Mixed Reality Game-Based Simulator for Arthroscopy Skills Training

Marta Tedim, Gil Araújo, Adélio Vilaça, Luis Coelho, and Renato Magalhães

ISEP, Polytechnic of Porto, Porto, Portugal
ICBAS - Santo António Clinical Academic Center, Porto, Portugal
INESC TEC , Institute for Systems and Computer Engineering Technology and Science, Porto, Portugal
LabRP-CIR - Psychosocial Rehabilitation Laboratory - Center for Rehabilitation Research, ESS, Polytechnic of Porto, Porto, Portugal
School of Medicine and Biomedical Sciences (ICBAS), University of Porto, Porto, Portugal
Correspondence: rfm@ess.ipp.pt

DOI: *https://doi.org/10.17979/spu.23.c30*

Abstract: The acquisition of arthroscopic surgical skills remains a significant educational challenge due to the technical complexity and limited accessibility of traditional training methods, which often entail high costs, ethical concerns, and low interactivity. This study presents a Mixed Reality (MR) game-based simulator, developed in Unity for the Meta Quest 3, aimed at enhancing arthroscopy training. The core task involves navigating a virtual maze using simulated surgical instruments, replicating the visuomotor coordination required in real procedures. A study with ten participants assessed usability, engagement, and perceived workload. Results indicated high satisfaction with the intuitive interaction, reinforcing the simulator's potential as an effective and accessible training solution.

1 Introduction

Surgical training has traditionally relied on the use of anatomical models, cadavers, and real patients as the primary methods of instruction. Despite their historical significance, these approaches present considerable limitations, including limited availability, high costs, ethical concerns, and the inherent risks associated with practice in real clinical settings Goh et al. (2021); Mandal and Ambade (2022); Qi et al. (2024). The evolution of digital technologies has fostered the emergence of the concept of Extended Reality (XR), which encompasses three distinct modalities: Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) Walsh and Pawlowski (2002). VR immerses the user in a fully simulated environment, disconnected from the physical world Toni et al. (2024); AR overlays digital layers of information onto the real environment Arena et al. (2022); and MR combines both paradigms, enabling real-time coexistence and interaction between physical and virtual objects Toni et al. (2024). In the field of arthroscopy, the acquisition of technical skills poses additional challenges for surgical trainees. Major obstacles include the restricted operative field, the two-dimensional visualization of anatomical structures, the absence of haptic feedback, and the demand for high visuomotor coordination Jonmohamadi et al. (2020). In this context, medical simulation plays a strategic role by enabling repeated practice in safe and controlled environments, thereby supporting progressive, problem-based, and competency-oriented learning Jones et al. (2015). In parallel, gamification, the application of game mechanics to non-entertainment contexts Tung et al. (2024), has demonstrated a positive impact on motivation, engagement, and learning effectiveness. The integration of gamification principles into immersive simulators for surgical training therefore represents an opportunity to overcome the limitations of traditional methods and to enhance skill development in minimally invasive surgery (Tung et al., 2024). Within this framework, a MR simulator with integrated gamification techniques was developed, consisting of navigating a virtual maze using simulated surgical instruments. The prototype was evaluated through an experimental study aimed at assessing its usability, engagement, and perceived workload.

2 Methods

The simulator developed was inspired by the maze exercise of the Advanced FAST Program Nicandri, Gregg (2019). The software can be divided into two components: the Mixed Reality application and the supporting Web application.

2.1 Web Application

The WebApp was designed to provide functional support to the MR-based game, enabling the creation, management, and sharing of training scenarios. The application allows users to generate mazes, store them in a database, and edit or delete them as needed. In addition, it offers the possibility of creating universal game sessions, specifically conceived for educational contexts in which, for instance, an instructor may require all students to complete the same exercise with identical parameters, thereby ensuring uniformity and comparability of results.

On the home page, Figure 1, the user encounters a simple menu enabling the creation of a new maze, the configuration of a game, or the management of previously saved mazes. When accessing "Criar Labirinto", Create Maze,Figure 2, the user must configure three essential parameters: maze size (20×20, 40×40, or 60×60), wall height (1 to 5), and a unique maze name, in order to create and store it in the database. In the "Criar Jogo", Create Game, section, Figure3, the user must define the maze, set the ball size (small, medium, or large), and choose between two gameplay modes: Infinity Mode, without a time limit, or Expert Mode, with a duration of three minutes. The game created in this section is universal, allowing different users in the MR application to play exactly the same scenario.

