Mixed Reality Simulator for Orthopedic Surgical Skills Training

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Abstract: Considering the growing need for effective and accessible methods in surgical training, the potential of mixed reality (MR) was explored as an alternative to traditional methods. In pursuit of this goal, an immersive simulator for laparoscopy and arthroscopy was developed, combining virtual environments with gamification techniques. The approach integrates a simulator incorporating clinical exercises and a web platform that allows a training scenario to be customised. The evaluation using the System Usability Scale (SUS) revealed a perception of high usability, accompanied by improvements in the participants' autonomy and training experience. The results demonstrate that MR, together with gamification, is a viable and effective alternative to traditional surgical teaching methods.

1 Introduction

Over the past decade, the demand for effective and accessible surgical training has grown, driven by the increasing complexity of minimally invasive procedures such as laparoscopy and arthroscopy. Traditional methods, including cadaver practice and physical simulators, face limitations such as high costs, logistical challenges, and limited performance assessment, prompting the exploration of immersive technologies to enhance education and patient safety (Ogbonnaya et al., 2025).

Among these technologies, MR emerges as a promising approach by combining virtual and augmented reality to offers interactive environments for repetitive, risk-free training with objective feedback, promoting skill acquisition through immersive, multi-sensory learning (Prasetya et al., 2024).In minimally invasive and orthopedic surgery, the development of fine motor skills and spatial awareness is essential, but traditional training often restricts repetition and dynamic evaluation. Incorporating gamification into MR simulators can increase motivation, engagement, and knowledge retention (Masoumian Hosseini et al., 2023).

The aim of this project is to leverage recent advances in immersive reality technology to develop a MR training simulator, OrthoSim, in order to help medical students refine their motor skills, making training exercises more accessible to them. The system provides interactive virtual surgical exercises, configurable through a web platform, and integrates gamification to enhance engagement and encourage continuous practice.This MR training program offers a virtual environment for safe and accessible surgical training through two exercises. It integrates

gamified activities that foster skill acquisition and user motivation, while a complementary web platform allows exercise management, performance monitoring, and adaptation of difficulty levels.

2 Methods

The development of the OrthoSim MR simulator involved several key considerations, starting with the selection of the hardware platform. After evaluating available options, Meta Quest 3 head-mounted displays (HMDs) were selected for their portability, high-resolution visualization, and native MR support (Vervoorn et al., 2023). The simulator was designed based on the guidelines of an orthopaedic specialist, to reproduce fundamental laparoscopic and arthroscopic training scenarios through two gamified exercises, "Encontrar Objeto" and "Transferência de Pinos".

The simulator was developed using the Unity 3D engine, with C# scripts implementing the simulation logic, scoring system, and event tracking, and 3D assets were modelled in Blender. A complementary web platform, hosted on x10Hosting with MySQL database, enabled exercise configuration, user accounts, and leaderboards.

The system architecture comprised two main components, with the Game Component handling simulation, object spawning and interaction, while the Data Component managing performance data and synchronisation with the web platform (Figure 1) .

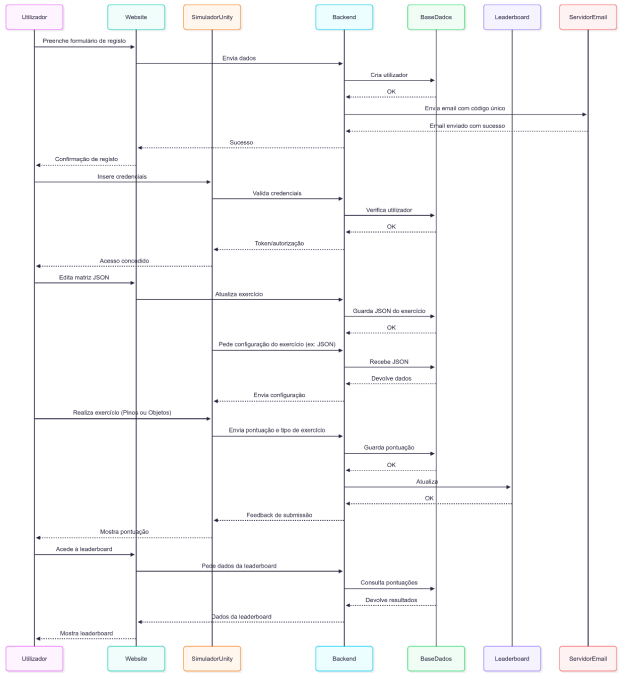

Figure 1: Sequence diagram.

