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Accuracy of Acetabular Component Positioning Using a Mixed Reality-Guided Navigation System During Total Hip Arthroplasty

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Background: Surgeons increasingly recognize the importance of patient-specific considerations in determining ideal cup alignments. In addition, various surgical navigation systems have been reported to improve cup placement accuracy during total hip arthroplasty (THA). Recently, a novel computed tomography (CT)–based planning and mixed-reality (MR) guidance system was developed to enable patient-specific 3-dimensional planning of the ideal cup position and further improve intraoperative achievement of the planned orientation.

Methods: This is retrospective, observational study of 40 patients (40 hips) who underwent MR-guided THA. Patient-specific CT-based surgical planning with definition of target operative anteversion and inclination of the acetabular cup in relation to the anterior pelvic plane was performed. 3D holograms of the cup and cup impactor in the selected target position were created and exported. Intraoperatively, automatic holographic registration was performed using a smart tool–based linked-paired-point matching method. Patient-specific content was displayed on a head-mounted display, and the acetabular component was inserted by matching the spatial position of the cup impactor with the hologram of the cup impactor in the target position. Postoperatively, patients underwent biplane simultaneous imaging for measurement of achieved cup alignment using a validated measurement method.

Results: Mean planned operative anteversion and inclination angles were 28.4° ± 1.6° (95% confidence interval [CI], 27.9°-28.8°) and 39.9° ± 0.3° (95% CI, 39.8°-40.0°), respectively. The mean absolute target error between preoperative target operative anteversion and the achieved operative anteversion was 0.7° ± 1.1° (95% CI, 0.3°-1.0°; range, 0°-4°). The mean absolute target error between preoperative target operative inclination and the achieved operative inclination was 1.1° ± 1.2° (95% CI, 0.7°-1.4°; range, 0°-4°).

Conclusion: Acetabular component positioning using a mixed reality guidance system during THA was highly accurate and well within the accuracy reported for other navigation systems.

Level of Evidence: Level III. See Instructions for Authors for a complete description of levels of evidence.

Introduction

Optimal acetabular component positioning is a key aspect during total hip arthroplasty (THA) to ensure a stable prosthesis with an impingement-free range of motion and ideal wear characteristics. While historically surgeons mostly aimed for the Lewinnek safe zone of 45° ± 10° inclination and 15° ± 10° anteversion[1] during surgery, its clinical utility has recently been challenged[2]. Increasingly, surgeons are recognizing the

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TABLE I Patient Demographics*

Women	19 (48)
Age, yr	65 ± 8 (63-68)
Height, m	1.73 ± 0.10 (1.70-1.76)
Weight, kg	82.0 ± 18.8 (76.2-87.8)
BMI, kg/m^2	27.1 ± 4.6 (25.7-28.6)
Right side	21 (53)
Previous contralateral THA	18 (45)

*Categorical data are depicted as n (%). Numerical data are depicted as mean ± standard deviation (95% confidence interval). BMI = body mass index and THA = total hip arthroplasty.

importance of patient-specific considerations, including femoral and pelvic mobility, as well as individual pelvic morphology, in determining ideal cup alignments[3-6].

In response to these evolving paradigms, various navigation techniques have emerged to enhance the precision of conventional THA procedures and achieve the desired target cup position intraoperatively. Notably, both computed tomography (CT)–based robotic-assisted THA[7-13] and image-less navigation-assisted THA[14-19] have demonstrated improved accuracy compared with traditional methods. In addition, CT-based and image-free augmented reality-assisted THA (AR-THA)[20-30] has shown promising results in optimizing acetabular cup positioning.

However, existing AR-THA solutions oblige the surgeon to perceive the overlay of digital content with the real world on a smartphone screen or monitor, partially reproducing the line-of-sight impediment of optical tracking systems and limiting barrier-free interaction with digital content anchored to the real 3-dimensional space.

By contrast, mixed reality (MR) offers a novel approach by enabling real-time, 3-dimensional anchoring and embedding of digital information through head-mounted displays (HMD) into the surgical environment[31]. MR, as opposed to AR, provides enhanced perception of depth and perspective, thereby significantly improving the 3D visualization of surgical anatomy[32].

Recently, a novel CT-based planning and MR-based navigation system for THA has been developed (HipInsight; Surgical Planning Associates). This combines cloud-based, comprehensive patient-specific planning with an MR-based execution system for THA for pelvis-sided guidance. On the acetabular side, it enables planning of cup alignment with indication of the clinically relevant operative anteversion and inclination in relation to the anterior pelvic plane (APP) coordinate system. The software's planning module facilitates the creation and export of 3D holograms of the cup, impactor, and planned screw hole locations in the selected target position. These holograms are then displayed intraoperatively using an HMD (HoloLens2; Microsoft) and used for real-time virtual guidance during THA.

The aim of this study was to evaluate the clinical accuracy of acetabular component placement during MR-guided THA. We therefore compared the planned and achieved operative anteversion and inclination using a validated measurement methodology based on postoperative biplane simultaneous radiographic imaging and calculated the mean absolute target error.

