Understanding How Different Visual Aids for Augmented Reality Influence Tool-Patient Alignment in Surgical Tasks: A Preliminary Study

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Abstract: This study explores the impact of several visual aids on the accuracy of tool-patient alignment in augmented reality (AR) assisted surgical tasks. AR has gained prominence across surgical specialties, integrating virtual models derived from patient anatomy into the surgical field. This opens avenues for innovative visual aids and feedback which can facilitate surgical operations. To assess the influence of different visual aids on surgeon performance, we conducted a tool-patient alignment test on a 3D-printed frame, involving 12 surgical residents. Each participant inserted 12 toothpicks with a release tool into predefined target positions on the frame simulating patient targets, under AR visualization through a Magic Leap 2 Head-Mounted-Display. As visual aids, four holographic solutions were employed, with two of them offering graphical feedback upon the correct alignment to the target. Linear and angular positioning errors were measured, alongside participant responses to a satisfaction questionnaire. The tests maintained a consistent tracking system for estimating target and tool poses in the real-world, ensuring evaluation stability. Preliminary results indicated statistically significant differences among the proposed visual aids, suggesting the need for further exploration in the realm of their usability in relation to the specific surgical task and the expected overall surgical accuracy.

1 INTRODUCTION

Augmented Reality (AR) technology, emerged in the early 1990s, enables users to observe both real-world images and computer-generated images, supplementing and prompting information to the user to achieve "augmentation" of the real world (Jiang et al., 2023; Fraga-Lamas et al., 2018; Carmigniani and Furht, 2011). In recent years the use of AR in medicine has arisen in many surgical specialties because of the ability of AR systems to integrate the virtual models built from medical image data and the real surgical scenes into a unified view. This augmented visualization offers an unparalleled avenue for surgeons to access critical anatomical details and to visualize the guidance information directly onto the patient's body. Ensuring surgical accuracy with AR guidance depends, among others, on careful pre-operative planning. This is crucial because we need highly precise virtual models (i.e.: high quality 3D reconstruction from CT or MR patient' scan) overlaid onto the real-world scenario during surgery. Moreover, ensuring the dependable operation of real-world tracking systems is crucial for accurately overlaying virtual objects and facilitating effective coordination between the surgeon's vision and manual dexterity (Condino et al., 2023; Cercenelli et al., 2022; Fitzpatrick, 2010). The effectiveness of this coordination could even depend on the choice of visual aids, (Cercenelli et al., 2023; Ruggiero et al., 2023; Schiavina et al., 2021; Battaglia et al., 2020; Cercenelli et al., 2020; Fida et al., 2018; Meola et al., 2017), and this is what we want to investigate in our study.

Several studies have been done regarding the accuracy of "image-to-patient" registration with different AR technologies, for example using AR in virtual nasal endoscopy found an accuracy of 1.3 cm (Barber et al., 2018), while others reported a target position error of 1.19±0.42 mm in a similar setting (Li et al., 2016). It has also been demonstrated that the use of markers directly positioned onto the patient's body near the anatomical region of interest can further

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reduce the registration error (Scherl et al., 2021; van Doormaal et al., 2019). Moreover, with the advancements of technologies, some studies have shown that results obtained with AR systems can be compared to the standard navigation systems in different surgical specialties (Mai et al., 2023; Thabit et al., 2022; Peh et al., 2020), even with faster execution times (Agten et al., 2018). It has been demonstrated that the use of different overlays can have an impact on the ”image-to-patient” registration checks (Condino et al., 2023). Despite this, only a few studies focused on the use of different visual aids for AR-guided surgery and our findings underscored the substantial implications of the visual aid employed during surgical tasks.

The digital information can be visualized on the real world in many ways and most of the studies focus on just one visual aid when assessing the achieved surgical precision under AR guidance. This means they do not consider how different visual aids might affect the final surgical outcome. Because of this, we are missing a complete picture of how different graphical solutions can impact final results and if working on them can enhance the surgical performance (Verhellen et al., 2023; Scherl et al., 2021; Jud et al., 2020).

Therefore, we questioned whether the type of visual aid used in AR guidance systems makes a difference in the achieved surgical accuracy, while employing the same image-to-patient registration method. To explore this, we conducted a phantom test, simulating the alignment between a surgical tool and a target position on the patient (“tool-patient alignment”), using four different graphic solutions as visual aids. Then we measured, for each aid, how accurately the simulated tool is positioned and perceived under AR guidance.

