Immersive Mixed Reality Training Enhances Pedicle Screw Placement Skills in Undergraduate Medical Students: A Randomized Controlled Trial

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Abstract

Background: Amidst a growing need for improved surgical training, the conventional "see one, do one, teach one" model falls short, particularly for complex procedures like pedicle screw placement. This study introduces an Immersive Mixed Reality Training Framework (IMR-STF) designed to bridge this gap by integrating advanced mixed reality technologies with traditional surgical training to provide comprehensive, hands-on experience without the logistical constraints and ethical concerns of traditional methods.

Objective: With the increasing constraints in surgical training, this study aimed to propose a novel Immersive Mixed Reality Surgical Training Framework(IMR-STF) to facilitate surgical skill development among medical students and evaluate its efficacy. Under IMR-STF, the authors developed the Immersive Mixed Reality Surgical Self-Training System(IMR-SS) for pedicle screw placement, seeking to overcome the limitations of traditional training by providing an immersive, interactive, and high-fidelity training environment

Methods: A conceptual Immersive Mixed Reality Surgical Training Framework (IMR-STF) was proposed, under which a self-training system was prototyped as IMR-SS for pedicle screw placement for validation. The system integrates 3D-printed models, real surgical instruments, and IMR technology to provide an immersive learning experience and high-fidelity haptic feedback. A randomized controlled trial was conducted with 32 undergraduate medical students from two centers. Participants were randomly assigned to either the IMR Group(using IMR-SS) or the Control Group (using a digital textbook). Both groups underwent theoretical and practical training, followed by identical assessments.

Results: The IMR Group demonstrated significantly higher completion rates (0.99±0.02 vs. 0.87±0.11, p=0.000) and fewer errors(0.06±0.25 vs. 2.13±1.54, p=0.000) compared to the Control Group. Additionally, the IMR Group showed better performance in screw placement angles(13.88°±6.98° vs. 20.89°±11.59°, p=0.049) and more stable performance with smaller variances. No cortical bone breaches were observed in the IMR Group, while the Control Group had breaches in 4 out of 16 cases during the exercise session (p=0.051). The theoretical assessment showed no significant difference between the groups, indicating equivalent baseline knowledge. The IMR Group reported higher satisfaction and confidence in learning outcomes.

Conclusions: The IMR-SS is a feasible and effective method for enhancing surgical education for novice medical students, providing superior hands-on training experiences, and improving practical skills. Future research should focus on long-term learning curve validation, skill transferability, and developing curricula for more surgeries for generalizability validation. Clinical Trial: This study was deemed exempt by the Peking Union Medical College Hospital(K5533-K24C0630) and The First Affiliated Hospital of Xi'an Jiaotong University(XJTU1AF2024LSYY-097).

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Keywords: Augmented and virtual reality; Simulations; Architectures for educational technology system

1 Introduction

One major hurdle that the current orthopedic surgical training faces is the necessity of a prolonged training period to develop competent surgeons(LaPorte et al., 2019; Wang & Shen, 2022). The traditional “see one, do one, teach one” model might not be capable of coping with the growing demands in surgical training and education(Bashankaev et al., 2011; Viglialoro et al., 2021). For pedicle screwing, one needs to place approximately 80 screws and 25 cases to be proficient as attending surgeons(Gonzalvo et al., 2009). While surgical training with cadaver training has long been the golden standard, it is limited by ethical concerns, unstable sources and maintenance(Condino et al., 2021; Karam et al., 2013). Commercial phantoms could resolve the issues in cadavers, like Sawbones, but they are usually too expensive for regular training, and are limited in variation of pathologies and individual differences(Condino et al., 2018; Tack et al., 2016) Moreover, the increasing demand for academic outcomes and residency regulations also lead to fewer opportunities for hands-on practicing and lack of expert instruction(LaPorte et al., 2019; Rosenbaum, 2016; Sadati et al., 2021). These problems call for independent self-training systems for surgical education, which provide customizable resources and expert instructions for regular surgical

practice.
In Extended Reality(XR), studies have already addressed many valid and effective solutions, especially in Immersive Virtual Reality(IVR) training(Nazzal et al., 2023; Tang et al., 2022; Azad et al., 2024; McCloskey et al., 2023). IVR systems with simulated feedback are feasible for laparoscopic surgery training, but the lack of genuine haptic feedback might be a limitation for orthopedic open surgery training, as it usually involves a variety of instruments and intricate handling(Condino et al., 2018).
However, Mixed Reality (MR) could be the ultimate answer for immersive training(Anderson et al., 2021; Wang & Shen, 2022). By wearing a head-mounted display(HMD), MR allows direct interaction between the virtual and the physical world by spatial mapping of virtual objects in real-time with real-world coordinates. MR has been largely adopted in surgical navigation with solid validations(Azad et al., 2024; Nazzal et al., 2023; Viglialoro et al., 2021), but it also holds prospects for fostering surgical education. According to a review study in medical education with XR technologies, only 22.7% of the studies focus on practical skill training(Tang et al., 2022). When combined with a physical phantom, MR could provide both the immersive training environment and haptic feedback with higher fidelity(Nazzal et al., 2023). To our knowledge, current research on MR training systems often focuses on real-time navigational overlapped virtual information. This approach is useful, but the data could be further processed as instructional feedback for trainees with instant responses to performance, which could be beneficial to both the training experience and effectiveness.
Therefore, this study proposes a conceptual Immersed MR surgical training framework (IMR-STF), to create a fully ubiquitous training environment between the virtual and physical world with MR technologies. With IMR-STF, an IMR self-training system(IMR-SS) prototype for pedicle screwing is fully developed to validate this framework. The framework aims to provide self-reflection and controlled agency to promote the learning experience(Kneebone, 2005). Visual tracking is adopted to trace the transform information of surgical instruments and the physical phantom to achieve real-time evaluation. The physical phantom is modularized and 3D printed for economical and customizable surgical training. To our knowledge, this system could be the first IMR surgical self-training system for pedicle screwing. Our study aims to: (1) propose IMR-STF, (2) build a prototype (the IMR-SS for pedicle screwing) based on IMR-STF, and lastly, (3) conduct a randomized controlled trial with the prototype to validate the effectiveness of IMR-STF.

