Impact of CT-based navigation, large femoral head, and dual-mobility liner on achieving the required range of motion in total hip arthroplasty

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Aims

This study aimed to investigate whether the use of CT-based navigation enhances: 1) the accuracy of cup placement; and 2) the achievement rate of required range of motion (ROM). Additionally, we investigated the impact of using a large femoral head and dual-mobility liner on the achievement rates.

Methods

This retrospective study analyzed 60 manual and 51 CT-based navigated primary total hip arthroplasties performed at a single facility. Postoperative CT scans and CT-based simulation software were employed to measure the cup orientation and to simulate the ROM. We compared the absolute errors for radiological inclination (RI) and radiological anteversion (RA) between the two groups. We also examined whether the simulated ROM met the required ROM criteria, defined as flexion > 110°, internal rotation > 30°, extension > 30°, and external rotation > 30°. Furthermore, we performed simulations with 36 mm femoral head and dual-mobility liner.

Results

The absolute errors of RI and RA from the preoperative plan were significantly smaller in the CT-based navigation group (3.7° (SD 3.5°) vs 5.1° (SD 3.5°); $p = 0.022$, and 3.9° (SD 3.5°) vs 6.8° (SD 5.0°); $p = 0.001$, respectively). The proportion of cases achieving the required ROM in all directions was significantly higher in the CT-based navigation group (42% vs 63%; $p = 0.036$). The achievement rates of the required ROM were significantly higher with the use of a 36 mm ball or dual-mobility liner compared to the use of a 32 mm ball (65% vs 51%; $p = 0.040$ and 77% vs 51%; $p \leq 0.001$, respectively).

Conclusion

CT-based navigation enhanced required ROM achievement rates by > 20%, regardless of the ball diameter. The improved accuracy of cup placement through CT-based navigation likely contributed to the enhancement. Furthermore, the use of large femoral heads and dual-mobility liners also improved the required ROM achievement rates. In cases with a high risk of dislocation, use of these devices is preferred.

Take home message

- CT-based navigation significantly improves the accuracy of cup placement and the achievement of impingement-free required range of motion.
- Combining CT navigation with a large femoral head or dual-mobility liner further enhances impingement-free mobility.
- These findings highlight the potential of advanced navigation and implant selection to reduce dislocation risk in total hip arthroplasty.

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Introduction

Total hip arthroplasty (THA) demonstrates favourable clinical outcomes, and the number of cases has been increasing.[1-3] However, the incidence of revision surgery has increased simultaneously.[4] Mechanical failure and dislocation predominantly lead to these revisions;[5,6] impingement between the cup and stem contributes to mechanical failure and dislocation.[7,8] To prevent impingement, obtaining an adequate range of motion (ROM) is crucial, and cup placement significantly influences this range.[9-11] Therefore, surgeons should ensure appropriate component placement to expand ROM and reduce the risk of dislocation. Furthermore, larger femoral heads and dual-mobility liners can lead to an expanded ROM.[12]

Some studies have reported on improved accuracy of cup placement using CT-based navigation.[13,14] In addition, reports suggest a decrease in dislocation rates with the use of CT-based navigation.[15] Whereas reduced dislocation rates are attributed to enhanced ROM,[16] no prior reports have addressed the impact of CT-based navigation on required ROM achievement specifically. Additionally, there are reports indicating that the use of a large femoral head and dual-mobility liner reduces dislocation rates and impingement.[17–23]

Therefore, the objectives of this study were: 1) to evaluate whether CT-based navigation improves cup placement accuracy; and 2) to assess its impact on increasing impingement-free ROM achievement rates. Moreover, we intended to determine the rate of achieving the required ROM when changing the implant to a large femoral head or a dual-mobility liner.

Methods

Patients

This retrospective cohort study was conducted in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology statement,[24] and was approved by our facility's Institutional Review Board (IRB no. 30-91). Informed consent was obtained from all the patients before commencing the study. The population consisted of patients who underwent primary THA for osteoarthritis (OA) and osteonecrosis of the femoral head between April 2019 and December 2022 using Accolade2 (Stryker, USA), Trident HA (Stryker), and Trident Linear X3 (Stryker). The surgeries were performed by ten surgeons at a single institution. The inclusion criteria were as follows: 1) no neuromuscular disorders; 2) no history of surgical interventions on the analyzed hip joint; 3) no history or current symptoms of surgeries or conditions involving other joints or the spine; and 4) postoperative CT scans including the anterior superior iliac spine (ASIS) and distal femoral condyle. The patients were divided into two groups as follows: 1) a manual group (M-THA), where manual techniques were employed; and 2) a CT-based navigation group (N-THA), where CT-based navigation was used. The decision to use CT-based navigation was at the discretion of the operating surgeon or patient. During the study, primary THA was performed in 122 patients and 132 hips. Within this cohort, 67 patients (71 hips) and 59 patients (61 hips) were categorized into the M-THA and N-THA groups, respectively. In the N-THA group, five hips were excluded because of intraoperative registration errors. In addition, 11 and five hips were excluded in the M-THA and N-THA groups, respectively, because of the inability of the patients to undergo CT imaging. Finally, 60 and 51 hips in the M-THA and N-THA groups, respectively, were included in the analysis (Figure 1).

