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RESEARCH INVENTION JOURNAL OF RESEARCH IN MEDICAL SCIENCES 4(2):80-87, 2025

©RIJRMS Publications

ONLINE ISSN: 1115- 6198

Print ISSN: 1597-3107

https://doi.org/10.59298/RIJRMS/2025/428087

Virtual Reality for Medical Training: Engineering Realistic Simulations

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ABSTRACT

As virtual reality (VR) technology continues to evolve, its integration into medical training has emerged as a powerful tool to supplement traditional methods. Historically limited by the costs and logistics of manikin-based simulations, medical education is now being transformed through immersive, interactive VR environments. This paper examines the growing role of VR in medical training, discussing its historical context, system types, educational applications, and technical challenges. It introduces the Build Reality framework, a practical guide to designing and deploying VR-based medical simulations. Key aspects such as simulation fidelity, user experience, and performance assessment are critically examined. Through case studies and a review of current trends, the paper highlights VR's potential to enhance procedural knowledge, reduce training costs, and democratize access to quality medical education. By focusing on design principles, system compatibility, and evaluation metrics, this work contributes to the strategic integration of VR in health professions education.

Keywords: Virtual Reality, Medical Education, Simulation-Based Training, Immersive Technology, Build Reality Framework, Mixed Reality.

INTRODUCTION

As technology continues to advance, so too does the exponential growth of virtual reality (VR). VR combines hardware and software to create immersive experiences that make one feel as though they are present inhabiting a simulated world, even though they are in a different, real-world location. Traditionally, VR has seen entertainment applications but is now entering a new field: medical education and training. Manikin-based simulation of medical procedures is an effective and important teaching method in medical school curricula, allowing trainees to practice individually or collaboratively in a safe environment. However, it is resource-intensive, requiring dedicated space, extensive and expensive hardware and equipment, and trained personnel such as simulation specialists and simulation technicians, and therefore not usable at all institutions. Currently, in the wake of the COVID-19 pandemic and the rise of distance learning, VR-based simulation of medical procedures is emerging as a new mode of delivery. Even without a manikin, VR can still create experiences resembling a manikin-based simulation, but in a computer-generated, 3D environment. Compared to conventional 2D video-based methods of simulation, VR is often more immersive and more effective at engaging the user. Although VR technology itself is relatively recent, there is currently much interest in its use in medical training. Medical VR-based training has the potential to transform how simulations and case scenarios are delivered in medical education, allowing for a more standardized means of educational delivery. In this paper, we will outline the BUILD REALITY framework, which contains suggestions for immersive design principles, and interactively demonstrate our experience of creating a medical VR simulation [1, 2].

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History of Medical Training Technologies

The advancement of technology has transformed the way the world learns and teaches new content. Delivery methods using the internet are gaining popularity as they can be accessed anywhere, and the hands-on nature of simulations is effective in knowledge retention. This change also affects medical education, which is traditionally based on classes and lectures followed by clinical training under the supervision of broadly trained medical professionals. While this system is proven to be highly effective, current medical education has its drawbacks, such as increased misalignment with the demands of clinical functioning, long schooling time, shortages in medical personnel, and the biases or outdated practices of senior personnel. As a result, manikin-based simulation is desired by medical regulators as a novel teaching modality to help standardize the classes and make the teaching method uniform. However, the gold standard of clinical training is believed to be resource-intensive. Manikin-based simulation requires dedicated space, equipment, and personnel to run simulation sessions for the medical trainees. A learning measure must be built into the simulation to justify the expenses and provide evidence that the students have become better medical professionals. However, building a realistic computer-based environment is difficult and requires not only unreasonably high resources but also programming expertise not found in a medical environment. Additionally, dedicated space is often not available for computer-based simulation, limiting this flexible teaching method. Virtual reality is emerging as a new, flexible method of delivering simulation sessions. The rising popularity of gaming devices and their affordable price point, thereby the creation of decently convincing VR environments, have afforded new possibilities to deliver reproducibly standardized sessions to the education of educators. VR-based learning material should also be considered in the implementation and could use the developing interest in self-driving, remote, or web-based simulations [3, 4].

