Augmented Reality Registration System for Visualization of Skull Landmarks

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■ BACKGROUND: **Augmented reality (AR) is an emerging technology in neurosurgery with the potential to become a strategic tool in the delivery of care and education for trainees. Advances in technology have demonstrated promising use for improving visualization and spatial awareness of critical neuroanatomic structures. In this report, we employ a novel AR registration system for the visualization and targeting of skull landmarks.**

■ METHODS: **A markerless AR system was used to register 3-dimensional reconstructions of suture lines onto the head via a head-mounted display. Participants were required to identify craniometric points with and without AR assistance. Targeting error was measured as the Euclidian distance between the user-defined location and the true craniometric point on the subjects' heads.**

■ RESULTS: **All participants successfully registered 3-dimensional reconstructions onto the subjects' heads. Targeting accuracy was significantly improved with AR (3.59 ± 1.29 mm). Across all target points, AR increased accuracy by an average of 19.96 ± 3.80 mm. Posttest surveys revealed that participants felt the technology increased their confidence in identifying landmarks (4.6/5) and that the technology will be useful for clinical care (4.2/5).**

■ CONCLUSIONS: **While several areas of improvement and innovation can further enhance the use of AR in neurosurgery, this report demonstrates the feasibility of a markerless headset-based AR system for visualizing craniometric points on the skull. As the technology continues to advance, AR is expected to play an increasingly significant role in neurosurgery, transforming how surgeries are performed and improving patient care.**

INTRODUCTION

In neurosurgery, technologic advancements continue to revolutionize how we diagnose and treat various conditions. One such technology that has gained significant attention is augmented reality (AR).[1-4] AR merges digital information with the real world, enhancing our perception and interaction with the physical environment. While AR has been utilized in many fields and industries, it is increasingly being explored for its potential in neurologic imaging and neurosurgical interventions.[5-7]

Precision and accuracy constitute fundamental elements for achieving successful outcomes in neurosurgery. One factor that can significantly influence neurosurgical procedures pertains to the correct identification of cranial landmarks, particularly suture lines. This landmark serves as a reference point for surgical planning, navigation, and precise targeting of distinct cerebral regions. Recognizing suture lines empowers neurosurgeons to strategically plan their incisions and craniotomies, thus minimizing postoperative complications and optimizing patient outcomes. By leveraging suture lines as reliable anatomic guides, neurosurgeons can navigate the 3-dimensional (3D) terrain of the skull with precision and accuracy.[8,9]

Traditionally, the identification of cranial suture lines on patients has been done through methods such as 2-dimensional neuronavigation, manual palpation of the head, or during the surgical procedure following skin exposure. However, these approaches are subjective and susceptible to human error. Prior research has showcased the value of AR in presenting digital representations of anatomic structures including ventricles, tumors, and vasculature to enhance targeting accuracy and facilitate safe approaches to

Key words
- Augmented reality
- Craniometric
- Mixed reality
- Suture line

Abbreviations and Acronyms
3D: 3-Dimensional
AR: Augmented reality
HMD: Head-mounted display

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different lesions.[10-15] With the emergence of AR technology, there exists an opportunity to capitalize on the identification and assessment of cranial sutures, as well as deeper anatomic structures under the skull. By employing AR, surgeons can visualize and precisely locate cranial sutures even before making incisions, thereby facilitating improved surgical planning and execution. The utilization of this technology holds promise for streamlining procedures, reducing surgical complications, and enhancing patient outcomes. The present study employs innovative AR technology to overlay anatomic reconstructions onto the head for the identification of cranial suture lines and craniometric points. We assess the accuracy and usability of the system among participants at various levels of neurosurgical expertise. This study aims to describe and validate this novel technology, with the hope of promoting its widespread adoption and integration into clinical practice.

MATERIALS AND METHODS

Specimen Preparation and Imaging

A formalin-fixed cadaveric head was used to validate the accuracy and robustness of the AR registration system. For the study, the cadaver scalp was removed and replaced with silicon foam latex (Monster Makers Inc, Cleveland, Ohio, USA). The silicon was specifically molded to fit around the cadaver's skull to effectively have a "removable" scalp to measure targeting accuracy and allow similar touch perception as would be provided through the scalp (Figure 1). After replacing the scalp tissue, computed tomography (CT) images of the cadaver head were obtained at a slice thickness of 0.625 mm with a 512 × 512 resolution.