2 Methods

The study was conducted in 3 phases. Firstly, IMR-STF for surgical self-training is proposed. Directed by IMR-STF, a mixed reality modular surgical training system and a training curriculum for pedicle screwing were developed and implemented in Hololens2. Then a randomized controlled trial was conducted to evaluate the effectiveness of the system.

2.1 IMR Surgical Training Framework(IMR-STF)

IMR-STF consists of three modules with close integration and cooperation: Teaching Module, Hands-on Module, and Assessment Module. The three modules work closely with each other via data sharing and cooperation, to provide the ideal immersive mixed reality surgical training. Figure (1) presents the framework of IMR-STF.
Teaching Module includes the immersed curriculums and an IMR application. The curriculums consist of 4 stages: preparation, exploration, exercise, and reflection to foster procedural knowledge with solid practice. The IMR application implemented on MR devices enhances the ubiquitous experience(Di Mitri et al., 2022) with natural multimodal interactions, including voice, gesture and eye-tracking(Makransky & Petersen, 2021).
Hands-on Module allows for hands-on practice, including physical phantom (PP) and spatial tracking

system(STS). PP provides high-fidelity haptic simulation at low cost. Produced by modularized 3D printing, each part in PP can be re-printed and assembled respectively to cater to different scenarios. STS includes a tracking device and tracking markers. The digital twin of PP and surgical instruments are replicated in the IMR application. With the spatial tracking system, virtual data is coordinated with PP to allow the combination of realistic haptic feedback and real-time changes in PP and the digital twin. STS also provides data for Assessment Module.

Assessment Module constitutes an evaluation system and feedback system. The evaluation system offers real-time operation evaluation based on precision and safety metrics, with data from STS. Simultaneously, real-time feedbacks are delivered through the MR application. Long-term performance data are analyzed to form learning curves and to optimize teaching schedules and evaluation algorithms.

2.2 Prototype Development

Our study developed a prototype of IMR-SS for pedicle screwing to validate the IMR-STF framework.

The IMR application was built on Unity(2021.3.9LTS) with MRTK(2.6.2). The curriculum was developed following the steps in IMR-STF. The procedure of pedicle screwing was split into 9 steps, respectively with a benchmark and several node tasks. Objective operation benchmarks and specific requirements for each step are designed with reference to current textbooks and expert surgeons. The PP of the L1-L5 lumbar segment is developed from CT data from a real case(Li et al., 2023), It includes replaceable 3D-printed PLA vertebras and other tissues, with a digital replica in the IMR application. Binocular cameras and markers are used for spatial tracking. The precision and safety metrics integrated into the IMR application were defined by expert surgeons.

2.3 Evaluation

2.3.1 Experiment Setting

The system was evaluated under ethical approval from two centers (K5533-K24C0630, XJTU1AF2024LSYY-097). A total of 32 clinical medical students participated, evenly from both centers. All participants were undergraduates who had studied systematic anatomy but had no prior learning or observation experience of this surgery. All participants are open to MR technologies and are willing to wear a Head-mounted display(HMD) for learning and practicing. Applicants not meeting these criteria were excluded.

The experiment used a parallel design. Students from the two centers were randomly and evenly divided into an IMR Group and a Control Group (16 participants per group, 8 from each center), randomized with a C# program. The experiment lasted from January 3 to January 28, 2024, and was held in pre-prepared idle classrooms. Informed consent was obtained from all participants before the experiment. Different scripts were used to ensure blindness between groups. No relevant personnel participated in the experiment as subjects. Table (1) shows the baseline and characteristics of participants in both groups.

2.3.2 Experiment Design

Figure (2) presents the experiment design and participant flow.

Firstly, both groups were engaged in Interaction Learning Session with an IMR blank system. This blank system kept the basic structure of IMR-SS, but without any content.

Then, both groups went through three surgical learning sessions —instrument preview (introduces instruments and usage), model preview (introduces vertebrae anatomy), and procedure instructions (instructs pedicle screwing and its requirements). Then they performed an exercise of inserting one screw into the L3 vertebra on PP. IMR Group used IMR-SS for the learning sessions and completed the exercise session with instructions provided by MR-SS(shown in Figures (1) & (3) in SDC). Control Group used a digital textbook with the same content in IMR-SS, which resembles the traditional method, and completed the exercise session with reference to an operation animation clip(shown in Figures (2) & (4) in SDC). Both groups had identical time allocations. Once reaching the time limit, they were told to move on to the next session. Paper and pens were provided for note-taking.

