



Effect of improved navigation performance on the accuracy of implant placement in total hip arthroplasty with a CT-based navigation system

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Abstract

A computed tomography (CT)-based navigation system is one of the support tools to place implant with appropriate alignment and position in total hip arthroplasty (THA). To determine whether the higher performance of the navigation would further improve the accuracy of implant placement in the clinical setting, we retrospectively compared the navigation accuracy of two different versions of a navigation system. The newer version of the navigation system had an upgraded optical sensor with superior positional accuracy. Navigation accuracy, defined as differences between postoperative measurements on CT images and intraoperative records on the navigation system, of 49 THAs performed with the newer version of the navigation system was compared with that of 49 THAs performed with the older version. With the newer version, the mean absolute accuracy (95% limits of agreement) of implant alignment was $1.2^\circ (\pm 3.3^\circ)$ for cup inclination, $1.0^\circ (\pm 2.4^\circ)$ for cup anteversion, $2.0^\circ (\pm 4.9^\circ)$ for stem anteversion, and $1.1^\circ (\pm 2.4^\circ)$ for stem valgus angle. The accuracy of the implant position was 1.5 mm (± 3.1 mm), 1.3 mm (± 3.0 mm), and 1.5 mm (± 3.1 mm) for cup *x*-, *y*-, and *z*-axes, respectively, 1.6 mm (± 3.2 mm), 1.4 mm (± 2.9 mm), and 1.5 mm (± 2.7 mm) for stem *x*-, *y*-, and *z*-axes, respectively, and 2.4 mm (± 4.5 mm) for leg length discrepancy. The values for the newer version were significantly more accurate with less variation compared to those of the older version. With upgraded navigation performance, more accurate implant placement was demonstrated in the clinical setting.

Keywords Total hip arthroplasty · CT-based navigation · Implant alignment · Implant position · Accuracy

Introduction

In total hip arthroplasty (THA), implant malalignment is one of the major technical problems leading to clinical complications due to edge loading [1, 2] or implant impingement [3–6]. Clinical complications include accelerated wear [1], dislocation [3, 4], implant breakage [2], and implant loosening [5, 6]. Postoperative leg length discrepancy (LLD) is another complication of THA. Excessive LLD may cause back pain, gait disorders, or limping, which leads to patient

dissatisfaction [7]. Therefore, implant placement with appropriate alignment and position is essential to make the artificial joint function well without these problems.

Computed tomography (CT)-based navigation systems can help to minimize these technical errors. Use of this navigation system involves the following steps: (1) preoperative planning of target alignment and positioning using a computer model created from preoperative CT images; (2) registration of the computer model and actual bone landmarks; and (3) tracking and measurement of the target bone and surgical tools or implants during the operation. Therefore, to best support surgeons, the tracked and measured implant alignment and position information should be shown as accurately as possible. This accuracy is based on several factors, including the quality of the optical sensor and other hardware, the quality of software, technical errors, and system measurement error [8–10]. Accordingly, hardware improvement has been attempted to provide a more accurate system. However, no reports have shown that

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improved performance has provided a more accurate display for implant alignment and positioning in the clinical setting.

To confirm whether a better performance of the CT-based navigation system improves the accuracy of implant placement in the clinical setting, we retrospectively compared the accuracy of THA implant placement between an older version of the navigation system and a newer version with upgraded performance.

Materials and methods

Navigation systems

Two different versions of the CT-based navigation system were used for THA. The older version (Stryker Navigation Cart System, Stryker Leibinger GmbH & Co. KG, Freiberg, Germany) had an optical sensor (Stryker FlashPoint 5000 Sensor Array Camera, Stryker Leibinger GmbH & Co. KG, Freiberg, Germany), and the newer version (Stryker Navigation System2 Cart, Stryker Leibinger GmbH & Co. KG, Freiberg, Germany) had a higher quality optical sensor (Stryker FlashPoint 6000 Sensor Array Camera, Stryker Leibinger GmbH & Co. KG, Freiberg, Germany). The FlashPoint 6000 showed superior positional accuracy with superior spatial reasoning capacity, a wider optical sensor sweet spot, and a digital communication line (Table 1).