Segmenting Target Structures

The cadaver's skull was segmented and reconstructed into 3D objects via autosegmentation algorithms (Hoth Intelligence Inc, Philadelphia, Pennsylvania, USA) trained on various CT datasets. To improve the visualization of the suture lines, the suture lines were manually segmented/annotated using ITKsnap (Figure 2). For the study, the coronal and sagittal suture lines were segmented. All segmented structures—skull, and suture lines—were merged and converted into a 3D digital model. The digital models underwent basic processing to reduce the file size to optimize performance, visual quality, and usability for an AR head-mounted display (HMD).

Technology Platform

The AR application was developed by Hoth Intelligence (Philadelphia, Pennsylvania, USA) to operate on the Microsoft Hololens 2 HMD (Redmond, Washington, USA). The Microsoft Hololens 2 is an untethered optical see-through HMD that superimposes virtual content (i.e., holograms, images, screens) onto the users' real-world field of view (Figure 3).[16-18]

The application used in this study superimposes 3D digital models onto the head using a proprietary ultrafast, markerless registration process. This allows a user to accurately register preoperative patient imaging for navigation quickly, in any clinical setting.

1. The registration system operates entirely from the 1.2 lb HMD. No other camera system or computer system is required.
2. To register anatomy with the subject, the only requirement is that the user looks at the subjects' head while wearing the HMD. The system registers 3D models in <10 seconds and does not require fiducial markers or tracing of the face.
3. The system uses the color (red-blue-green) camera, infrared sensors, and stereosensors of the Microsoft Hololens to extract facial features, head shape, distance from camera, and body pose to precisely estimate the position and orientation of the subjects' heads.
4. Alignment and orientation algorithms process information from the various sensor streams, which are then merged with coordinate data from the CT scan to align corresponding points from the head CT to the subjects' head.
5. After registering the 3D digital model to the cadaver head, the user can visualize the location of a digital representation of the suture lines overlaid on the cadaver head.

Measuring Targeting Accuracy

To determine the quality of registration, target registration error was measured. The targets selected in this study were bregma,

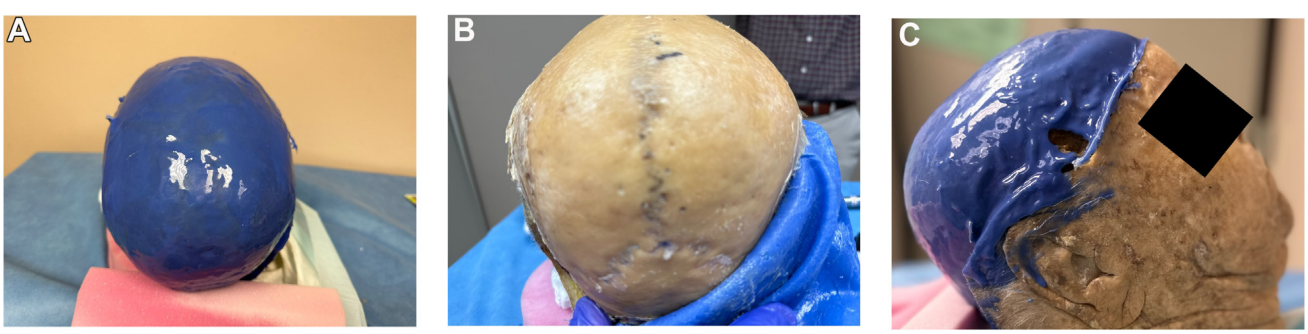

Figure 1. Representative images of cadaver head setup showing (**A** and **B**) silicon scalp covering cadaveric skull. (**C**) Silicone scalp removed to allow for visualization of "true" target points.

