in the oblique sagittal plane. We thereby avoided varus placement, resulting in no femoral loosening or femoral neck fracture.

There are several limitations in this study. First, the number of patients in whom we tested the CT-based navigation system during HRA was small. Second, the follow-up period was short. Whereas femoral neck fracture is reported to occur frequently within 1 year after surgery [28], ARMD and stem loosening are considered to occur during a longer follow-up. Langton et al. reported that pseudotumors associated with ARMD were found during 10-year follow-up periods after metal-on-metal HRA [29]. Hence, we believe that further follow-up is necessary to clarify whether the use of the CT-based navigation lowers the risk of ARMD and stem loosening. Third, there was no control group in whom HRA was performed without CT-based navigation.

Conclusion

The CT-based navigation system for HRA showed accurate component placement according to the preoperative plan, with a mean deviation of $1.1° \pm 2.8°$ cup anteversion and $-2.3° \pm 3.0°$ cup inclination. Also, the mean stem angular deviation was $0.8° \pm 1.9°$ in the oblique coronal plane and $0.3° \pm 2.5°$ in the oblique sagittal plane.

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Compliance with ethical standards

Conflict of Interest

The authors declare that they have no conflicts of interest.

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Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards."

Informed consent

Formal consent is not required for this type of retrospective cohort study.

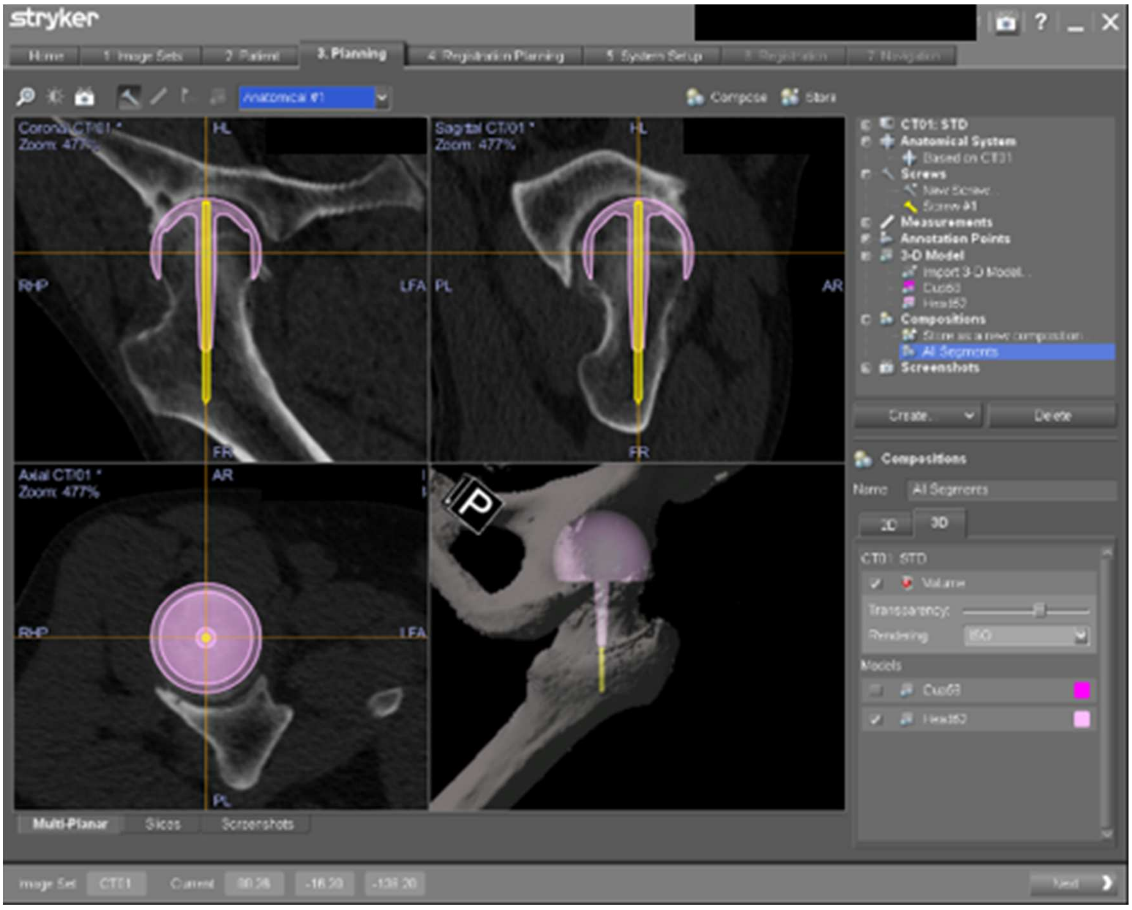

Fig. 1 Preoperative planning for femoral component placement was performed using the planning module of the computed tomography (CT)-based navigation system