Table I summarizes the patient demographics and lists the implant sizes. We observed no significant differences between the groups regarding demographic characteristics or implants used.

Implants and navigation

In all cases, we used a femoral head measuring 32 mm. Implant neck-shaft angles that closely matched the preoperative neck-shaft angles were selected and used at 127° and 132°. In addition, the offsets were selected from -4 mm, 0 mm, and 4 mm based on preoperative planning and intraoperative soft-tissue tension. CT-based hip navigation (v. 1.3; Stryker Leibinger, Germany) was used in the N-THA group.

Surgical procedure

All surgeries were performed using the posterolateral approach. Preoperative CT scans were performed for all cases in both the M-THA and N-THA groups, and the preoperative planning was performed using ZedHip (Lexi, Japan)

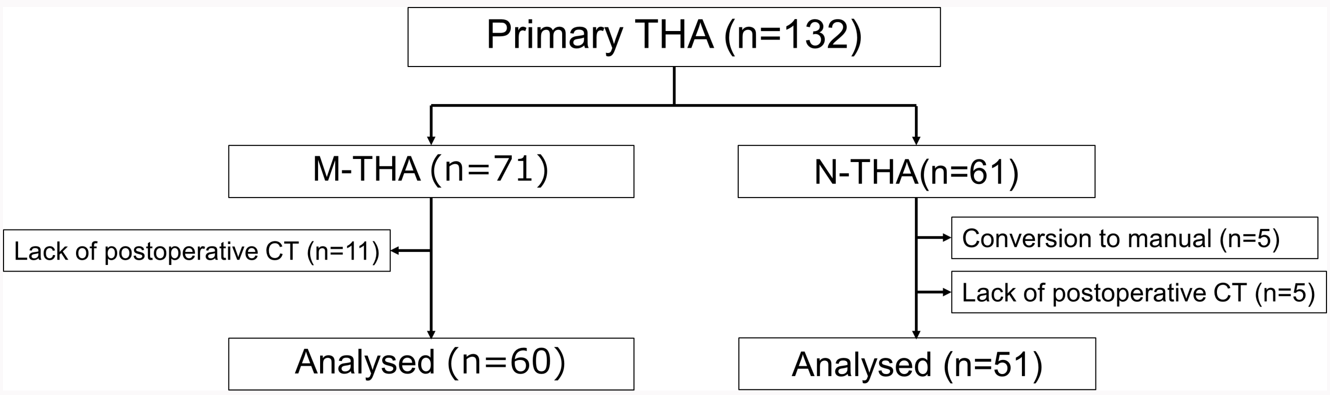

Fig. 1
Flowchart depicting the total number of primary total hip arthroplasties (THAs) performed during the study and the number of hips analyzed in each group. M-THA, manual THA; N-THA, CT-based navigated THA.

Table I. Patient demographics and implant sizes.

Patient demographics	M-THA group	N-THA group	p-value
Cases, n	60	51	
Mean age, yrs (SD)	66.6 (10.3)	65.5 (9.7)	0.326*
Sex (F/M), n	44/16	41/10	0.382†
Mean BMI, kg/m² (SD)	25.5 (5.5)	24.9 (4.0)	0.866*
Disease, n	OA 54 hips ONFH 6 hips	OA 48 hips ONFH 3 hips	0.428†
Crowe type (1/2/3), n	60/0/0	47/3/1	0.096†
Implant size			
Neck-shaft angle (127°/132°), n	46/14	38/13	0.792†
Stem size (2/3/4/5/6/7 mm), n	7/13/22/13/4/1	6/20/16/4/4/1	0.253†
Cup size (46/48/50/52/54/56/58 mm), n	2/18/17/7/11/4/1	2/22/14/7/3/3/0	0.456†
Ball diameter, mm	32 in all cases		N/A
Ball offset (-4/0/+4 mm), n	15/26/19	8/24/19	0.475†

*Mann-Whitney U test.
† Pearson's chi-squared test.
M-THA, manual total hip arthroplasty; N/A, not applicable; N-THA, CT-based navigated total hip arthroplasty; OA, osteoarthritis; OFNH, osteonecrosis of the femoral head.