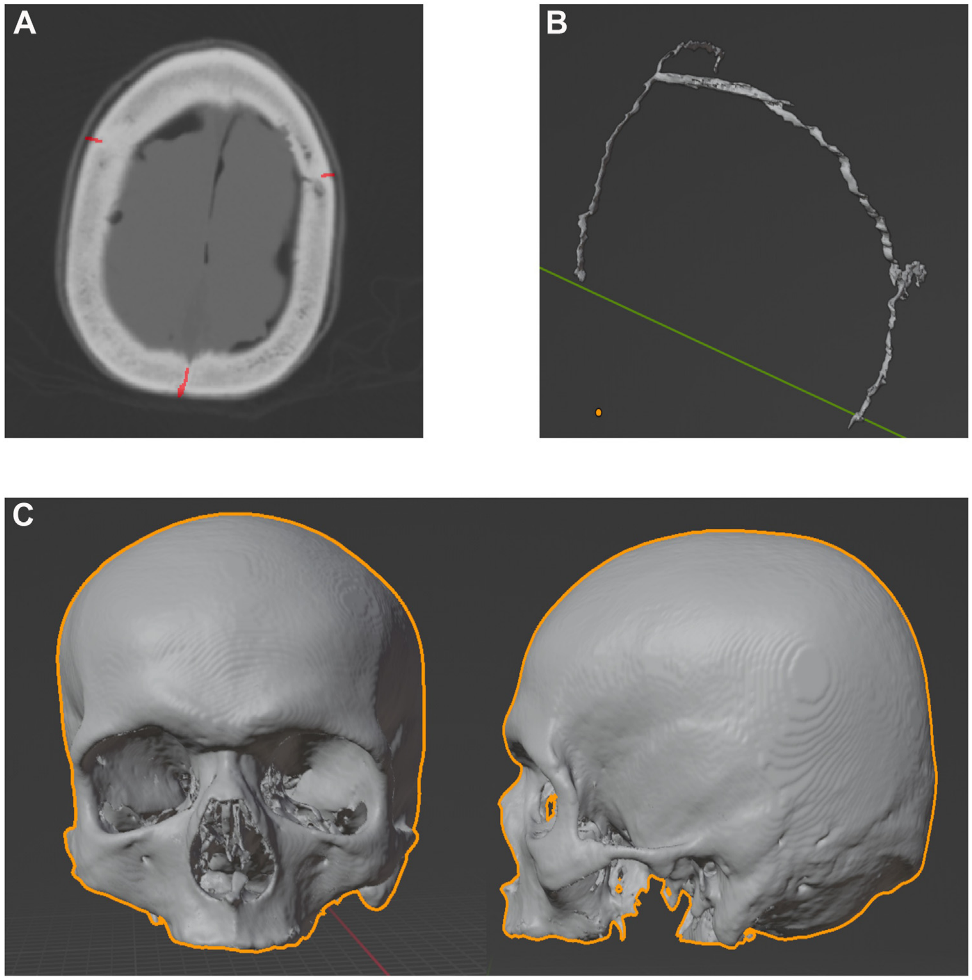

Figure 2. Representative images of (**A**) suture line segmentation (red lines) from cadaver computed tomography scan and 3-dimensional reconstructions of cadaver (**B**) suture lines and (**C**) skull.

lambda, right, and left midpoints between bregma and superior temporal line along coronal suture, midpoint between bregma, and lambda along sagittal suture. To determine whether AR can improve the targeting of the selected points, users were asked to target each point both with and without the assistance of AR. For the non-AR condition, participants could interact with a generic skull model to develop a general understanding of the location of these target points. The skull model was not a replica of the cadaver skull. Without being able to visualize the suture lines beneath the silicon scalp, participants were asked to insert a small nail into the estimated location of each target point (Figure 3B). Once nails were inserted into each target location, the nails and the silicone scalp were removed from the skull, revealing a small hole where each nail was inserted. Accuracy was determined by measuring the distance between the location marked by the participant with the true location of each target point on the skull using a caliper. Participants registered the cadaver-specific 3D model onto the cadaver head while wearing the HMD to test whether AR improved targeting accuracy. While visualizing the digital reconstruction of the skull and suture lines, participants were asked to insert a nail at the location of each target point based on the digital model overlaid on the head. Each participant performed the non-AR condition 1 week before performing the AR-assisted condition to minimize recall bias. Primarily, this study was carried out to determine and demonstrate accuracy of the AR system, and although the coronal suture is frequently used in neurosurgical procedures, the other sutures and craniometric points were selected to simply provide more than 1 targetable area.