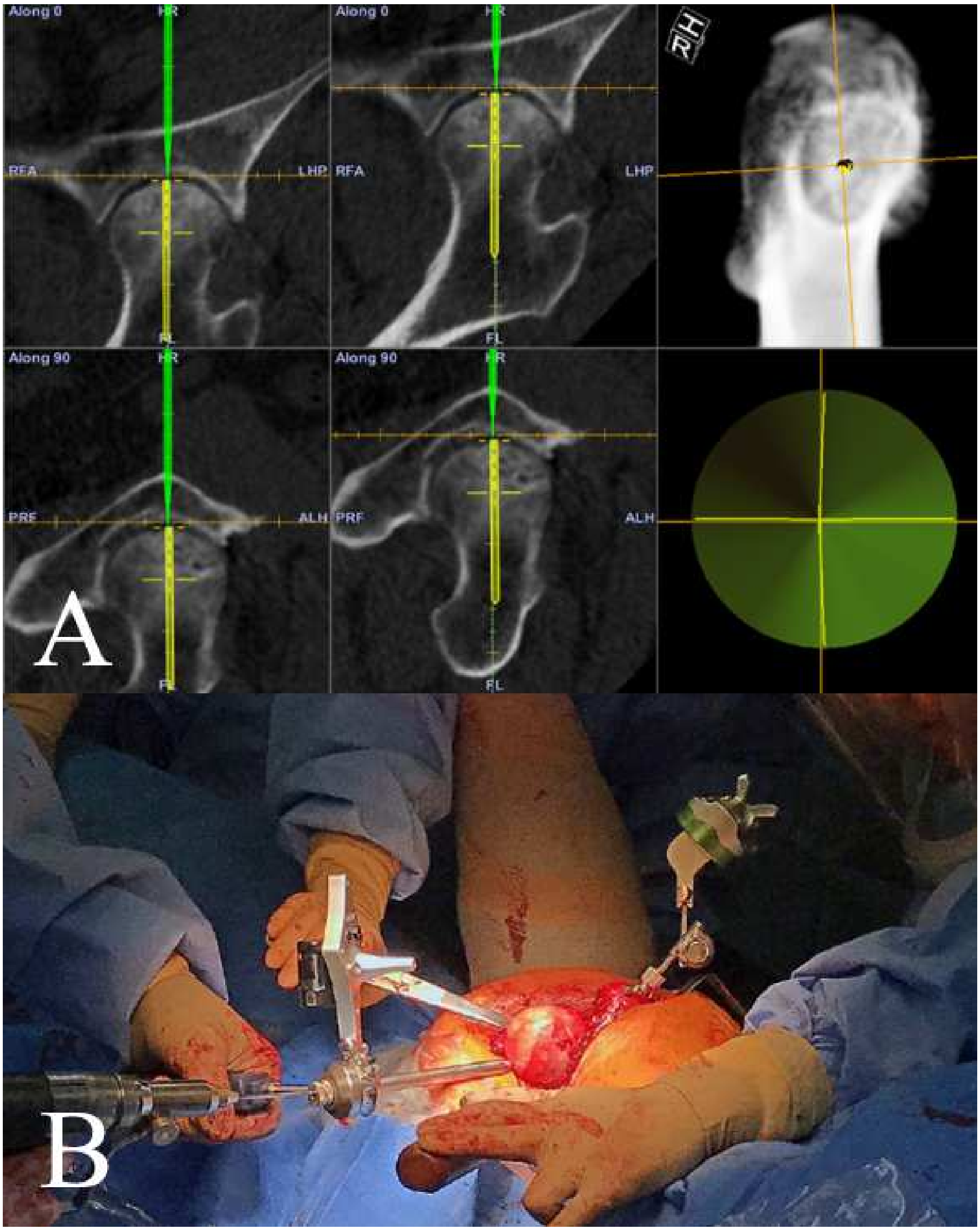

Fig. 2 (**A)** Position and direction of a guidewire sleeve is shown on the navigation monitor in real time. (**B)** The guidewire is inserted from the femoral head surface using the navigated guidewire