The participants were then assessed with a quiz and performance evaluation without access to any reference. The quiz consisted of 12 multiple-choice questions: 3 on the vertebral anatomy, and 9 on procedures and instruments. All questions were based on the curriculum. Performance evaluation involved placing another screw on L3. Both groups were told to follow the tutorial content and techniques. Throughout the experiment, the conductor controlled the time for each session without intervening in the learning process.

Finally, two groups filled out a questionnaire on training and system satisfaction (IMR Group on IMR-SS, Control Group on digital textbook and the blank system). Both questionnaires used Likert scales.

2.3.3 Data Analysis

The quiz results were analyzed, including the accuracy rates of each question and the total accuracy rates. All performance evaluations were recorded, from which completion time for each step, terror details, and Completion Rate (CR) were analyzed. CR was assessed by, analyzing each operation sub-step according to the formula below:

$$CR_{substep} = \begin{cases} \dfrac{Number\ of\ Completed\ Node\ Tasks}{Number\ of\ Node\ Tasks} ¿(Benmark\ Achievced)¿¿0¿(Benmark\ Not\ Achievced)¿ \\ ¿ \end{cases}$$

$$CR = \frac{CR_{substep1} + CR_{substep2} + \ldots + CR_{substepn}}{n}$$

The operated L3 models during exercise and assessment were scanned into CT images with screws. Screw angles in lateral and transverse are measured and recorded. Gertzbein and Robbins System (GRS) was also used to evaluate screw placement accuracy.

A priori power analysis determined a minimum of 15 participants to detect a 5% difference for each group. Normality was assessed using S-W and K-S tests. Fisher's Exact Test, independent 2-tailed t-tests, U tests, and Tukey box-and-whisker plots were used for analysis. Significance was set at $p < 0.05$. SPSS, Excel, and R were used for data analysis.

3 Results

All the 32 participants completed all the sessions of the experiment. In IMR Group, 56.25% of the participants had prior experience with MR/VR HMDs, compared to 50% in Control Group (p = 0.723). All the participants included in the experiment reached the qualifications for the experiment. Medical students from both institutions were evenly and randomly assigned to ensure fair representation and randomization. All data has reached a level suitable for analysis.

3.1 Performance Outcome

During the evaluation session, the CR in IMR Group was significantly higher (0.99±0.02) than in Control Group (0.87±0.11, p=0.000)(shown in Figure (3)). Errors per individual in IMR Group were significantly lower (0.06±0.25) compared to Control Group (2.13±1.54, p=0.000) (shown in Figure (4).). Most of the error occurred in the last step, as it involved more instruments and node steps. Errors were categorized into instrument usage errors, procedure benchmark errors, and node task errors. IMR Group made significantly fewer errors in all categories(0.000, 0.043, 0.037; all p<0.05).

In Exercise Session, there was no significant difference between the two groups in terms of placement angles. However, 25%(4/16) in Control Group had breaches, whereas IMR Group had none (p = 0.051). During the evaluation phase, 12.5%(2/16) of Control Group had breaches, while IMR Group had none.

In assessment session, the transverse angle in IMR Group was significantly smaller (13.88°±6.98°) compared to Control Group (20.89°±11.59°, p=0.049). Additionally, the variance of screw placement angles in both transverse and lateral of IMR Group was significantly smaller, indicating more stable performance compared to Control Group (shown in Figure 5).

Additionally, for IMR Group, the transverse angles in exercise session were significantly smaller than in evaluation session (11.07°±6.88°, 13.88°±6.98°, p=0.040) (shown in Figure 5). It can be explained by the real-time instructions provided by IMR-SS during the exercise session, which in turn proves the validity of IMR-SS. Despite the increase in placement angle, the transverse angle of IMR Group remained significantly smaller than Control Group during evaluation session.

3.2 General Knowledge Learning

There was no significant difference between two groups in the quiz session. Participants might have the relevant knowledge as they had learned systematic anatomy. Also, for general knowledge learning, studies argue that IMR might not offer significant advantages over traditional method(Makransky & Petersen, 2021).

3.3 Learning Experience

The confidence in knowledge mastery of IMR Group was significantly higher than Control Group (instrument usage: p=0.003, autonomy: p=0.037, procedure: p=0.010). IMR Group rated curriculum quality, helpfulness, and effectiveness higher than Control Group (p=0.010; p=0.042; p=0.042).

For system usability, IMR Group rated system integration and ease of learning higher than Control Group (integration: p=0.044; ease of learning: p=0.047). Notably, IMR Group reported higher confidence in using the curriculum(p=0.000).

4 Discussion

In this study, the effectiveness of a conceptual surgical training structure—IMR-STF was evaluated, using the IMR-SS prototype developed entirely under this framework through a randomized controlled trial. All participants were undergraduate clinical students without training experiences, and completed each session independently. However, the IMR Group significantly outperformed Control Group in screw placement angle and made fewer mistakes. Our study found that IMR-STF and IMR-SS are feasible and efficient, which improves training outcomes and offers better training experiences than traditional approaches.

4.1 System Design

To cope with the increasing work and academic pressure of medical students and doctors(Lewandrowski et al., 2023), it is important to develop efficient independent self-training systems that provide expert guidance. In the era of spatial computing, MR can offer a more comprehensive learning experience than only virtual systems(Tonbul et al., 2023; Nazzal et al., 2023). To enhance the ubiquitous interception of data during training with MR, the IMR-STF incorporates a fully immersive training environment, where virtual real-time instructions and navigations are synchronized with practical hands-on operations on real surgical instruments over physical phantoms. This design distinguishes our study from previous research of mixed reality training. The high-fidelity haptic feedback provided by PP helps to develop psychomotor skills and improve techniques before clinical practice.