Materials and Methods

Patients

This was an institutional review board–approved (local IRB-number 2024-10), retrospective, single-center, single-surgeon, observational study. We reviewed a consecutive

TABLE II Preoperative Diagnoses, Osteoarthritis Grades, Radiographic Parameters, and Patient-Specific Planning Parameters

Parameter	Study Group 40 Patients (40 Hips)
Diagnosis	
Osteoarthritis	30 (75)
Developmental dysplasia of the hip	7 (18)
Crowe 1	7 (100)
Osteonecrosis	2 (5)
Legg-Calvé-Perthes disease	1 (3)
Tönnis grade of osteoarthritis	
1	2 (5)
2	9 (23)
3	29 (73)
Radiographic parameters	
Pelvic tilt, °	3 ± 5 (−8 to 17)
Pelvic rotation, °	0 ± 3 (−6 to 6)
Pelvic inclination, °	0 ± 2 (−5 to 7)
Native femoral version, °	16 ± 11 (−5 to 54)
Increased femoral version (>30°)	3 (8)
Decreased femoral version (<5°)	4 (10)
Coxa valga (neck-shaft angle > 140°)	6 (15)
Coxa vara (neck-shaft angle < 126°)	2 (5)
Implant plan	
Planned cup diameter, mm	54 ± 4 (48 to 64)
Implanted as planned	40 (100)
Planned femoral stem size	9 ± 4 (3 to 16)
Implanted as planned*	27 (68)
Within ± 1 size of plan	13 (100†)
Planned change in leg length, mm	3.0 ± 1.8 (0.9 to 9.8)
Planned change in global offset, mm	0.6 ± 2.7 (−4.9 to 8.2)

*Femoral stems were not implanted using Mixed-Reality guidance. †All 13 hips with deviation from the planned femoral stem size were within ±1 size of the original plan. Numeric values are depicted as mean ± standard deviation (range). Categorical values are depicted as the number of hips (%).

TABLE III Standardized Protocol for Preoperative CT*

Parameter	Requirements
Patient orientation	Supine, feet first, legs parallel in neutral rotation
Slice thickness/scan range	• Two scan regions: pelvis and femoral condyles • Exclusion of surrounding soft tissues in larger patients • Width and height (x, y) of both fields of view must be equal, so that the center points have the same x, y coordinates Region 1: The Pelvis • Whole pelvis and proximal femur (20 cm below the tip of the greater trochanter) • Slice thickness 1 to 1.25 mm • Interslice distance 1 to 1.25 mm Region 2: Femoral condyles • 50 mm of both distal femurs • Slice thickness maximum 5 mm
Scout view	Anteroposterior and lateral scout views from above the iliac crest to below the ankles
Image/pixel size	Identical for both scan regions
Scan properties	Primary purpose is bone detail. In the case of an existing implant, scan must be performed with sufficient power to allow visualization of the ischium behind the posterior/ inferior acetabulum
Scan technique	• Sequential scans: continuous or overlapping slices with no gaps • Helical scans: pitch (table:scan ratio) = 1:1 recommended • Slice thickness can be changed during the scan
Gantry tilt	None
Table height	Remains the same during the scan
Matrix size	Squared 512 × 512
Scan direction	Cranial to caudal or caudal to cranial
Storing	Both scanning sets as one patient file

*CT = computed tomography.

series of patients undergoing primary THA between September 2023 and October 2023 in our institution. We included all patients who underwent primary MR-guided THA using the navigation system HipInsight (Surgical Planning Associates) and who had postoperative biplane simultaneous radiographic imaging allowing for accurate and reliable measurement of postoperative cup orientation. Hips that underwent revision THA were excluded. Application of the aforementioned criteria yielded a study group of 40 patients (40 hips). Patient demographics are presented in Table I. Preoperative diagnoses included osteoarthritis (OA) in 30 hips (75%), developmental dysplasia of the hip (Crowe Type 1) in 7 hips (18%), osteonecrosis in 2 hips (5%), and Legg-Calvé-Perthes disease in one hip (3%). The preoperative Tönnis grade of OA[33] and key radiographic and 3D planning parameters are shown in Table II.

All MR-guided THA procedures were performed by the same board-certified orthopedic surgeon (S.B.M.) with extensive experience in arthroplasty surgery using a minimally invasive approach with a superior capsulotomy in a lateral decubitus position[34]. A cementless acetabular cup with either a ceramic or highly cross-linked polyethylene liner was used in all hips. On the femoral side, only uncemented stems were used.

Preoperative Image Acquisition

All patients underwent preoperative CT imaging according to our standardized institutional protocol (Table III). The scout views and axial image data were then uploaded to a cloud. This, in turn, then allowed for patient-specific surgical planning using dedicated planning software (HipInsight Navigation System Application, Version 1.5.0; Surgical Planning Associates).

Patient-Specific Surgical Planning

On upload of the patient's imaging data into the planning software, a semiautomatic segmentation allowed for the creation of a patient-specific 3D model. In addition, axial, coronal, and sagittal views of the original CT images were simultaneously depicted. This enabled a precise definition of a set of anatomic landmarks. The definition of both anterior superior iliac spines and the pubic symphysis allowed for definition of