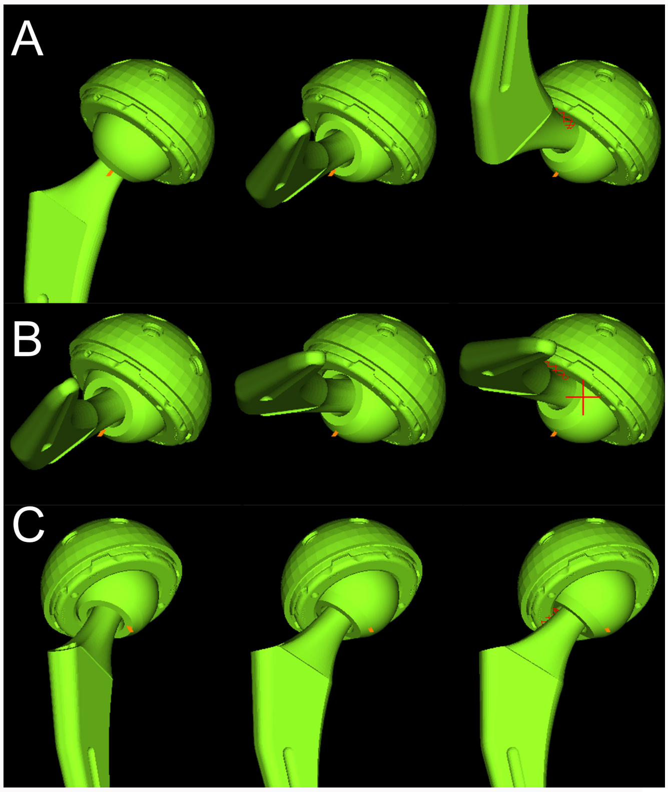

Fig. 2
Range of motion simulation is based on postoperative CT data using CT-based simulation software (ZedHip; Lexi, Japan). a) Flexion, b) internal rotation at 90° flexion, and c) external rotation. The red line indicates stem and cup impingements.

or 3D Template (Kyocera, Japan) according to surgeons' preference. The femur was operated on before cup placement to determine stem anteversion. We measured the stem anteversion angle intraoperatively using a goniometer with the knee flexed, the tibia in a vertical position, and the angle formed between the tibia and trial stem axes.[25] Cup orientation was determined based on the radiological definition.[26] The radiological inclination (RI) was targeted at 40° in all cases. The target angle for radiological anteversion (RA) was determined intraoperatively such that the sum of the stem anteversion and cup RA ranged from 40° to 60° based on intraoperative measurements.[25,27]

Postoperative measurement and ROM simulation

Approximately one to two weeks postoperatively, CT scans were acquired using Aquilion (Toshiba, Japan) in all cases. The images were obtained at 1 mm intervals from the ASIS to the knee, including the distal femoral condyles. RI and RA were measured using CT images obtained postoperatively and were analyzed using computer software (ZedHip; Lexi). The functional pelvic plane (FPP) was used as the reference frame for the pelvic coordinate system. Briefly, the axial and coronal planes were integrated with the bilateral ASISs, whereas the sagittal plane was aligned with the plane on the tabletop. The software incorporated various implant data, allowing the implants to be superimposed onto their actual positions for the automatic measurement of placement angles.

After placing the implant in its actual position, we performed ROM simulation (Figure 2).[10,28] The simulation involved measuring the maximum flexion angle, maximum internal rotation angle at 90° flexion, maximum extension angle, and maximum external rotation angle at 0° extension until impingement between the implants at supine FPP. To eliminate the influence of the liner type and the elevated wall position, all cases were simulated using a flat liner. These measurements were evaluated to determine whether they met the required ROM criteria of flexion > 110°, internal rotation (at 90° flexion) > 30°, extension > 30°, and external rotation (at 0° extension) > 30°.[10,29]

As a supplementary analysis, we performed simulations with a 36 mm femoral head diameter and dual-mobility implants (Figure 3). Both simulations were performed by replacing the implants in their original positions. Owing to the incompatibility of a 36 mm femoral head with a 46 mm cup, we excluded two cases from each group from the 36 mm femoral head simulation. For this simulation, we selected offsets of -5 mm, 0 mm, and +5 mm to closely match the original offsets. With dual-mobility implants, the bearing sizes were determined based on the cup sizes as follows: 36 mm for 46 mm cups, 38 mm for 48 mm and 50 mm cups, 42 mm for 52 mm and 54 mm cups, and 46 mm for 56 mm cups. The offsets were selected to match the original offsets. The total ROM in the four directions (flexion, extension, internal rotation, and external rotation) was calculated.

