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A new navigation system for radius osteotomy surgery based on holographic computing: An in vitro study

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ABSTRACT

The use of surgical navigation using holograms provided by mixed reality glasses is already a reality in other fields of orthopaedics as the shoulder or knee. Due to this, this study aimed to develop and evaluate a mixed reality–based system for navigation in derotational radius osteotomies, focusing on its accuracy and reproducibility. To this end, a holographic computing software based on C++ language and code integrable in MRTK 2 (Microsoft, Redmond, USA) was generated to be implemented in Microsoft Hololens 2. Using the 3D Builder software, positioners and trackers, recognisable by mixed reality glasses, were designed and patented, allowing us to know the changes in spatial relationship between two trackers.

A total of 41 radius biomodels were used. A hand surgery consultant and an orthopaedics resident each performed ten rotational osteotomies using freehand technique and ten with the navigation system. Afterwards, a CT scan was performed, measuring the variation achieved. The error was defined as the difference between the planned and obtained orientation in both techniques and analyzed statistically.

Under these conditions, the median error of the navigated system was 1º [0–2.25°], compared to 11º [7-19.5°] with the freehand technique ($p<0.05$). Error did not significantly increase with greater osteotomy magnitudes. The navigated system demonstrated higher accuracy and reproducibility. No significant inter-surgeon differences were observed in either technique.

In conclusion, surgical navigation based on holographic computerization improves the accuracy of radius rotational osteotomies. Due to its reproducibility and simplicity, it represents a potential technique for future surgical navigation.

Keywords: Osteotomy, computer-assited surgery, mixed reality, bone rotation, surgical navigation, and holographic computing.

INTRODUCTION

Radial deformities are relatively common, primarily resulting from malunions secondary to traumatic fractures or, in some cases, developmental abnormalities such as Madelung's deformity. The clinical relevance of these deformities lies in their potential to cause pain, limitation of wrist range of motion—particularly at the radiocarpal joint and in forearm pronation-supination and may also lead to distal radioulnar joint (DRUJ) instability, among other complications[1-3].

Corrective osteotomy is the standard surgical intervention for addressing these pathological angulations. However, thorough preoperative evaluation is essential in order to appropriately plan the intended correction[4].

In recent years, specialized software has emerged to facilitate the analysis of radial deformities and to aid in preoperative planning. Additionally, patient-specific cutting guides and custom fixation plates have become available[5]. Nevertheless, while such software enables precise preoperative planning, it lacks intraoperative systems capable of translating this planning into real-time surgical execution. On the other hand, patient-

specific guides and plates are often costly, inflexible, and require several days or weeks from production to surgical availability[6].

An emerging alternative is mixed reality–based surgical navigation, a technology that has transitioned from concept to clinical application, particularly in orthopedic procedures involving the shoulder and knee. Complementary three-dimensional visualization platforms have likewise been applied for preoperative simulation in orthopaedic tumor surgery, highlighting a broader trend toward immersive digital support in complex orthopaedic interventions[7,8].

Recent advances in computational power and three-dimensional visualization have enabled the development of lightweight, compact, and accessible navigation systems based on mixed reality. This technology, which overlays virtual elements onto the real world using holographic projections, offers surgeons an effective tool for precise implant positioning and real-time monitoring of intraoperative corrections. Its application in shoulder, hip, and knee arthroplasty has yielded promising results in terms of accuracy and efficiency, broadening the scope of intraoperative surgical assistance. Moreover, its cost-effective and scalable design renders it potentially applicable in a wide range of healthcare settings, including those with limited resources[7,9].

Despite these advances, questions remain regarding the applicability and effectiveness of this technology for corrective osteotomies of the radius. Is it truly a viable alternative? Does it provide accurate and reproducible results?

The aim of this study is to assess the accuracy of rotational corrective osteotomies of the radius using a novel surgical navigation system based on holographic computation, with particular attention to its reliability and reproducibility as a surgical technique. We hypothesized that the MR-based navigation system would provide greater accuracy and reproducibility than the conventional freehand technique.