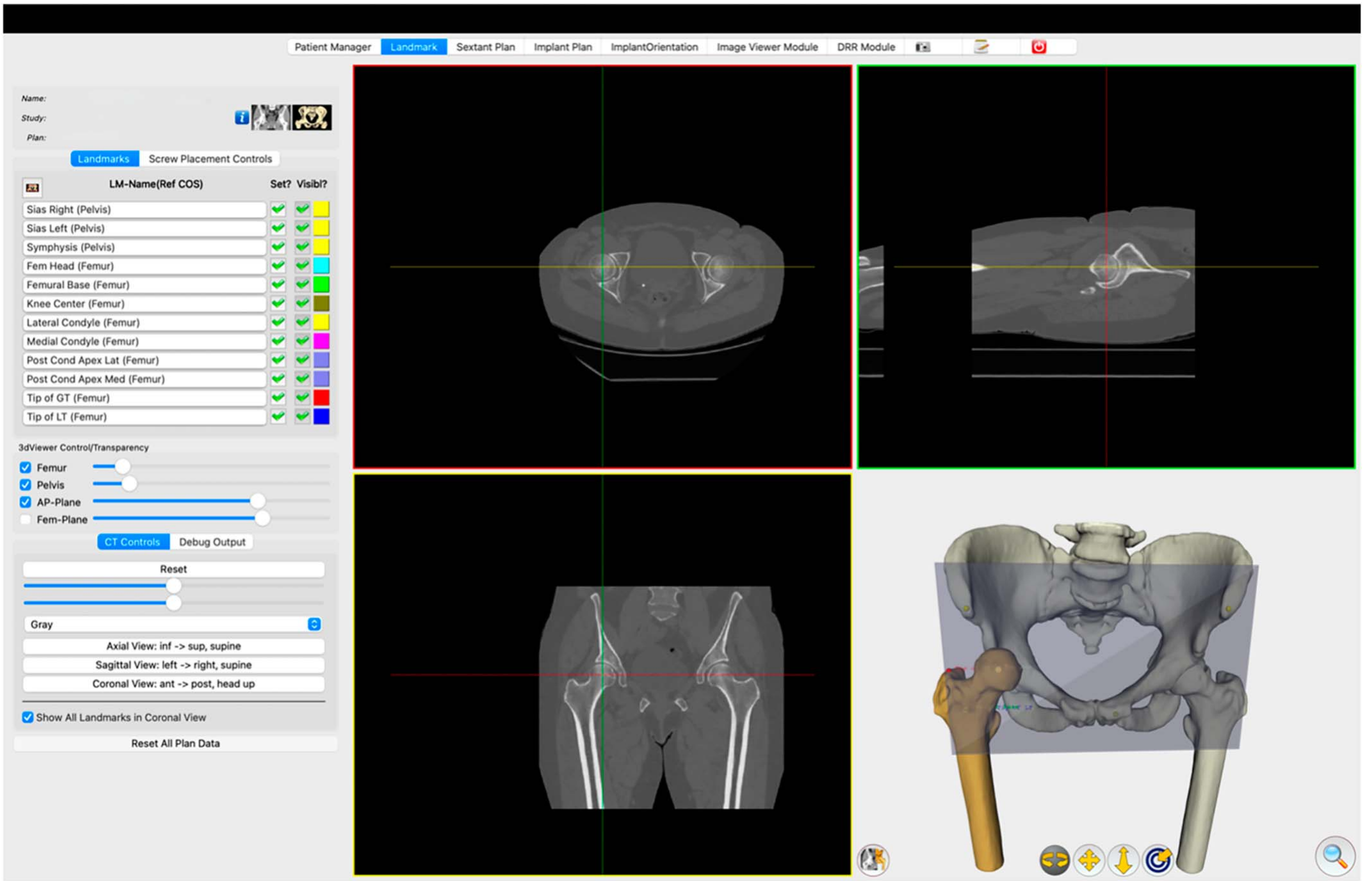

Fig. 1

Mixed Reality Navigation System Planning Application with original CT imaging data and created 3D model of the pelvis and proximal femur allowing for definition of various anatomic landmarks. Marking of both anterior superior iliac spines and the pubic symphysis enabled definition of the patient-specific anterior pelvic plane (APP). CT = computed tomography.

the APP (Fig. 1). The software automatically calculated pelvic tilt, rotation, and obliquity in relation to the APP. Next, an acetabular cup was planned using the software's component positioning module in a patient-specific position (Fig. 2). Based on published reference values for operative anteversion and inclination[4], the default target orientation was set to 29° of operative anteversion and 40° of operative inclination, according to the definition by Murray[35]. Depending on pelvic tilt and bony morphology, the definitive, patient-specific ideal cup size and target orientation were then defined in each case. In addition, CT-based 3D planning of the femoral stem with automated calculation of femoral anteversion[36] allowed patient-specific planning of leg length and offset (Fig. 3).

To allow for intraoperative automated holographic registration using a Food & Drug Administration–cleared smart tool, the tool docking points were defined in the planning software. Given the known geometry and leg length of the tripod smart tool used, the 3D definition of a base, iliac crest, and landing point enabled the calculation of the orientation of the docked smart tool, to which an image tracker was attached in a known position, in relation to the pelvis and the APP (Fig. 4).

The preoperative planning process was completed by the export of a series of patient-specific 3D models of the pelvis, cup impactor in the desired position, cup, and the final construct (Fig. 5).

Mixed Reality-guided Total Hip Arthroplasty

Before surgery, the patient-specific 3D models were placed on an HMD. Intraoperatively, after completion of the surgical exposure and resection of the femoral head, automatic holographic registration was performed using the preset smart tool with the affixed image tracker. To this end, the surgeon identified the planned base point, which is usually located slightly posterior to the posteroinferior acetabular rim. Once identified, the smart tool with the affixed image tracker was then fixed to the pelvis using a partially threaded 2.0-mm K-wire. The other 2 legs were subsequently inserted through stab incisions to the skin at their respective entry points, and with sharp trocars in place, the legs were manually pushed down to ensure the secure positioning of the legs on the bone surface, as