Meanwhile, IMR-STF may allow for a closer collaboration between in-school and clinical education. As the open-source workflow for extracting model bone data from CT scans is well established(Clifton et al., 2019), all the curricula in IMR-SS can be developed directly from typical real cases(Li et al., 2023). The training curriculum and evaluation system of IMR are also evolving to cater to more real-world scenarios.

4.2 Application

For medical students, early exposure to procedural training in surgery can cultivate their professional skill acquisition and future career development in medicine. Our study proposed. The IMR-STF framework and proved its effectiveness in providing surgical training for undergraduate medical students with better training outcomes and learning experiences compared to the traditional training method. In our study, the prototype IMR-SS for validation of IMR-STF consists of HoloLens2®, spatial tracking cameras, 3D-printed phantoms, and real surgical instruments. Though the initial setup may be relatively expensive as it involves Mixed Reality HMDs and spatial tracking, the per-use cost is minimal owing to the modularization of the PP, by only replacing the used 3D-printed tissues, which can be easily and cheaply produced on a 3D printer(Tan & Sarker, 2011). he vertebrae models of PP in the IMR-SS prototype were 3D-printed from PLA with customized fill patterns that simulate bone anatomy(Bohl et al., 2019). The concept of modularization in IMR-STF allows for portable, easy-assemble deployment after simple implementation. It is also possible to detach models from PP to conduct further analysis like CT scanning and expert review. Meanwhile, IMR is becoming more affordable. In our IMR-SS prototype, more economical MR devices e.g., Quest3®, can be alternatives to HoloLens2®.

IMR-STF emphasizes data integration between the virtual and physical to provide an immersive learning environment with high-fidelity haptic feedback for psychomotor skill acquisition(Kneebone, 2005). It is well-suited for training on complex open surgery. Based on IMR-STF, these curricula can be easily developed in IMR-SS. Additionally, the direct adoption of real surgical instruments could potentially encourage transfer into real-world practice.

4.3 Training Effectiveness and Experience

Procedural knowledge and operation precision are important factors when assessing surgical training proficiency(Andreatta et al., 2023). Surgical training theories underscore the importance of hands-on practice in mastering procedural knowledge and psychomotor skills(Pakkasjärvi et al., 2024). Our findings show that IMR Group significantly outperformed Control Group in both factors. It may indicate that IMR Group benefited more from IMR-STF than Control Group with the traditional method. It can be attributed to real-time instruction and navigation of IMR-SS, which helped in more accurate placement position and angle determination. Performance evaluation showed that IMR Group could apply visuospatial information during the exercise section to performance evaluation, which is identical to the findings using other immersive training tools(Logishetty et al., 2020).

The experiment design ensured that the training method was the only difference between the two groups. Under identical training time settings and cognitive load, our study demonstrated that IMR learning is more effective than the traditional method. The interaction learning session before the surgical training minimized the impact of technical familiarity on learning outcomes and the baselines of cognitive load, which could otherwise affect learning effectiveness and training immersiveness(Makransky & Petersen, 2021; Nagayo et al., 2022). Moreover, IMR-STF highlights the interactive and immersive training experience to promote training outcomes, which aligns with learning theories that advocate experiential and multimodal learning(Cevallos et al., 2022; Mottrie et al., 2022). IMR Group reported higher satisfaction in learning experience, and confidence in skill acquisition, which are consistent with previous findings on immersive training tools(Gardeck et al., 2020). Immersive training. The combination of immersive training, real-time instruction, and high-fidelity haptic feedback is beneficial to understanding procedural knowledge, enforcing the transform of visuospatial information, and improving both training effectiveness and user experience(Ende, 1983; Nazzal et al., 2023).

4.4 Limitations

Our study has several limitations. We did not include transfer studies on cadavers or in the operating room. However, the use of physical phantoms derived from real cases and authentic surgical instruments in IMR-STF framework could enhance the transferability of acquired skills. Our study focused on the short-term effectiveness of IMR-SS for pedicle screwing. While the learning curve of pedicle screwing has been well described(Gang et al., 2012; Gonzalvo et al., 2009; Park et al., 2018), further study will investigate whether this framework can foster a shorter learning curve. Our study only assessed procedural and operational learning outcomes. Soft tissue handling and non-technical skills such as risk decision-making and teamwork were not evaluated. As they are fundamental skills in surgical practice(Pakkasjärvi et al., 2024; Viglialoro et al., 2021), future research could incorporate emergency event simulations and cooperation management into IMR-STF framework to assess their effectiveness in enhancing these non-technical skills.

Our study investigated the effectiveness of IMR-STF with a prototype IMR-SS on pedicle screwing, a classic procedure in spine surgery(Park et al., 2018). It serves as a successful case for IMR-STF to design curricula for more complex surgeries in IMR-SS. Future research will explore the effectiveness of IMR-STF in a wider range of surgeries to validate its generalizability.

5 Conclusion

In this study, we proposed a conceptual framework IMR-STF for immersive Mixed Reality surgical training and developed IMR-SS for validation. Through a randomized controlled trial, our study validated the effectiveness of IMR-SS in enhancing operation performance and learning experience among medical students.-

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7 Table and Figure Legends

7.1 Tables

Table (1) Baseline and characteristics of participants.