MATERIALS AND METHODS

Design and development of a holographic computation-based surgical navigation system

For this study, we utilized the Microsoft HoloLens 2 mixed reality headset, an optical see-through head-mounted display (OST-HMD). A holographic computation software application was developed using C++ and integrated with the Mixed Reality Toolkit 2 (MRTK 2) provided by Microsoft (Redmond, WA, USA). MRTK serves as the software development kit for creating applications compatible with HoloLens devices (https://docs.microsoft.com/windows/mixed-reality/mrtk-unity/). This toolkit can be integrated into Unity (https://unity.com) or Unreal Engine (https://www.unrealengine.com), both of which support functionalities such as device tracking, hand input, and eye tracking. Although the original retail price of the HoloLens 2 was approximately USD 3,500 in 2019, its current average market cost ranges between USD 1,000 and 1,500, a price range comparable to other commercially available mixed-reality headsets such as Google Glass (Google Inc., Mountain View, CA, USA) and Meta Quest (Meta Inc., Menlo Park, CA, USA)[10].

This setup enables surgeons to simultaneously visualize the physical environment and superimposed holographic elements. Interaction with these holograms is facilitated through hand gestures or voice commands. The application is operable in both indoor and outdoor settings, unaffected by ambient light variations, and can be customized to meet specific surgical requirements.

Recognition system: positioners and trackers

Using the 3D Builder software (Microsoft Corporation®, Redmond, WA, USA), available for free from the Microsoft Store, we designed two mirror-image positioners. These positioners accommodate two distinct trackers recognized by the HoloLens 2 image recognition system, allowing for spatial tracking of positional changes between the trackers. The design process involved creating components of predetermined sizes and shapes, which were subsequently merged to form the final design (Figure 1A).

Each positioner has a quadrangular shape and includes provisions for inserting up to three Kirschner wires to secure it to the target bone segment; however, adequate stability can be achieved with only two wires. Two mirrored versions—left and right—were designed to facilitate placement on either side of the intended osteotomy site. Although no formal mechanical testing protocol was implemented, the stability of the Kirschner-wire fixation was systematically assessed through repeated controlled rotational and translational maneuvers, combined with visual inspection and manual palpation to detect any potential loosening or positional drift. In addition, reference landmarks on the model and wires were checked before and after testing to identify any relative displacement. No measurable or perceptible

