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Augmented Reality-Based Femur Registration With Head-Mounted Display and Infrared Tracking Device as Stand-Alone Navigation Tool: A Preclinical Validation Study

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ABSTRACT

Background and Aims: This study evaluated the accuracy of a standalone augmented reality (AR) navigation system using the Microsoft HoloLens 2 for total hip arthroplasty (THA). The system integrates infrared (IR) tracking and a preoperative 3D CT model for intraoperative visualization and guidance. The aim was to assess whether this AR-based solution could achieve clinically acceptable accuracy for use as a surgical navigation tool.

Methods: A dedicated AR application was developed to perform six-degrees-of-freedom pose estimation using inside-out tracking. Registration accuracy was assessed using six femur replicas with predefined target points. The registration pipeline combined landmark-based initialization with iterative surface refinement. Target registration error (TRE) was calculated for each point, and the influence of anatomical region, axis, surgical approach (anterior vs. posterior), and user experience level was analyzed.

Results: The system achieved a mean TRE of 3.61 ± 2.18 mm. Significant variations in accuracy were observed between anatomical regions ($p = 0.019$) and along different axes ($p < 0.001$), with the highest errors noted along the anteroposterior axis and in distal femoral regions. No significant differences were found between anterior and posterior approaches or among users with varying levels of experience, indicating operator-independent performance.

Conclusion: The AR navigation system demonstrated consistent and accurate registration performance across users and approaches. With a mean TRE of ~3 mm, the system meets accuracy requirements for potential clinical application in THA. Further cadaveric validation is recommended to confirm surgical feasibility and applicability.

Nicolas Himpe and Quentin Neuville contributed equally to this study.

1 | Introduction

Augmented Reality (AR) Head-Mounted Displays (HMDs), such as Microsoft's HoloLens, are increasingly applied in medicine. By merging virtual and real imagery in real time, AR allows surgeons to access critical information directly in their field of view without diverting attention from the patient. In orthopedics, and particularly in total hip arthroplasty (THA), AR is promising [1].

Recent studies have introduced AR simulators for THA that offer self-paced training using various visualization techniques, including overlays, virtual twins, and sectional views. By combining optical tracking and AR-HMDs, these systems achieve high spatial accuracy, with reported errors below 3 mm and 3°.

However, technical challenges persist. Current AR-HMD hardware struggles to meet the high precision demands of complex surgery. Visual self-registration is prone to drift, often requiring hybrid tracking solutions. Designing intuitive user interfaces remains critical to avoid cognitive overload during surgery. Moreover, the absence of standardized clinical validation of AR tools hinders widespread adoption.

Nevertheless, initial applications demonstrate that AR-HMDs may play a pivotal role in enhancing surgical training and intraoperative guidance. Particularly in complex procedures such as THA, AR may improve surgical accuracy, safety, and efficiency [1, 2].

In THA, the restoration of biomechanics is essential in achieving a good long-term functional outcome [3–5]. Preoperative templating allows one to anticipate intraoperative difficulties and can help optimize both implant positioning and sizing [6, 7]. As such, it has the potential to improve prosthetic fit, to reduce wear and to decrease the dislocation risk [8, 9].

During two-dimensional (2D) templating, transparent films or software are used to overlay an implant's contour on standardized radiographs of the hip or pelvis. Despite its widespread adoption, 2D templating remains inaccurate as magnification issues, radiographic distortion and the 2D projection of a three-dimensional (3D) structure will induce measurement errors [10]. Furthermore, 2D imaging may not adequately capture the complex 3D anatomy of the patient [11].

3D templating based on preoperative computer tomography (CT) imaging and 3D computer-assisted design models of the implants overcomes most drawbacks of 2D templating. However, executing the preoperative plan during surgery remains challenging as it relies on anatomic landmarks for both bone preparation and implant positioning. Computer-assisted navigation (CAN) systems decrease the surgeon's dependency on anatomical landmarks and facilitate the intraoperative execution of the preoperative plan [12, 13]. Nevertheless, both 3D templating and CAN have important shortcomings, thus limiting their use in routine practice. First, 3D templating requires a preoperative CT scan, which exposes patients to higher radiation doses than conventional radiographs. Second, CAN systems comprise of a computer unit, an external tracking camera and one or more screens, which consumes space in the operating theater. Moreover, these devices, as well as the aforenoted CT device, place a greater financial burden on the operating center, while also increasing the preoperative planning time due to their added workflow [14, 15]. Third, during navigation, surgeons and operating room staff divert their attention from the surgical field to the screen, potentially disrupting the surgical workflow and leading to distraction from the patient [16]. This could compromise the sterility, delay the surgical process, and increase the risk of errors. Furthermore, the use of an external screen requires the surgeon to mentally convert the 2D data on the screen into the 3D surgical field [17]. Finally, staff members, instruments, sterile drapes and/or poor tracker orientation can disrupt the line of sight between navigation markers and the camera, further interrupting the navigation procedure [18]. These drawbacks should be evaluated against increased accuracy, especially in complex cases.