Data Collection

Participants completed a posttest survey to assess attitudes toward the comfort, usability, and perceived value of the AR technology.

Statistical Analysis

Statistical analysis was performed using Graphpad Prism. The mean accuracy measurements for both the non-AR and AR-

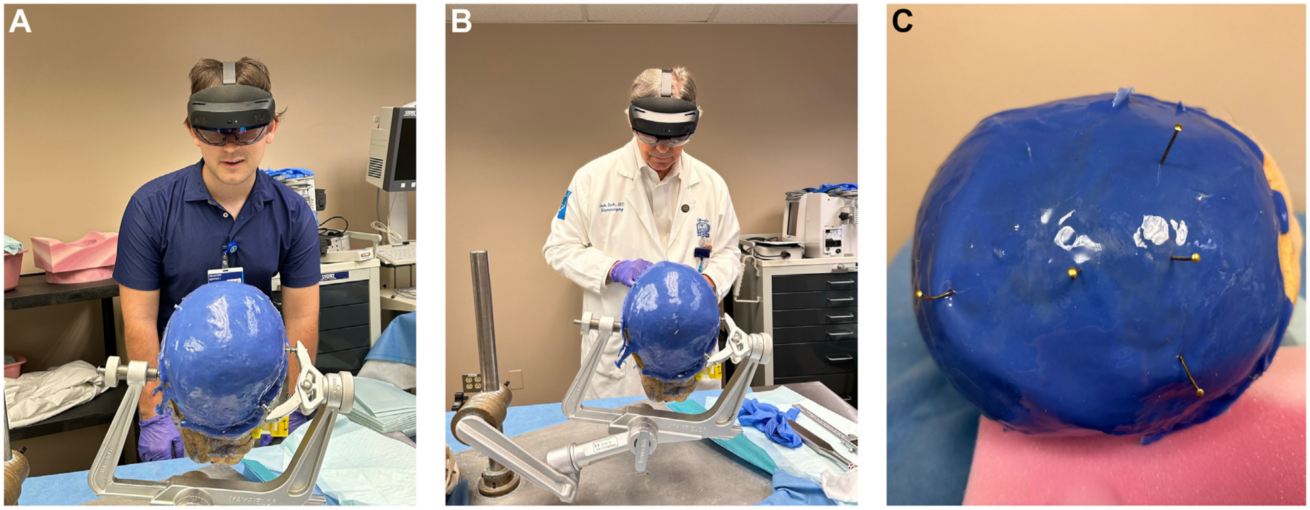

Figure 3. Representative images of (**A,B**) participants wearing Microsoft HoloLens 2 and registering 3-dimensional models to subjects' heads. (**C**) To mark location of target point, participants placed nails into the skull at the perceived location of each target point.

assisted conditions were compared. For each given target point (i.e., bregma, lambda) the means of the non-AR and AR-assisted conditions were analyzed using a paired Student's *t*-test. To compare the targeting accuracy between multiple target points, a 1-way analysis of variance was performed on the mean accuracies.

RESULTS

Demographics

Five participants were included in the study. Participants had a range of neurosurgical experiences from undergraduate to PGY7 (**Table 1**). Several participants had previous experience using an AR HMD.

Augmented Reality Visualization of 3-Dimensional Reconstruction

Without the use of AR, participants cannot visualize the underlying skull anatomy and location of suture lines even though they can palpate the artificial scalp and skull, just as is done in the operating room. The AR display superimposes the reconstructed cadaver anatomy onto the head, allowing the user to visualize suture lines and skull beneath the skin (**Figure 4**). Once the 3D model is registered to the cadaver, the 3D model is locked in XYZ positional space. This allows the participant to move around the cadaver head and visualize the 3D model from different viewpoints without displacing its location (**Video 1**).