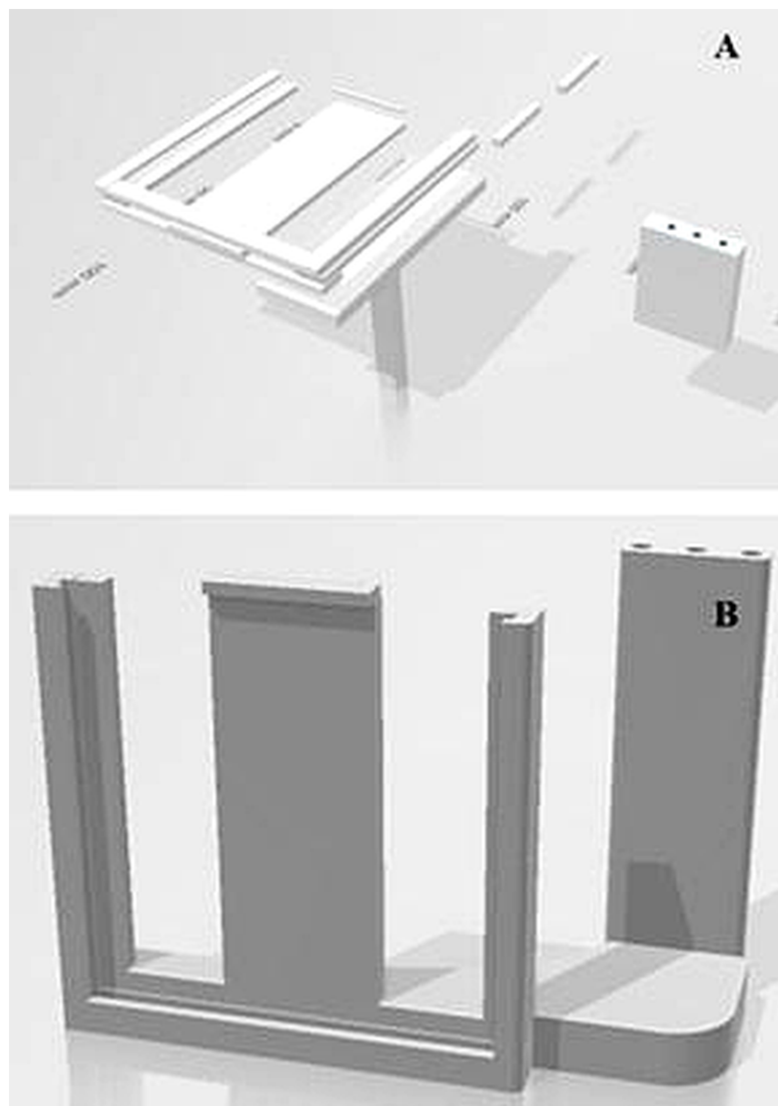

Fig. 1 — 3D Builder interface. A: Component creation. B: Final design of the left positioner.

displacement was observed under these conditions, supporting the adequacy of fixation stability for the purposes of the experimental setup.

Trackers, represented by two distinct QR codes, are affixed to these positioners. The mixed reality headset recognizes these markers, establishing the osteotomy site and subsequently indicating the angular deviation between the two trackers across the three spatial planes (x, y, z). Prior to conducting the osteotomies, the accuracy of QR-code recognition was assessed through repeated static and dynamic tests. Static tests consisted of positioning the radial model and the trackers at fixed distances (30–60 cm) and orientations (0–45° of tilt) and confirming consistent marker acquisition over 60-second intervals. Dynamic tests involved manually rotating and translating the bone segment while monitoring for tracking continuity, evaluating potential positional drift, loss of recognition, or angular jitter. Across all tests, the mixed-reality headset consistently detected both QR-codes without noticeable drift or tracking interruptions within the working distances and angles used in the experiment.

Biomodel fabrication

A standard-sized, non-deformed radial bone model was designed using 3D Builder (3D Builder, Microsoft Corporation®, version 18.0.1931.0). The reference geometry corresponded to a true-to-size adult radius with a total length of 24.5 cm, a value consistent with osteometric measurements reported in European adult populations, including those described by Charisi et al. in a modern Greek sample[11]. A total of 41 identical biomodels were produced.

The models were fabricated using polylactic acid (PLA) through additive manufacturing with an Ender 3 Pro printer (Creality, Shenzhen, China), using a 0.4-mm nozzle and a layer height of 0.12–0.28 mm. According to manufacturer specifications and independent evaluations of this printer class, the dimensional accuracy typically falls within ±0.1–0.2 mm. PLA was selected due to its widespread availability, ease of printing, and adequate dimensional stability under standard printing conditions; however, as with any thermoplastic, slight thermal deformation may occur, potentially introducing minor geometric variations.

Study design

Two surgeons—a trainee and a specialist in hand, wrist, and peripheral nerve surgery—performed osteotomies on these biomodels. Ten target rotational osteotomies were defined through consensus among the researchers. Each surgeon performed ten osteotomies using the ARIS (VLN ST) navigation system and ten freehand osteotomies (Figure 2). In the freehand technique, a Kirschner wire was placed on either side of the intended osteotomy site, followed by application of the predefined rotational correction without any guiding assistance.

Upon achieving the desired rotation—either through navigation or manual technique—the two bone fragments were rejoined by thermally fusing the PLA material.