Statistical analysis

All data were expressed as mean and SD. The Mann-Whitney U test was used for continuous variables, and the Pearson's chi-squared test was used for categorical variables. We performed a multivariate linear regression analysis and logistic

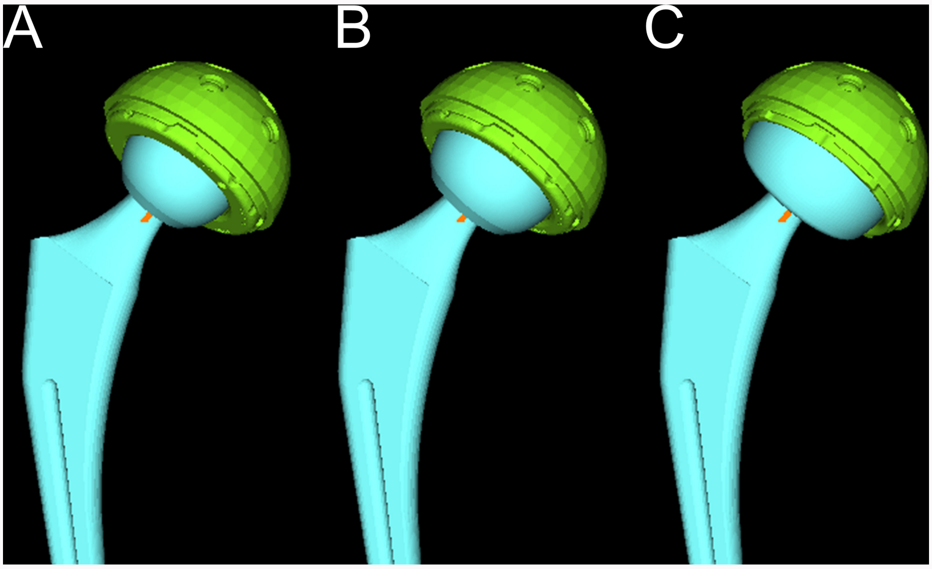

Fig. 3
Simulation with the implant is changed to a 36 mm ball and dual-mobility liner, without changing the cup diameter and placement position. a) 32 mm ball, b) 36 mm ball, and c) dual-mobility liner.

Table II. Preoperative planning and postoperative measurement of the implant position.

Variable	M-THA group	N-THA group	p-value
Mean preoperative plan, ° (SD)			
RI	40 in all cases		N/A
RA	20.6 (3.1)	18.8 (5.3)	0.029†
Stem neck anteversion	33.9 (7.4)	35.8 (8.1)	0.148†
Mean postoperative measurement, ° (SD)			
RI	37.6 (5.7)	39.6 (5.1)	0.046†
RA	24.0 (8.5)	17.6 (6.5)	< 0.001†
Stem neck anteversion	29.0 (9.8)	30.8 (12)	0.373†
Combined anteversion*	53.1 (13)	48.4 (10)	0.060†
Combined anteversion > 40 < 60, %	62	67	0.692‡
Mean error from planning, ° (SD)			
RI	-2.4 (5.7)	-0.4 (5.1)	0.046†
RA	3.4 (7.8)	-1.2 (5.1)	< 0.001†
Absolute error from planning, ° (SD)			
RI	5.1 (3.5)	3.7 (3.5)	0.022†
RA	6.8 (5.0)	3.9 (3.5)	0.001†

*Combined anteversion is the sum of stem neck and cup radiological anteversions.
†Mann-Whitney U test.
‡Pearson's chi-squared test.
M-THA, manual total hip arthroplasty; N/A, not applicable; N-THA, CT-based navigated total hip arthroplasty; RA, radiological anteroposterior; RI, radiological inclination.

regression analysis using a stepwise variable entry method to determine the factors associated with the total ROM in four directions (flexion, extension, internal rotation, and external rotation). Variables were added or removed based on a significance threshold of $p < 0.2$ in the analyses. The candidate factors consisted of the cup size, stem size, neck-shaft angle, ball offset, stem anteversion, CT-based navigation, and simulated implants (32 mm ball, 36 mm ball, or dual-mobility liner). A p-value < 0.05 was considered statistically significant. Statistical analyses were performed using the JMP Software v. 16 (SAS Institute, USA). The absolute value of cup anteversion error was 4.4° and 8° in the N-THA and M-THA groups, respectively.[30,31] A sample size calculation suggested that 45 hips per cohort would facilitate detecting a 3.6° (SD 6°) difference in the absolute value of error in postoperative cup anteversion (power = 0.8, $\alpha = 0.05$) between the N-THA and M-THA groups.

Results

Implant orientation

The mean absolute values of differences between the cup placement angles measured on CT images and those planned preoperatively were approximately one-third lower in the N-THA group than in the M-THA group in both inclination and anteversion (3.7° (SD 3.5°) vs 5.1° (SD 3.5°); p = 0.022, and 3.9° (SD 3.5°) vs 6.8° (SD 5.0°); p = 0.001, respectively) (Table II).

The proportion of cases within the target range of 10° for both RI and RA was significantly higher in the N-THA group than in the M-THA group (86% vs 65%; p = 0.010). Similarly, the percentage of cases falling within the 5° range was significantly higher, by 2.5 times, in the N-THA group than in the M-THA group (59% vs 22%; p < 0.001) (Figure 4).