AR can visualize a 3D preoperative plan superposed over the surgical field. Therefore, its use for surgical guidance has been on the rise in recent years [19]. However, most systems are either not accurate enough or require an external tracking camera [20–22]. We believe an AR head-mounted display and tracking device (AR-HMDTD) with inside-out tracking software can function as a stand-alone unit. Such a unit should allow tracking the patient's position and display an accurately registered overlay of anatomical structures and surgical plans on the operation filed. The combination of accuracy, low cost, decreased line of sight issues, and ergonomics has the potential to increase acceptance of navigation during THA procedures [23].

In this phantom trial, we investigated an AR application created on the HoloLens 2 (Microsoft Corp., Redmond, WA, USA), a low-cost AR headset compared to current CAN systems. Our framework is device-agnostic and designed to be transferable to other, more affordable and/or more user-friendly AR hardware as technology evolves. This should ensure potential scalability and improve accessibility in the future.

The goal of our study was to evaluate the accuracy of a registration procedure of a segmented 3D CT scan in a plastic femur replica model and to compare it between different users. The aim of this study was not to assess the outcome of a whole procedure, that is, implant positioning or surgical training (simulator), which is what most other articles do. The purpose of our study was to evaluate specifically the accuracy of AR registration step. By isolating that critical step, we avoided the problem of the accuracy of a whole pipeline being the sum of the accuracies of each step separately. We hypothesize that a wearable AR-based guidance system can provide sufficient registration accuracy for orthopedic surgical applications while improving workflow efficiency and reducing reliance on external tracking hardware.

2 | Materials and Methods

For this study, we developed a dedicated application deployable to AR-HMD using the Unity game development environment (version 2019.4.40f1). Taking advantage of the device's integrated infrared (IR) sensor, an inside-out tracking algorithm capable of estimating the six-degree-of-freedom pose of objects labeled with IR markers was developed [24, 25]. Prior VICON experiments validated the tracking accuracy below 2 mm and 2° in 95% of cases [26]. The application guided the surgeon through the different steps required to register CT scan data sets to their corresponding plastic femur replicas.

TABLE 1 | Morphological characteristics of plastic femur replicas.

Model	Article n°	Side	Length	NSA	Anteversion	Head Ø
Femur large recon	LS2335	Left	474 mm	130°	20°	48 mm
Femur large recon	LS2625	Right	490 mm	105°	15°	53 mm
Femur medium recon	LS2340	Left	450 mm	128°	11°	45 mm
Femur medium recon	LS2643	Right	450 mm	130°	15°	46 mm
Femur small recon	LS2330	Left	425 mm	130°	16°	44 mm
Femur small recon	LS2630	Right	425 mm	130°	16°	43 mm

Abbreviation: NSA = neck-shaft angle.

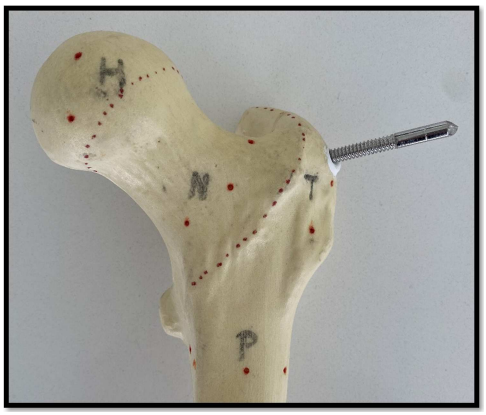

FIGURE 1 | Plastic femur replica with the four regions: H = head, N = neck, P = proximal T = trochanter. Each was marked with four holes of 1 mm diameter. The delineated area indicates the bony surface of the hip that would be visible during a surgical procedure, in this case, through an anterior approach. The pin in the greater trochanter was used to fix the reference IR reflective tracker.

FIGURE 2 | Superior view of a plastic femur replica mimicking the anterior approach of the hip. A Steinman pin was drilled in the greater trochanter region to fix the IR reference tracker.

2.1 | Experimental Setup

To simulate variability in femoral morphology, we used six plastic femur phantoms (Synbone, Zizers, Graubünden, Switzerland) that were distinct in side, length, head size, and anteversion (Table 1). All femurs were classified into four regions: head, neck, trochanter, and subtrochanteric (hereinafter called "proximal") region. In each region, we drilled four holes of 1 mm diameter and ~1 mm depth (Figure 1). These 16 holes were used as target points to assess the target registration error (TRE) [27]. To evaluate differences in accuracy when using the application in a simulated anterior or posterior surgical hip approach, the holes were drilled anteriorly in Femurs 1–3 and posteriorly on Femurs 4–6.

All femurs were CT-scanned (Siemens AG, Erlangen, Germany) with a slice thickness of 0.31 mm. The narrow slice thickness allowed the drill holes to be well appreciated on two to three CT scan images. We marked the location of the drill holes in 3D slicer (version 5.22, https://www.slicer.org/) and logged the corresponding coordinates as ground truth values to determine the TRE. Next, the CT data set was segmented in 3D slicer and 3D femur surface models were produced.