Subsequently, computed tomography (CT) scans were conducted on the 40 osteotomized biomodels and the one non-osteotomized model (Figure 3). Rotational correction achieved in each model was measured on CT images and used for subsequent analysis.

The achieved rotational angle was determined by calculating the difference between the bicipital tuberosity axis and the transtyloid axis of each osteotomized radius (Figure 4), compared to the same measurement in the prototype (non-osteotomized) model.

Measurement reliability

To assess the reliability of CT-based rotational measurements, intra- and inter-observer agreement were evaluated using intraclass correlation coefficients (ICC) based on repeated measurements. Two musculoskeletal radiologists independently performed all measurements on two separate occasions, with a minimum interval of two weeks between sessions, and were blinded to the planned correction values and the surgical technique used.

ICCs were calculated using a two-way random-effects model with absolute agreement (ICC [2,1]). Intra-observer reliability was excellent, with an ICC of 0.94 (95% confidence interval [CI], 0.90–0.97). Inter-observer reliability was similarly high, with an ICC of 0.91 (95% CI, 0.86–0.95). These results indicate excellent reproducibility of the CT-based measurement protocol.

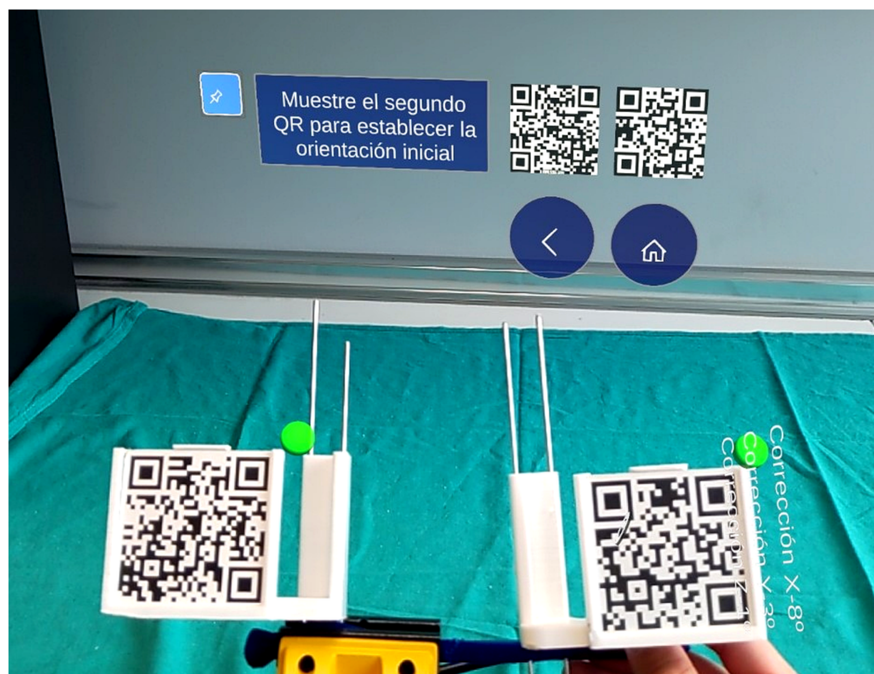

Fig. 2 — Osteotomy using the navigated system.

Fig. 3 — CT scan of the biomodels after the osteotomy.

