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ANALYSIS - EVALUATION - OPPORTUNITIES - KEY DEVELOPMENTS

Extended Reality in Medical Education

Extended Reality (XR)—including Virtual, Augmented and Mixed Reality—is reshaping medical education by providing immersive, interactive tools for anatomy, surgical training, clinical skills and emergency preparedness. These technologies enhance learning, improve outcomes and foster collaboration. Despite challenges like high costs, limited access and lack of standardisation, XR shows strong global growth and potential for personalised, efficient medical training.

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key points

- XR enables immersive simulations that improve medical skill development and clinical competence.
- VR, AR and MR tools are widely used in anatomy, surgical training and emergency preparedness.
- Studies show XR shortens learning curves and boosts confidence in complex medical procedures.
- Cost, access, standardisation and user resistance hinder widespread XR integration in education.
- XR supports personalised, interactive and collaborative learning across healthcare professions.

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Introduction

Medical knowledge is evolving at an unprecedented pace, creating a growing need for innovative tools that enhance both medical education and practice. Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR) and other immersive technologies, represents a cutting-edge approach to simulation-based training. Research in various fields, such as healthcare, education and crisis management, indicates that immersive technology can significantly improve learning experiences, promote cooperation and foster creativity among learners.

Current Landscape of Extended Reality in Medical Education

The analysis of existing research reveals that VR is the most frequently discussed immersive technology, followed by AR and MR. VR's prominence in simulation and training contexts is well-established, while AR and MR are gaining importance, particularly in surgical training. The focus on medical students and surgeons highlights the relevance of immersive technologies in educational and professional development. However, there is a notable gap in studies addressing medical specialities such as orthopaedics and neurosurgery, suggesting a need for further exploration of these areas.

The Promise of Extended Reality

XR technologies have shown significant potential in revolutionising medical training. VR creates fully

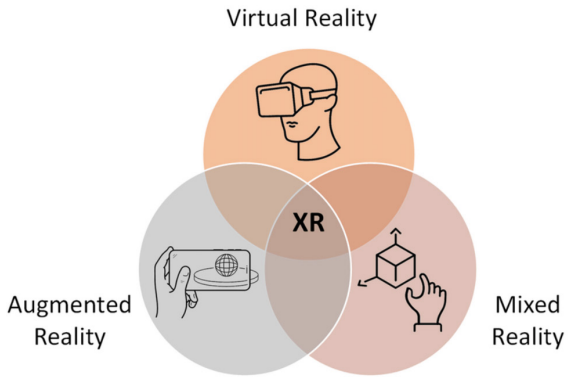

Figure 1. Definition of realities. Source: Janiszewski et al., 2021.

immersive environments where medical students can practice procedures repetitively, refining their skills without the risk of harming patients. AR overlays digital information onto the real world, aiding in the visualisation of anatomical structures and surgical procedures. MR combines elements of both VR and AR, allowing for interaction with both physical and digital objects in real time, which is particularly useful in surgical simulations.

- **Clinical Skills Development:** XR is also used to develop clinical skills, such as patient interaction and diagnostic procedures. Simulations can recreate various clinical scenarios, allowing students to practice and refine their skills in a controlled setting. This is particularly beneficial for developing soft skills, such as communication and empathy, which are crucial for patient care.
- **Emergency Medicine:** In emergency medicine, XR simulations prepare medical first responders for crisis situations. These simulations can replicate high-stress environments, helping responders develop the necessary skills to manage real-life emergencies effectively. By practicing in a virtual environment, responders can improve their decision-making and procedural skills, which are critical in emergency situations.

Challenges and Limitations

Despite its potential, the integration of XR in medical education faces several challenges:

> "Immersive technology can significantly improve learning experiences, promote cooperation and foster creativity among learners."

Current Applications and Benefits of XR Technologies in Medical Education

- **Anatomy Education:** XR technologies, especially AR, have been widely adopted in anatomy education. Tools like Microsoft's HoloLens allow students to visualise and interact with 3D models of the human body, enhancing their understanding of complex anatomical structures. This interactive approach helps bridge the gap between theoretical knowledge and practical application, making learning more engaging and effective.
- Surgical Training: VR simulators provide a risk-free environment for surgical training. Surgeons can practice intricate procedures, such as laparoscopic and neurosurgery, improving their precision and confidence. Studies have shown that VR training can significantly reduce the learning curve and improve surgical outcomes. For instance, VR platforms can simulate various surgical scenarios, allowing trainees to develop their skills in a controlled setting and receive immediate feedback on their performance.