To evaluate the registration process, we fixed the femurs on a bench vise. Femurs 1–3 were fixed mimicking a direct anterior surgical hip approach and femurs 4–6 were fixed mimicking a posterolateral approach. All plastic replicas were equipped with an IR reflective tracker (Sure Track 2, Medtronic, Minneapolis, Minnesota, USA) fixed to a self-tapping Steinmann pin drilled into the accessible part of the greater trochanter (Figures 1 and 2). An experienced hip surgeon (T. S.) delineated the "working area," that is, the part of the femur that is visible during an anterior or posterolateral hip approach (Figure 1).

2.2 | Workflow of the Registration Process

A hardware calibration of the HoloLens device was performed once to calibrate the IR camera such that proper tracking of the IR-labelled markers could be performed based on our inside-out IR tracking algorithm [28]. A second calibration was performed at the beginning of each experiment to calibrate the AR-HMD's visuals to the specific wearer's eye geometry using the device's built-in eye calibration procedure.

Next, the users started the AR application that guided them through the registration process. The workflow was broken down into three stages: landmark-based core registration, surface-based registration refinement, and data collection. During the landmark registration, the surgeon used an IR-tracked stylus to indicate four points on the virtual AR model, then identified the corresponding locations on the working area of the phantom model. This registration allowed a first rough alignment between the virtual and the

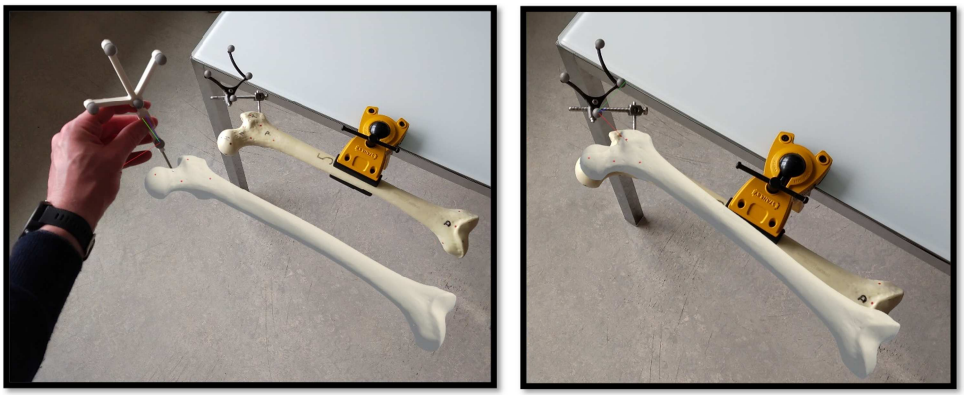

FIGURE 3 | Left: Picture taken by the HoloLens built-in camera showing the core registration. Four dots visualized on the AR model (red dots). These dots were pointed in the same order on the model and on the working surface of the femoral replica with an IR-tracked stylus. Right: Picture taken by the HoloLens built-in camera showing the result of the core registration. Although the registration improved, it was not yet accurate.

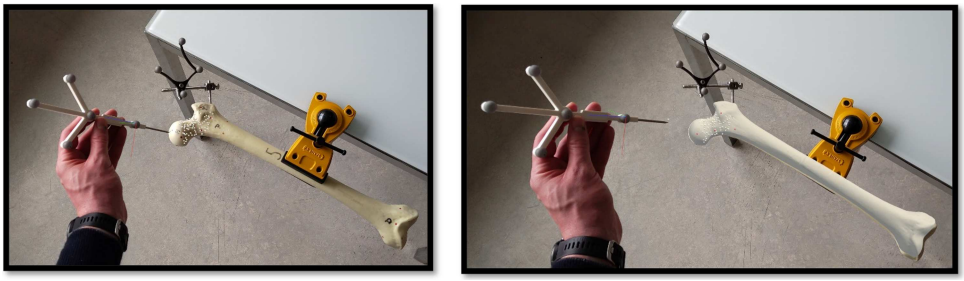

FIGURE 4 | Left: Picture taken by the HoloLens built-in camera showing the collection of a point cloud on the working area of the femur with the IR-tracked stylus. Right: Picture taken by the HoloLens built-in camera showing the result of the refined registration step. Note the improved overlay of the 3D model on the femur replica.

physical model (Figure 3). Next, the registration was refined by sampling additional points along the surface of the working area of the femur (Figure 4). These additional data refined the initial registration between the virtual model's surface and collected surface points using an iterative closest point algorithm [29, 30]. Then, the operator checked the registration quality visually. If it was judged inaccurate, saved points were removed by voice command and the registration process was preformed again until visually satisfying. In most cases, a visually satisfying registration was achieved during the first attempt.

2.3 | Points Collection and Processing

To evaluate the registration accuracy, the surgeon identified, with the IR-tracked stylus, the 16 target points on the femoral phantom and logged their positions through a voice command. The coordinates of all these points were in the space of the registered phantom surface model, and could be compared to the ground truth values obtained from the CT scan data set.

Four investigators (N. H., Q. N., T. F., and L. V. V.) performed the AR registration process twice on each of the six femurs, resulting in 48 data sets. The first three investigators had experience with AR. The last (L. V. V.) was a fellow in physical medicine and rehabilitation without prior experience with AR and was included to assess novice performance of the technique.