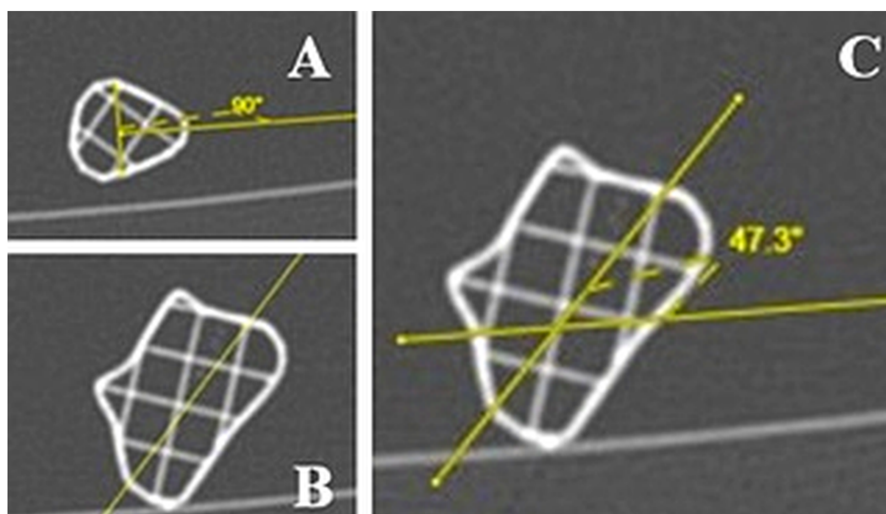

Fig. 4 — Measurement of achieved angulation. A: Bicipital tuberosity axis. B: Transtyloid axis. C: Angular difference.

CT acquisition and axis definition

Computed tomography scans were acquired using a standardized clinical protocol with isotropic voxel reconstruction. Images were obtained with a slice thickness of 0.6 mm and reconstructed in the axial, coronal, and sagittal planes using a bone kernel.

Rotational alignment was quantified by measuring the angular difference between the bicipital tuberosity axis proximally and the transtyloid axis distally. The bicipital tuberosity axis was defined as the line connecting the center of the bicipital tuberosity to the geometric center of the proximal radial shaft. The transtyloid axis was defined as the line connecting the radial and ulnar styloid reference points on distal axial images. All measurements were performed

on multiplanar reconstructions using the same workstation and software settings.

Statistical analysis

Data distribution was assessed using the Shapiro–Wilk test. As the angular error data did not follow a normal distribution, non-parametric statistical methods were applied throughout the analysis. Continuous variables are therefore reported as median and interquartile range (IQR).

Comparisons between the mixed-reality navigation system and the freehand technique were performed using the Mann-Whitney U test. Differences in angular error between surgeons were analyzed separately for each technique using the same non-parametric approach.

Variability between groups was primarily assessed using Bartlett's test for homogeneity of variances. Given the non-normal distribution of the data, a robust Levene-type variance analysis was additionally performed, yielding concordant results and supporting the observed difference in variability between techniques.

The relationship between planned rotational correction magnitude and achieved angular error was explored using Spearman's rank correlation coefficient. The reported coefficient of determination ($R^2 = 0.16$) was derived from this non-parametric model and should be interpreted as an exploratory measure of association rather than a predictive parameter.

All statistical analyses were conducted using R software (version 3.5.2). A two-sided p value < 0.05 was considered statistically significant.

Human ethics and consent to participate declarations

This study was conducted as an in vitro experimental investigation using synthetic radial biomodels. No human participants were involved, and no patient-specific clinical data or imaging studies were collected or analyzed; therefore, informed consent was not required.

The biomodels were designed as generic, standard-sized radial geometries based on published osteometric data, without using patient-derived imaging datasets. Institutional ethical approval covered the experimental evaluation of the navigation system in a non-clinical setting (approval code: 2025-0206-1), in accordance with institutional research governance policies.

RESULTS

The angular measurements obtained from each osteotomy performed on the biomodels, using both the mixed reality–based navigation system and the freehand technique by the two surgeons, are presented in Table I.

The data followed a non-parametric distribution (Shapiro–Wilk test, $p = 0.00002$).

The Mann-Whitney U test was used to compare differences in outcomes between the mixed reality navigation system and the freehand technique, regardless of surgeon experience (Figure 5). The median angular error with the navigation system was 1° [0–2.25°]. In contrast, the freehand technique yielded a median error of 11° [7-19.5°]. This difference was statistically significant ($p < 0.0001$).