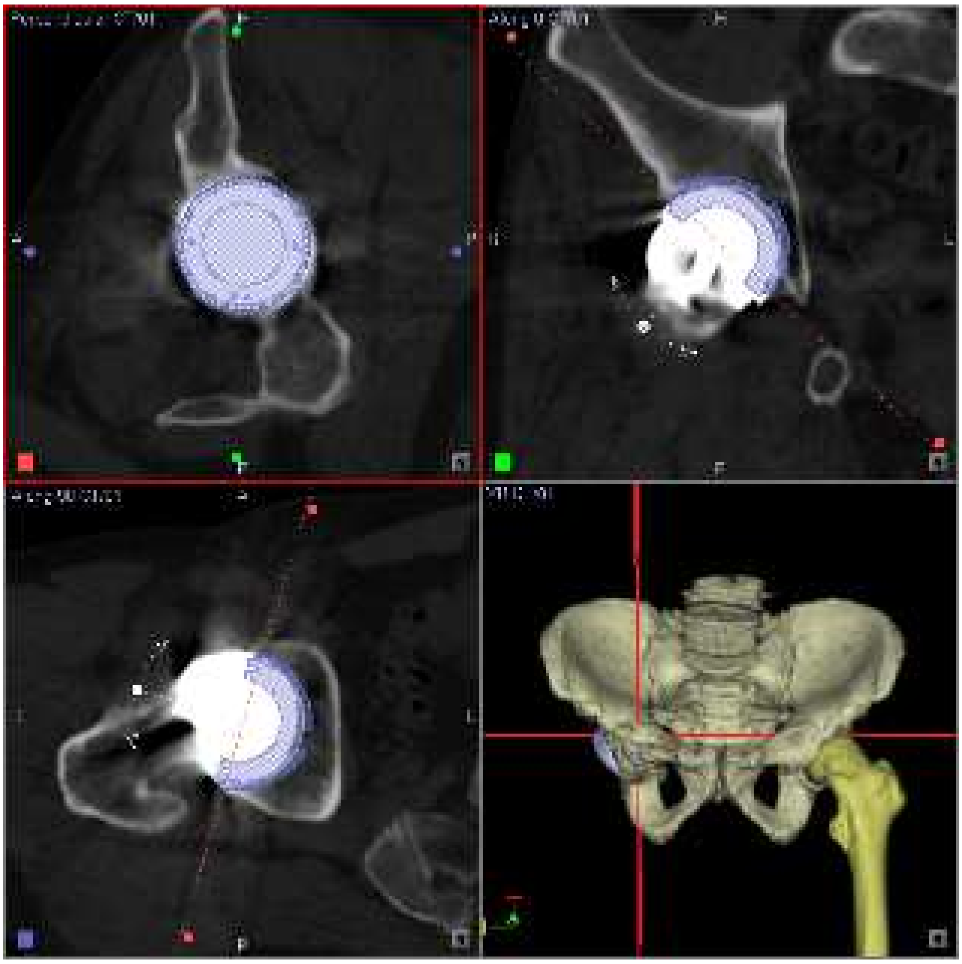

Fig. 3 A cup computational model was overlapped on the postoperative CT data to assess the accuracy of cup placement using postoperative CT data. The pelvic reference coordinate was matched with the preoperative pelvic coordinate using the landmark-matching method