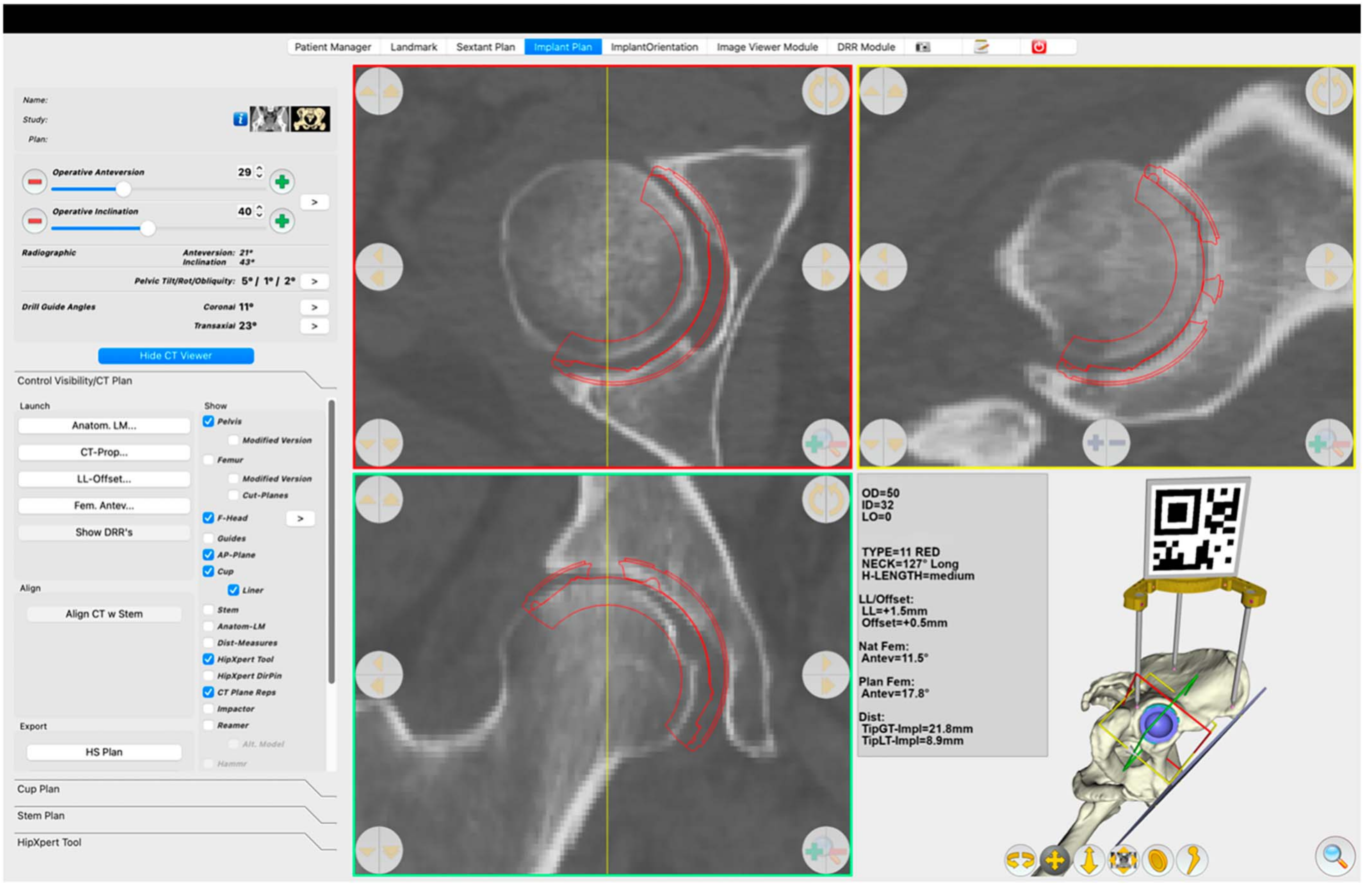

Fig. 2

Depiction of the component positioning module of the Mixed Reality Navigation System Planning Application. An acetabular cup could be positioned 3-dimensionally, and both the operative anteversion and inclination in relation to the anterior pelvic plane coordinate system are shown.

planned. The surgeon then opened a custom-developed Mixed Reality application (SPQ Registration Application version 1.0.2; Surgical Planning Associates) on the HMD and loaded the patient-specific content. The software automatically began searching for an image tracker, and when the application identified the image target, the first hologram was automatically loaded. The quality of the overlay of the digital content with the real world was reviewed by the operator. If the overlay was considered ideal, the patient-specific registration of the pelvis using this linked-paired-point matching method was completed. Using the patient-specific holograms of the reamer and cup impactor, the acetabular component was then inserted according to the preoperative plan by matching the spatial position of the real cup impactor with the hologram of the cup impactor in the target position (Fig. 6).

Postoperative Measurement of Achieved Cup Alignment

All patients underwent postoperative simultaneous biplanar radiographic imaging with the EOS system (ATEC), in which an AP and a orthogonal lateral scan of the pelvis were taken simultaneously in a functional standing position[37]. The achieved implant position was then measured using a validated software module of the used Mixed Reality navigation system planning application[38]. In brief, the EOS images were positioned in the isocenter of the EOS coordinate system, allowing for the reconstruction of the patient-specific APP and creation of a cup model that perfectly overlaid the appearance of the implanted acetabular components, which, in turn, allowed for precise and reliable determination of the operative anteversion and inclination in relation to the APP (Fig. 7)[38]. All postoperative measurements were performed by one observer (A.F.H.).

Data Analyses

To evaluate the clinical accuracy of acetabular component placement during MR-guided THA, we calculated the mean absolute target error between the planned and achieved operative anteversion and inclination according to Murray[35]. The demographic data of the patients were described with the help of usual position and dispersion measures of descriptive statistics, such as mean value, standard deviation, and 95% confidence interval (95% CI).