We evaluated the accuracy of AR registration through TRE [27], comparing the coordinates of the drill holes determined in 3D slicer with the coordinates of the points recorded with the stylus after registration. To address aberrant point data, due to either instrument tracking and/or user error, outlier detection was performed following data collection using moderately conservative rejection criteria of 2.5 times its median absolute deviation [27].

2.4 | Statistical Analysis

Results of the TRE were reported as means and standard deviations, medians and 95% confidence intervals (CI) and minimum–maximum and/or graphically. Differences between the four regions of the proximal femur, differences along the three anatomic axes (medio-lateral, antero-posterior, supero-inferior) and differences between researchers were investigated with a Kruskal–Wallis nonparametric test. Differences between the anterior and posterior approaches were explored with a nonparametric Mann–Whitney *U* rank test. Statistical analysis was performed in Python (3.12.4) using Pandas (2.2.3) and NumPy (1.26.0) libraries. $p < 0.05$ was considered statistically significant.

3 | Results

Registration Accuracy Per Region and Along Anatomical Axes.

TABLE 2 | Mean, standard deviation (std. dev.), median, minimal (min.), maximal (max.), and 95% confidence interval (CI) of the target registration error (TRE) measured in millimeters for all femurs and per region.

Region	Mean ± std. dev.	Median	Min.	Max.	95% CI
All	3.61 ± 2.18	2.96	0.25	10.05	3.41–3.80
Head	4.11 ± 2.34	3.71	0.33	8.53	3.70–4.52
Neck	3.36 ± 2.23	2.71	0.40	7.98	2.99–3.74
Trochanter	3.35 ± 2.15	2.84	0.25	9.83	2.98–3.72
Proximal	3.63 ± 2.38	2.96	0.31	10.00	3.22–4.04

3.1 | From the 592 Logged Landmarks, 58 Were Identified as Outliers

The overall registration accuracy of our method, reported as the TRE taking into account all useful data ($n = 534$), was 3.61 ± 2.18 mm (Table 2). The TRE was smaller in the trochanter and neck region and larger in the head and proximal region. Although differences between regions were statistically significant (Kruskal–Wallis $p = 0.019$), their means TRE varied 0.5 mm or less.

The distribution of the TRE along the three anatomical axes, medio-lateral, antero-posterior, and supero-inferior, was statistically significant different (Kruskal–Wallis test $p < 0.001$). Results along the AP axis significantly differing (Mann–Whitney U rank test, Bonferroni $\alpha = 0.017$) from the ML ($p < 0.001$) and SI ($p = 0.002$) axes. However, the differences between the means were below 1 mm. Both the magnitude and the variance of the TRE were greatest in the antero-posterior direction (Figure 5).

This finding along the AP axis was consistent throughout all regions (Figure 6), suggesting that there was a systemic error or bias in the methods or technique.

3.2 | Effect of the Approaches and the Researchers

Femurs 1, 2, and 3 were approached anteriorly and Femurs 4, 5, and 6 posteriorly. A Mann–Whitney U rank test did not show a significant difference in registration accuracy between approaches ($p = 0.367$). The mean intra-observer variability based on a repeated measurement by one researcher (N. H.) in six femora (152 reference points) was 2.55 ± 1.91 mm. The TRE was not statistically significant between the novice and experienced users (Mann–Whitney U rank test $p = 0.527$).

4 | Discussion

The goal of this experiment was to evaluate the registration accuracy of our head-mounted AR-based IR navigation tool, using six plastic femur replicas. Overall, the mean TRE was 3.61 ± 2.30 mm. The TRE varied between four regions of the proximal femur and along the anatomical axes. The region of the femoral head and just below the lesser trochanter performed worse than the neck and trochanter region, and the registration was less accurate along the antero-posterior axis. However, differences in TRE between regions and axes were below 1 mm.

We believe differences in region-dependent accuracy could be explained by the position of the anchor, which is placed on the greater trochanter. As such, it was further from the head and subtrochanteric region, which could result in accuracy loss. On the other hand, differences in accuracy along the anatomical axes could be explained by the stylus that was inserted into the predrilled hole in the AP direction. Even though this was done carefully, it still could have caused an AP translation of the femur resulting in a larger error along that axis. Also, the accuracy of the navigation system along the view axis of the HoloLens proved inferior compared to both perpendicular axes. This may have been caused by a minor difference in scale between the designed and 3D printed handheld stylus, affecting the pose estimation along that axis. Quality control mechanisms in future trials should take this into account when working with 3D printed plastic tools where dimensionality is critical.

The use a head-mounted device combined with AR rendering, as an intra-operative navigation tool has not been documented extensively, especially for hip surgery. In 2022, Sun and colleagues published a systematic review on the use of AR and VR in hip surgery [22]. Of the 40 papers included, only 1 described the use of an AR application as a navigation tool in combination with a head-mounted device as a stand-alone unit [31]. Since the accuracy described in this article was calculated only in degrees, a comparison with our study is not possible.