The "Encontrar Objeto" exercise aims to find, using a camera, certain objects (cubes or spheres) of specific colours inside the opaque training dome, locate them in the shortest possible time and keep them focused and framed in the camera for 3 seconds, for a total of 10 repetitions. This exercise was developed to promote visual attention and initial coordination in Meta Quest 3 (Figure 2).

Figure 2: Execution of the exercise "Encontrar Objeto".

Regarding Figure 3, the exercise "Transferência de Pinos" is shown, which focuses mainly on arthroscopy and its initial purpose is to transfer frames from one pin to another inside the opaque training dome using surgical forceps. In the second phase, the user must repeat the process, now transferring the same frames to new empty pins. The entire procedure must be performed with as few errors as possible and in the shortest time possible.

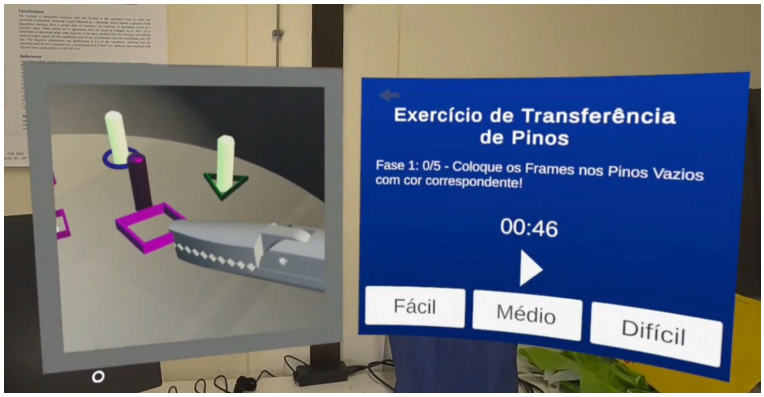

Figure 3: Execution of the exercise "Transferência de Pinos".

This exercise will provide an editing feature through the website (Figure 4), allowing the user to customise its components, such as the position of the pins in the opaque training dome, the type of frame, and the colour and size of the pins. This configuration is done through the developed website, where it is also possible to select the desired level of difficulty for the exercise, which differs in the number of components required. For the easy level, 10 components are required, for the medium level, 20, and for the difficult level, 30.

Figure 4: Editing page for the exercise "Transferência de Pinos" with demonstration.

The scores obtained by users are displayed on the website in leaderboard format, specific to each exercise, allowing performance to be tracked over time. In addition, to ensure a personalised and secure experience, both the website and the simulator require prior user authentication.

3 Results

In the final phase of system validation, following the implementation of the system, functionality and usability tests were carried out to ensure correct operation and evaluate the user experience. The system was tested on different devices, ensuring responsiveness and visual consistency. The usability assessment used the SUS questionnaire, which converts user responses into a score between 0 and 100, classified using the Curved Grading Scale (CGS).

The study involved 11 participants, eight without surgical training and three surgeons, aged between 17 and 50. In the first exercise ("Encontrar Objeto"), all completed the task, with surgeons showing greater naturalness and precision. In the more complex second exercise ("Transferência de Pinos"), none of the non-surgeons succeeded. On the other hand, one surgeon completed it while the others stopped due to time constraints, though all demonstrated superior control, highlighting the simulator's realism and ability to distinguish skill levels.