Video

Video available at www.sciencedirect.com

Impact of Augmented Reality on Targeting Accuracy

Participants were asked to target the location of the following 5 skull points both with and without the assistance of AR: bregma, lambda, right, and left midpoints between bregma and the superior temporal line along the coronal suture, midpoint between bregma and lambda along the sagittal suture. In the non-AR group, the average targeting error across all targets was 23.59 ± 13.01 mm. There was no significant difference in targeting error between each target; however, in the absence of AR assistance, the largest and smallest targeting error was observed with lambda (30.11 ± 14.05 mm) and bregma (21.38 ± 10.91 mm), respectively (**Figure 5A**).

The average targeting error was 3.59 ± 1.29 mm when using AR to assist with targets. Across all target points, the average differences between the non-AR and the AR-assisted groups were 19.96 ± 3.80 mm with the most significant improvement observed when targeting lambda. Overall, the participants were significantly more accurate with AR assistance than without ($P < 0.0005$). In the AR-assisted group, there was no difference in the targeting accuracy between each target points.

Impact of Targeting Accuracy Across Training Levels

There was an inverse correlation between training level and target error without AR assistance. The undergraduate participant had the lowest accuracy across all target points (33.50 ± 12.75 mm), whereas the greatest accuracy was observed with the PGY7 resident (12.73 ± 2.50 mm). The largest improvement (average difference) between non-AR and AR-assisted groups was observed with the undergraduate participant. With AR assistance, we no longer observed any relationships between targeting accuracy and training level, suggesting that AR enables participants with different experience levels to target skull landmarks with comparable accuracy (**Figure 5B**).

Qualitative Assessment of Augmented Reality Technology

After the study, all participants were asked to complete a survey about their attitude and experience working with AR technology

Table 1. Demographics of Study Participants

Demographics (N = 5)	Number (%)
Year in training	
Undergrad	1 (20%)
PGY2	2 (40%)
PGY5	1 (20%)
PGY7	1 (20%)
Previously used augmented reality	
Yes	3 (60%)
No	2 (40%)
Previously used augmented reality head-mounted display	
Yes	3 (60%)
No	2 (40%)

(Table 2). Overall, participants felt more confident locating the target point with AR assistance (4.6 out of 5) versus without AR assistance (3.6 out of 5) and thought that the technology significantly improved their spatial awareness of the skull landmarks (4.2 out of 5). Importantly, participants thought that the technology would be helpful in planning cases (4.2 out of 5) and, more generally, for clinical care (4.2 out of 5).

DISCUSSION

AR has shown great potential in neurosurgery to enhance surgical accuracy and provide surgeons with real-time, context-aware information during procedures. By overlaying virtual images onto the surgical field, AR enables surgeons to see critical structures that may not be easily visible to the naked eye.[19-21] We sought to explore the potential benefits of AR in determining if an AR display of 3D anatomy helps visualize specific craniometric points on the skull using a novel registration process.

Across all target points, the average differences between the non-AR and AR-assisted groups were 19.96 ± 3.80 mm with the most significant improvement observed when targeting lambda. Overall, the participants were significantly more accurate with AR assistance than without ($P < 0.0005$). In the AR-assisted group, there was no difference in the targeting accuracy between each target points. Altogether, the data demonstrate that the use of AR can significantly improve the accuracy of targeting skull landmarks. With AR assistance, we no longer observed any relationships between targeting accuracy and training level, suggesting that AR enables participants with different experience levels to target skull landmarks with comparable accuracy.

We used an AR head-mounted display to overlay 3D reconstructions of cadaver cranial anatomy onto the physical cadaver head. Specifically, we reconstructed and overlaid the cadaver skull and suture lines (coronal suture and sagittal suture) and chose 5 target points along the suture lines. We asked participants to locate each target point with and without the assistance of AR. While wearing the headset, the 3D model was registered onto the cadaver head, allowing the user to visualize the anatomy (skull and suture lines) beneath the cadaver's skin. Unsurprisingly, by overlaying the cadaver-specific 3D anatomic reconstruction onto the surgical field, participants were able to better understand the spatial relationships between the craniometric landmarks, which significantly improved their ability to locate targets. This is substantiated by the fact that participants responded they were more confident and AR technology improved their spatial awareness of the craniometric landmarks.