Variability in the freehand group was significantly greater than in the navigated group, suggesting that osteotomies performed with the mixed reality system were more reliable in terms of reproducibility. This was supported by Bartlett's test for homogeneity of variances ($p = 0.003$), and confirmed by a robust

Table I. — Target angle and measured angular correction (in degrees) for each osteotomy performed using mixed reality navigation and the freehand technique by both surgeons.

Number of Osteotomy	Resident			Senior surgeon		
	Target	Mixed reality	Freehand	Target	Mixed reality	Freehand
1	10	11	20	13	24	21
2	16	14	43	25	26	44
3	27	30	42.2	31	50	67
4	20	20	17	18	20	43
5	4	5	12	29	27	55
6	17	14	3	0	0	4
7	5	5	14	17	20	21
8	9	9	21	12	12	8
9	9	10	18	8	8	22
10	15	17	19	14	15	35

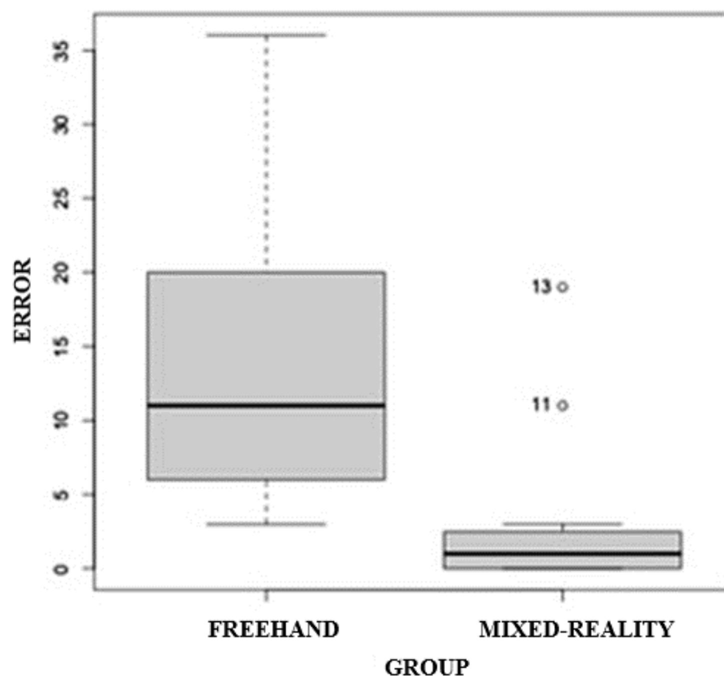

Fig. 5 — Comparison of median angular error between the freehand technique and mixed reality navigation.

Levene-type variance analysis, which yielded concordant results.

No statistically significant association was observed between planned osteotomy magnitude and angular error. Although a positive trend was noted—indicating that larger planned corrections tended to produce greater deviations—the correlation was weak (Spearman $\rho = 0.34$; $R^2 = 0.11$; $p = 0.03$).

When comparing the median error between the two surgeons, no statistically significant difference was found using the freehand technique (Figure 6A). The senior surgeon, a specialist in hand, wrist, and peripheral nerve surgery, had a median error of 16.5° [5-24°], while the resident had a median error of 9.5° [8.25–14.25°]. Similarly, there were no significant differences between the two surgeons when using the navigation system (Figure 6B). The senior surgeon had a median error of 1.5° [0.25–2.25°], while the resident showed a median error of 1° [0.25–2°].

DISCUSSION

In recent years, computer-assisted planning and 3D-printed patient-specific cutting guides have improved the precision of osteotomies of the radius and ulna. However, their clinical adoption remains limited due to high production costs, long manufacturing times, and the lack of real-time intraoperative feedback[1,2,5,12,13]. Mixed-reality–based navigation has recently emerged as an alternative capable of providing intraoperative spatial guidance with greater flexibility and reduced cost compared with patient-specific instrumentation. Although its use has been best documented in shoulder, hip, and knee procedures, evidence regarding its application in corrective osteotomies of long bones is still scarce[7,14-18].