Subjects

This retrospective study was approved by the institutional review board of our hospital. In our institution, a CT-based navigation system has been used to perform THA since October 2007. The older version of the navigation system was replaced with the newer version in January 2012. To investigate the accuracy of both navigation systems, subjects who underwent primary cementless THA with the same brand of prosthesis were selected according to the following criteria: (1) both cup and stem implantation were carried out

under the guidance of the CT-based navigation system without any intraoperative failure of the navigation system; (2) the same brand of cementless acetabular cup (Trident PSL, Stryker Orthopaedics, Mahwah, NJ) and cementless femoral stem (Accolade TMZF, Stryker Orthopaedics, Mahwah, NJ) were implanted; and (3) there were no intraoperative or postoperative complications related to implant fixation, such as early implant migration or periprosthetic fracture. We selected the femoral stem to evaluate accuracy, because this stem was implanted with both versions of the navigation system and a sufficient period of time had elapsed to eliminate the influence of the initial learning curve for using the navigation system. 49 hips from 48 patients who underwent THA with the prostheses between July 2010 and December 2011 were included for the older version group. Consecutive 49 hips from 47 patients who underwent THA between January 2012 and June 2012 were included for the newer version group. All operations were performed by three surgeons: 1 senior surgeon (experienced surgeon) who was performing more than 100 THAs annually, and 2 resident surgeons (inexperienced surgeons) who were performing less than 30 THAs annually. Table 2 shows the demographic data and operator of both cohorts.

Preoperative planning

Preoperative CT images of the entire pelvis and bilateral femurs from each patient were taken using a helical CT scanner with 3-mm slice thickness. CT data were uploaded to the navigation planning workstation. Eight reference points for the pelvis (bilateral anterior superior iliac spines, bilateral pubic tubercles, the most distal point of bilateral ischia, mid pubic symphysis, and sacral mid-plane) and six reference points for each femur (center of femoral head, trochanteric fossa, the most posterior point of the greater trochanter, bilateral posterior condyles, and the center of the knee) were

Table 1 Differences in specifications between navigation systems

	Older version	Newer version
Navigation system	Cart system	System2 Cart
Optical sensor	FlashPoint 5000	FlashPoint 6000
Sweet spot (distance from the sensor)	1.5 m	1.625 m
Sweet spot (field of view in diameter)	1 m	1.25 m
Wire cable	Serial wire	Fire wire
Type of communication	Analog	Digital
Accuracy of LED marker recognition	0.3 mm	0.07 mm

Table 2 Demographic data by cohort

	Older version group <i>N</i> =49	Newer version group <i>N</i> =49	<i>p</i> value
Age at operation	67 ± 13	65 ± 12	0.44
Gender (male/female)	16 / 33	10 / 39	0.17
BMI	24 ± 2	24 ± 4	0.34
Diagnosis			0.52
Primary osteoarthritis	4	2	
Secondary osteoarthritis	40	43	
Osteonecrosis	5	3	
Rheumatoid arthritis	0	1	
Surgeon distribution			0.83
Experienced surgeon	33	34	
Inexperienced surgeons	16	15	

taken to create the pelvic and femoral coordinate systems. Three-dimensional (3D) surface models of the pelvis and bilateral femurs were then constructed using a semiautomatic segmentation procedure. The optimal alignment and position of the cup and stem were planned using three multiplanar reconstruction views and a 3D volume-rendering view. Cup alignment was adjusted based on stem anteversion [11].