Several other papers describing the use of a head-mounted device and AR-based surgical navigation system have been published since 2022 [32–36]. Of these papers, three used an additional external tracking camera, and in four, the headset did work as a stand-alone unit. Only one paper describes the intrinsic accuracy of the AR application based on a stand-alone headset, as we did. The authors used an AR application to navigate the entry point of a guide wire during a dynamic hip screw insertion procedure. However, they positioned the AR overlay of the segmented proximal femur manually and their registration errors were a magnitude larger compared to ours (smallest mean error for the entry point was 12.00 ± 6.63 mm) [34].

On the other hand, Wu and colleagues presented an AR simulator for orthopedic surgical training, specifically targeting THA. While HMDs like the HoloLens 2 offer built-in tracking through inside-out SLAM algorithms, their inherent limitations regarding drift, lag, and insufficient precision restrict their suitability for tasks requiring millimetric or submillimetric accuracy. To overcome these limitations, the researchers integrated an external optical tracking system (SpryTrack 300)

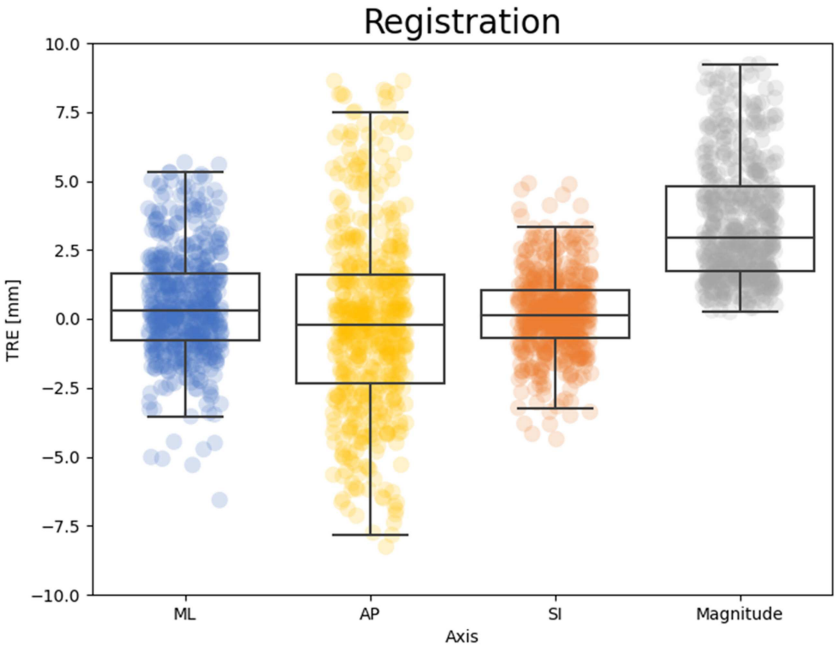

FIGURE 5 | Overall TRE and distribution of the TRE along the different axes (AP = antero-posterior, ML = medio-lateral, SI = supero-inferior).

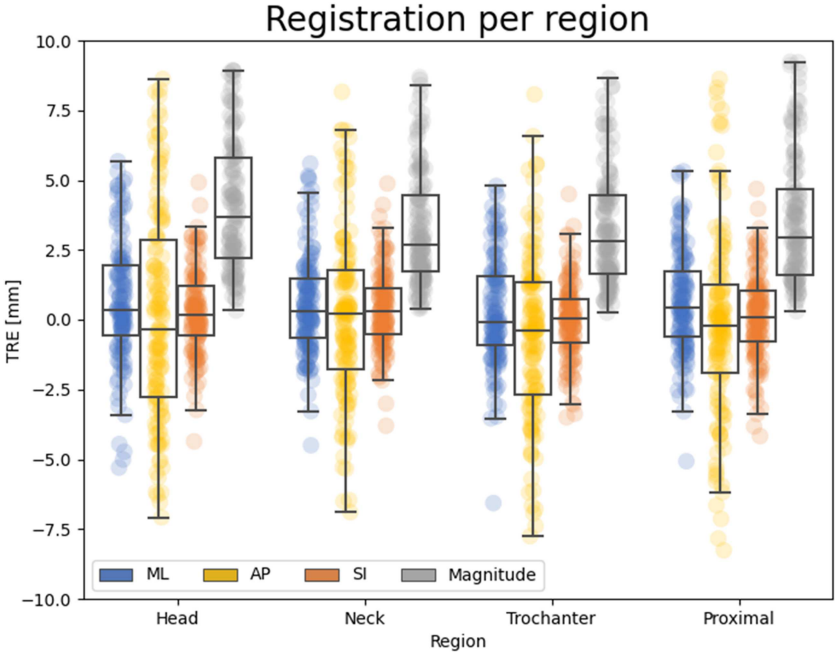

FIGURE 6 | Distribution of the TRE per axis and per region (AP = antero-posterior, ASI = supero-inferior, ML = medio-lateral).

providing outside-in tracking of both instruments and bone phantoms.

The system's calibration achieved a mean point-to-point alignment accuracy of 1.425 mm after matching virtual and real anatomical models. In the performance evaluation, the automated system (relying on hybrid tracking data) was compared against manual measurements based on post-operative CT scans. The Bland–Altman analysis showed small biases of 0.22 mm (distance), 0.94° (yaw), and −0.34° (pitch), with limits of agreement within ±2–3 mm and ±5° for rotational deviations. No statistically significant differences were found ($p > 0.05$), indicating equivalence between automated and manual evaluations. These results demonstrate that the hybrid AR system can achieve clinical-level accuracy, surpassing what is currently feasible with stand-alone HMD tracking alone [2].