In this study, a surgical navigation system based on holographic computation was developed and implemented through the Microsoft HoloLens 2 mixed reality device. On synthetic radius models, the results demonstrated that this system reduced the angular error in radial osteotomy by approximately 90% compared with the conventional freehand technique. Moreover, no statistically significant differences in accuracy were observed between participating surgeons, suggesting a high degree of reproducibility, independent of operator experience.

It is noteworthy that the senior surgeon exhibited a median error of 16.5° [5-24°], whereas the resident demonstrated a median error of 9.5° [8.25–14.25°]. These differences suggest that the mixed-reality system may help mitigate variability related to surgical experience, although this hypothesis requires confirmation in clinical settings. Although both surgeons completed a standardized familiarization session with the mixed-reality system prior to the experimental phase, the order in which navigated and freehand osteotomies were performed was not randomized or counterbalanced. As a result, a potential

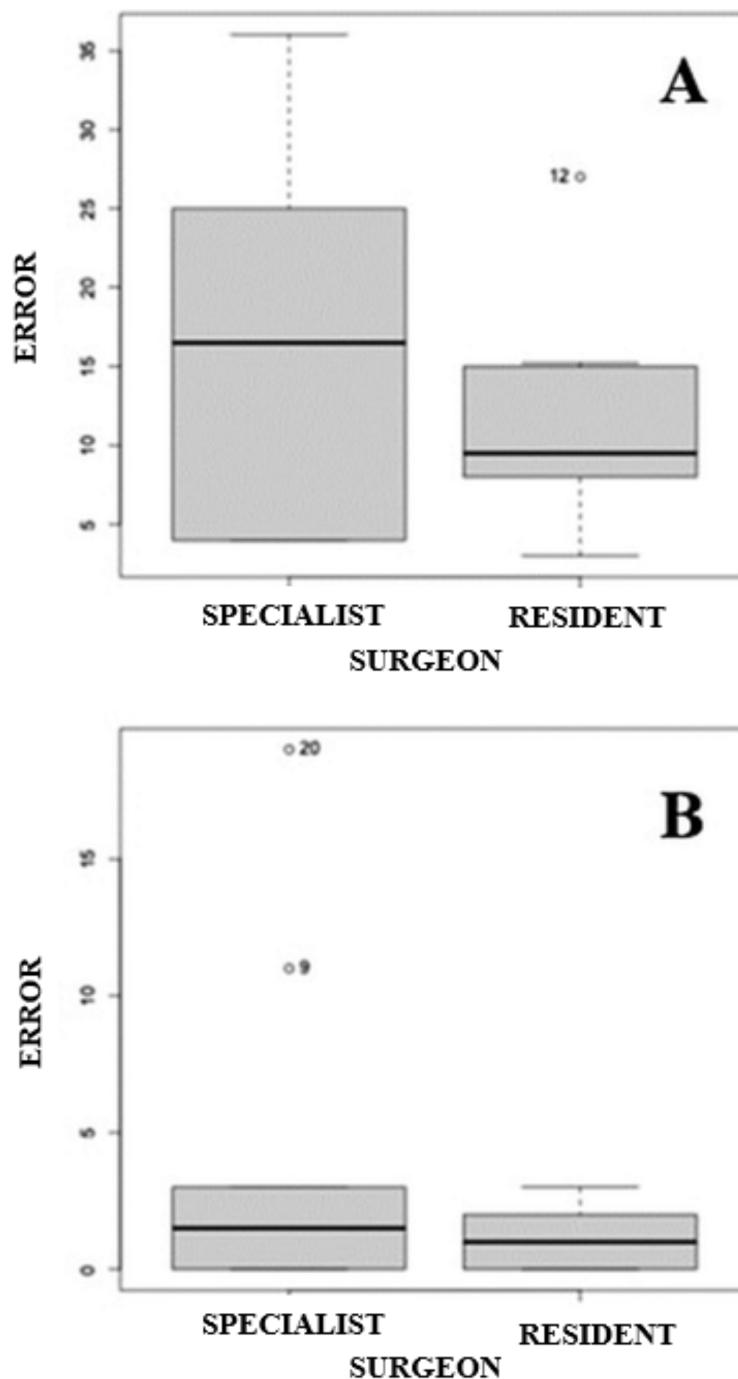

Fig. 6 — Comparison of median angular error between surgeons. A: Freehand technique. B: Mixed reality navigation system.