Surgical procedure

All THAs were performed using either version of the navigation system through a mini-posterior approach. In both the groups, operation including registration was performed in the same manner consistently. A pelvic tracker was percutaneously fixed on the ilium before skin incision. Following dislocation of the hip joint, a femoral tracker was fixed on the greater trochanter. Registration of the femur was performed by surface-matched digitizing of at least 30 points on the femoral surface with a pointer, confirmed by touching characteristic points of the femur such as the greater trochanter, lesser trochanter, trochanteric fossa, and medial and lateral epicondyles. A verification point of the femur to check for intraoperative loosening of femoral tracker fixation was created on the greater trochanter. After femoral rasping was performed, orientation (anteversion and valgus angle) and position were checked.

Registration of the pelvis was performed by surface matching and was confirmed by touching characteristic points of the pelvis such as the anterior, posterior, and superior rim of the acetabulum, acetabular fossa, anterior superior iliac spine, and greater sciatic notch. A verification point for the pelvis was created on the posterosuperior portion of the acetabular rim. After reaming, the acetabular cup was implanted using the navigation guide, and final alignment (anteversion and inclination) and position of the cup were recorded. Fixation of the pelvic tracker was checked by touching its verification point.

Subsequently, the femoral stem was implanted, and the final alignment (anteversion and valgus angle) and position of the stem and LLD were recorded after changing the neck length of the femoral head to achieve optimal leg length. Fixation of the femoral tracker was checked by touching its verification point. Hips in which stability of either the pelvic or femoral trackers could not be verified were excluded.

Postoperative measurements

Postoperative CT images were routinely obtained within 2-week postoperation to detect the early complications. To adjust for the differences in the pelvic and femoral coordinate systems between the pre- and postoperative CT images, the semiautomatic volume registration technique was used

with 3D image-processing software (Virtual Place-M; Medical Imaging Laboratory, Tokyo, Japan) [12, 13]. The reproducibility of this method has been reported as within 0.7° and 0.8 mm [14]. Then, the same-sized computer-aided design (CAD) model of the implanted cup or stem was superimposed on the postoperative images of the actually implanted prostheses. Thereafter, the postoperative alignment (anteversion and inclination) and position of the cup, the postoperative alignment (anteversion and valgus angle) and position of the stem, and LLD were recorded. Navigation accuracy, defined as the difference between postoperative measurements on CT images and intraoperative records on the navigation system, was evaluated in both groups. The radiographic definition of cup anteversion and inclination was used for the cup alignment [15]. To spatially evaluate the cup and stem position, three orthogonal axes [x -(transverse) axis, y -(sagittal) axis, and z -(longitudinal) axis] were defined in the pelvic and femoral coordinate systems. Cup position was evaluated based on the location of the point of the cup's spherical center, and stem position was evaluated based on the location of the point where the stem neck axis and stem body axis intersected.

Statistical analysis

Power analysis suggested that 32 hips would be required in each group to achieve adequate power of 0.8 for detecting a minimum difference of 1° ($\alpha=0.05$, one-sided), which was assumed according to a previous report [16]. Statistical analyses were performed between the groups using the two-sided Student's t test for age and body mass index (BMI) and the χ^2 test for gender, diagnosis, and distribution of surgeons. To compare navigation accuracy, one-sided Student's t tests for comparisons of absolute differences and F tests for comparisons of variation were performed. The 95% limits of agreement ($\pm 1.96 \times$ standard deviation) were used to show variation. To assess inter- and intra-observer error with this measurement method, 20 cases were randomly selected and the alignment and position of the cup and stem were measured twice at a 1-month interval by two of the authors. The Pearson's correlation coefficients (r) were evaluated to determine inter- and intra-observer variability. Statistical significance was assigned for p values less than 0.05.

Results

There were no significant differences between the groups in age, sex, BMI, preoperative diagnosis, and distribution of surgeons (Table 2).