Finally, in the "Gerir Labirintos", Manage Mazes section, Figure 4, a list of all scenarios stored in the database is displayed, with the option to edit or remove each one, thus ensuring the flexibility required to adapt exercises to training needs.

Figure 1: Home page "Menu".

Figure 2: "Configuração do Labirinto", Maze Configuration, Page.

Figure 3: "Configuração do Jogo", Game Configuration, Page.

Figure 4: "Gestão de Labirintos", Manage Mazes, Page.

2.2 MR Application

The prototype was developed in Unity 3D and implemented on the MetaQuest3 device Unity Technologies (2025). Users can choose to play in a predefined maze, set within the Web application, or select a specific maze. If the latter option is chosen, the user must also define the ball size and game mode Figure 5.

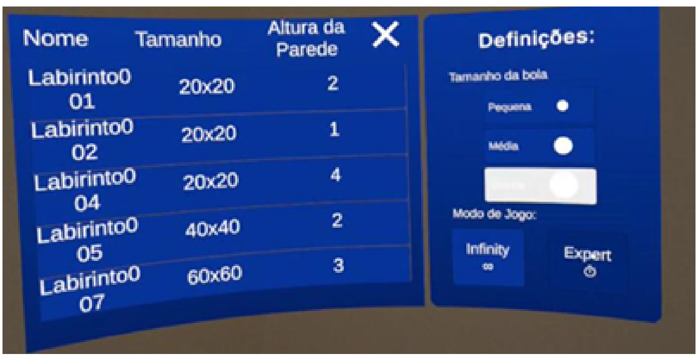

Figure 5: Game's Inicial Menu.

Upon entering the game environment, Figure 6, the user is presented with a menu displaying relevant information, including the game title, selected mode, current score, and a timer. In Infinity Mode, the timer increments continuously, whereas in Expert Mode, the timer counts down. Additionally, a bell-shaped enclosure contains the maze. The user must navigate the ball through the maze using the available virtual instruments, guided by the arthroscope image displayed on the visualization screen.

Figure 6: Game environment.

Gamification Strategies

The gamification strategies implemented are illustrated in the diagram in Figure 7. As previously mentioned, the serious game offers two modes: Infinity Mode, without a time limit, and Expert Mode, with a duration of three minutes. Upon expiration of the time in Expert Mode, a Game Over occurs.

Within the maze, there are two types of coins: normal coins, colored silver, and special coins, colored gold. Normal coins are distributed in hard-to-reach locations. Collecting a normal coin results in an increment of 100 points to the user's score, and new normal coins appear randomly in other difficult-to-reach locations within the maze. Special coins are positioned at the edges of the maze, and their collection adds 200 points to the user's score.

The user receives a penalty of 100 points if the ball ascends a wall, contrary to the main objective of the serious game. If the ball surpasses a wall and exits the maze, a Game Over occurs, which also happens if the user's score falls below zero.

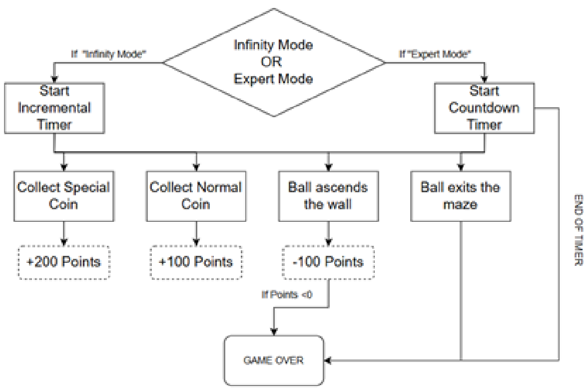

Figure 7: Gamification Strategies Diagram".

2.3 Experimental Study

To evaluate the software developed, an experimental study was conducted with ten participants. They were asked to complete the MR exercise and subsequently explore the Web application freely. All participants performed the task in the same scenario, using the largest ball size in Expert Mode.

After interacting with both applications, participants completed two questionnaires. The first focused on collecting qualitative data regarding the user experience with the MR application. The second was based on the NASA Task Load Index (NASA-TLX), designed to assess the workload perceived by users in both the Web and MR applications.

3 Results

3.1 Sample's Characterization

The sample consisted of ten participants, aged between under 25 and over 50 years, with a balanced gender distribution (four women and six men). Only three participants reported prior experience with XR technologies, while the remaining had never used such applications.