Furthermore, we are obliged to also consider several commercial initiatives that have recently adopted AR for arthroplasty, most notably HipInsight and PolarisAR. While their overall AR concepts are broadly aligned with our approach, important technical and methodological differences remain.

HipInsight translates PC-based preoperative planning to the patient using a pelvis-mounted sextant with a fixed QR code, relying on accurate interventional pin placement for registration. Although reported clinical accuracy is high, relevant outliers persist, and the authors themselves suggest that an additional registration refinement step—such as the one proposed in our work—could further improve outcomes [37]. Moreover, HipInsight relies on RGB-camera–based QR tracking using Microsoft HoloLens, which introduces limitations in field-of-view, robustness, and operative practicality when compared with IR-based tracking approaches [38].

PolarisAR's Stellar Knee system employs inside-out IR tracking with anchor markers and a stylus and has demonstrated industry-standard tracking accuracy in benchtop testing. However, public technical documentation is limited, registration accuracy is not reported independently from overall surgical outcomes, and validation was performed by a single surgeon involved in product development. In addition, its application to total knee arthroplasty benefits from relatively straightforward tracker placement and favorable bone geometry, which differs substantially from the more challenging registration conditions encountered at the hip [39].

In contrast, our approach explicitly separates tracking and registration error, restricts point acquisition to anatomically and operatively accessible regions, and directly addresses the unique geometric challenges of hip arthroplasty, thereby providing a more transparent and clinically relevant performance assessment.

Although we used a rigorous method to assess the registration accuracy of a true standalone head-mounted AR-based IR navigation system, our study has some limitations. First, we evaluated our technology on plastic replicas of six different femora in a laboratory setting. For availability reasons, we could not evaluate registration accuracy in a cadaver setting, taking into account the soft tissues. However, we believe six different femurs considers anatomical variability. Moreover, as we took only into account the region accessible during an anterior or posterior approach, we believe our results could be extrapolated to a surgical situation. Second, we evaluated the registration accuracy of the whole procedure. This includes the sum of multiple sources of error including eye-calibration, IR tracking, inaccurate pointing with the stylus during core registration, detailed registration, and point collection as well as possible deformation or movements of the model compared the reference marker on the greater trochanter. Our study did not intend to grade each of these potential sources of error separately.

5 | Conclusion

We evaluated the registration error of an AR IR based navigation system that can project a segmented CT scan data set on a femur model through the Microsoft HoloLens 2. The registration error of the proximal femur data had a TRE of ~3 mm. The method was equally accurate for an anterior and a posterior hip approach and was operator independent. As such, we believe our AR navigation solution could be used as a navigation tool to visualize an accurately registered preoperative 3D templating on the operation field during hip arthroplasty. However, before clinical use, additional cadaver trials, better reproducing the surgical situation, should be conducted.

Finally, although numerous companies currently offer AR-based surgical solutions, the majority rely heavily on HoloLens hardware. This platform is expected to reach end-of-life support from Microsoft by the end of 2027, with no successor device announced to date. We therefore believe that demonstrating methodologies which are not intrinsically tied to a specific headset—such as the approach presented in this study—remains an important contribution to academic research. We hope that the insights provided may complement existing or emerging AR applications by offering transferable principles that support the development of more robust, accurate, and clinically effective surgical workflows across a broad range of AR HMDs.

Author Contributions

Nicolas Himpe: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, validation, visualization, writing – original draft, writing – review and editing. **Quentin Neuville:** conceptualization, data curation, investigation, writing – review and editing. **Taylor Frantz:** conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, validation, visualization, writing – original draft, writing – review and editing. **Jef Vandemeulebroucke:** supervision. **Lieven Moke:** supervision. **Georges Vles:** project administration, supervision, validation, writing – review and editing. **Stijn Ghijselings:** supervision. **Thierry Scheerlinck:** conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation, writing – original draft, writing – review and editing. All authors have read and approved the final version of the manuscript. Nicolas Himpe had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

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Disclosure

The lead author Nicolas Himpe affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Ethics Statement

Ethics approval was waived for this study because no patients' data were reported.

Consent

Patient consent was waived for this study because no patients were involved.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its Supporting Materials.

References

1. C. Gsaxner, J. Li, A. Pepe, et al., "The HoloLens in Medicine: A Systematic Review and Taxonomy," *Medical Image Analysis* 85 (2023): 102757, https://doi.org/10.1016/j.media.2023.102757.

2. L. Wu, M. Seibold, N. A. Cavalcanti, et al., "A Novel Augmented Reality-Based Simulator for Enhancing Orthopedic Surgical Training," *Computers in Biology and Medicine* 185 (2025): 109536, https://doi.org/10.1016/j.compbiomed.2024.109536.

3. L. A. Lim, S. W. Carmichael, and M. E. Cabanela, "Biomechanics of Total Hip Arthroplasty," *Anatomical Record* 257 (1999): 110–116.