In all the alignment parameters, the navigation accuracy in the newer version group showed significantly smaller absolute differences and less variation than the older version

group (Table 3). For cup inclination, cup anteversion, stem anteversion, and stem valgus angle, 95% limits of agreement were within $\pm 3.3^\circ$, $\pm 2.4^\circ$, $\pm 4.9^\circ$, and $\pm 2.4^\circ$ in the newer version group and $\pm 4.8^\circ$, $\pm 3.9^\circ$, $\pm 7.4^\circ$, and $\pm 3.4^\circ$ in the older version group, respectively. The improvement of the mean absolute difference was 0.7°, 0.6°, 1.2°, and 0.7° for cup inclination, cup anteversion, stem anteversion, and stem valgus angle, respectively.

In all positional parameters of implants and LLD, the navigation accuracy in the newer version group showed significantly smaller absolute differences and less variation than the older version group (Table 3). For cup *x*-, *y*-, and *z*-axes, stem *x*-, *y*-, and *z*-axes, and LLD, 95% limits of agreement were within ± 3.1 , ± 3.0 , ± 3.1 , ± 3.2 , ± 2.9 , ± 2.7 , and ± 4.5 mm in the newer version group and ± 5.5 , ± 5.1 , ± 5.7 , ± 5.2 , ± 5.5 , and ± 9.4 mm in the older version group, respectively. The improvement in the mean

absolute difference was 0.7, 0.6, 0.7, 0.7, 0.9, 0.8, and 1.4 mm for cup *x*-, *y*-, *z*-axes, stem *x*-, *y*-, *z*-axes, and LLD, respectively.

Inter- and intra-observer variabilities for implant alignment were $0.4^\circ \pm 1.8^\circ$ and $0.1^\circ \pm 0.8^\circ$ for cup inclination, $0.1^\circ \pm 1.8^\circ$ and $0.1^\circ \pm 1.1^\circ$ for cup anteversion, $0.7^\circ \pm 1.5$ and $0.2^\circ \pm 1.0^\circ$ for stem anteversion, and $0.1^\circ \pm 0.5^\circ$ and $0.1^\circ \pm 0.2^\circ$ for stem valgus angle. The Pearson’s correlation coefficients for implant alignment were 0.90, 0.92, 0.78, 0.96, 0.97, 0.99, 0.96, and 0.94, respectively. Inter- and intra-observer variabilities for implant position were $0.1^\circ \pm 0.4$ mm and $0.1^\circ \pm 0.3$ mm for cup *x*-axis, 0.2 ± 0.3 mm and $0.2^\circ \pm 0.3$ mm for cup *y*-axis, $0.4^\circ \pm 0.8$ mm and $0.0^\circ \pm 0.6$ mm for cup *z*-axis, $0.0^\circ \pm 0.6$ mm and $0.2^\circ \pm 0.3$ mm for stem *x*-axis, $0.3^\circ \pm 0.5$ mm and $0.0^\circ \pm 0.3$ mm for stem *y*-axis, and $0.5^\circ \pm 0.9$ mm and $0.4^\circ \pm 1.0$ mm for stem *z*-axis. All the

Table 3 Navigation accuracy (postoperative measurement-intraoperative final record) and absolute value in both the groups