The Role of Simulations in Medical Education

Simulations have been used across various fields since the 1960s, offering realistic and immersive experiences while minimizing real-world risks. Medical education has embraced these technologies as they developed, encompassing a range from simple narratives to complex 3D scenarios in virtual environments. Initially, 'simulation' referred to non-existent real situations emulated with various devices. The rise of computer technology enabled more realistic and programmable simulations, expanding their use in medical training and assessment. Medical simulations can be classified into low, medium, and high fidelity. Low-fidelity simulations involve scripted scenarios featuring multimedia and interaction with actors or non-player characters; a basic example is a narrated presentation. Medium fidelity blends live actors with technology, typically seen in training centers with simple cases. High fidelity simulations, involving robotic patient models, require extensive setup and collaboration among professionals. Training through simulation allows medical trainees to acquire necessary skills safely, especially when real clinical exposure is limited. Surgical simulators have historically been low-fidelity task trainers, but an educational institution outside a medical university has developed a center of excellence with multi-fidelity simulations addressing traditional training gaps. This includes individual task trainers and interactive 2D scenarios, culminating in a programming engine for creating custom cases. Currently, the focus is on developing multi-fidelity devices for procedural training as part of preparation for the 2026 Western European undergraduate medical training standards. This initiative has led to the creation and validation of training materials, including videos and advanced 3D simulation devices, to enhance the assessment of periprocedural skills [5, 6].

Types of Virtual Reality Systems

This review explores immersive interactive technologies for surgery simulation (IITS) as essential tools in surgical training, specifically focusing on minimally invasive surgery (MIS) and open surgery. It highlights how IITS replicate key visual and interactive aspects of real surgical procedures. Virtual reality (VR) is emphasized for its immersive qualities, involving engagement, agency, and social interaction. The theoretical framework of VR systems is examined through two paradigms: environmental realism, which aims to accurately replicate the real world, and technocentric sourcing, which emphasizes user interaction within the VR system. These paradigms influence technology choice and educational fidelity. The review also addresses depth perception in virtual environments, influenced by stereoscopic displays and field of view. Key psycho-physical aspects significant to VR simulation design include sensorial dominance, spatial presence, and flow, along with socio-cultural considerations. Research findings showcase participatory design in developing VR educational solutions to bridge identified technical skill gaps in podium training. It also discusses technological capabilities crucial to

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simulation development, demonstrating how VR simulations can improve interaction flexibility and enhance learning experiences. Moreover, the study focuses on addressing deficiencies in MIS training skills through portable VR solutions, such as UART for endoscopic navigation practice. A workshop examined engineering deficiencies in podium training, revealing participants' knowledge gaps regarding equipment operation and troubleshooting steps related to potential malfunctions [7, 8].

Designing Realistic Medical Simulations

Recently, there has been a growing interest in using Virtual Reality (VR) to simulate medical procedures and assessments. VR-based medical simulations are a feasible, flexible, and standardized way to deliver simulation sessions. They can enhance learning while saving time and costs, developing knowledge and skills without involving other personnel in training. With further development and incorporation of assessment metrics, VR-based medical simulation could become part of standard medical education in the future. While the development of VR-based simulation is becoming more feasible, there are comparatively few publications focused on providing practical guidance for educators designing and implementing VR-Simulation through headset devices. This tutorial aims to provide practical suggestions for medical educators from diverse fields, stages of VR development, and programming skill levels to design and implement a VR-based medical education session. The key questions of what to use VR, who needs to buy the headset, and how to execute the simulation on deployment in class are approached at different levels. This guidance will help medical educators successfully train their students through the use of VR simulation-learning approaches. Derived from the practical experience of the authors in developing VR, an outline of the approach for the development and implementation of VR-based medical simulation sessions was constructed and named Build Reality (from thought body of Step I to execution and assessment of Step VI). This outline is comprehensive, from ideas to implementation, and is broadly applicable to health, engineering, art, and other curricula using VR simulation in education. A flexibly recorded 360° demo VR environment for demonstrating how to follow this outline in practice is available. Examples and applications using both commercial and academic software are presented [9, 10].

Technical Challenges in VR Development

VR technology for medical education and training aims to create simulations that closely replicate real-life medical situations, yet developing such VR-based simulations poses technical challenges, particularly in compatibility and spatial understanding. Professional expertise in computational physics is necessary for crafting these realistic simulations. Key technical challenges include the need for robust VR rendering engines capable of generating realistic environments and implementing photorealistic or stylized textures through well-documented shaders and techniques. This will ensure that rendering engines remain compatible with advanced graphical user interface features and can incorporate precise models of patient anatomy, instruments, and environments for enhanced realism. These models must be interactive and well-coded to maintain frame rates above 20 Hz to prevent discomfort for users. VR technology is often misunderstood as a stand-alone solution utilized by various stakeholders, but it requires in-depth knowledge and design to maximize its integration with other technologies like computers and 2D systems. Compatibility issues may force users to either abandon existing technologies or develop new VR platforms. Additionally, transporting 3D models from research environments to clinical or educational settings entails addressing network mobility for continuity in training. VR technology enhances understanding and collaboration through spatial improvement, making it essential for the fidelity of VR devices to align with training objectives. Careful consideration is needed when selecting between handheld systems that promote mobility and immersion versus static options that enhance fidelity and spatial involvement [11, 12].