3.2 MR Game's Performance

The main reason for game ending was time expiration, indicating that most participants were able to complete the intended experience. Only one participant ended prematurely due to the ball exiting the maze.

Scores ranged from 0 to 1300 points. The minimum score corresponded to the participant who lost at the very beginning, while the remaining participants achieved results between 200 and 1300, demonstrating different levels of adaptation to the immersive environment. All participants who completed the allotted time achieved at least one game objective, confirming both the playability and the educational potential of the application.

3.3 Questionnaire on the MR Application

Overall, the application was well received by participants. Regarding gameplay, Figure 8, all users understood the game instructions, and no symptoms of cybersickness were reported. Perceptions related to physical comfort and movement accuracy were generally positive, although some participants mentioned initial difficulties associated with the lack of prior experience with XR technologies.

Navigation within the virtual environment was considered clear and intuitive. Most participants rated the visual quality very positively, although they suggested the inclusion of more detailed initial instructions, as shown in Figure 9.

The clarity of the game objectives and the effectiveness of the scoring system received high ratings overall. However, some participants emphasized the need for greater support in identifying and correcting errors during gameplay, as reflected in Figure 10.

According to Figure 11, the application was also considered motivating and engaging by most users, confirming the effectiveness of the gamification strategies implemented. Nevertheless, a small portion of the sample reported that the difficulty level might be unbalanced.

It is important to note that no technical failures were recorded during the sessions, as shown in Figure 12. However, the coupling system of the virtual instruments requires revision.

The overall mean rating assigned to the application was 4.6 out of 5, and all participants expressed interest in repeating the experience. The main suggestions for improvement included: increasing instrument precision, introducing auditory or visual feedback at the end of the game, and clarifying the reasons that lead to failure.

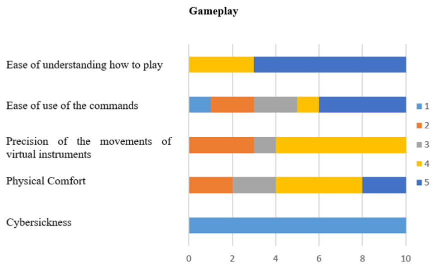

Figure 8: Participants' Responses to the 'Gameplay' Section.

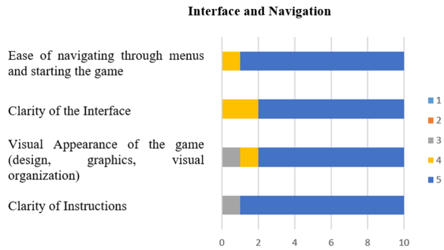

Figure 9: Participants' Responses to the 'Interface and Navigation' Section.

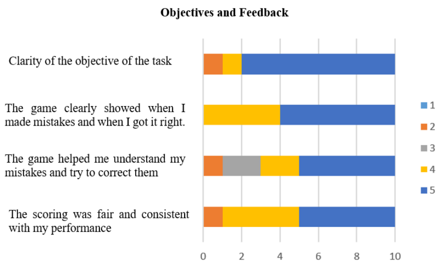

Figure 10: Participants' Responses to the 'Objectives and Feedback' Section.

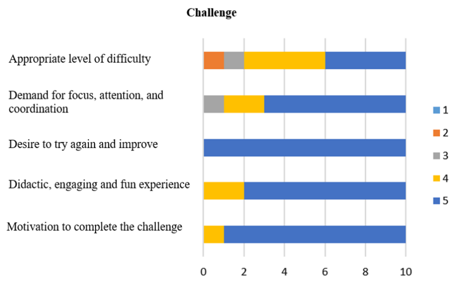

Figure 11: Participants' Responses to the 'Challenge' Section.

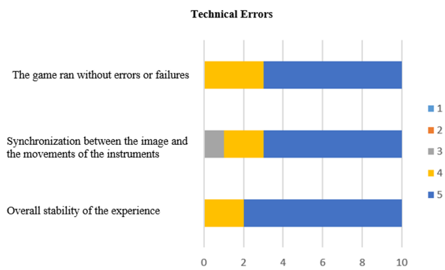

Figure 12: Participants' Responses to the 'Technical Errors' Section..