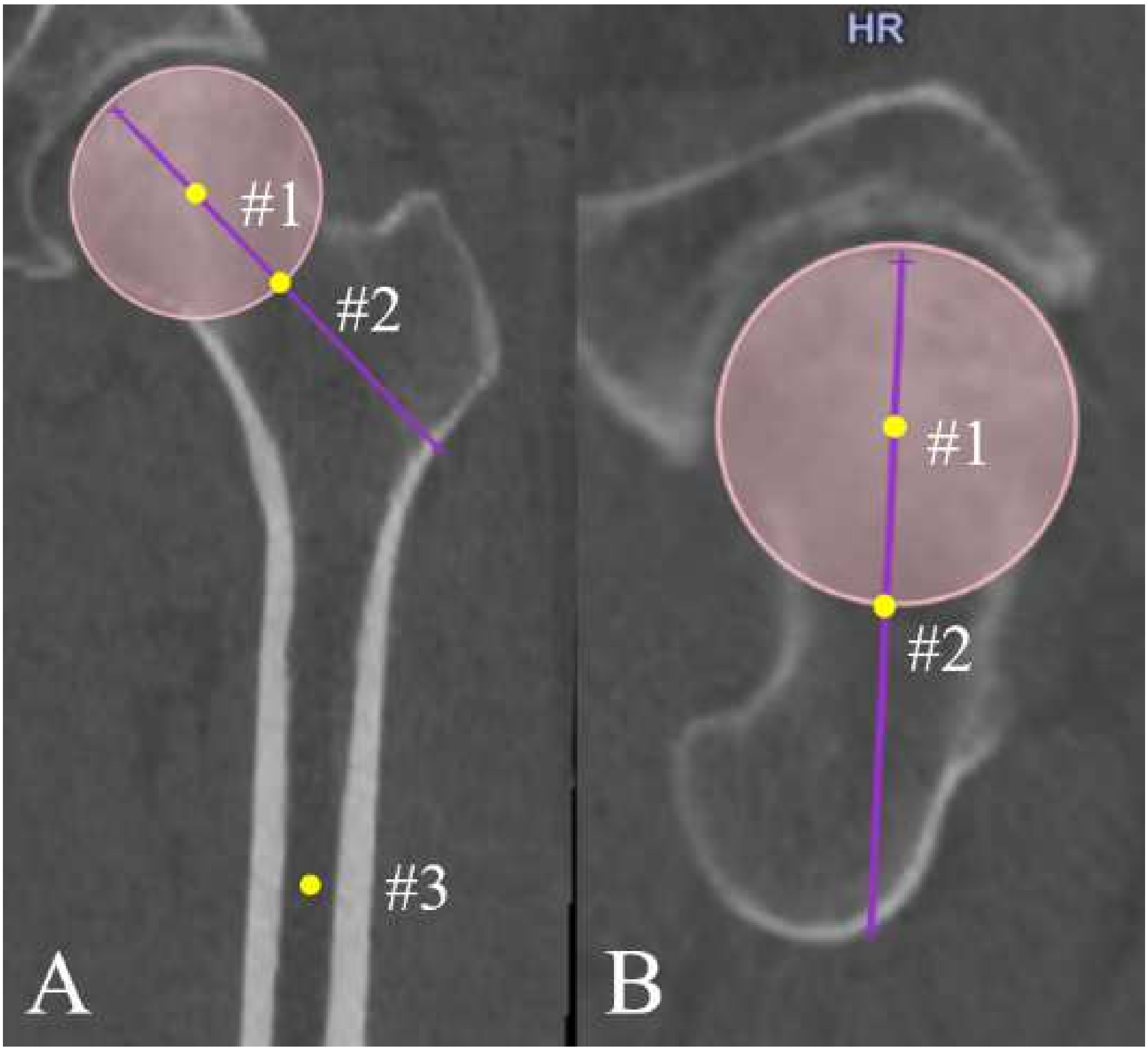

Fig. 4 Femoral neck axis (purple lines) was defined as the line between the center of the femoral head (*#1*) and the center of the femoral neck (*#2*). (**A**) Oblique coronal plane of the femoral neck was defined as the plane consisting of the femoral neck axis and the center of the femoral medullary canal 15 cm distal from the tip of the greater trochanter (*#3*). (**B**) Oblique sagittal plane of the femoral neck was defined as the plane perpendicular to the oblique coronal plane through the femoral neck axis