learning or carry-over effect cannot be completely excluded. This factor may have influenced performance, particularly in the freehand group, and should be considered when interpreting the comparative results. Future studies incorporating randomization or crossover designs will be required to formally address this issue.

Our results are in line with previous reports from other orthopedic applications of mixed-reality navigation, which have demonstrated improved accuracy compared with conventional methods. Studies in shoulder and hip arthroplasty, for example, have reported reductions in angular error ranging from 30% to 70% relative to freehand techniques[6,7,9,10,14,15]. The magnitude of improvement observed in the present investigation falls within the upper range of previously reported values, although direct extrapolation is limited by differences in anatomical regions, surgical tasks, and validation models.

Compared with patient-specific guides, the navigation system evaluated here offers key advantages in terms of reusability and the absence of manufacturing lead times. In addition, currently available mixed-reality headsets are typically procured within the low four-figure USD range, whereas patient-specific cutting guides may add several thousand USD to each procedure depending on local manufacturing and procurement pathways. These approximate ranges suggest a potentially more favorable economic profile for mixed-reality navigation, particularly in settings where rapid case turnaround or resource constraints are relevant considerations[19,20]. Nevertheless, full clinical validation remains necessary before widespread implementation.

Among the limitations of our study, the small number of participating surgeons and the limited number of biomodels used should be acknowledged. Furthermore, although the technical results are promising, it remains unclear whether these improvements will translate into clinically meaningful benefits. To date, no clinical evidence is available to support this hypothesis, and long-term follow-up studies will likely be required to determine the true impact of this technology on patient outcomes. In addition, the study evaluated only rotational deformities, without including angular or translational malalignments, which limits the generalizability of the findings to more complex clinical scenarios. Although the Kirschner-wire fixation provided sufficient stability for the experimental setup, no formal quantitative assessment of fixation strength, loosening, or positional drift during rotational manipulation was performed, representing an additional limitation.

Several limitations inherent to the experimental model should be acknowledged. First, the use of 3D-printed PLA biomodels does not fully replicate the mechanical properties of human cortical bone. Although PLA provides sufficient dimensional stability for laboratory testing, its thermoplastic nature and the thermal fusion process used to rejoin osteotomized segments may introduce minor alignment artifacts.

Second, fixation of the tracking positioners using Kirschner wires, while adequate for the purposes of this experimental setup, does not reproduce the stability conditions of clinical fixation. Although no perceptible loosening or positional drift was observed during testing, no formal quantitative mechanical assessment of fixation strength or tracker stability was performed.

Finally, the accuracy of the mixed-reality navigation system is dependent on optical tracking of QR-code markers and line-of-sight conditions. While tracking performance was stable within the working distances and angles used in this study, potential loss of tracking or environmental interference could affect accuracy in more complex or dynamic surgical settings.

Accordingly, the present results should be interpreted as a technical in vitro validation of the navigation system. Further cadaveric and clinical studies are required to determine its performance under realistic surgical conditions and to assess its potential impact on clinical outcomes.

CONCLUSION

In this in vitro experimental study, holographic computer-assisted navigation demonstrated a significantly lower rotational error in corrective radius osteotomies compared with the conventional freehand technique, independently of the surgeon's level of experience.

The system showed high reproducibility and technical feasibility under controlled laboratory conditions, suggesting its potential utility as an intraoperative guidance tool. However, these findings represent a technical validation only. Further cadaveric and clinical studies are required to confirm the accuracy, robustness, and clinical relevance of this mixed-reality navigation approach before it can be recommended for routine clinical use.

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