	Older version group	Newer version group	<i>p</i> value
Cup alignment (°)			
Inclination	-0.5 ± 2.5 (−6.1 to 5.3)	-0.5 ± 1.7 (−4.8 to 3.2)	0.008**
(Absolute value)	1.9 ± 1.6 (0.0 to 6.1)	1.2 ± 1.3 (0.0 to 4.8)	0.012*
Anteversion	-0.7 ± 2.0 (−5.0 to 3.7)	-0.2 ± 1.2 (−3.1 to 2.5)	0.001**
(Absolute value)	1.6 ± 1.4 (0.0 to 5.0)	1.0 ± 0.8 (0.0 to 3.1)	0.002*
Stem alignment (°)			
Anteversion	1.1 ± 3.8 (−8.0 to 8.0)	0.6 ± 2.5 (−5.0 to 5.0)	0.004**
(Absolute value)	3.2 ± 2.3 (0.0 to 8.0)	2.0 ± 1.6 (0.0 to 5.0)	0.002*
Valgus angle	1.5 ± 1.8 (−2.0 to 7.0)	0.7 ± 1.2 (−1.0 to 3.0)	0.016**
(Absolute value)	1.8 ± 1.5 (0.0 to 7.0)	1.1 ± 0.8 (0.0 to 3.0)	0.004*
Cup position (mm)			
<i>x</i>	-0.3 ± 2.8 (−5.8 to 8.2)	-1.0 ± 1.6 (−4.2 to 2.9)	<0.001**
(Absolute value)	2.2 ± 1.8 (0.0 to 8.2)	1.5 ± 1.1 (0.0 to 4.2)	0.015*
<i>y</i>	0.1 ± 2.6 (−7.9 to 5.3)	0.2 ± 1.5 (−2.8 to 3.4)	<0.001**
(Absolute value)	1.9 ± 1.7 (0.0 to 7.9)	1.3 ± 0.8 (0.0 to 3.4)	0.011*
<i>z</i>	-0.7 ± 2.9 (−8.2 to 4.7)	0.8 ± 1.6 (−2.3 to 4.2)	<0.001**
(Absolute value)	2.2 ± 2.0 (0.0 to 8.2)	1.5 ± 0.9 (0.0 to 4.2)	0.022*
Stem position (mm)			
<i>x</i>	-1.3 ± 2.6 (−6.8 to 6.2)	-1.2 ± 1.6 (−4.4 to 2.5)	0.001**
(Absolute value)	2.3 ± 1.8 (0.0 to 6.8)	1.6 ± 1.2 (0.0 to 4.4)	0.013*
<i>y</i>	1.4 ± 2.6 (−3.1 to 9.1)	1.0 ± 1.5 (−2.2 to 4.4)	<0.001**
(Absolute value)	2.3 ± 1.9 (0.0 to 9.1)	1.4 ± 1.1 (0.0 to 4.4)	0.002*
<i>z</i>	-1.4 ± 2.8 (−9.4 to 4.2)	-1.2 ± 1.4 (−5.2 to 1.6)	<0.001**
(Absolute value)	2.3 ± 2.1 (0.0 to 9.4)	1.5 ± 1.1 (0.0 to 5.2)	0.009**
LLD (mm)			
	0.0 ± 4.8 (−11.0 to 11.0)	-1.9 ± 2.3 (−6.0 to 3.0)	<0.001**
(Absolute value)	3.8 ± 2.9 (0.0 to 11.0)	2.4 ± 1.7 (0.0 to 6.0)	0.002*

Value of standard deviation is significant for the navigation accuracy, and mean value is significant for the absolute value (bold)

Data show the mean ± standard deviation (range)

*One-sided Student’s *t* test

***F* test

Pearson's correlation coefficients for implant position were 0.99.

Discussion

This study was the first to compare navigation accuracy between older and newer navigation system versions in the clinical setting. In the present study, the same implant, the same operation technique, and the same postoperative measurement method were used in two similar cohorts. Significantly superior navigation accuracy could then be demonstrated in the newer version group, including superior alignment, positioning, and LLD. Some previous reports have investigated accuracy of imageless navigation systems [17–25] and CT-based navigation systems [16, 25–29] (Table 4). The in the older version group was comparable to the reported accuracy of the CT-based navigation systems and was superior to the reported accuracy of the imageless navigation systems. The accuracy in the newer version group was further improved compared to those reported previously.