- **Technical Limitations:** High-quality XR experiences require advanced hardware and software, which can be expensive and technically demanding. Ensuring smooth and realistic simulations is crucial for effective training. Technical issues, such as latency and motion sickness, can also affect the user experience and limit the effectiveness of XR training.
- **Accessibility:** The cost and availability of XR technologies can limit their widespread adoption, particularly in resource-constrained settings. Efforts are needed to make these technologies more accessible to a broader audience. This includes developing cost-effective solutions and providing training and support to educators and students.
- **Standardisation:** There is a lack of standardised protocols and guidelines for the use of XR in medical education. Establishing best practices and ensuring consistency across different training programmes is essential. This will help ensure that XR technologies are used effectively and that the training provided is of high quality.

- **User Acceptance:** Resistance to new technologies can be a barrier. Educators and students need to be convinced of the benefits of XR and trained to use these tools effectively. Overcoming this resistance requires demonstrating the effectiveness of XR in improving learning outcomes and providing ongoing support and training.

To support the discussion of XR's potential and limitations, a bibliometric analysis was conducted to assess how systematic reviews have addressed the integration of XR technologies into medical education. The study aimed to synthesise findings from multiple systematic reviews to provide a comprehensive overview of the current state of research, identifying trends, gaps and potential areas for future investigation.

Bibliometric Study of Systematic Reviews on XR in Medical Education

Methodology

The analysis followed the PRISMA guidelines for systematic reviews, ensuring a rigorous and transparent selection process. The search strategy involved combining key terms related to XR technologies and medical education across several databases, including PubMed, Web of Science, EBSCO, ScienceDirect and Embase. The inclusion criteria were strictly defined to focus on systematic reviews involving medical students, surgeons and other relevant healthcare professionals. 44 articles were included.

Results

- **Publication Trends:** The study identified a significant increase in the number of systematic reviews on XR in medical education from 2016 onwards, with a peak in 2021. This surge is attributed to the COVID-19 pandemic, which necessitated innovative educational solutions.
- **Populations Studied:** The majority of the reviews focused on medical students (54.5%) and surgeons (29.5%), highlighting the importance of XR technologies in both initial training and ongoing professional development.
- **Areas of Focus:** Surgery was the most frequently studied area, followed by medical education and anatomy. This indicates a strong interest in using XR for surgical training and anatomical education.
- **Technologies Used:** Virtual reality (VR) was the predominant technology discussed in the reviews (75%), followed by augmented reality (AR) (36%). Mixed reality (MR) and extended reality (XR) were less frequently mentioned, suggesting these technologies are still emerging in the field.