For the study we employed the Magic Leap 2 head-mounted-display (HMD) for rendering holograms (three-dimensional images formed by the interference of light beams from a laser or other coherent light source) serving as visual aids and for ensuring accurate tracking in the spatial domain, i.e. 6 degrees of freedom (6DoF) pose of both the target position on the patient and the surgical tool. Among the overlays tested, two of them displayed only the target position, without providing feedback on the correct alignment. In contrast, the other two overlays provide feedback on the correct alignment, giving visual information to identify a correctly aligned tool and a misaligned one. This comparison helped us to assess the significance of graphical feedback in improving accuracy during AR-assisted surgical procedures.

2 MATERIALS AND METHODS

2.1 Study Design and Participants

In our comparative study, aimed at determining whether and to what extent the use of different visual aids influence the accuracy of AR-assisted surgical tasks, we recruited 12 surgical residents from IRCCS Azienda Ospedaliero-Universitaria of Bologna. Among them, 6 were residents in maxillofacial surgery and 6 residents in orthopedics, ranging from 25 to 38 years. To be eligible for the test, participants were required to have observed at least 50 surgical procedures, even of the same type. Each participant was instructed to place 12 toothpicks in 12 different planned positions on a 3D printed frame filled with modeling clay, using a release tool of similar dimensions to a syringe. The positioning was AR-guided using four different types of visual aids displayed through the Magic Leap 2 HMD. At the end of the test, participants were asked to complete a Likert-scale questionnaire to measure their appreciation of the different graphic solutions, ranging from 1 (totally disagree) to 5 (totally agree), with the following questions:

1. “I think the overlay “X” speeds up the alignment surgical operations.”
2. “I think the overlay “X” is clear and intuitive to use.”
3. “I think the overlay “X” is not occlusive with respect to the operating field.”
4. “I think the overlay “X” is well suited for High Accuracy surgery operations.”

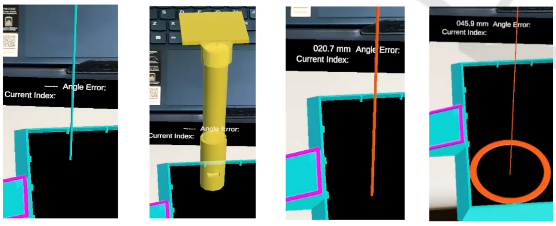
Finally, linear and angular positioning accuracy were measured.

The simulated task can be related to lumbar facet joint injections (Agten et al., 2018), however, since it focuses on the alignment of a surgical instrument to a specific target position on the patient’s anatomy, it may also hold significance for surgical procedures in other specialties such as orthopedic milling for the insertion of patient-specific prosthetics (Fotouhi et al., 2018) or the placement of screws in the thoracic and lumbar spine (Peh et al., 2020).

2.2 Study Process

For the execution of the test, an Android application was developed for the Magic Leap 2 device (1.4.1 OS Release) using the Unity development platform (version 2022.3.9f1) and the Magic Leap SDK (Software Development Kit, version 1.4.0). The purpose of the application was to sequentially display properly positioned visual support holograms indicating the target positions where the 12 toothpicks should be inserted on the 3D printed frame filled with modeling clay.

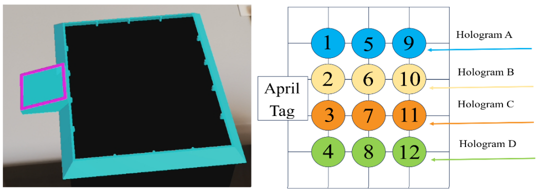
At the beginning of the test, each surgical resident was shown each adopted visual aid (shown in figure 1), and the order in which they would be presented was explained to them (shown in figure 2b). Specifically, the first solution (referred to as “A” from now on) involved displaying a simple blue axis with a diameter of 5 mm perfectly aligned with the target entry point and direction. The second solution (“B”) displayed the transparent phantom of the tool (transparency is adjustable based on the instructions given by the surgeon) in the position where the real tool should be located to align the toothpick accurately in the target entry point and direction. The third proposed solution (“C”) showed a virtual orange axis with a diameter of 5 mm, which turned into green when the tool (tracked in space using an AprilTag marker placed above it) was aligned in the target position within a deviation of less than 3 mm and 3 degrees. This color change provides feedback to the user on the correct alignment. Finally, the fourth solution (“D”), presented the same system as solution “C” but with the addition of a circle around the target entry point. The diameter of the circle expanded and contracted proportionally to the deviation of the tooltip from the target entry position. Also in this case, the proposed visual aid gives graphical feedback on the correct alignment.