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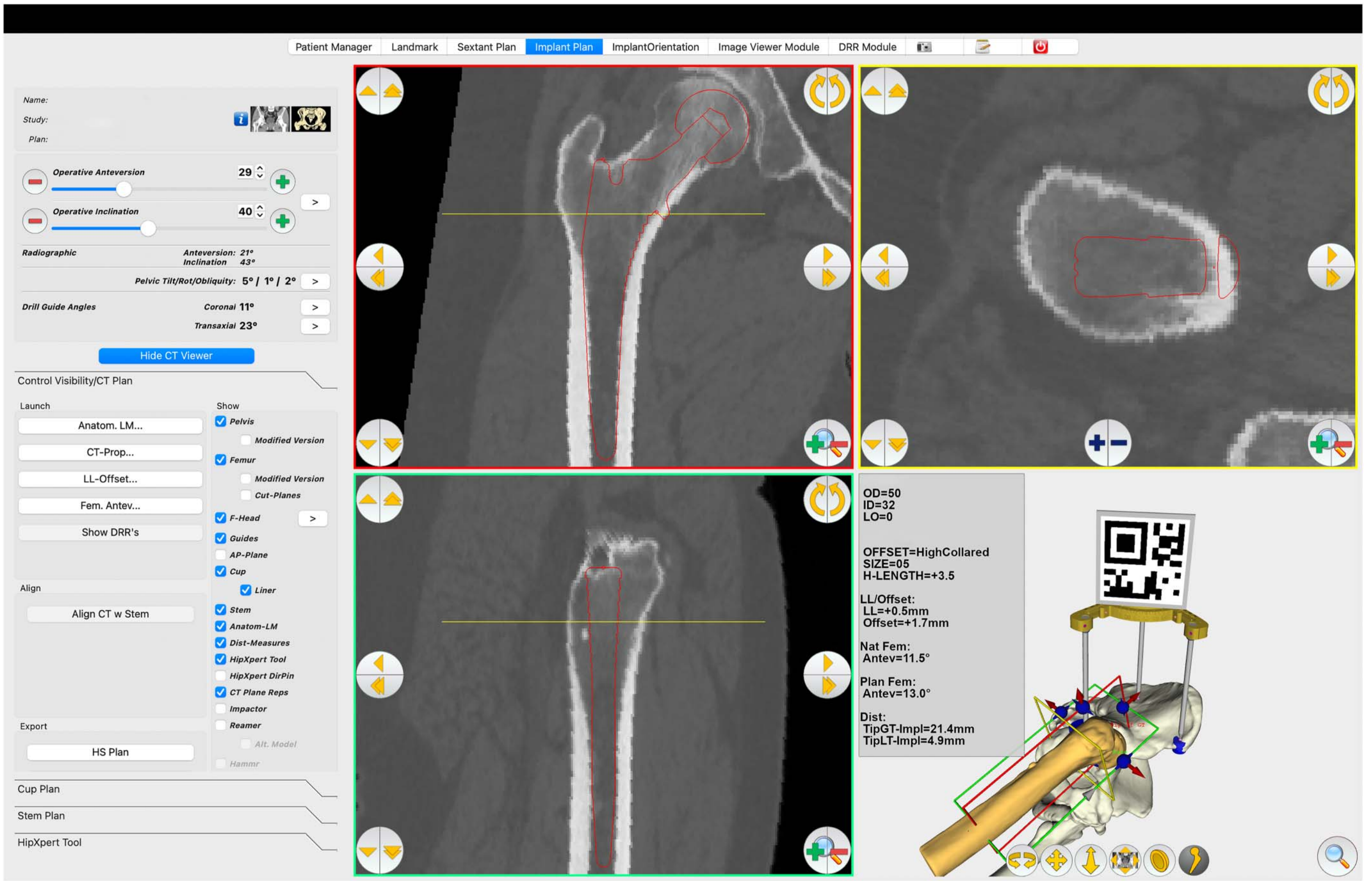

Fig. 3

Depiction of the component positioning module of the Mixed Reality Navigation System Planning Application. A femoral stem could be positioned 3-dimensionally, and automated calculation of femoral anteversion was performed. Known stem geometry and exact positioning allowed for calculation of leg length and offset.

Results

All 40 patients (40 hips) were included in the analysis. The mean planned operative anteversion and inclination angles were 28.4° ± 1.6° (95% CI, 27.9°-28.8°) and 39.9° ± 0.3° (95% CI, 39.8°-40.0°), respectively.

The mean absolute target error between preoperative target operative anteversion in relation to the APP and the achieved operative anteversion measured on the postoperative simultaneous biplanar radiographic imaging was 0.7° ± 1.1° (95% CI, 0.3°-1.0°; range, 0° to 4°). The mean absolute target error between preoperative target operative inclination in relation to the APP and the achieved operative inclination measured on the postoperative simultaneous biplanar radiographic imaging was 1.1° ± 1.2° (95% CI, 0.7°-1.4°; range, 0°-4°). A visual depiction of the combined anteversion and inclination errors is shown in Figure 8.

Discussion

The purpose of this retrospective, observational study was to evaluate the accuracy of a novel, MR-guided surgical navigation system for acetabular cup placement in THA. This study demonstrates that the investigated MR guidance–based hip navigation system enabled highly accurate acetabular component positioning in relation to operative anteversion and inclination.

The use of surgical navigation systems in THA improves the accuracy of acetabular cup positioning[7-16,18-24,28,29]. However, to the best of our knowledge, this is the first patient-specific MR-based THA guidance system to be investigated. Hasegawa et al. recently provided an up-to-date comparison between the accuracy of different navigation systems for THA and reported mean absolute target errors ranging between 2.8° ± 2.2° and 4.2° ± 4.0° for inclination and between 2.7° ± 2.2° and 5.3° ± 5.3° for anteversion[22]. There are several possible explanations as to why the accuracy observed in our study seems to be superior to the one reported for other navigation systems. In this study, all patients underwent preoperative CT imaging. During 3-dimensional surgical planning, this allows for an ideal visualization of the patient-specific anatomy, including a comprehensive assessment of acetabular and femoral version, osteophytes, and relevant anatomic landmarks. This, in turn, might lead to a more