4. M. De Fine, M. Romagnoli, A. Toscano, et al., "Is There a Role for Femoral Offset Restoration During Total Hip Arthroplasty? A Systematic Review," *Orthopaedics and Traumatology: Surgery and Research* 103 (2017): 349–355.

5. X. Flecher, M. Ollivier, and J. N. Argenson, "Lower Limb Length and Offset in Total Hip Arthroplasty," *Orthopaedics and Traumatology: Surgery and Research* 102 (2016): S9–S20.

6. S. Eggli, M. Pisan, and M. E. Müller, "The Value of Preoperative Planning for Total Hip Arthroplasty," *Journal of Bone and Joint Surgery* 80, no. 3 (1998): 382–390, https://doi.org/10.1302/0301-620x.80b3.7764.

7. A. Colombi, D. Schena, and C. C. Castelli, "Total Hip Arthroplasty Planning," *EFORT Open Reviews* 4 (2019): 626–632, https://doi.org/10.1302/2058-5241.4.180075.

8. A. G. Della Valle, D. E. Padgett, and E. A. Salvati, "Preoperative Planning for Primary Total Hip Arthroplasty," *Journal of the American Academy of Orthopaedic Surgeons* 13 (2005): 455–462, https://doi.org/10.5435/00124635-200511000-00005.

9. L. A. Holzer, G. Scholler, S. Wagner, et al., "The Accuracy of Digital Templating in Uncemented Total Hip Arthroplasty," *Archives of Orthopaedic and Trauma Surgery* 139 (2019): 263–268, https://doi.org/10.1007/s00402-018-3080-0.

10. G. Heinert, J. Hendricks, and M. D. Loeffler, "Digital Templating in Hip Replacement With and Without Radiological Markers," *Journal of Bone and Joint Surgery* 91 (2009): 459, https://doi.org/10.1302/0301-620X.91B4.

11. M. Brenneis, S. Braun, S. van Drongelen, et al., "Accuracy of Preoperative Templating in Total Hip Arthroplasty With Special Focus on Stem Morphology: A Randomized Comparison Between Common Digital and Three-Dimensional Planning Using Biplanar Radiographs," *Journal of Arthroplasty* 36 (2021): 1149–1155, https://doi.org/10.1016/j.arth.2020.10.016.

12. P. Savov, S. Budde, S. Tsamassiotis, et al., "Three-Dimensional Templating in Hip Arthroplasty: The Basis for Template-Directed Instrumentation?," *Archives of Orthopaedic and Trauma Surgery* 140 (2020): 827–833, https://doi.org/10.1007/s00402-020-03394-7.

13. M. Moralidou, A. Di Laura, J. Henckel, et al., "Three-Dimensional Pre-Operative Planning of Primary Hip Arthroplasty: A Systematic Literature Review," *EFORT Open Reviews* 5 (2020): 845–855, https://doi.org/10.1302/2058-5241.5.200046.

14. M. E. Ivan, D. G. Eichberg, L. Di, et al., "Augmented Reality Head-Mounted Display-Based Incision Planning in Cranial Neurosurgery: A Prospective Pilot Study," *Neurosurgical Focus* 51 (2021): 1–9, https://doi.org/10.3171/2021.5.FOCUS20735.

15. R. Krishnan, E. Hermann, R. Wolff, et al., "Automated Fiducial Marker Detection for Patient Registration in Image-Guided Neurosurgery," *Computer Aided Surgery* 8 (2003): 17–23, https://doi.org/10.3109/10929080309146098.

16. H. Wang, F. Wang, A. P. Y. Leong, et al., "Precision Insertion of Percutaneous Sacroiliac Screws Using a Novel Augmented Reality-Based Navigation System: A Pilot Study," *International Orthopaedics* 40 (2016): 1941–1947, https://doi.org/10.1007/s00264-015-3028-8.

17. X. Chen, L. Xu, Y. Wang, et al., "Development of a Surgical Navigation System Based on Augmented Reality Using an Optical See-Through Head-Mounted Display," *Journal of Biomedical Informatics* 55 (2015): 124–131, https://doi.org/10.1016/j.jbi.2015.04.003.

18. A. Sorriento, M. B. Porfido, S. Mazzoleni, et al., "Optical and Electromagnetic Tracking Systems for Biomedical Applications: A Critical Review on Potentialities and Limitations," *IEEE Reviews in Biomedical Engineering* 13 (2020): 212–232.

19. M. Birlo, P. J. E. Edwards, M. Clarkson, and D. Stoyanov, "Utility of Optical See-Through Head Mounted Displays in Augmented Reality-Assisted Surgery: A Systematic Review," *Medical Image Analysis* 77 (2022), https://doi.org/10.1016/j.media.2022.102361.

20. C. Dennler, D. E. Bauer, A. G. Scheibler, et al., "Augmented Reality in the Operating Room: A Clinical Feasibility Study," *BMC Musculoskeletal Disorders* 22 (2021), https://doi.org/10.1186/s12891-021-04339-w.

21. S. Condino, M. Carbone, R. Piazza, et al., "Perceptual Limits of Optical See-Through Visors for Augmented Reality Guidance of Manual Tasks," *IEEE Transactions on Biomedical Engineering* 67 (2021): 411–419, https://doi.org/10.1109/TBME.2019.2914517.