ROM simulation with actual implants

The ROM achievement rates required for flexion and internal rotation did not differ between the N-THA and M-THA groups (88% vs 90%; p = 0.765, and 86% vs 87%; p = 0.952,

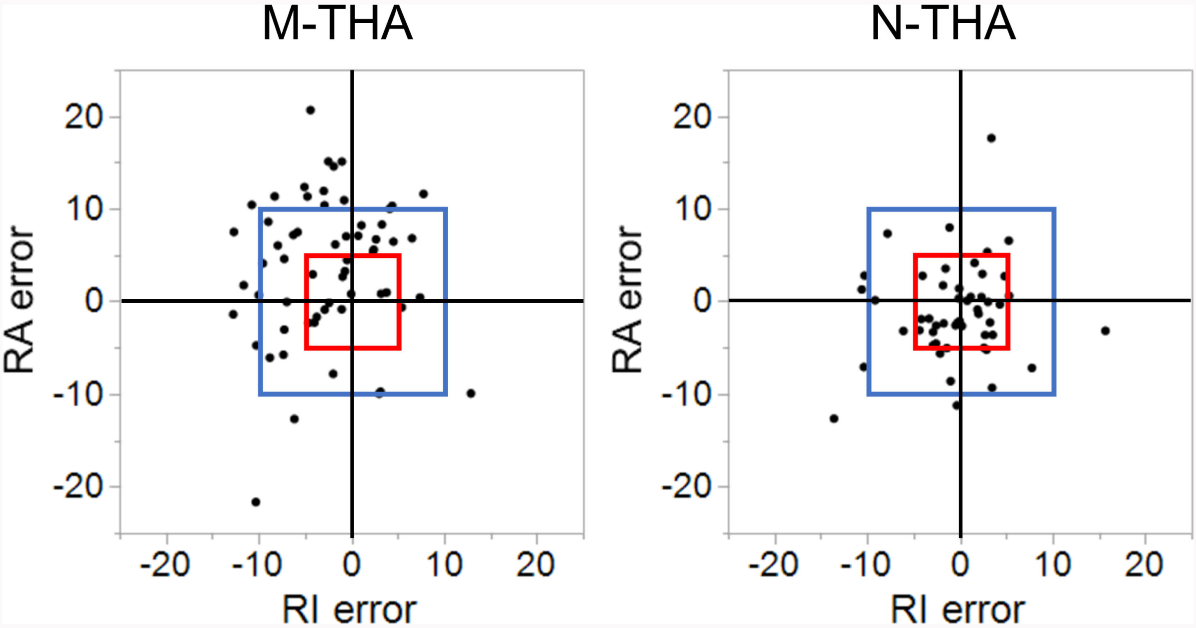

Fig. 4
Scatter plot of the differences in radiological inclination (RI) and radiological anteversion (RA) between postoperative measurement and planning in each group. The blue square represents the area within 10° (65% vs 86%; p = 0.010), and the red square represents the area within 5° (22% vs 59%; p < 0.001). M-THA, manual total hip arthroplasty (THA); N-THA, CT-based navigated THA.