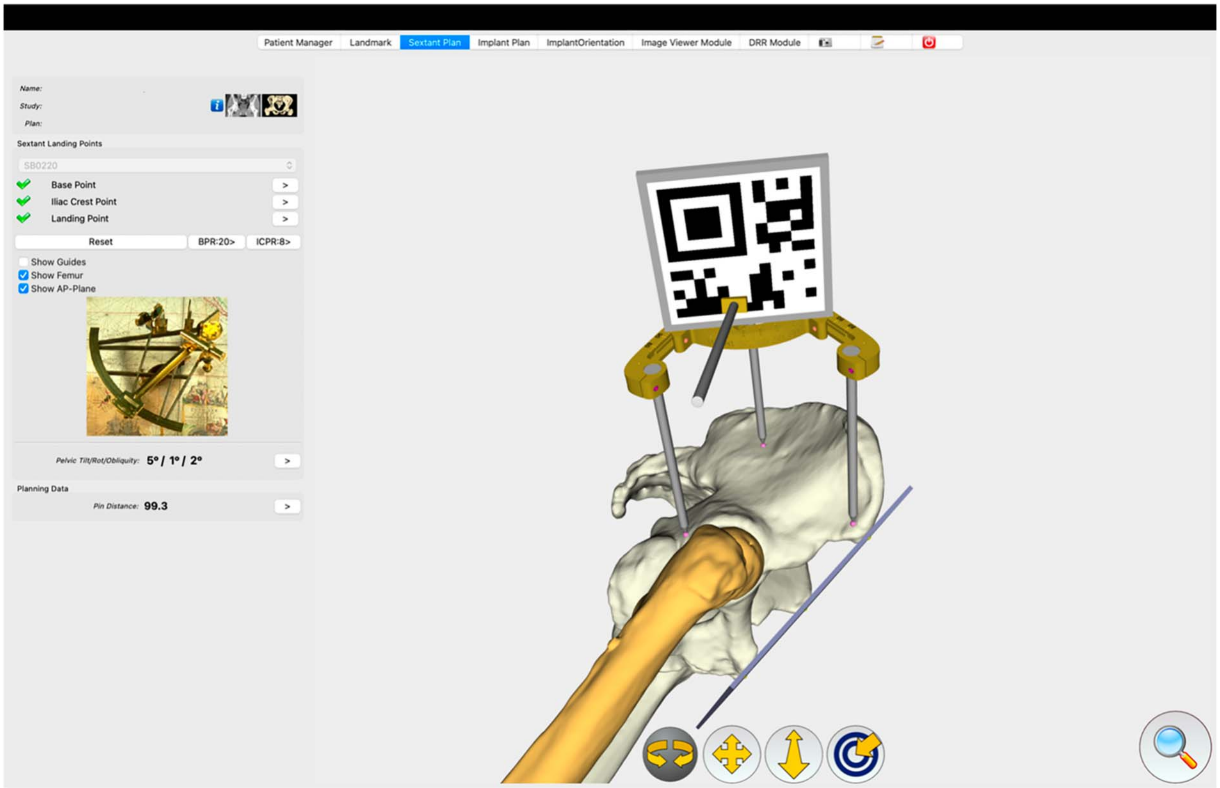

Fig. 4
Planned position of the tripod smart tool used for automated holographic registration intraoperatively with an affixed image tracker in a known position.

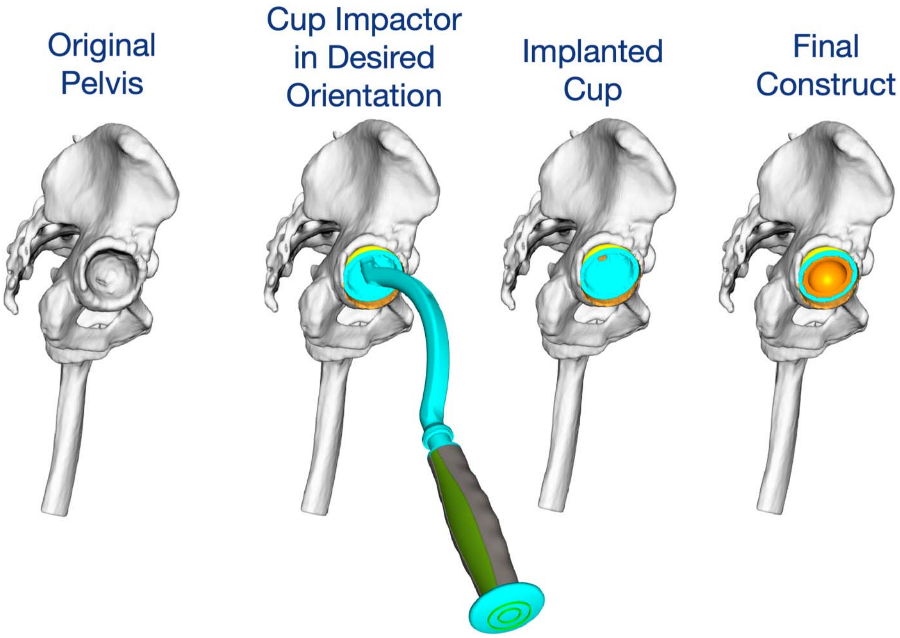

Fig. 5
Example of the holographic workflow based on exported, patient-specific 3D models.