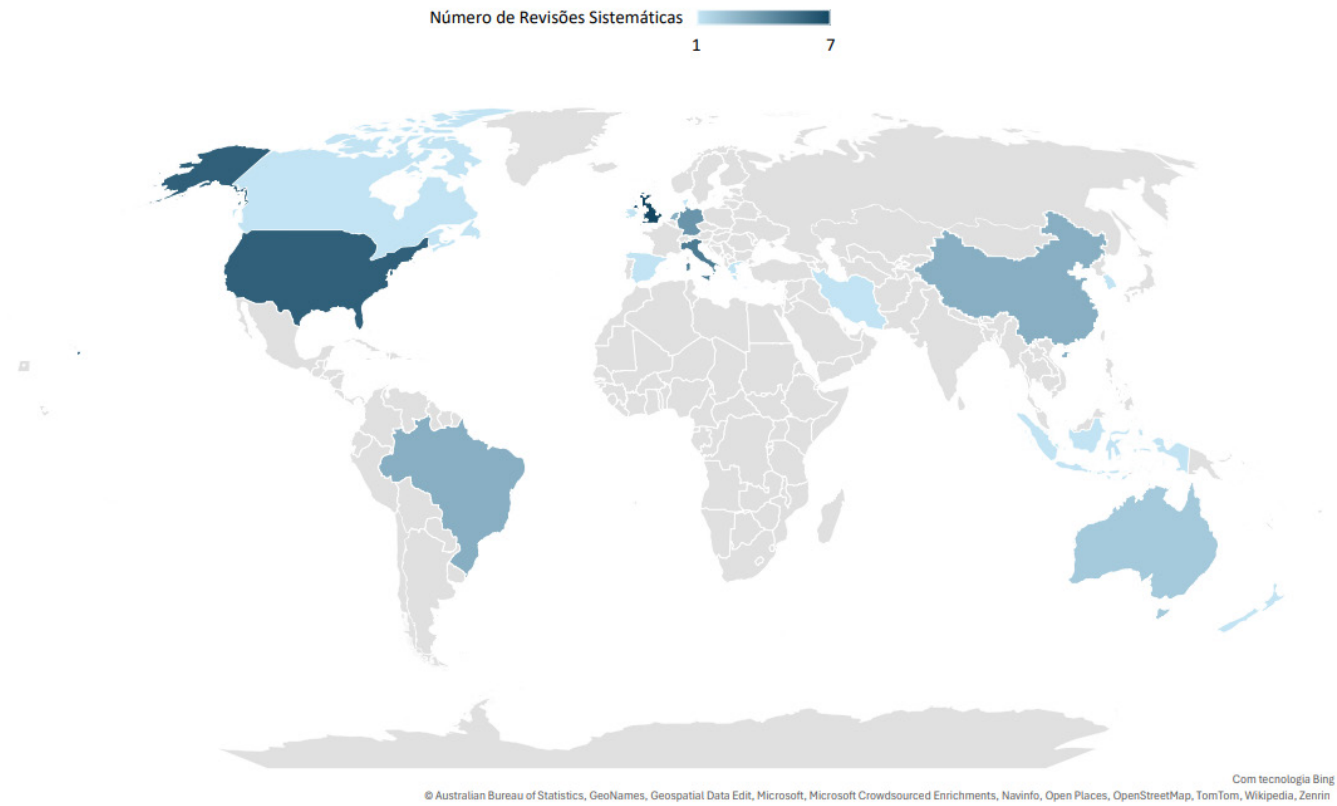

Figure 2. Geographic distribution of the included systematic reviews

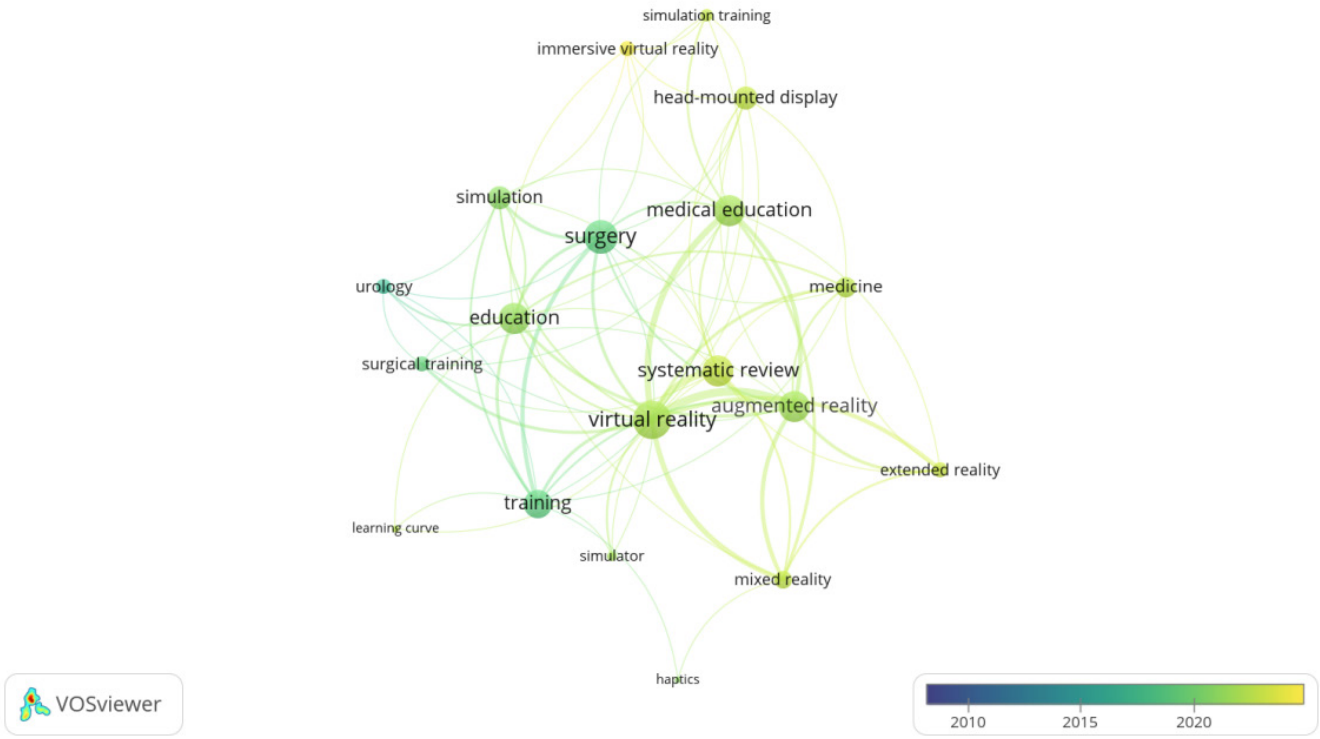

Figure 3. Chronological network of VOSviewer keyword co-occurrences with at least 2 occurrences in the set of studied publications.

- **Geographical Distribution:** The United Kingdom, the United States and Italy were the leading countries in terms of the number of publications. This reflects substantial investment and interest in XR technologies in these regions.
- **Meta-Analysis:** Only 14% of the systematic reviews included a meta-analysis, indicating a need for more rigorous statistical synthesis in future research.

Evaluation of XR Tools: An Essay

Extended Reality (XR) technologies, encompassing Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR), have emerged as transformative tools in medical education. These technologies offer immersive and interactive environments that enhance learning experiences, promote cooperation and foster creativity among learners. This essay critically evaluates various XR tools designed for medical education, focusing on their features, specifications and potential impact on medical training and practice.

> "VR training can significantly reduce the learning curve and improve surgical outcomes."

The analysis reveals a growing interest in XR technologies for medical education, particularly in surgical training and anatomy. However, there are notable gaps in research on specific medical specialities and the use of MR and XR technologies. Future studies should explore these areas to provide a more comprehensive understanding of the potential applications and benefits of XR in medical education.

In addition to reviewing the existing literature, a practical evaluation was carried out to examine the functionality and usability of selected XR applications currently used in medical education settings.

Overview of XR Tools

The integration of XR in medical education represents a cutting-edge approach to simulation-based training. A comprehensive evaluation of XR tools reveals a predominance of functional software compatible with Microsoft HoloLens and Meta Quest devices, which account for 62% of the market. Apple Vision Pro and