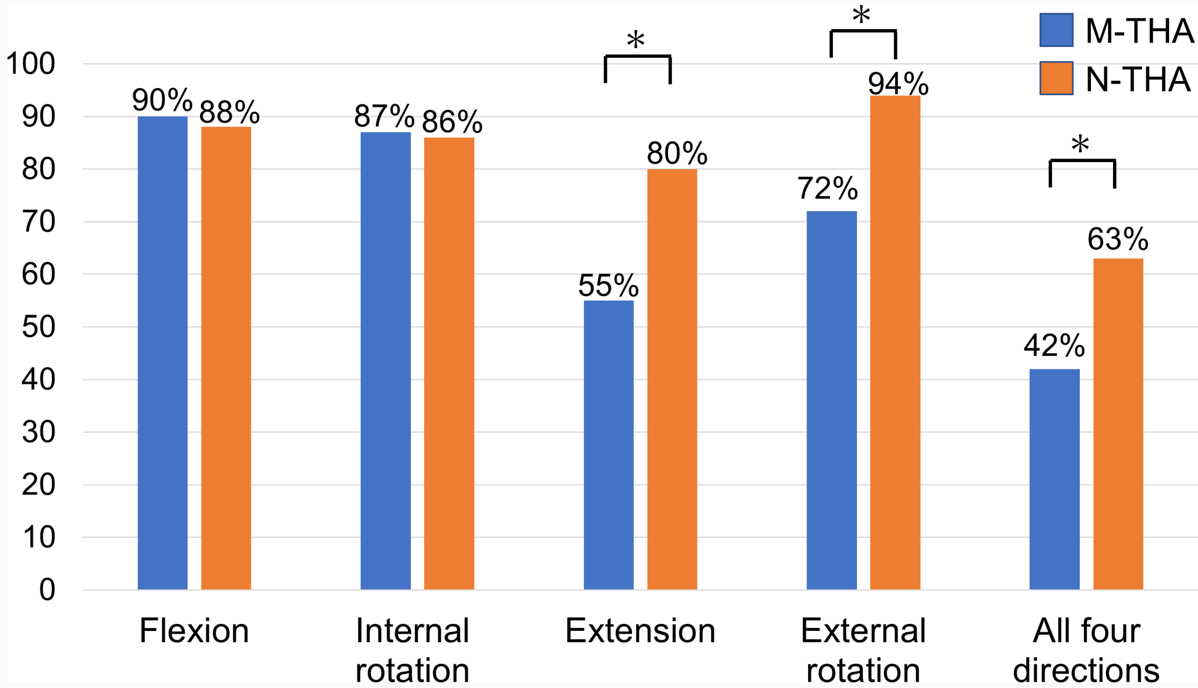

Fig. 5
Rate of achievement of range of motion (ROM) in four directions with a 32 mm ball. In the CT-based navigation total hip arthroplasty (N-THA) group, the achievement rates of the required ROM in extension and external rotation are higher (p = 0.005 and p = 0.002, respectively), and the achievement rates in all four directions are elevated (p = 0.036). M-THA, manual THA.

respectively). Conversely, the achievement rates for extension and external rotation were higher in the N-THA group than in the M-THA group (80% vs 55%; p = 0.005, and 94% vs 72%; p = 0.003). The proportion of cases achieving the required ROM in all directions was higher in the N-THA group than in the M-THA group (63% vs 42%; p = 0.036) (Figure 5).

ROM simulation with a 36 mm ball or dual-mobility liner
Regardless of the use of CT-based navigation, the achievement rates of the required ROM were significantly higher with the use of a 36 mm ball or dual-mobility liner compared to the use of a 32 mm ball (65% vs 51%; p = 0.040, and 77% vs 51%; p < 0.001, respectively). The N-THA group comprised a significantly higher percentage of patients (78% vs 55%; p =

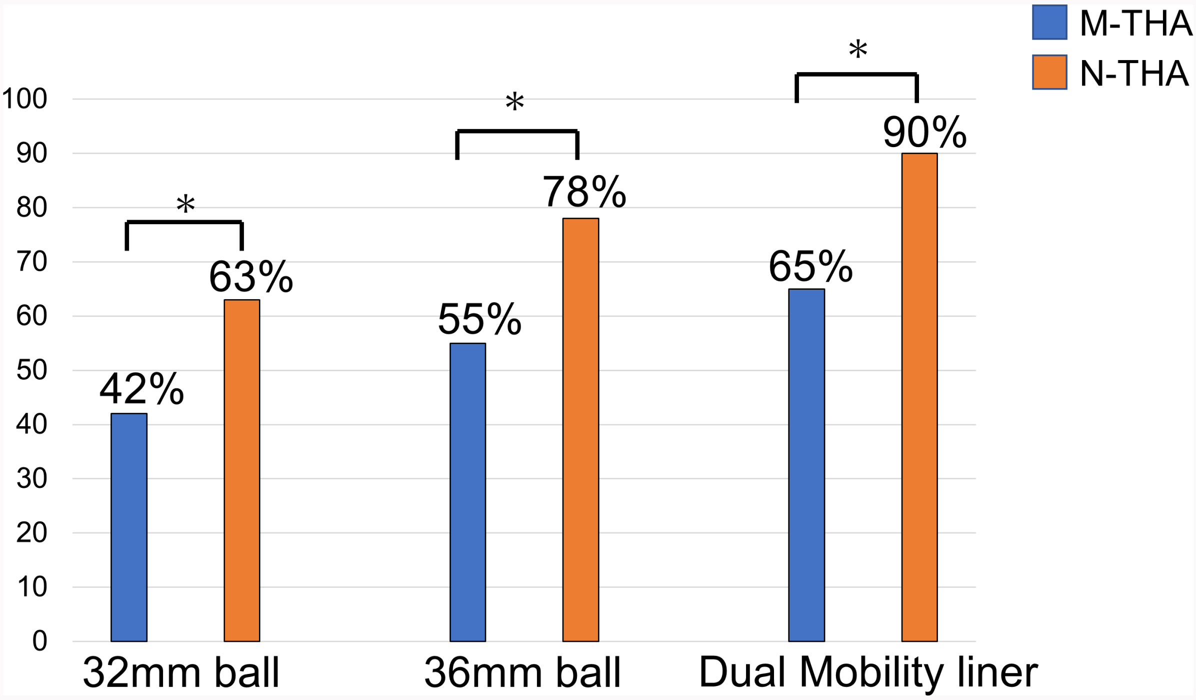

Fig. 6
Achievement rate of the required range of motion in all four directions with a 32 mm, 36 mm ball, and dual-mobility liner, with and without CT-based navigation. CT-based navigation improves the achievement rates for all implant types (p = 0.040, 0.024, and 0.003, respectively).