Characteristics	IMR Group	Control Group
Male: Female	7:9	7:9
Undergraduate Year (UGY)		
UGY-2	8	8
UGY-4	3	4
UGY-5	4	5
Experience learning or observing Pedicle Screwing:	0	0
Experience with VR/MR: YES: NO	9:7	8:8
Attitude toward VR/MR: Positive: Negative	16:0	16:0

7.2 Figures:

Figure (1)
The Immersive Mixed Reality Surgical Training.
Framework(STF). The arrows imply the implementation order and the flow of data. The 3 modules are shown in different colours. Hands-on Module in red, Assessment Module in yellow, and Teaching Module in green.

Figure (2)
The experiment design and participant flow. IMR-SS refers to the Immersive Mixed Reality self-training system. PP refers to the physical phantom.

Figure (3)
Box plots comparing the error count, completion rates, and pedicle screw placement angles between the IMR and control groups. The dark areas within the box plots represent the confidence intervals (CI = 95%). The light-coloured horizontal line in the middle of the box plot denotes the median, while the dark horizontal line represents the mean. The scatter points in the box plots indicate the actual values for each sample.

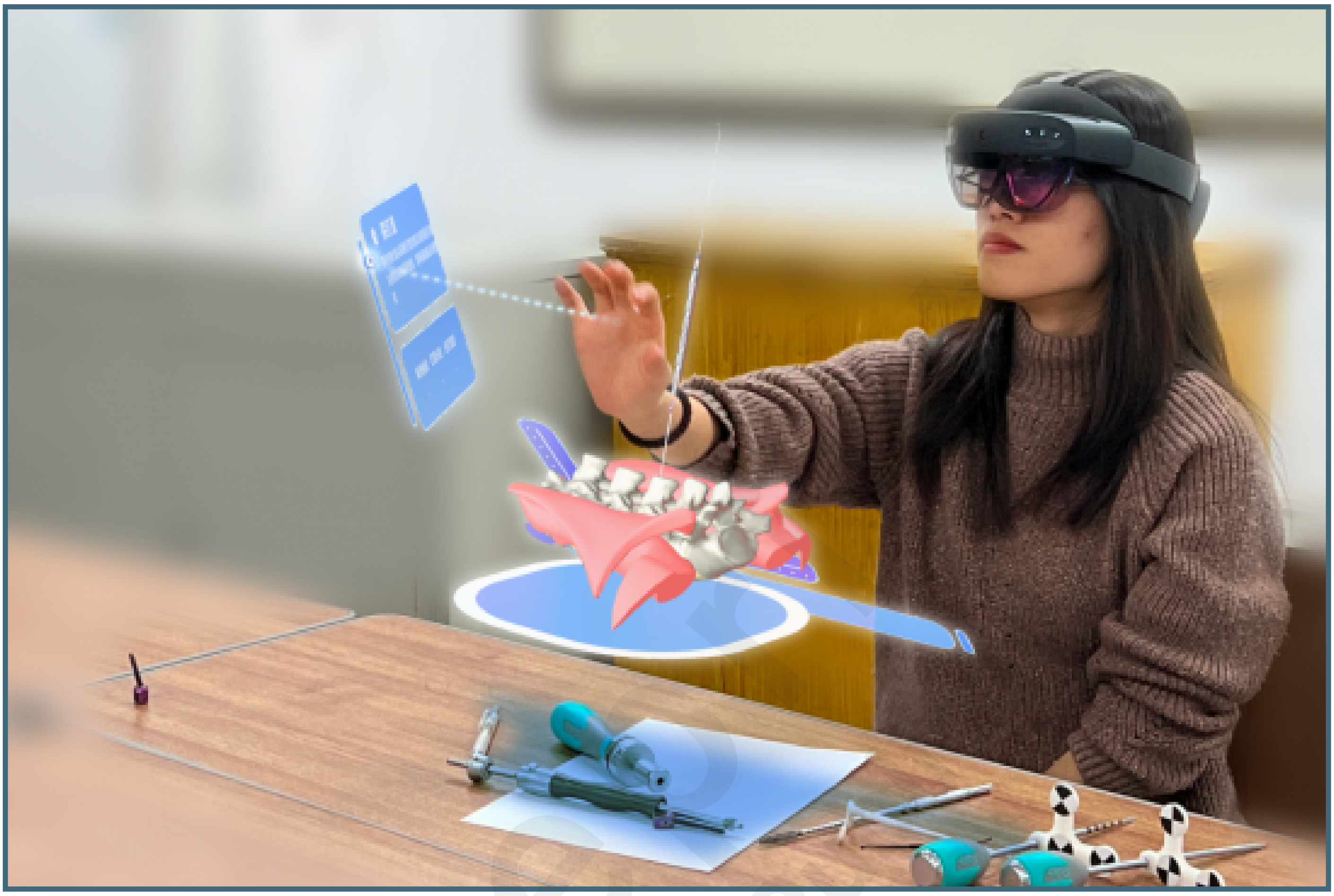
Figure (4)
Error counts statistics for the IMR and control groups. Includes individual values and mean for the IMR group, as well as individual values and mean for the control group. The dark areas within the box plots represent the confidence intervals (CI = 95%). The light-coloured horizontal line in the middle of the box plot denotes the median, while the dark horizontal line represents the mean. The scatter points in the box plots indicate the actual values for each sample.