22. P. Sun, Y. Zhao, J. Men, et al., "Application of Virtual and Augmented Reality Technology in Hip Surgery: Systematic Review," *Journal of Medical Internet Research* 25 (2023): e37599, https://doi.org/10.2196/37599.

23. H. Ogawa, K. Kurosaka, A. Sato, et al., "Does an Augmented Reality-Based Portable Navigation System Improve the Accuracy of Acetabular Component Orientation During THA? A Randomized Controlled Trial," *Clinical Orthopaedics and Related Research* 478 (2020): 935–943, https://doi.org/10.1097/CORR.0000000000001083.

24. F. Van Gestel, T. Frantz, M. H. Soomro, et al., "Augmented Reality-Assisted Neurosurgical Drain Placement (ARANED): Technical Note," in *Acta Neurochirurgica Supplement* (Springer, 2021), 267–273.

25. F. Van Gestel, T. Frantz, F. Buyck, et al., "Neuro-Oncological Augmented Reality Planning for Intracranial Tumor Resection," *Frontiers in Neurology* 14 (2023): 1104571, https://doi.org/10.3389/fneur.2023.1104571.

26. F. Van Gestel, T. Frantz, C. Vannerom, et al., "The Effect of Augmented Reality on the Accuracy and Learning Curve of External Ventricular Drain Placement," *Neurosurgical Focus* 51 (2021): 1–9, https://doi.org/10.3171/2021.5.FOCUS21215.

27. J. M. Fitzpatrick and J. B. West, "The Distribution of Target Registration Error in Rigid-Body Point-Based Registration," *IEEE Transactions on Medical Imaging* 20, no. 9 (2001): 917–927, https://doi.org/10.1109/42.952729.

28. Z. Zhang, "A Flexible New Technique for Camera Calibration," *IEEE Transactions on Pattern Analysis and Machine Intelligence* 22 (2000): 1330–1334.

29. P. J. Besl and N. D. Mckay, "A Method for Registration of 3-D Shapes," in *IEEE Transactions on Pattern Analysis and Machine Intelligence* (1992), vol 14, 239–256, https://doi.org/10.1109/34.121791.

30. K.-L. Low, "Linear Least-Squares Optimization for Point-to-Plane ICP Surface Registration," Technical Report TR04-004, Department of Computer Science, University of North Carolina at Chapel Hill, February 2004.

31. K. Logishetty, L. Western, R. Morgan, et al., "Can an Augmented Reality Headset Improve Accuracy of Acetabular Cup Orientation in Simulated THA? A Randomized Trial," *Clinical Orthopaedics and*

Related Research 477 (2019): 1190–1199, https://doi.org/10.1097/CORR.0000000000000542.

32. P.-F. Lei, S.-L. Su, L.-Y. Kong, C. Wang, D. Zhong, and Y. Hu, "Mixed Reality Combined With Three-Dimensional Printing Technology in Total Hip Arthroplasty: An Updated Review With a Preliminary Case Presentation," *Orthopaedic Surgery* 11 (2019): 914–920, https://doi.org/10.1111/os.12537.

33. T. Song, M. Sommersperger, T. A. Baran, et al., "HAPPY: Hip Arthroscopy Portal Placement Using Augmented Reality," *Journal of Imaging* 8 (2022), https://doi.org/10.3390/jimaging8110302.

34. C. Laverdière, J. Corban, S. Ge, et al., "Augmented-Reality-Guided Insertion of Sliding Hip Screw Guidewire: A Preclinical Investigation," *Canadian Journal of Surgery* 65 (2022): E364–E371, https://doi.org/10.1503/cjs.025620.

35. P. Kiarostami, C. Dennler, S. Roner, et al., "Augmented Reality-Guided Periacetabular Osteotomy—Proof of Concept," *Journal of Orthopaedic Surgery and Research* 15 (2020), https://doi.org/10.1186/s13018-020-02066-x.

36. A. Teatini, R. P. Kumar, O. J. Elle, and O. Wiig, "Mixed Reality as a Novel Tool for Diagnostic and Surgical Navigation in Orthopaedics," *International Journal of Computer Assisted Radiology and Surgery* 16 (2021): 407–414, https://doi.org/10.1007/s11548-020-02302-z.

37. A. F. Heimann, W. S. Murphy, D. C. Sun, and S. B. Murphy, "Accuracy of Acetabular Component Positioning Using a Mixed Reality-Guided Navigation System During Total Hip Arthroplasty," *JBJS Open Access* 10 (2025), https://doi.org/10.2106/JBJS.OA.24.00144.

38. P. Hübner, K. Clintworth, Q. Liu, et al., "Evaluation of HoloLens Tracking and Depth Sensing for Indoor Mapping Applications," *Sensors* 20 (2020), https://doi.org/10.3390/s20041021.

39. H. J. Cooper, A. Young, J. B. Brenza, et al., "Accuracy of a Novel Mixed Reality Surgical Platform for Total Knee Arthroplasty," *Arthroplasty* 7 (2025), https://doi.org/10.1186/s42836-025-00340-z.