(a) (b) (c) (d)

Figure 1: Visual aids used during the test with Magic Leap 2: Hologram “A” (a), Hologram “B” (b), Hologram “C” (c) and Hologram “D” (d).

To ensure accurate registration of the holograms in the virtual world relative to the real world, AprilTag markers (used dictionary: 25h9, length: 40 mm) securely attached to the frame target and to the toothpick release tool were used to estimate their 6DoF pose (see figure 3c). AprilTag markers provide a crucial advantage compared to the use of QR-codes, namely the ability to detect the marker even when smaller in size. This represents a fundamental benefit for surgery as it allows for less occlusion of the operative field.



(a) (b)

Figure 2: The target frame used during the test (a) and the order of execution of tasks under the 4 different visual aids, i.e. holograms A, B, C, D (b).

The software implementation of 6DoF pose estimation exploited the *MLMarkerTracker* library provided by Magic Leap itself for use with their AR headset. In particular, the marker tracking back-end has been set to use the 3-world-cameras of the Magic Leap 2 in order to ensure stereo-vision of the markers (i.e.: the provided marker tracking algorithm can be configured with several options). This guarantees a much higher field of view and even better accuracy, if compared to only the frontal RGB camera. During the execution of each test, the time required for the insertion of each toothpick was measured.

2.3 Outcome Measurements

Firstly, the tracking accuracy is visually checked by ensuring the alignment between the virtual frame and the real one. This ensures the correct positioning of the holograms during testing. Then for measuring the execution times, a standard stopwatch was used. The start time was considered as the moment in which the target position was displayed, while the end time was taken manually by an external operator when the toothpick was inserted and fully released. Times were recorded in whole seconds (error < 1 s).

To measure the linear positioning error, a standard analogic Vernier caliper was used (accuracy of 0.05 mm). The distance between the center of the hole left by the toothpick inside the modeling clay and the ideal insertion position was measured. The ideal insertion position was identifiable through grooves present in the frame target (as shown in figures 2a and 3a), which served as reference for the grid construction. This deviation was measured in millimeters (error < 1 mm).

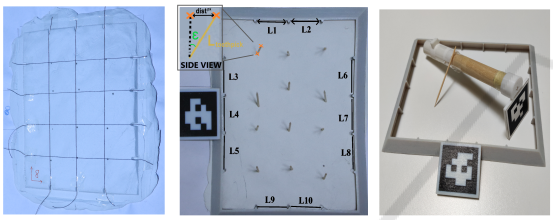
Finally, for measuring the angular positioning error, a photograph was taken using a Canon Eos 77D equipped with a standard 18-135mm lens at the maximum possible zoom level. The photograph was taken from approximately 1 meter away from the toothpick insertion surface. To compute the angular error the following equation, derived from elementary geometrical principles, has been used:

$$\varepsilon = arcsin(\frac{dist^{px} * px2mm}{L_{toothpick}}) \qquad (1)$$

where $dist^{px}$ is the norm of the difference between the coordinates in the photograph of the toothpick tip and entry point (see figure 3b). The conversion factor from pixel to millimeters (px2mm) is obtained by comparing the mean length in pixel between each image's reference grooves with their ideal distance which corresponds to 30 mm. This can be write compactly as follows:

$$px2mm = \frac{30^{mm} * 10}{\sum_{i=1}^{10} L_i^{px}} \qquad (2)$$

The ε angle was calculated as the angle between the axis of the toothpick and the axis perpendicular to the plane of the insertion surface. (error $< 3°$).



(a) (b) (c)

Figure 3: Resultant dry clay with grid lines used for positioning accuracy (a), mock target frame (b and c) and mock tool used for the experiments (c).

2.4 Statistical Analysis

Qualitative and quantitative data have been registered and analyzed on an Excel document. Statistical validation was performed using the Friedman test (Friedman, 1940; Friedman, 1939; Friedman, 1937), a non-parametric statistical test developed by Milton Friedman used to detect differences in treatments (ie: different visual aids) across multiple test attempts. The hypothesis being tested was whether there were significant differences in mean positioning accuracy and appreciation among the four proposed visual aids. In the calculation of the p-value (the probability of the *null hypothesis*), the first four (out of 12) inserted toothpicks were excluded as they were used as training by the surgical residents. Additionally, to ensure that each graphic solution was tested with approximately the same amount of practice by the surgeons, they have been shown in the following sequence: A-B-C-D, A-B-C-D, A-B-C-D. At the end, the following measurements were separately validated: execution times, positioning errors, angular positioning errors, and individual questionnaire answers. A statistically significant p-value of 0.05 was chosen.