Figure (5)
Comparison of lateral and transverse angles between the experimental and control groups during the exercise and assessment sessions. The dark areas within the box plots represent the confidence intervals (CI = 95%). The light-coloured horizontal line in the middle of the box plot denotes the

median, while the dark horizontal line represents the mean. The scatter points in the box plots indicate the actual values for each sample.

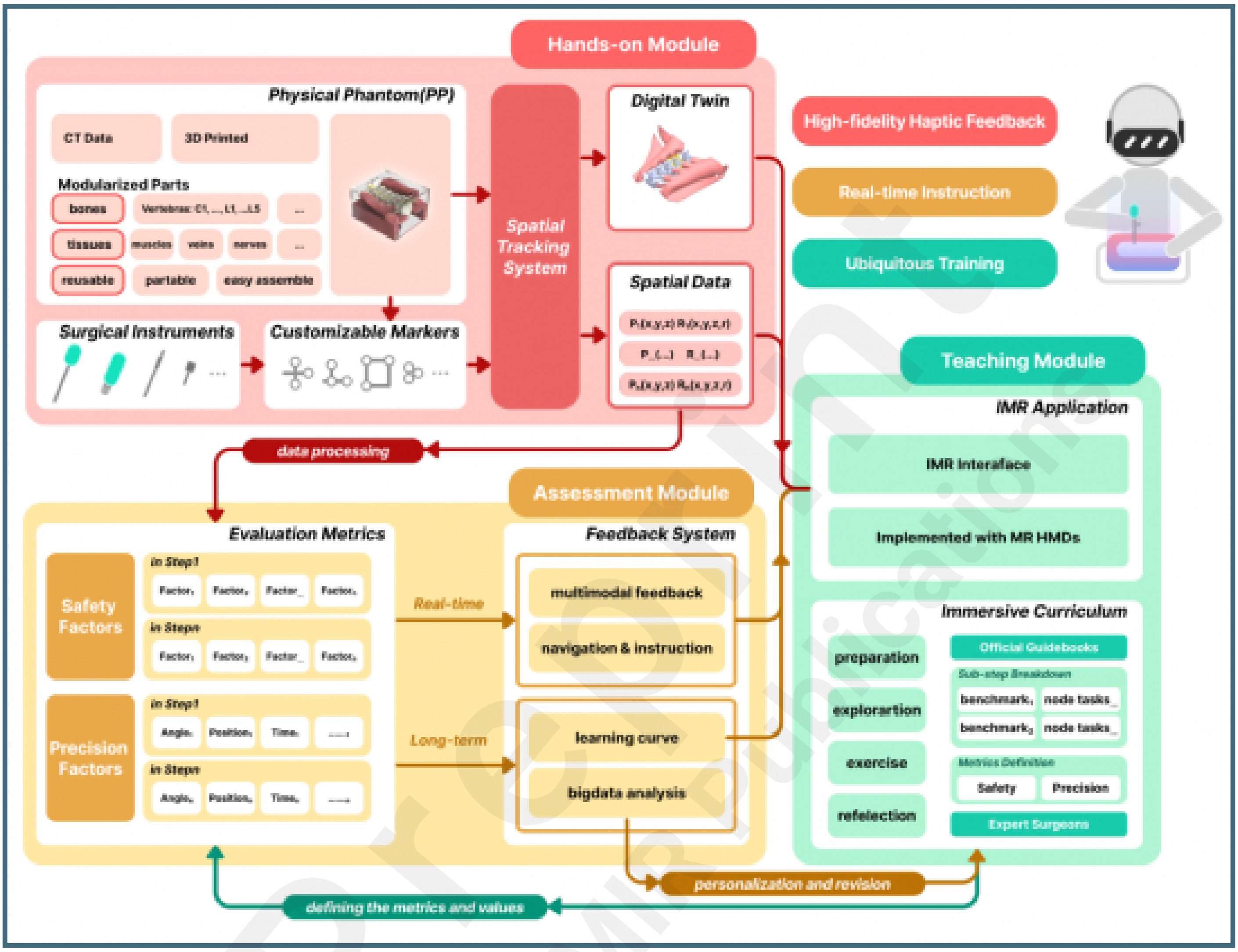
Supplementary Files

Untitled.