There are some conceivable causes for differences between the intraoperative record and postoperative measurement, including navigation error and postoperative measurement error. Postoperative measurement error may be caused by differences in evaluated coordinate systems between the intraoperative record and postoperative measurement [30] as well as measurement error from postoperative CT images by manual CAD templating. Therefore, we created postoperative coordinate systems using the volume registration technique to minimize the deviation. Moreover, inter- and intra-observer variability analysis for the manual CAD templating demonstrated high reliability. These indicated that postoperative measurement error could be minimized and the differences between the intraoperative record and postoperative measurement were mainly caused by navigation error.

In addition to the superior spatial reasoning capacity of the optical sensor, the wider sweet spot of the optical sensor can have reduced errors associated with operation at a boundary area of the sweet spot. Moreover, fast communication by digitalization can have reduced errors associated with time lag between operation of navigation tools and computer recognition. These improved navigation specifications might enable more accurate intraoperative measurement of implant alignment and position as well as more acceptable registration. Then, the improved navigation specifications lead to the superior accuracy in clinical setting.

It was reported that cup inclination less than 35° significantly reduced prosthetic range of motion [31] and cup inclination more than 45° accelerated wear [1]. Widmer et al. [32] suggested that acetabular cups should be oriented between 20° and 28° of anteversion to clear the required

range of motion in the simulation. In clinical setting, Sugano et al. [33] suggested that the true safe zone to avoid dislocation or mechanical complication seemed to be 36°–45° of inclination and 10°–24° of anteversion. Accordingly, acceptable range of cup alignment is about 10° and navigation accuracy for cup alignment should preferably be within $\pm 5^\circ$ to prevent complications. In the present study, although significant differences could be noticed in navigation accuracy for cup alignment, variations of navigation accuracy were within $\pm 5^\circ$ in both groups, which indicated that the difference was negligible in terms of the impact on clinical results.

Stem orientation is also an important factor for achieving optimal range of motion and joint stability in THA [32]. Previously, however, there has been no report on the required accuracy for stem alignment. In consideration of our target angle [11], approximately 5° of cup anteversion change is necessary for each 10° increment of stem anteversion. Thus, the navigation accuracy for stem anteversion should be within $\pm 10^\circ$ when the required accuracy for cup alignment was set to $\pm 5^\circ$. In the present study, although there were significant differences between the groups, variations of navigation accuracy for stem anteversion were within $\pm 10^\circ$ in both groups, which indicated that the difference may also be negligible in consideration of clinical results.

In the current CT-based navigation system, acetabular reaming and cup placement could be performed by checking the alignment and position in real time on the monitor. The positional navigation accuracy was, therefore, important, because surgeons could be informed of correct position of the implant in bone and thereby perform the operation safely. In a simulation, perforation of the acetabular wall could be observed when an acetabular cup was displaced 5-mm backward from the optimal position (Fig. 1). In such a case, the actual cup position in the bone should also be verified to confirm that perforation did not occur. One anatomical report showed that the minimum thickness of the medial acetabular wall in Crowe-I was an average of 3.8 ± 2.1 mm [34], suggesting that the acetabular bone stock is relatively thin and high positional accuracy is required to accurately display the cup position. The newer version group demonstrated within ± 3.1 mm of variation in any direction, while the older version group demonstrated within ± 5.7 mm of variation in any direction. This result indicates that safer surgery can be performed with trust of surgeons when the newer version navigation system is used. Standardization of treatment outcome can be expected by eliminating an error the navigation system.

LLD following THA is a common reason for patient dissatisfaction [7]. Some reports indicate that an LLD greater than 10 mm will cause patient dissatisfaction following THA [35, 36]. In the present study, the newer version group showed 2.4 mm of mean absolute navigation accuracy with ± 4.6 mm of variation, while the older

Table 4 Accuracy of imageless and CT-based navigation systems reported in the literature (Mean ± standard deviation)