While AR significantly improved targeting accuracy across all participants, the most significant improvement was observed among trainees with the least experience. Notably, the data suggest that targeting accuracy was similar among all trainee levels when using AR, highlighting the value of this technology in improving accuracy, especially for junior trainees.

As for the technology itself, there are several notable features worth discussing. The registration technology is markerless, meaning CT scan data can be registered to the physical space without needing additional markers. Furthermore, the registration is relatively fast (<10 seconds), highlighting its potential to integrate into typical clinical workflow seamlessly. Lastly, a significant advantage of the system is its ability to operate entirely out of the HMD. There is no need for additional hardware (cameras, computers, tracking tools) to function. Due to its small footprint, speed, and encouraging accuracy, participants responded that they would be highly likely to use the technology for clinical care.

To our knowledge, there are no reports describing the accuracy of a markerless AR registration system. Various reports have evaluated the use of fiducials (i.e., QR codes) for registration with reported accuracies ranging from 2 to 5 mm.[2,21] While similar accuracies have been reported, as previously stated, the system described in this report obviates the need for fiducials to be present during the medical scan, which has major advantages for clinical workflow.

Despite the advantages described in this report, the study does have notable limitations. Due to the small number of participants, we could not draw adequate comparisons about the impact of AR between trainees with different experience levels. While the pretest-posttest design increased the validity of the findings, expanding these studies to include more participants and cadaveric subjects may be warranted. Additionally, there were limitations to the registration experimentation that likely impacted targeting accuracy.

1. The registration system did not include tool tracking to allow participants to reference the location of a tool relative to the virtual target points.
2. The cadaver was not draped during targeting experiments and thus was less representative of a potential clinical scenario. While the 3D model remains fixed after registration, it will be interesting to evaluate if draping the patient after registration has an impact on the system's accuracy.
3. A single cadaveric specimen was used, which may limit the generalizability of the described technology.
4. Only select craniometric points were included in the testing. Many other craniometric points, cranial landmarks, and intracranial structures will be important to include in future studies.