Regarding the SUS questionnaire (Table 1), the sample obtained an average score of 74.3, corresponding to a B rating, indicative of a good user experience. Surgeons scored higher (78.3, B+) than non-surgeons (72.8, B-). Two participants achieved top scores (82.5, grade A), while the lowest were 62.5 and 57.5 (grade D). Younger users (17–25) averaged 75 points, while the 30–39 group averaged 70; notably, the oldest participant (50) achieved one of the best results, suggesting age is not a limiting factor. These results reinforce that the simulator offers an overall positive experience, with greater suitability and perception of usefulness among the specialised target audience.

Table 1: Percentages of participants' SUS scores

SUS score range	Classification	Percentile range	Number of participants	Percentage (%)
84,1 – 100	A+	96 – 100	0	0
80,8 – 84,0	A	90 – 95	2	18,2
78,9 – 80,7	A-	85 – 89	3	27,3
77,2 – 78,8	B+	80 – 84	1	9,1
74,1 – 77,1	B	70 – 79	0	0
72,6 – 74,0	B-	65 – 69	0	0
71,1 – 72,5	C+	60 – 64	2	18,2
65,0 – 71,0	C	41 – 59	1	9,1
62,7 – 64,9	C-	35 – 40	0	0
51,7 – 62,6	D	15 – 34	2	18,2
0,0 – 51,6	F	0 – 14	0	0

4 Discussion

The evaluation of the OrthoSim system, developed for basic training in laparoscopy and arthroscopy with Meta Quest 3, highlighted its potential as a complementary tool to traditional methods. The SUS questionnaire revealed good acceptance, particularly among surgeons, suggesting that immersion and gamification can enhance motivation and engagement, key factors in practical learning.

The system demonstrated significant advantages in terms of accessibility and portability, enabling training outside specialised facilities and reducing costs. The web platform allowed intuitive parameterisation of exercises, while real-time metrics and leaderboards promoted self-assessment and competitiveness, reinforcing the benefits of gamified training.

However, several limitations became evident, such as the small sample size ($n = 11$),and the lack of haptic feedback restricts sensory realism, which is crucial in minimally invasive surgery. Although controllers provided stable interaction, they fall short of replicating surgical instruments, potentially limiting skill transfer. Further studies with larger, more diverse samples are required to validate effectiveness against traditional methods, while issues such as ergonomics and adaptation to clinical environments also warrant investigation. In summary, despite these limitations, OrthoSim combines accessibility, interactivity, and flexibility, showing strong potential for early-stage surgical training.

5 Future Developments

Based on the limitations identified, future work will include usability evaluation with a larger sample of trainee surgeons to better assess pedagogical effectiveness and guide system improvements. The implementation of QR code authentication (pending Meta Quest 3 update) and an offline login mode is also planned, enabling local storage and later synchronisation of results.

In addition, further developments will expand the range of exercises, covering different surgical areas and levels of complexity. A version for laparoscopic procedures is proposed, with a larger operative field and support for two surgeons, aiming to train both new surgeons and those transitioning from open surgery.

Finally, one of the exercises may be included in a scientific article comparing outcomes between students using the physical simulator and those using the MR simulator, to assess technical skill acquisition.

6 Conclusion

This work contributes to the modernisation of surgical training by demonstrating the potential of MR and gamification in training technical skills. These technologies enable interactive surgical simulations that reinforce practical learning and make training more accessible, affordable and adaptable, while helping to overcome ethical and logistical limitations of traditional methods.

The testing of the system by the target audience showed the potential positive impact of OrthoSim on the positive impact of OrthoSim on acquiring laparoscopy and arthroscopy skills. The usability evaluation, with an average SUS score of 74.3, showed high user satisfaction, particularly among surgical professionals, reinforcing its value as a motivational and safe teaching tool. Nonetheless, larger studies with medical students are needed to further validate its effectiveness.

Although still experimental, the system will undergo optimisations to improve quality and pedagogical relevance. Overall, the objectives were achieved, laying a strong foundation for future development of innovative training tools and reinforcing the value of MR in surgical education.

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