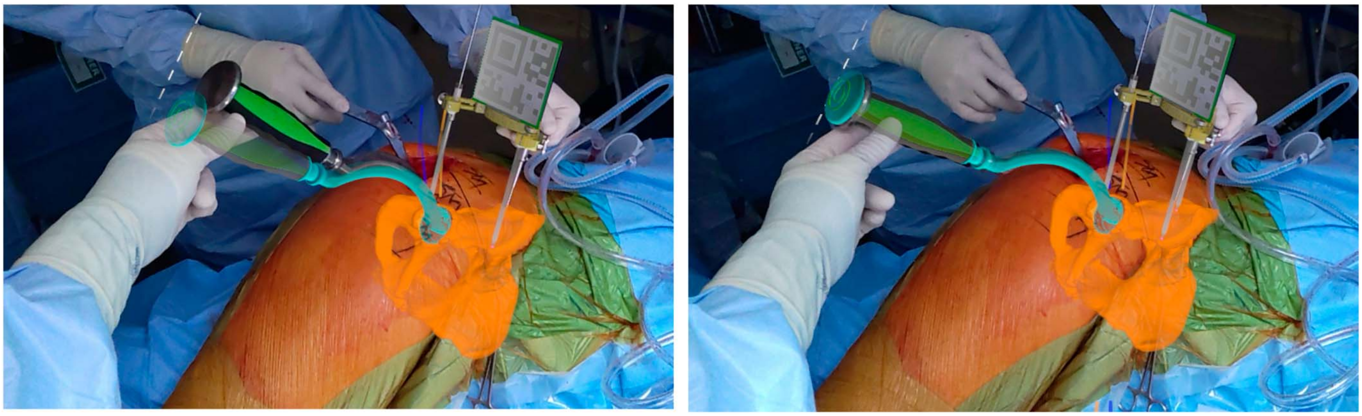

Fig. 6
The hologram of the cup impactor in the planned target position is depicted (left). By manually aligning the real cup impactor with the hologram (right), the surgeon identified the desired acetabular cup position intraoperatively.

accurate prediction of target implant sizes and position, compared with image-free navigation systems[39]. With the help of mixed reality guidance, this advantage can be maximized intraoperatively as the entire anatomy can be superimposed in real time during surgery, which could possibly explain the improved ability to achieve the target orientation compared with other CT-based navigation systems.

The capacity to enable a direct visual overlay of the target position of the cup impactor onto the real environment could represent an additional advantage compared with non–patient-specific AR-THA methods. Thanks to the anchoring and embedding of the holograms into the real world, the surgeon's gaze does not have to move back and forth between a monitor[27] or smartphone screen[20] and the situs when inserting the acetabular cup, but can insert the cup while simultaneously aligning the actual with the predefined target cup position under direct visualization of both the real and projected content.

Accurate registration is a core element of accurate navigation. It has been reported that APP-based registration that takes pelvic tilt into account contributes to higher navigational accuracy[24,25]. It might be that the additional use of automated smart tool registration methods like the one used in this study further allows for improved registration accuracy and therefore allows for an improved cup positioning accuracy during navigated THA.

In the context of value-based health care, cost-effectiveness of THA using enabling technologies is an important consideration[40]. Despite increased per-procedural costs, robotic-assisted THA has consistently been shown to be cost-effective compared with manual THA[41-45]. Cost-savings are largely attributed to improved implant positioning, resulting in lower complication and rehospitalization rates after primary THA, with cost-effectiveness being highly dependent on index operative costs[44]. While CT-guided 3D surgical planning increases costs in both MR-guided and robotic THA[39], the direct costs of HMDs for MR guidance are significantly lower than those of robotic systems[40,46]. Therefore, MR guidance has the potential to further enhance the cost-effectiveness of THA by lowering surgical costs while ensuring precise implant positioning, as supported by findings in this study.

This study had several limitations. This was a single-center, single-surgeon study, limiting the external generalizability of our findings. However, MR navigation is intuitive and easy to integrate into existing surgical workflows, which do not need to be modified for this purpose, but simply expanded to include a novel visual component. We are therefore convinced that the results of our study can be reproduced by others in the future. In addition, this study is associated with the drawbacks of a retrospective study. Although we analyzed a consecutive series of patients, a remaining selection bias cannot be fully excluded. To date, it remains unclear how and to what extent further improvements in cup positioning accuracy during THA would translate into improved clinical outcomes, a question beyond the scope of this study. All MR-THA procedures were performed using a minimally invasive technique with a superior capsulotomy in a lateral decubitus position. A direct transfer of our results to patients undergoing THA using other surgical methods is therefore not possible and is yet to be confirmed.

Future prospective studies comparing the accuracy of MR-THA with conventional THA, considering both radiologic and clinical end points with longer follow-up, are needed to demonstrate the clinically important superiority of MR-THA. Despite these limitations, we believe that this study provides useful insights into this novel navigation system for THA and has the potential to assist surgeons in identifying the most suitable navigation system.