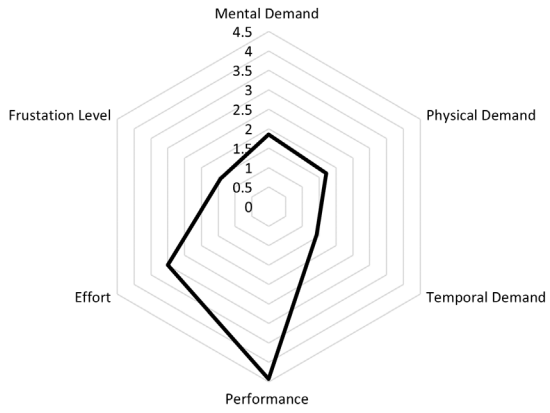

Figure 4. Radar chart summarising NASA-TLX results.

Magic Leap devices have a lower compatibility with the applications studied, each representing 13% of the market.

Medical Fields Targeted

Anatomy is the most targeted medical field, with 44% of applications focused on this area, followed by 26% dedicated to surgical purposes. The emphasis on anatomy-related software underscores its fundamental role in medical education, while the significant presence of surgical applications highlights the necessity for simulation and planning tools to enhance surgeons' skills and improve patient safety. Orthopaedics accounts for 15% of applications, benefiting from 3D visualisation and simulation for diagnosis and treatment planning.

Technologies Used

The technologies used in the studied software predominantly fall into virtual reality (37%) and mixed reality (36%), indicating a strong preference for immersive virtual experiences and interactive environments. Augmented reality also has a significant presence (27%), proving useful in simulation and teaching.

Geographical Distribution

The United States dominates the market, accounting for 62% of the tools developed, likely due to substantial investment in research and development. Germany follows with 9%, making it the second-largest contributor. Other countries, including Canada, Slovenia, Japan, Belgium, the United Kingdom and Switzerland, each represent 4-5%, reflecting global interest in the development of these technologies.

Software Launch Timeline

From 2016 to 2024, the highest number of software launches occurred in 2019, representing 28% of the applications studied. There was a significant increase in new applications from 2016 to 2019, followed by a sharp decline in 2020 and 2021, likely due to the onset of the pandemic and reduced productivity. A recovery was observed in 2022, with 14% of the applications introduced, followed by a decrease in 2023 and 2024.