User Experience in Medical VR Training

Mixed Reality (MR) is a more advanced display modality that combines elements of augmented reality (AR) and virtual reality (VR). With proper hardware, MR displays can track the user's viewpoint and perform real-time rendering of virtual products in a mixed space. Therefore, MR can provide better realism than AR and enable spatially better interactions than VR. A lot of MR hardware devices are now available on the market; some of them are just an upgrade from VR head-mounted displays with the addition of depth cameras, and some of them are completely new, enabling the extension of economies of scale for Hi-Res and Hi-FOV lenses. The points of contact in physical interactions, between the real hand and a real object, need to be estimated. These contact points will be world coordinates to MR devices and displayed in virtual space in the MR display device, and then can be supplied to MR engines to perform the interaction in virtual space. The realistic-feeling haptic effect in interactions in MR has been explored

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in some publications. But how to manipulate the geometry and dynamic parameters in virtual space to let a virtual object feel the same as a physical object, notably its shape, mass, angular acceleration, etc. Still a lot of research potential in the field of Computer Graphics and Computer Haptics. The target of this chapter is to explore potential applications of MR in the medical training field and display experiences in the design and implementation of this Mixed Reality-based medical training system. The guidelines for MR medical simulation design proposed in this chapter could serve as a reference for the design of MR simulation for other applications. Possible future developments of MR applications in medicine are also explored [13, 14].

Assessment and Evaluation of VR Training

The proposed framework offers a comprehensive evaluation of VR training's impact, including expected outcomes. Evaluation design involves comparing user performance before and after training; those partially trained should be identified, considering control variables like age. Anticipating and managing co-interventions ensures that any outcome differences can be attributed solely to the training. Training content fidelity must be assessed through compliance checks or expert ratings on core design principles. This assessment should also evaluate training executors' competency and may include anecdotal reports. Users can reflect on missing actions during virtual scenarios through interviews or quizzes, which simulate readiness misjudgment. Training receivers should rate VR training impact using metrics like satisfaction and perceived usefulness, with options for automated feedback. For scenarios with fewer variations, specific measures can assess satisfaction consequences. Tech-health realism engagement measures may be tested for simulator sickness. Reusing validated assessments of training integrity from previous studies helps adjust parameters to align with current VR goals while considering technological differences. Such integration alongside established methodologies can effectively measure transfer, situational awareness, self-efficacy, and cognitive load [15, 16].

Case Studies of VR In Medical Training

VR training solutions have proven to be highly successful and effective in a wide range of hospital departments as well as in various medical training contexts. Numerous implementations have demonstrated their impact. One notable example is the VR Simulation Scenario for Anesthesia Machine Familiarization, which has been specifically developed and rigorously applied for the training of anesthesiology residents. This VR experience incorporates immersive and detailed 3D models of the anesthesia machine that is in use, delivered within a fully interactive 3D environment. Along with presenting an effective narrative learning series, this VR experience holds the distinction of being the first of its kind that was deliberately designed and critically evaluated for medical resident training. It supports nonchalant strategies that aid in the introduction of complex content and adheres to the well-structured narrative learning design framework that is commonly used in educational settings. Utilizing VR technology also notably enhances excitement, presence, and immersion during the learning process. Furthermore, it achieves high fidelity through the incorporation of vehicle motion, which significantly improves learning outcomes by boosting motivation among the learners. The presence of strong learner interactivity is another crucial factor that greatly enhances the effectiveness of learning transfer. By integrating VR with serious gamified interaction, there is substantial potential to elevate medical resident training situations and improve the overall outcomes of their educational experiences [17, 18].

Future Trends in VR Medical Training

Job-related training typically occurs in actual working environments, which can sometimes be dangerous or impractical. Consequently, many training programs are now using virtual worlds, including in health care. Ideally, training would occur in real health care settings, but the rapid changes in this field mean that students can no longer practice on expensive equipment with patients. As a result, health care is increasingly turning to virtual worlds for training. Virtual reality (VR) is emerging as a crucial tool for creating these immersive environments, allowing students to learn about patients and improve their skills in a simulated context. The advancement of VR technology is occurring at an unprecedented pace, paralleling the modernization of health care facilities. However, many aspects of VR training's impact on health care remain uncertain, such as the specific challenges it addresses and the scenarios it can simulate. Ongoing projects showcase the potential of VR simulation training in health care, offering innovative training opportunities that would have been unimaginable previously. With advances in 3D technologies and computing power, institutions can create diverse student training scenarios that accommodate a range of health issues and contexts. This approach promises to enhance the quality of health care education while significantly lowering training costs [19, 20].