Table III. Multivariable analysis of factors influencing the total range of motion in four directions.

Variable	Positive factor	β-value (95% CI)	p-value
Simulated implants	DM, 36 mm ball	15.4 (13.4 to 17.5)	< 0.001*
Use of CT-based navigation	CT-based navigation	5.4 (4.0 to 6.9)	< 0.001*
Ball offset	Larger offset	1.4 (0.9 to 1.9)	< 0.001†
Cup size	Larger cup	1.1 (0.5 to 1.6)	<0.001†
Stem neck anteversion	Smaller anteversion	0.2 (0.1 to 0.4)	0.002†
Neck-shaft angle	132°	0.5 (-0.1 to 1.2)	0.113*

The variables were selected using stepwise multiple regression analysis.
Total range of motion (ROM) in four directions: sum of ROM in flexion, extension, internal rotation, and external rotation.
β-value is the standard regression coefficient.
*Logistic regression analysis.
†Linear regression analysis.
DM, dual-mobility liner.

0.024) who achieved the required ROM in all directions in the simulation with a 36 mm ball. The rate was also significantly higher in the N-THA group (90% vs 65%; p = 0.003) in the simulation using the dual-mobility liner (Figure 6).

We observed no difference in the achievement rates of the required ROM among the 32 mm ball with CT-based navigation (63%) and the 36 mm ball (55%; p = 0.443) and dual-mobility liner (65%; p = 0.845) without navigation.

Total ROM in four directions

In the simulation using the 32 mm ball, the total ROM was greater in the N-THA group than in the M-THA group (250° (SD 11°) vs 240° (SD 15°); p < 0.001). In the multivariable analysis for total ROM, the implant type (dual-mobility liner, > 36 mm ball, > 32 mm ball), CT-based navigation, large ball offset, large cup, and small stem anteversion appeared to be significant positive factors (Table III).

The risk ratio of impingement within the required ROM

Figure 7 demonstrates the risk ratio of impingement within the required ROM, using the manual group with a 32 mm ball as a reference. The use of a 36 mm ball and a dual-mobility liner individually resulted in a decrease to 0.73 and 0.58, respectively. Furthermore, combining CT-based navigation with either a 36 mm ball or a dual-mobility liner further reduced the risk ratio to 0.35 and 0.19, respectively.

Discussion

This study is the first to report the contribution of CT-based navigation, along with large femoral heads and dual-mobility liners, to the achievement of required ROM. CT-based navigation demonstrated a significant improvement in the required ROM achievement rates compared with manual techniques, regardless of the head size used (32 mm, 36 mm, or dual-mobility liner). This improvement in the achievement rate can be attributed to the improved accuracy of cup placement through CT-based navigation.

Regarding cup placement accuracy, the N-THA group exhibited significantly smaller absolute value errors than the M-THA group. This finding aligns with prior research indicating that CT-based navigation reduces placement errors.[14,32,33] In addition, the percentage of cases within the target ranges