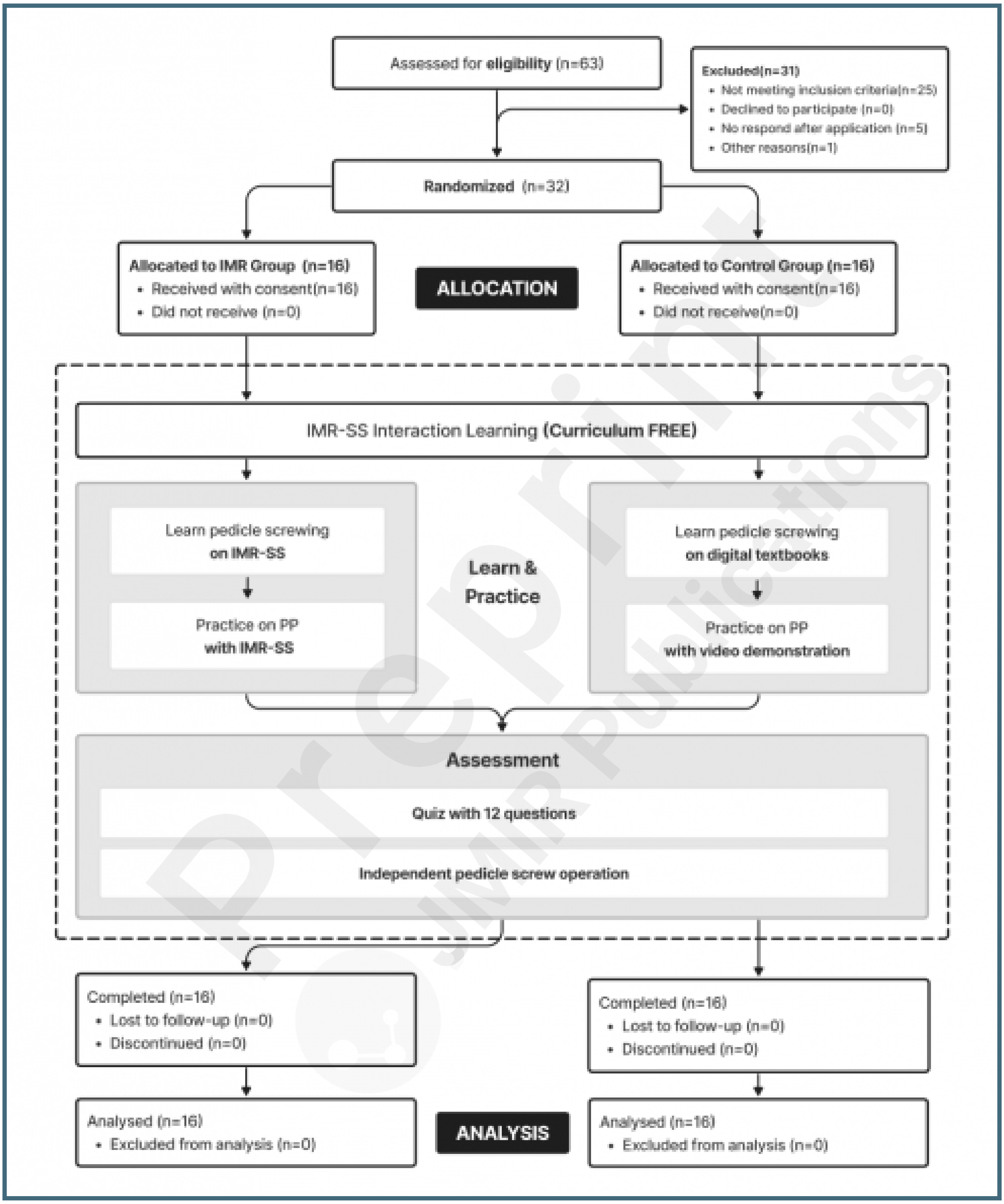


Figures

The Immersive Mixed Reality Surgical Training Framework (STF). The arrows imply the implementation order, and the flow of data. The 3 modules are shown in different colors: Hands-on Module in red, Assessment Module in yellow, and Teaching Module in green.