Authors	Type	Navigation system	Cup alignment		Stem alignment		Cup position			LLD
			Inclination	Anteversión	Anteversión	Valgus angle	x	y	z	
Ybinger et al. [17]	Imageless	Plus Orthopaedics PiGalileo	3.5 ± 4.4 ^a	6.5 ± 7.3 ^a						
Parratte et al. [18]	Imageless	Hiplogics Universal Protocol	4 ± 2.8 ^a	3.4 ± 3.6 ^a	For BMI < 27					
			3.3 ± 3.06	11.6 ± 6.1	For BMI ≥ 27					
Ryan et al. [19]	Imageless	Ci System	1.8 ± 1.2 ^{a,c}	2.0 ± 2.0 ^{a,c}						
Jenny et al. [20]	Imageless	B. Braun Aesculap OrthoPilot	-2 ± 4 ^d	-4 ± 8 ^d						
Fukunishi et al. [21]	Imageless	B. Braun Aesculap OrthoPilot	3.0 ± 2.6 ^a	5.0 ± 3.5 ^a	5.9 ± 4.2 ^a					
Takeda et al. [22]	Imageless	B. Braun Aesculap OrthoPilot	3.6 ± 2.7 ^a	6.9 ± 3.6 ^a	5.8 ± 4.6 ^a					4.3 ± 4.5 ^a
Lin et al. [23]	Imageless	Stryker Imageless Navigation system	0.0 ± 2.8	3.4 ± 3.6						
Sendtner et al. [24]	Imageless	BrainLAB Hip unlimited 5.0	0.4 ± 3.3 ^c	-5.6 ± 6.5 ^c						
Kalteis et al. [25]	Imageless	BrainLAB VectorVision 3.0	2.9 ± 2.2 ^{a,c}	4.2 ± 3.3 ^{a,c}						
Kalteis et al. [25]	CT-based	BrainLAB VectorVision 3.0	3.0 ± 2.6 ^{a,c}	3.3 ± 2.3 ^{a,c}						
Hananouchi et al. [26]	CT-based	Stryker CT-Hip System (Older version)	2.4 ± 2.0 ^a	2.0 ± 1.4 ^a	For mini-posterior approach					
			2.0 ± 1.4 ^a	2.7 ± 1.9 ^a	For mini-anterior approach					
Hirasawa et al. [27]	CT-based	Stryker CT-Hip System (Older version)	3.2 ± 2.7 ^a	3.8 ± 3.4 ^a	5.2 ± 4.8 ^a	2.2 ± 2.0 ^a				2.2 ± 1.8 ^a
Kitada et al. [28]	CT-based	Stryker CT-Hip System (Older version)	0.4 ± 2.5 ^b	-0.8 ± 4.1 ^b	-0.6 ± 4.8	-0.2 ± 1.8				-0.6 ± 4.8
Kajino et al. [29]	CT-based	Stryker CT-Hip System (Older version)	1.5 ± 1.2 ^{a,b}	2.5 ± 1.7 ^{a,b}	For severe pelvic deformities					
			1.4 ± 1.1 ^{a,b}	2.7 ± 1.4 ^{a,b}	For low-grade subluxation					
Iwana et al. [16]	CT-based	Stryker CT-Hip System (Older version)	0.5 ± 2.3	-0.3 ± 1.6						
			1.8 ± 1.6 ^a	1.2 ± 1.1 ^a						
Current study	CT-based	Stryker CT-Hip System (Older version)	-0.5 ± 2.5	-0.7 ± 2.0	1.1 ± 3.8	1.5 ± 1.8	-1.4 ± 2.0	-0.07 ± 1.9	0.5 ± 2.2	
			1.9 ± 1.6 ^a	1.6 ± 1.4 ^a	3.2 ± 2.3 ^a	1.8 ± 1.5 ^a	1.9 ± 1.5 ^a	1.4 ± 1.2 ^a	1.9 ± 1.3 ^a	
			-0.5 ± 1.7	-0.2 ± 1.2	0.6 ± 2.5	0.7 ± 1.2	-0.3 ± 2.8	0.1 ± 2.6	-0.7 ± 2.9	0.0 ± 4.8
			1.2 ± 1.3 ^a	1.0 ± 0.8 ^a	2.0 ± 1.6 ^a	1.1 ± 0.8 ^a	2.2 ± 2.0 ^a	1.9 ± 1.7 ^a	2.2 ± 2.0 ^a	3.8 ± 2.9 ^a
							-1.0 ± 1.6	0.2 ± 1.5	0.8 ± 1.6	-1.9 ± 2.3
							1.5 ± 1.1 ^a	1.3 ± 0.8 ^a	1.5 ± 0.9 ^a	2.4 ± 1.7 ^a