3 RESULTS

3.1 Feasibility and Acceptability

The Friedman statistical hypothesis test has been conducted for several variables in order to understand if and at which level each visual aid influenced the final accuracy and appreciation. The results are shown in table 1.

Table 1: Resultant p-values from the Friedman Test.

Variable	P-value	Percentage
Execution Times	0.0006	0.06 %
Linear Positioning Error	0.0023	0.23%
Angular Positioning Error	0.0615	6.15 %
Question 1	0.0236	2.36 %
Question 2	0.4619	46.19 %
Question 3	0.0093	0.93 %
Question 4	0.0019	0.19 %

A p-value below the predetermined significance level (0.05) suggests evidence to reject the null hypothesis, indicating significant differences among the tested conditions. In this context, execution times, linear positioning error, and certain questionnaire answers exhibited statistically significant differences among the proposed visual aids. However, the angular positioning error and the second question regarding the clarity and intuitiveness of the specific hologram did not show significant differences.

3.2 Procedural Times

The obtained execution times demonstrate that the two solutions without graphical feedback (i.e. Holograms A and B) are faster compared to the other two (Holograms C and D). This is likely since the surgical resident focused more on positioning until the guiding reference axis for task execution turned green. The average, minimum, maximum, and standard deviation values are reported in table 2.

Table 2: Mean values regarding the execution time.

TIME (sec)	Hol. A	Hol. B	Hol. C	Hol. D
Mean	16.27	14.81	35.50	23.27
Minimum	4.00	5.00	6.00	6.00
Maximum	55.00	32.00	105.00	76.00
St. Dev.	12.84	8.56	28.62	17.31

3.3 Task Accuracy

Regarding the dimensional positioning accuracy, it is most evident that the second solution ("Hologram B") performed worse than all others (as shown in figure 4). This aligns with its respective level of appreciation, reported in the questionnaire. Solution "B", lacking the display of the target axis, proved to be the least precise among the four and also the most occluding by covering the entire working tool. The average, minimum, maximum values, and standard deviations for linear and angular positioning accuracy are reported in tables 3 and 4, and in figure 4.

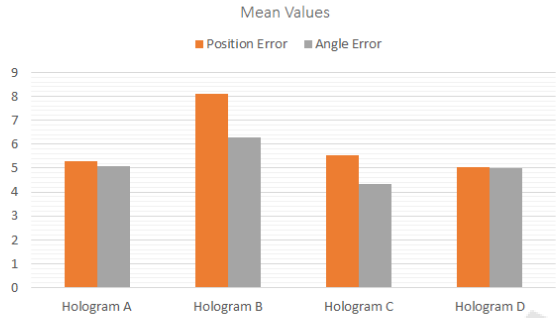


Figure 4: Mean values of linear and angular positioning errors, collected for the four visual aids.

Table 3: Mean values regarding linear positioning accuracy.

POS. (mm)	Hol. A	Hol. B	Hol. C	Hol. D
Mean	5.30	8.10	5.54	5.02
Minimum	0.50	2.40	1.45	1.10
Maximum	18.60	25.00	15.55	8.45
St. Dev.	4.48	5.71	2.91	1.97

Table 4: Mean values regarding angular positioning accuracy.

ANG. (°)	Hol. A	Hol. B	Hol. C	Hol. D
Mean	5.08	6.28	4.32	4.98
Minimum	0.58	1.32	0.31	2.16
Maximum	9.55	17.10	9.52	11.14
St. Dev.	2.25	3.67	2.49	2.77

3.4 Overall Satisfaction

The measurement of overall satisfaction was conducted through four appreciation questions (listed in section 2.1), where participants were required to assign an appreciation score for each proposed visual aid. The second question was excluded from the analysis due to its low statistical significance, as all four proposed solutions were found to be intuitively usable with minimal divergence in results. The remaining three questions were evaluated, encompassing aspects of speed, occlusion, and perceived accuracy. Solution "D" emerged as the overall preferred choice with an average total score of 11.83 out of 15. Following closely was solution "C" with a score of 11 out of 15, while solution "A" secured the third position with a total of 10.67 out of 15 points. Lastly, solution "B", identified as the most occlusive, received a final score of 6.67 out of 15, deemed insufficient. Figure 5 illustrates a graphical representation of the obtained results.