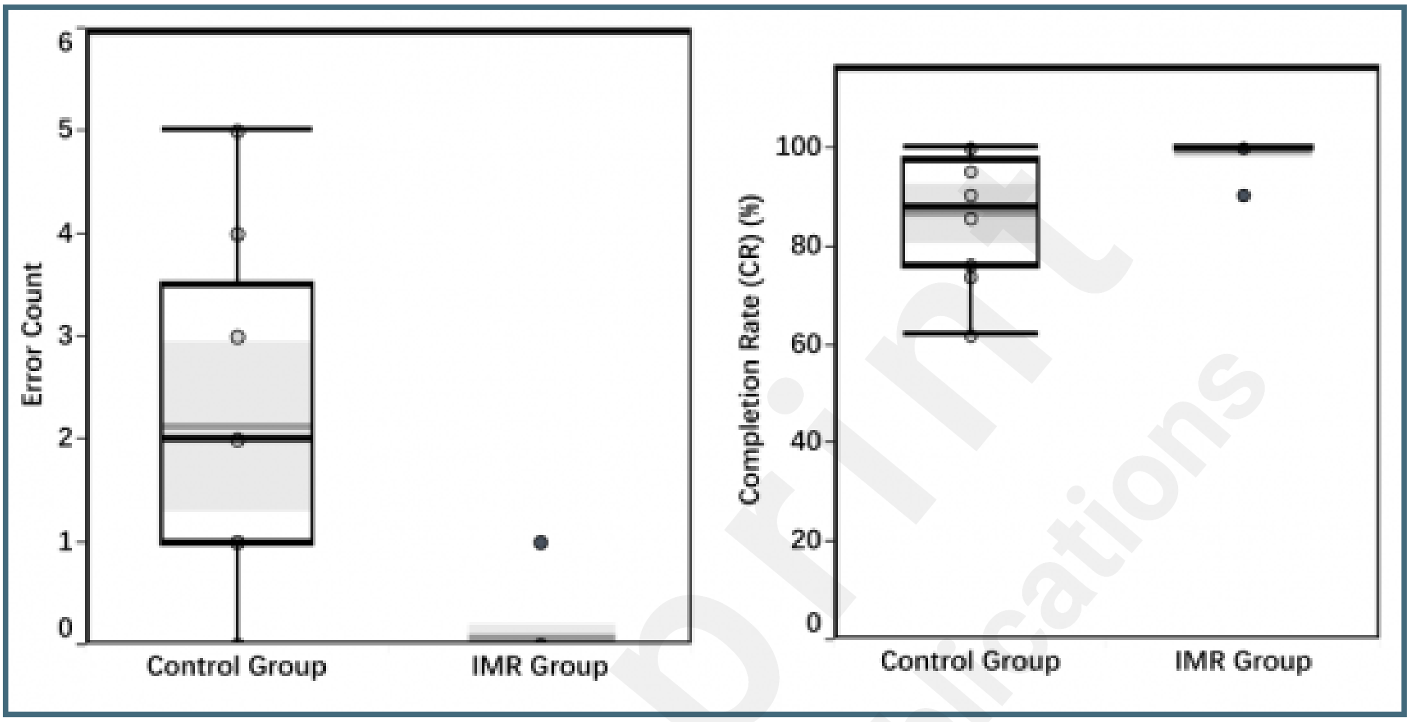


The experiment design and participant flow. IMR-SS refers to the Immersive Mixed Reality self-training system. PP refers to the physical phantom.

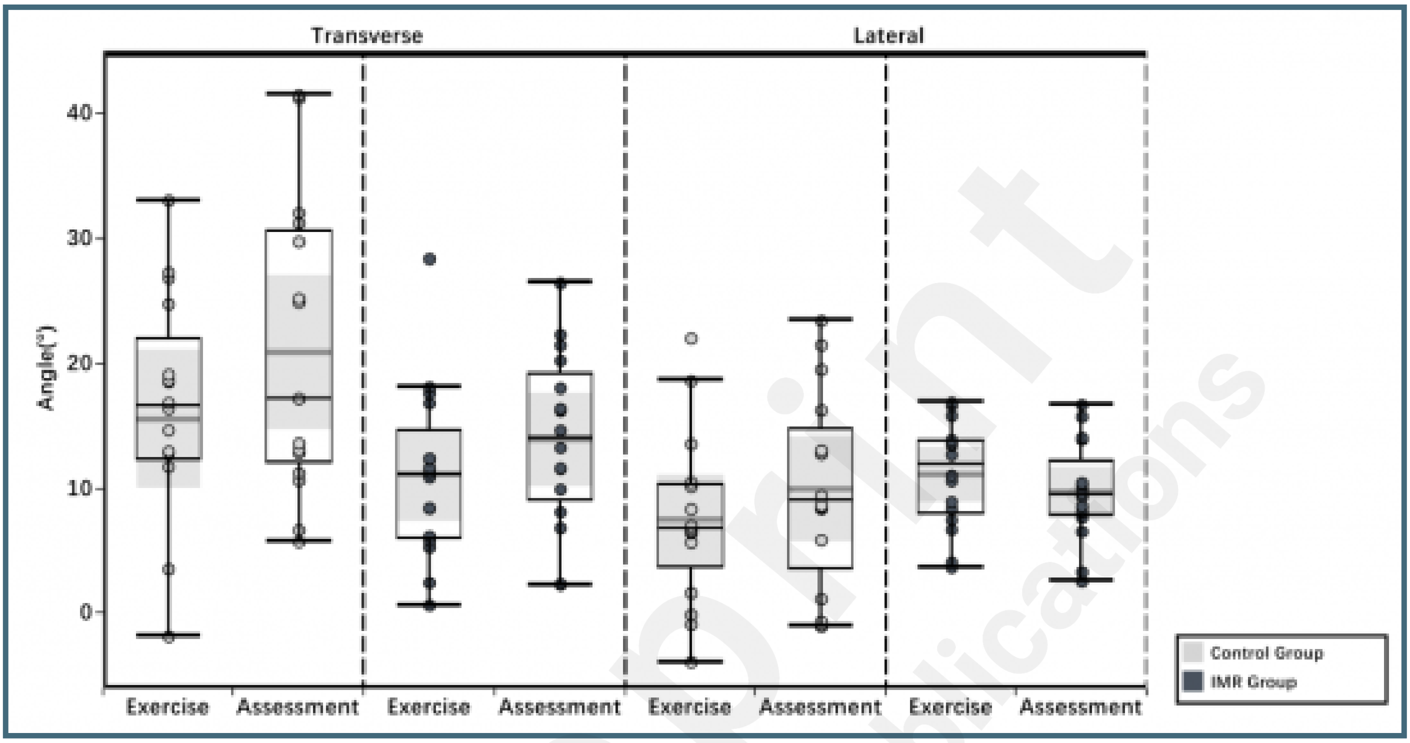


IMR Group Using IMR-SS and Control Group using digital textbook during the experiment sessions.

Error counts and CR for the IMR and control groups. Includes individual values and mean for the IMR group, as well as individual values and mean for the control group. The dark areas within the box plots represent the confidence intervals (CI = 95%). The light-colored horizontal line in the middle of the box plot denotes the median, while the dark horizontal line represents the mean. The scatter points in the box plots indicate the actual values for each sample.



Comparison of lateral and transverse angles between the experimental and control groups during the exercise and assessment sessions. The dark areas within the box plots represent the confidence intervals (CI = 95%). The light-colored horizontal line in the middle of the box plot denotes the median, while the dark horizontal line represents the mean. The scatter points in the box plots indicate the actual values for each sample.



Multimedia Appendixes

Trail dara, figures and a link of quick play of the IMR-SS.
URL: http://asset.jmir.pub/assets/3208fd3b83f13d5432e5f8408621bf34.docx

CONSORT (or other) checklists

Untitled.
URL: http://asset.jmir.pub/assets/4208f1b8f1bee58f9aeb57b8a2598e53.pdf