Value of standard deviation is significant for the navigation accuracy, and mean value is significant for the absolute value (bold)

^a Absolute value

^b Anatomical definition, ^c operative definition, ^d undefined [16]

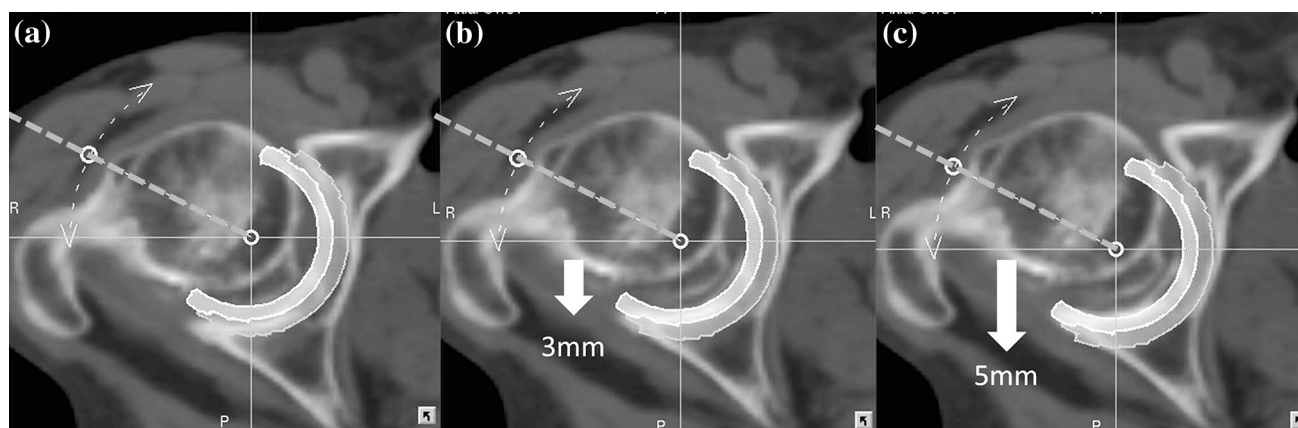


Fig. 1 Simulations show **a** optimal cup position, **b** cup position displaced 3 mm posteriorly, and **c** cup position displaced 5 mm posteriorly from the optimal position

version group showed 3.8 mm of mean absolute navigation accuracy with ± 9.6 mm of variation. This result indicated that the newer version navigation system was more reliable for the control of leg length in consideration of the safety margin. The superior positional accuracy also contributed to the reliable control of leg length using the newer navigation system.

There were a few limitations of the present study. Because period of operation was different between the groups, it might have been affected by a learning curve of the navigation. To eliminate the influence of the learning curve, we targeted cases in which THA was performed after sufficient time elapsed from the introduction of navigation. Although we observed a significant difference in accuracy between the groups, the effect of the difference on clinical results was not evaluated. Additional studies are needed to show clinical advantages of the upgraded navigation system. These clinical data will encourage further improvement of the navigation system.

Conclusion

The upgraded CT-based navigation system demonstrated superior navigation accuracy in terms of implant alignment and implant position. This improved accuracy of implant position helps surgeons to more easily adjust leg length and check accurate implant position in host bone in real time on the navigation monitor, which can result in safer surgery.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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