Testing of XR Tools

Seven applications offering a free trial period were selected for testing on HoloLens 2 or Meta Quest 3 devices. The evaluation focused on user interface intuitiveness, available functionalities, realism, task efficiency and user fatigue.

Virtual Reality Applications

- **Human Anatomy VR:** Enables manipulation of anatomical structures with detailed captions and descriptions. Its immersive nature may lead to user fatigue with prolonged use.

> "The future of XR in medical education looks promising, with ongoing advancements aimed at overcoming current limitations."

- **Body Map:** Features an intuitive interface and detailed descriptions, including insertions and innervations of anatomical structures. Allows assessments and analysis of CT scans, X-ray images and real anatomical images.
- **Oxford Medical Simulation:** Provides patient communication training and diagnostic assessments using virtual patients. Lacks high realism; prolonged use can lead to significant fatigue.

Augmented Reality Applications

- **OpenSight:** Excels in clinical utility, particularly for visualising patient data. Uses patented technology to overlay holograms on patients for preoperative surgical planning.
- **Medicalholodeck:** Creates immersive medical scans for manipulation and study from various angles. Facilitates direct comparisons between medical images and anatomical models.

Mixed Reality Applications

- **Mimics Viewer XR:** Provides 3D model visualisation for surgical planning, enhancing depth perception for personalised treatments. Offers broad functionality with minimal fatigue.
- **HoloAnatomy:** Innovative experience for exploring human anatomy without cadavers, featuring over 8,500 anatomical models. Promotes collaboration among students.

Comparative Analysis of HMD Devices

Both HoloLens 2 and Meta Quest 3 headsets were assessed for their effectiveness in manipulating virtual objects. Meta Quest was found to be easier to learn, more responsive and more efficient than HoloLens, leading to superior visualisation and faster task performance. This advantage stems from Meta Quest's motion controllers, which offer greater precision compared to HoloLens's gesture controls.

Evaluation of HoloAnatomy

To evaluate the feasibility of HoloAnatomy using HoloLens 2, seven healthcare professionals completed two questionnaires assessing its effectiveness in teaching anatomy. The NASA-TLX methodology was used to measure subjective mental workload, revealing generally low mental and physical effort. A second questionnaire provided a detailed analysis of user experience, indicating that the tool was intuitive, user-friendly and efficient for anatomy-related tasks.

The evaluation of the HoloAnatomy software assessed both cognitive and physical demands, revealing a generally low mental effort, as 43% of respondents rated mental demand as very low (1). Physical demand was similarly minimal, with 85.8% of participants rating it as 1 or 2. Most respondents perceived the pace of tasks as relaxed, and performance feedback was overwhelmingly positive, with 57.1% rating the application's efficiency at 4 or 5.

Subsequently, the evaluation of HoloAnatomy revealed that it features an intuitive interface, requiring minimal physical and mental effort from users, resulting in excellent performance in the study of anatomy. However, it is more suitable for individual study rather than classroom application, offering a valuable complement to practical classes in anatomical theatres. The high cost of HoloLens 2 presents a barrier to its application in education.

Future Directions

The future of XR in medical education looks promising, with ongoing advancements aimed at overcoming current limitations. Key areas of focus include:

- **Enhanced Realism:** Improving the realism of XR simulations through better graphics, haptic feedback and AI-driven interactions will make training more effective and engaging. Advances in technology will enable more realistic and immersive simulations, enhancing the learning experience.
- **Interoperability:** Developing interoperable XR systems that can integrate with existing medical education platforms and electronic health records will streamline training processes and enhance learning outcomes. This will enable seamless integration of XR technologies into the existing educational infrastructure.
- **Personalised Learning:** Leveraging data analytics and AI, XR can offer personalised learning experiences tailored to individual student needs, tracking progress and providing targeted feedback. This will help ensure that each student receives the support and training they need to succeed.
- **Collaborative Learning:** XR can facilitate collaborative learning experiences, allowing students and professionals from different locations to interact and learn together in a shared virtual environment. This will enable more effective teamwork and communication, which are essential skills in healthcare.

Taken together, the findings from both the literature review and empirical evaluation demonstrate that XR technologies offer substantial promise for enhancing medical education. While their effectiveness is well supported in areas such as anatomy and surgical training, challenges related to access, standardisation and cost remain critical factors to be addressed with the development of these tools.

Conflict of Interest

None

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