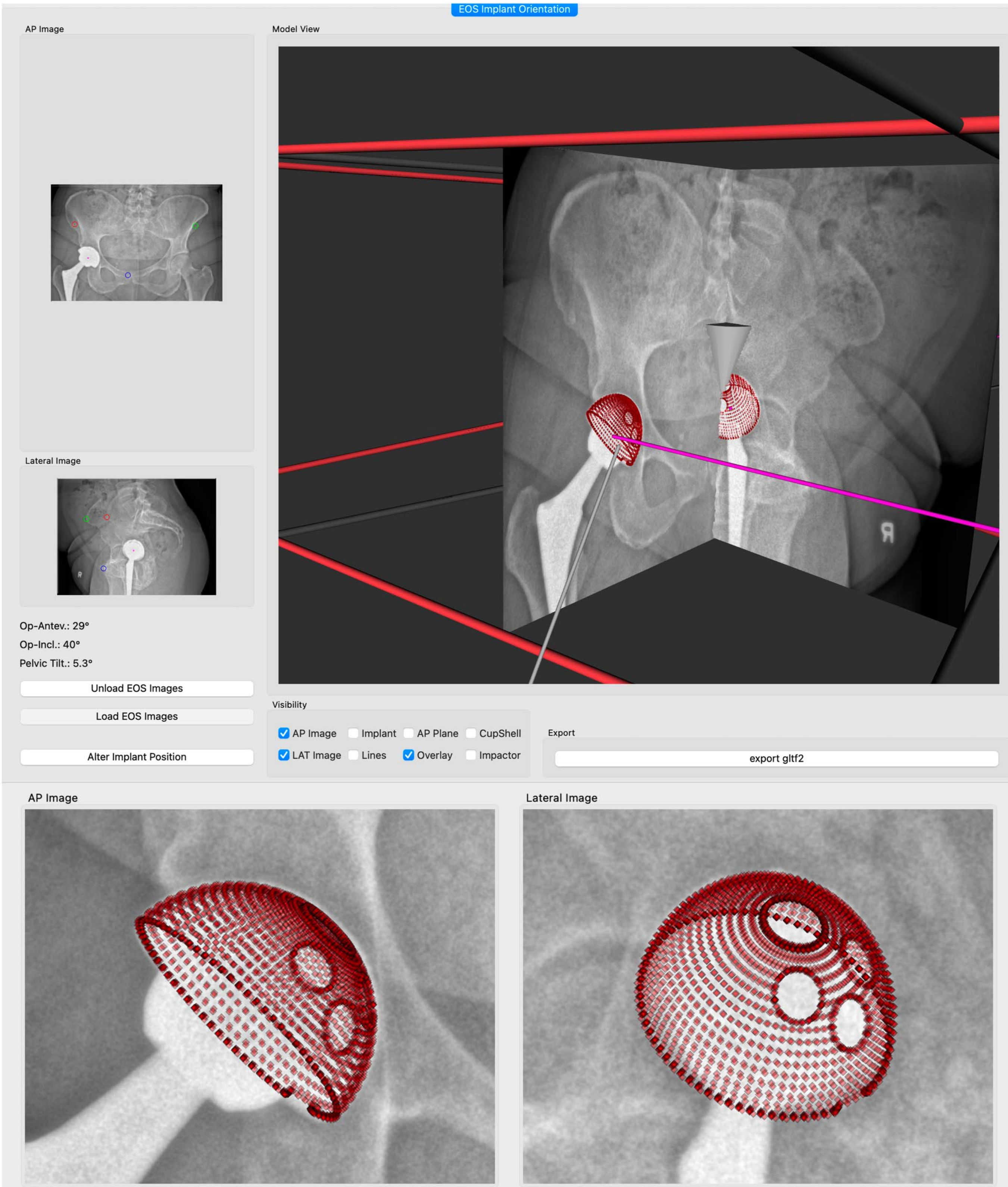

Fig. 7
Projection model of a simulated cup onto the centered biplanar simultaneous radiographic images overlaying the actual cup (top). Close-up view of the artificial cup projection onto the EOS images (bottom).

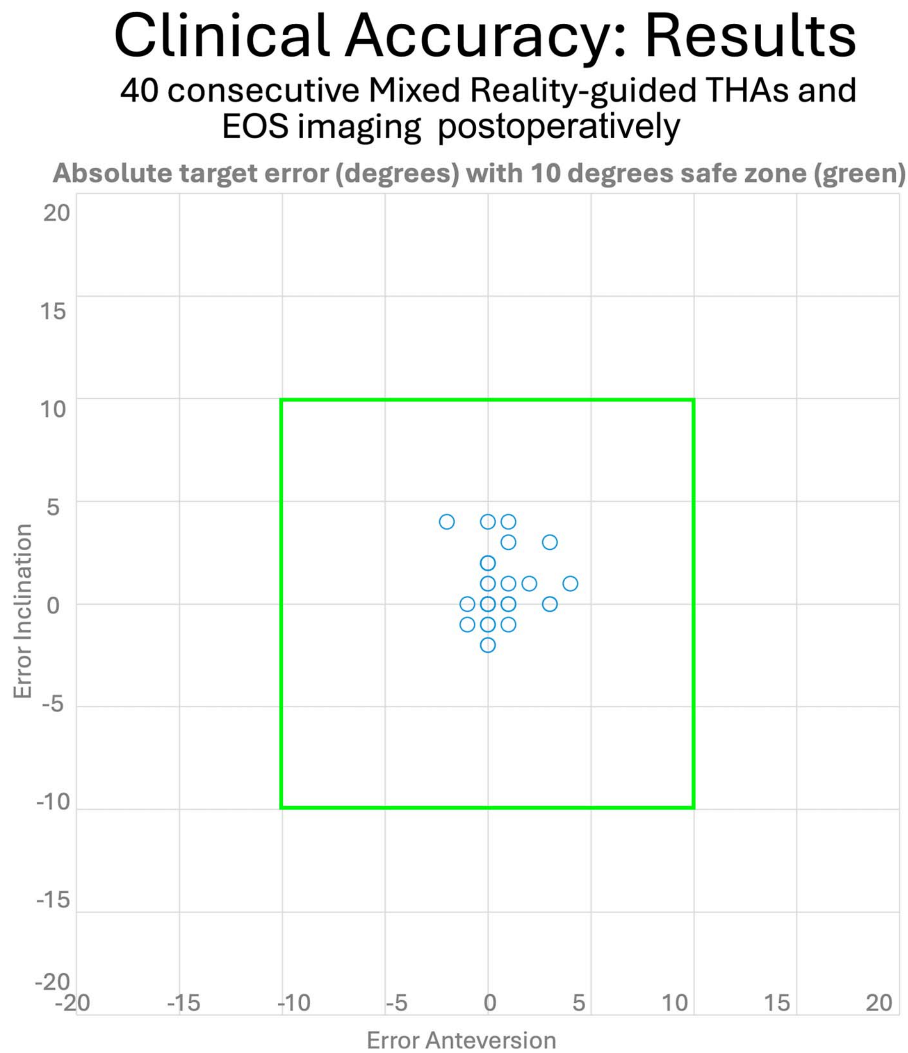

Fig. 8

Clinical accuracy of the Mixed Reality-guided THA. THA = total hip arthroplasty.

Conclusions

In conclusion, this study demonstrated high clinical accuracy of acetabular component positioning using a mixed reality guidance system during THA. ■

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