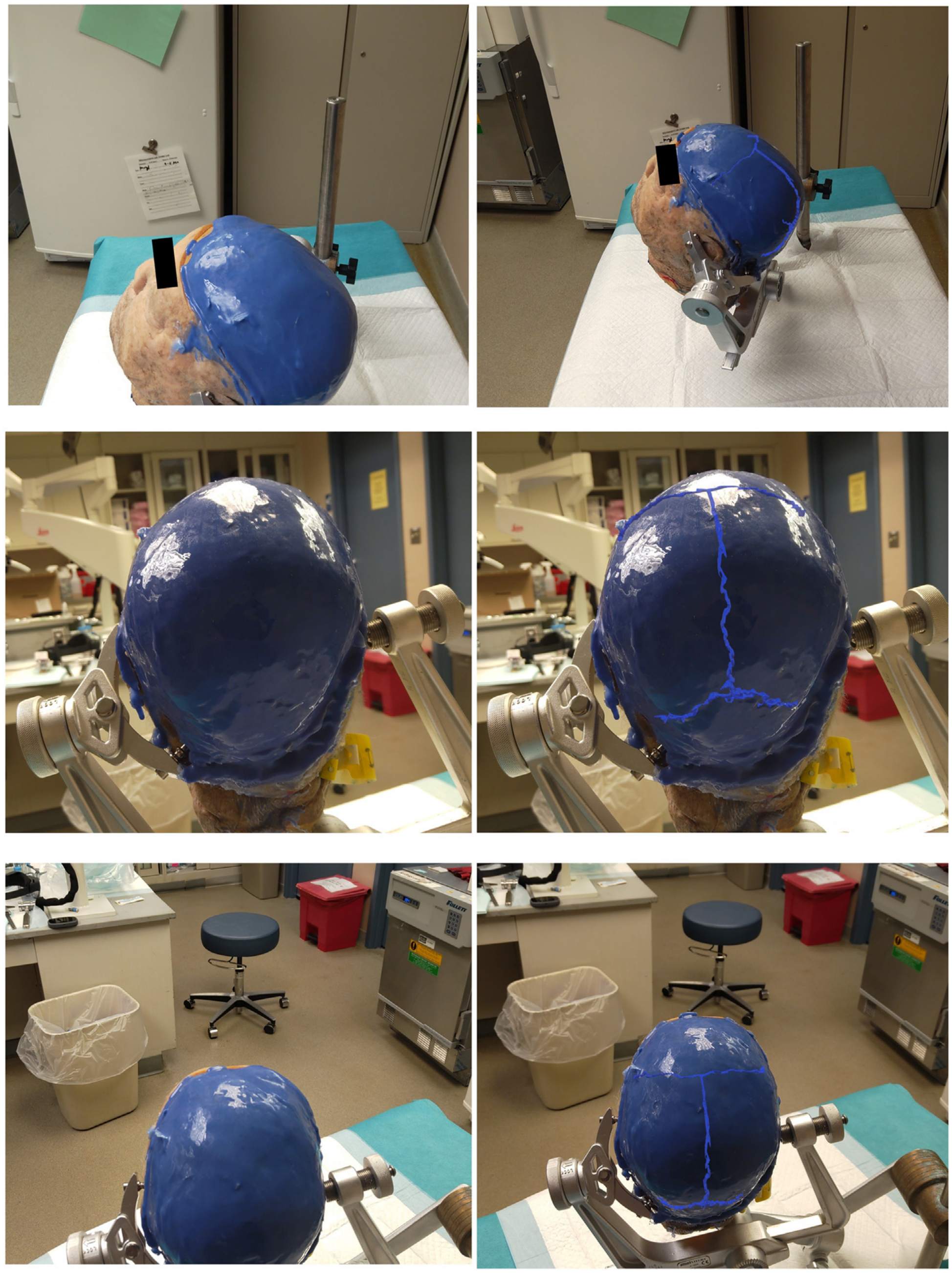

Figure 4. Representative images of 3-dimensional reconstruction as viewed through the Microsoft Hololens 2. Images are representative views through the headset. The left panel demonstrates the cadaver without the augmented reality (AR) display. The right panel demonstrated the AR display superimposed onto the head.

CONCLUSIONS

In conclusion, as a proof-of-concept study, the goal of this project was to demonstrate the potential of this AR technology. Our data demonstrate that AR can significantly improve the targeting accuracy of craniometric points and skull landmarks. AR holds great promise in neurosurgery, providing surgeons with enhanced visualization, guidance, and educational opportunities. Several areas of improvement and innovation will further validate the use