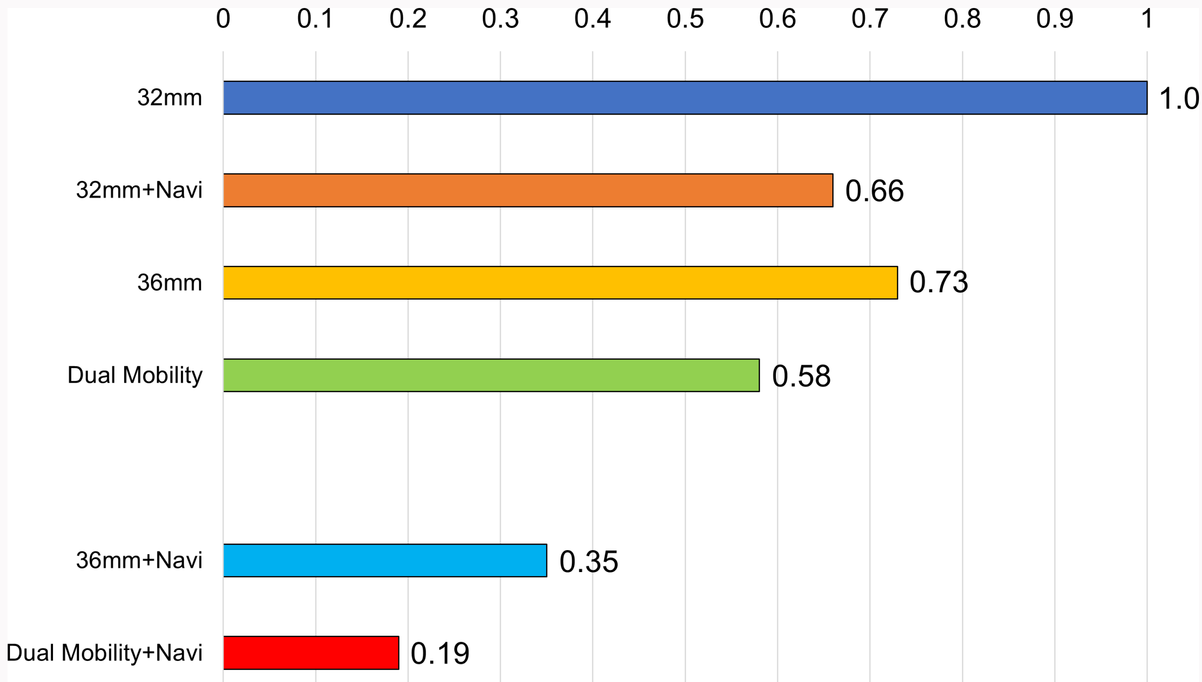

Fig. 7
The risk ratio of impingement within the required range of motion when using 32 mm ball in the manual group as a reference. Navi, CT-based navigation.

of 10° and 5° was significantly higher upon using CT-based navigation. Specifically, the proportion of cases within 5° of the target was > 2.5 times higher in the N-THA group. This trend was consistent with that reported by Tsutsui et al,[14] who suggested a reduction in outliers using CT-based navigation. Furthermore, the RI was smaller than the target in the M-THA group, possibly owing to concerns about overly steep placement angles. Moreover, the RA was greater than the target, which may be attributed to apprehensions related to posterior dislocation, considering the use of posterior approach in the surgeries.

In ROM simulation, where the implants were placed in their actual position, the N-THA group demonstrated > 20% higher achievement rate of the required ROM in extension and external rotation while maintaining those in flexion and internal rotation. Excessive cup anteversion was applied in the M-THA group, which potentially caused impingement during extension and external rotation. CT-based navigation avoided excessive anteversion and significantly improved the required ROM achievement rates by > 20%. A study comparing imageless navigation and manual techniques similarly reported a reduction in impingement in cases using navigation.[34]

Despite the use of CT-based navigation, only 67% cases achieved the required ROM with the 32 mm ball in the N-THA group. This finding can be attributed to the limited oscillation angle available with a 32 mm ball.[35] The use of larger head sizes or dual-mobility implants reduces the dislocation rates, which is supposedly influenced by the oscillation angle and jumping distance.[17] In this simulation, the combination of CT-based navigation with a 36 mm ball and dual-mobility liner improved the required ROM achievement rate to 78% and 90%, respectively. Wyles et al[36] reported on reduced post-THA dislocation rates in the following order: dual-mobility liner, 36 mm ball, and 32 mm ball.[31] Thus, CT-based navigation with a 32 mm ball resulted in no significantly different ROM achievement rates, compared with cases without navigation using a 36 mm ball or dual-mobility liner. Therefore, CT-based navigation exerts impingement prevention effects similar to those with using a 36 mm ball or dual-mobility liner.

In the multivariable analysis for the total ROM in four directions, simulated implant (dual-mobility liner, > 36 mm ball, > 32 mm ball), CT-based navigation, larger ball offset, larger cup, and smaller stem anteversion were the positive factors for expanding ROM. Excessive ball offset can lead to overstrain of the soft-tissue.[37] In cementless THA, cup size and stem anteversion are substantially influenced by bone morphology.[25] Therefore, it is beneficial to use CT-based navigation, a large femoral head, or a dual-mobility liner in patients with a high risk of dislocation. While the 36 mm ball has been reported to have favourable long-term outcomes similar to the 32 mm ball,[6] there are limited mid- to long-term reports on the dual-mobility liner, and there have been reports of intraprosthetic dislocation, early wear, and corrosion.[38,39] Therefore, using dual-mobility liners should be limited to cases with a high risk of dislocation.

Limitations

This study has some limitations. First, we did not perform a randomized controlled trial, and there may have been some bias in patient selection. However, we observed no significant differences in the patient demographics and implant size. Second, the simulations only detected impingement between the implants and did not consider impingement between implants and bone, or between bones considering the influence of bone morphology and osteophytes. Third, the ROM simulation was conducted based on the supine FPP reference, without considering pelvic movement due to different positions. Fourth, although simulation-based ROM measurements were performed, no actual hip ROM measurements were taken. However, the emphasis in this study was on impingement, which was considered appropriate for the method. Finally, the relatively small sample size prevented direct comparison of the actual dislocation rates. However, this study was primarily conducted to investigate whether the simulated ROM satisfied the required ROM.

In conclusion, the proportion of cases achieving the required ROM criteria was enhanced significantly by > 20% using CT-based navigation. The improved accuracy of cup placement through CT-based navigation likely contributed to the enhancement of the achievement rates of the required ROM. Furthermore, we observed improvements in the achievement rates of the required ROM by combining CT-based navigation with a larger femoral head or a dual-mobility liner.

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Data sharing

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