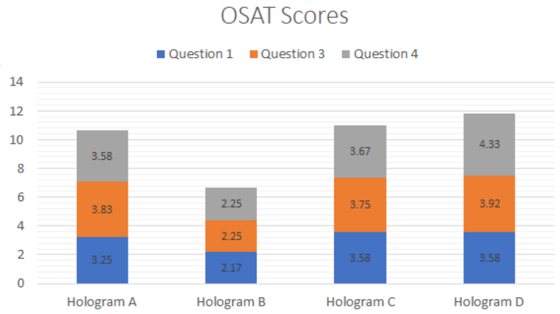


Figure 5: Mean appreciation values obtained from the OSAT (Overall Satisfaction) questionnaire.

4 DISCUSSION

The integration of AR technology in surgical settings has sparked significant interest due to its potential to integrate virtual models derived from medical imaging to the live surgical environment, providing a unified and enriched visual context. Our study delved into the pivotal aspect of visual aid within AR systems, exploring its influence on surgical precision. The investigation aimed to evaluate the impact of distinct graphical interfaces on surgical accuracy while employing the same registration technique.

The comparison among the four different overlays revealed distinct performances and results' validity is confirmed by the statistical analysis performed. It revealed significant differences among the proposed graphic solutions concerning execution times, linear positioning errors, and specific questionnaire responses, confirming that different graphic solutions mean statistically different results. While angular positioning error and the second questionnaire item did not demonstrate substantial differences, it is crucial to note that our study may not have been exhaustive enough in exploring these two aspects. A true differentiation in angular positioning was not conducted, as participants were instructed to insert toothpicks perpendicularly to the surface-plane. Similarly, for the second questionnaire item regarding the clarity and intuitiveness of the graphical support provided, residents were briefed on the functionality of the four graphical solutions, facilitating their understanding.

Notably, the solutions lacking explicit graphical feedback (A, B) exhibited swifter execution times and a mean accuracy error comparable to the overlays with feedback (C, D). These results suggest a potential tendency of surgeons to focus more intensely on positioning until the guidance cue was met and that this overlay can be preferable in surgeries where the instruments' tracking cannot be done. On the other hand, solutions providing visual cues for checking the correct alignment exhibited enhanced precision but were associated with slightly longer execution times.

Mean precision of axis-based solutions are similar, but the feedback-based ones achieve better scores in standard deviation: more or less the half for "C" and "D" if compared to solutions "A" and "B". Worth to mention, the second solution (B), lacking of a visible target axis, resulted in lower precision. This aligns with the corresponding lower level of appreciation reported for solution B in the questionnaire.

Moreover, this study shed light on the residents' perception about the proposed solutions, as indicated by their answers to the questionnaire. This aspect, coupled with the quantitative measurements, underscores the multifaceted impact of visual aids, encompassing both objective task performance and subjective user perception. Solution "D" has achieved the best overall satisfaction score. Similar to solution "C", it suggests that simple additional information, such as a circle that enlarges and shrinks proportionally to positioning error, can be of great use. It is worth mentioning that some residents have asked for arrows or similar indications in order to show the direction to which move the tool to ensure correct alignment.

Finally, another suggestion has been made by residents regarding the black bar showing quantitative linear and angular positioning errors in real time (it is partially visible in figure 1). It was appreciated by all participants, however it was difficult to read as it was positioned far from the task objective. This suggests that for future implementations it can be an additional visual aid if shown nearer the working area or in conjunction with the before-mentioned arrows.

Limitations

Limitations of this study primarily regard the restricted sample size of surgical residents involved from specific specialties, potentially limiting the generalizability of obtained findings across different surgical domains. Additionally, the test involved a specific set of tasks with toothpick insertions, potentially constraining the applicability of the results to broader surgical procedures. Last, but not least, angular measurement errors are notably high when compared to the measured values, making them less meaningful even if they were to achieve a p-value below 0.05. Future research encompassing a larger and more diverse cohort of surgeons across various specialties and diverse surgical tasks could further elucidate the nuanced relationship between visual aids and surgical accuracy.

5 CONCLUSIONS

Our study highlights the pivotal role of visual aids in AR-guided surgical procedures, emphasizing the correlation between proposed graphical solutions and task execution accuracy.

The inclusion of graphical feedback to address the proper alignment of surgical instruments with the patient diminishes the positioning jitter (lower standard deviation in positioning accuracy) which means diminished chances of making systematic or consistent errors.

The exploration of different graphical interfaces illuminates the need for tailored visual aids that strike an optimal balance between intuitive guidance and accurate task execution, thereby potentially enhancing surgical performance.

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