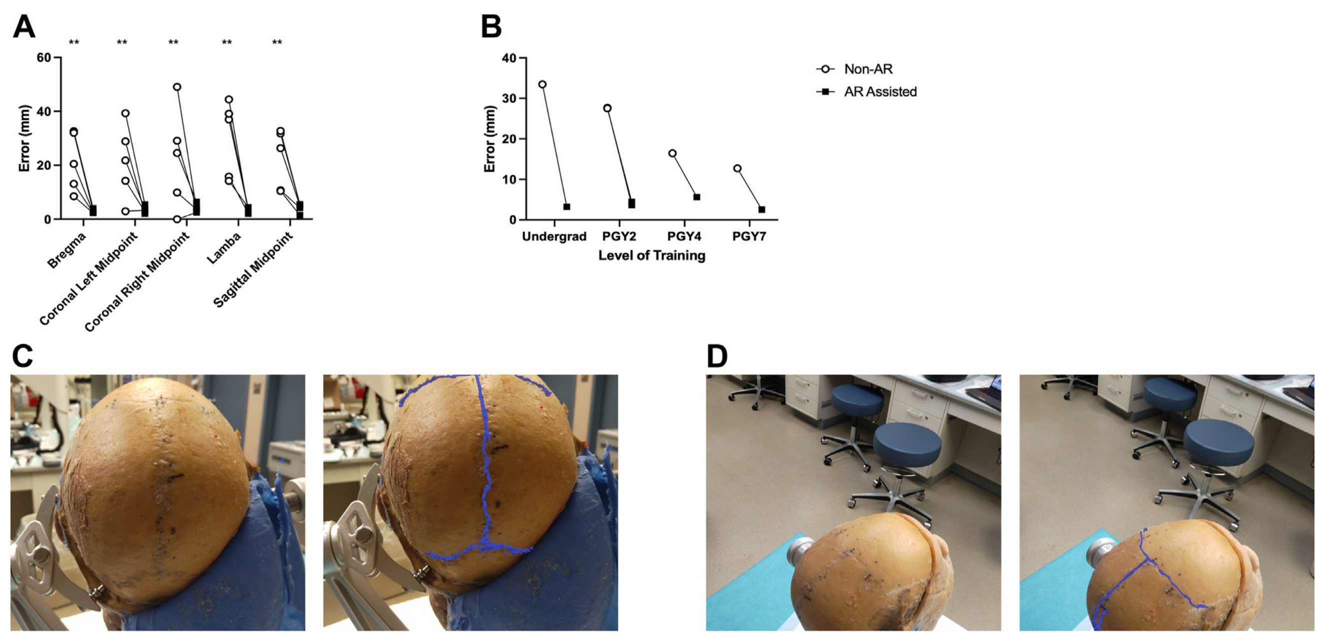

Figure 5. (**A**) Targeting error for each craniometric location without augmented reality (AR) assistance (open circles) and with AR assistance (closed circle). Data from the same participants are connected by a line. (**B**) Average error of all target points based on trainee experience level. (**C** and **D**) Views through the headset. Representative images with (*right panel*) and without (*left panel*) the AR display, demonstrating the precise overlay of the AR reconstruction onto the cadaver head. Results in all panels are represented from 5 participants. Significance was calculated using unpaired Student's *t*-test. $^{**}P < 0.005$.

Table 2. Qualitative Assessment of Augmented Reality (AR) Technology

Question	Average Likert Score (SD)
Did the headset cause any discomfort?	4.2 (0.84)
1 - Very uncomfortable	
5 - No discomfort at all	
Did you find the virtual display distracting?	4.2 (0.84)
1 - Very distracting	
5 - No distracting at all	
Do you think identifying craniometric points is helpful for clinical care?	4.8 (0.45)
1 - Not at all	
5 - Very helpful	
Would this AR application be useful for clinical care?	4.2 4.2 (0.84)
1 - Make it harder	
5 - Very useful	
How confident were you identifying target points without AR assistance?	3.6 (0.55)
1 - Not confident at all	
5 - Highly confident	
How confident were you identifying target points with AR assistance?	4.6 (0.55)
1 - Not confident at all	
5 - Highly confident	
How did AR impact your spatial awareness of the target points?	4.2 (0.84)
1 - Made it much worse	
5 - Greatly improved	
Would the technology improve planning for cases?	4.2 (0.45)
1 - Make it worse	
5 - Improve significantly	

Continues

Table 2. Continued

SD, standard deviation.

of AR in neurosurgery. As the hardware is made smaller and processing algorithms become more efficient, AR is expected to play an increasingly significant role in neurosurgery, transforming how surgeries are performed and improving patient care.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Pranish A. Kantak: Writing – review & editing, Writing – original draft, Investigation, Data curation. **Seamus Bartlett:** Methodology, Data curation. **Anisse Chaker:** Methodology, Investigation, Data curation. **Samuel Harmon:** Methodology, Investigation, Data curation. **Tarek Mansour:** Methodology, Investigation, Data curation. **Jacob Pawloski:** Methodology, Investigation, Data curation. **Edvin Telemi:** Methodology, Investigation, Data curation. **Heegook Yeo:** Methodology, Investigation, Data curation. **Samantha Winslow:** Project administration, Methodology, Data curation. **Jonathan Cohen:** Writing – review & editing, Conceptualization. **Lisa Scarpace:** Writing – original draft, Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Adam Robin:** Methodology, Investigation, Data curation, Conceptualization. **Jack P. Rock:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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