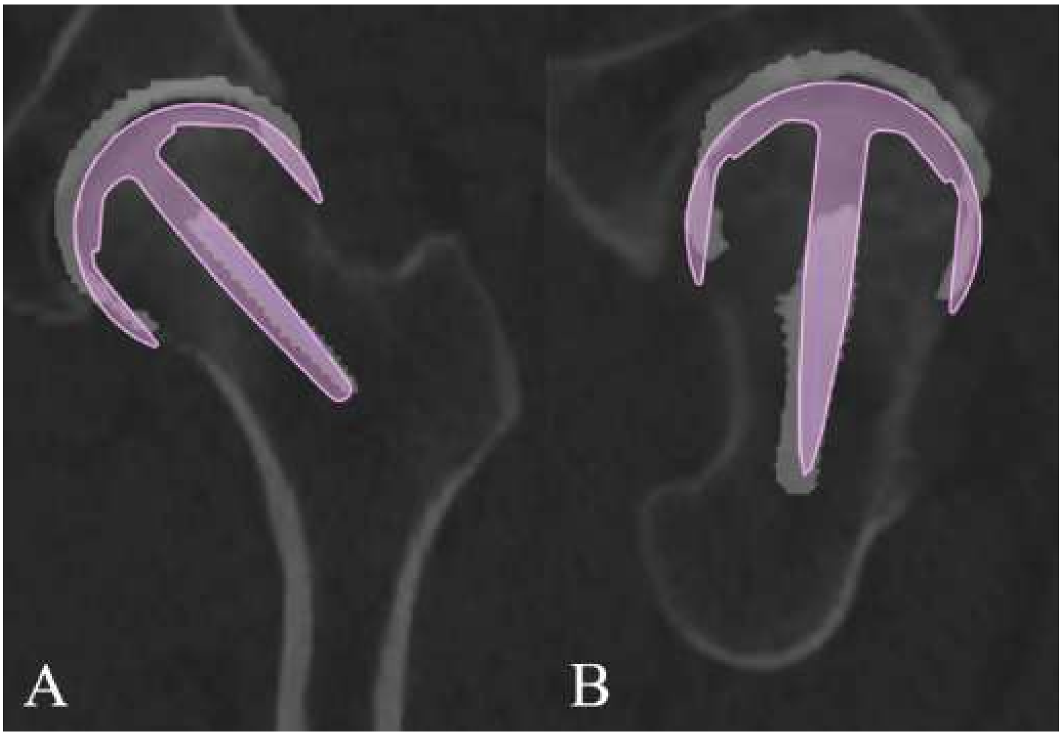

Fig. 5 To measure the deviation of the femoral component alignment and position from those of the plan, the preoperative CT-based plan of the femoral component (pink model) was superimposed on the postoperative CT by image volume registration between the preoperative and postoperative CT images. (**A**) Oblique coronal plane. (**B**) Oblique sagittal plane

Table 1. Radiologic Outcomes

Parameter	Value
Neck–shaft angle (NSA) (°)	129.4 ± 4.9 (120.6–137.3)
Stem–shaft angle (SSA) (°)	136.1 ± 4.0 (125.4–142.6)
Stem inclination (°)	6.8 ± 5.1 (0.4–16.7)
Stem version (°)	3.8 ± 4.3 (-1.8 to 12.0)
Deviation of the stem entry point (mm)	
Oblique coronal plane	0.6±1.9 (-3.4 to 3.4)
Oblique sagittal plane	0.2±2.2 (-3.9 to 3.8)
Angular difference in stem alignment (°)	
Oblique coronal plane	1.3 ± 1.6 (-3.4 to 3.0)
Oblique sagittal plane	1.9 ± 2.1 (-3.4 to 4.5)
Cup anteversion (°)	16.1 ± 2.8 (10.0–19.9)
Cup inclination (°)	37.7 ± 3.0 (31.9–42.7)
Deviation of cup anteversion (°)	1.1 ± 2.8 (-5.0 to 4.9)
Deviation of cup inclination (°)	-2.3 ± 3.0 (-8.1 to 3.0)

Table 2 Clinical studies on evaluation of stem placement in HRA using navigation systems

Study	No. of patients (hips)	Type of navigation	Method				Accuracy		
			Preop. plan	Postop. data	Image matching method	Referenced coordinate system	Stem inclination	Stem version	Entry point error
Olsen [9]	94 (100)	Imageless	Analog 2D template	Plain radiography	None	Radiographic plane	2.8° (mean)	N/A	N/A
Resubal [21]	45 (45)	Imageless	Analog 2D template	Plain radiography	None	Radiographic plane	1.4°±1.5°	-0.4°±1.5°	N/A
Ganapathi [22]	51 hips	Imageless	Analog 2D template	Plain radiography	None	Radiographic plane	1.3°±0.9°	N/A	N/A
Current study	16 (17)	CT-based	CT-based 3D template	CT	Volume matching	Femoral neck oblique plane	1.3°±1.6°	1.9°±2.1°	Oblique coronal plane: 0.6±1.9 mm Oblique sagittal plane: 0.2±2.2 mm

Table 3 Clinical studies on the accuracy of cup alignment using CT-based navigation

Study	No. of patients (hips)	Operation	Accuracy Evaluation Method					Accuracy	
			Planning image	Postop. data	Postop. analysis software	Image matching method	Referenced coordinate system	Cup inclination	Cup anteversion
Kitada [12]	25 (30)	THA	CT	CT	CT-based hip navigation systems (Stryker)	Landmark-based matching	Functional pelvic plane	-1.5 ± 3.5°	1.4 ± 5.6°
Iwana [13]	103(103)	THA	CT	CT	3D viewer software (Virtual Place)	Volume matching	Functional pelvic plane	1.5 ± 1.5°	1.3 ± 1.2°
Nakamura [17]	29 (30)	Revision THA	CT	CT	CT-based hip navigation systems (Stryker)	Landmark-based matching	Functional pelvic plane	-1.5 ± 3.0°	1.4 ± 6.0°
Kuroda [18]	29 (30)	Revision THA	CT	CT	CT-based hip navigation systems (Stryker)	Landmark-based matching	Functional pelvic plane	2.6 ± 1.8°	2.2 ± 2.2°
Current study	16 (17)	HRA	CT	CT	CT-based hip navigation systems (Stryker)	Landmark-based matching	Functional pelvic plane	-2.3 ± 3.0°	1.1 ± 2.8°

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