3.4 NASA-TLX

In the MR application, the mean perceived workload index was 5.98 (on a scale from 0 to 10). Mental effort and temporal demand registered high values (6.1 and 6.2, respectively), reflecting the need for concentration and the time pressure imposed by Expert Mode. Physical effort was considered low (4.9) but varied depending on the positioning of the bell enclosure. Frustration levels were relatively high (6.7), mainly associated with time constraints and the absence of initial instructions.

In the Web application, the overall mean workload index was significantly lower (2.1), demonstrating simplicity and ease of use. Mental, physical, and temporal demands were nearly negligible, while perceived performance was very high (8.7), confirming the effectiveness and clarity of the interface.

4 Conclusion

The present study demonstrated that the MR application features an intuitive interface and clear instructions, which favored its acceptance among participants, with no symptoms of cybersickness reported. The high cognitive load associated with its use, although challenging, proved suitable for stimulating focus, concentration, and mental effort, factors considered relevant for the development of technical skills in surgical contexts. The gamification strategies were shown to be effective, promoting user engagement and reinforcing motivation to improve performance, with all participants expressing interest in repeating the experience.

In contrast, the Web application was found to be minimally demanding in terms of physical and cognitive workload, aligning with its complementary function to the MR application.

Despite the encouraging results, it is important to highlight the limitations of this study, particularly the small sample size and its heterogeneity, which constrain the generalizability of the findings. Future work should include larger and more homogeneous samples, ideally composed of medical students, as well as more rigorous experimental methodologies in order to strengthen the scientific validity of the conclusions.

Regarding future developments, priorities include the implementation of more detailed tutorials, the introduction of multimodal feedback (visual and auditory), improvements in the coupling between instruments and controllers, and the development of a database capable of monitoring user progression and fostering healthy competition through ranking systems.

Bibliography

F. Arena, M. Collotta, G. Pau, and F. Termine. An overview of augmented reality. *Computers*, 11:28, 02 2022. doi: 10.3390/computers11020028.

G. S. Goh, R. Lohre, J. Parvizi, and D. P. Goel. Virtual and augmented reality for surgical training and simulation in knee arthroplasty. *Archives of Orthopaedic and Trauma Surgery*, 141(12): 2303–2312, 2021. doi: 10.1007/s00402-021-04037-1.

F. Jones, C. Passos-Neto, and O. Braghiroli. Simulation in medical education: Brief history and methodology. *Principles and Practice of Clinical Research Journal*, 1:56–63, 09 2015. doi: 10.21801/ppcrj.2015.12.8.

Y. Jonmohamadi, Y. Takeda, F. Liu, F. Sasazawa, G. Maicas, R. Crawford, J. Roberts, A. Pandey, and G. Carneiro. Automatic segmentation of multiple structures in knee arthroscopy using deep learning. *IEEE Access*, PP:1–1, 03 2020. doi: 10.1109/ACCESS.2020.2980025.

P. Mandal and R. Ambade. Surgery training and simulation using virtual and augmented reality for knee arthroplasty. *Cureus*, 14(9):e28823, Sept. 2022. doi: 10.7759/cureus.28823.

Nicandri, Gregg. Aana fundamentals of arthroscopic surgery training (fast) program, Aug. 2019.

Z. Qi, F. Corr, D. Grimm, C. Nimsky, and M. H. A. Bopp. Extended reality-based head-mounted displays for surgical education: A ten-year systematic review. *Bioengineering*, 11(8), 2024. ISSN 2306-5354. doi: 10.3390/bioengineering11080741. URL *https://www.mdpi.com/2306-5354/11/8/741*.

E. Toni, E. Toni, M. Fereidooni, and H. Ayatollahi. Acceptance and use of extended reality in surgical training: an umbrella review. *Systematic Reviews*, 13(1):299, 2024. doi: 10.1186/s13643-024-02723-w.

W. S. Tung, R. Baker, K. Toy, M. Eftekhari, G. Casey, R. Jahani, C. Bono, C. Harteveld, L. Bejarano-Pineda, and S. Ashkani-Esfahani. Gamification and serious games in orthopedic education: A systematic review. *Cureus*, 16(8):e68234, Aug. 2024. doi: 10.7759/cureus.68234.

Unity Technologies. Unity documentation. *https://docs.unity3d.com/Manual/index.html*, 2025. [Online; accessed 10-September-2025].

K. R. Walsh and S. D. Pawlowski. Virtual reality: A technology in need of is research. *Communications of the Association for Information Systems*, 8:296–314, 2002. doi: 10.17705/1CAIS.00820.