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Ethical Considerations in VR Training

The introduction of virtual reality (VR) technology in medical education presents ethical dilemmas, particularly regarding fidelity in simulations. This text discusses two dilemmas related to VR scenarios, especially those simulating intimate examinations, and offers a potential solution to enhance future research in medical education. The ethical challenges include defining boundaries for simulation and finding ways to mitigate these concerns. Two VR scenarios designed for intimate examinations teach postgraduate trainees through interactions with a virtual patient, creating immersive environments with realistic body and avatar animations, voice, and nonverbal cues. While such high-fidelity scenarios can aid trainees' learning, they also present complications, as intimate examinations are sensitive in nature. VR can replicate patient perspectives effectively, leading to realistic simulation experiences that may not always be appropriate in medical contexts. Engaging in scenarios with personal and sensitive body avatars raises ethical questions, making trainees hesitant to test their decision-making. Additionally, it is unclear if similar situations would be acceptable in non-VR environments. Despite efforts to address ethics in serious games, there is a lack of discussion on acceptable boundaries in educational scenarios. The core questions remain: are these situations appropriate, and how can educators and researchers navigate these ethical concerns to prevent controversy? [21, 22].

Cost Analysis of VR Training Solutions

An accurate cost analysis allows decision makers to explore different technologies, integration options, and respective costs. The financial implications of any of the proposed VR solutions, and their alternatives, can be calculated with the assistance of the dedicated investment analysis template. Analysis of VR implementation must encompass hardware costs (desktops, headsets, hand controllers, trackers, cameras), software licensing, labor costs (salaries, training, technical preparation), venue rental or purchase, diplomas, publicity, and maintenance, as well as utilities costs (internet, access passwords, repairs, and replacements). Commercially available platforms will tend to have less deployment costs, as setup is often centralized and simply needs to allot requisite hardware at the training sites, but may include a recurring component (monthly/annual service fees) above a non-returnable onetime purchase fee in case of a software buyout with local installation. Though preparation costs associated with take-home devices may be higher because a dedicated VR solution must be installed/updated at each workstation individually, a wider selection of compatible training content is possible. Ultimately, what is best for the institution at hand is subject to many variable influences. In smaller businesses with few employees (or a very small scope of pre-existing training), this could differ markedly from a well-known multinational corporation or a military establishment. Commercial platforms will tend to be simpler and cost-effective in these cases, but less flexible for simultaneous use. Hardware, in turn, creates an almost infinite array of prospective training solutions, and the potential margin for for-profit work and opportunity to leverage this might entice businesses with high anticipated returns on investment [23, 24].

Regulatory and Compliance Issues

The expanding application of virtual reality (VR) technology for training in medical education means that a variety of compliance and regulatory issues must be understood and addressed before meaningful simulations can be applied. This chapter provides an overview of the various regulatory and compliance issues related to health care technology. Emerging technologies, such as VR medical simulation, currently lack standards, which can make the initial creation of a compliant simulation difficult. However, with the acquisition of a sophisticated knowledge of regulations and compliance, existing standards can be examined and applied to create compliant, effective simulations. There are many issues to consider, but health care is a heavily regulated industry; compliance with existing regulations will allow most compliance issues to be broadly addressed. Virtual reality medical simulations provide a reliable, engaging way for educators to train medical students up to a proficient skill level and rapidly give feedback. There are many issues to consider before designing VR simulations and creating a compliant product. A comprehensive understanding of applicable regulations, standards, and organizations will help practitioners navigate the initial uncertain landscape of compliance and regulatory issues. The combination of this knowledge with the medical education and engineering expertise will allow for effective, compliant simulations to be created, regardless of the rapidly changing technology. Simulations designed with a thorough understanding of the regulatory landscape will transform medical education and enable the successful, widespread application of powerful technology. Medical technology and data security regulations and standards govern the collection, storage, and analysis of medical data. These

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regulations and standards include various standards and coding systems. Regulatory standards cannot diagnose or treat patients and hence do not apply directly to any VR simulations [25, 26].

Collaboration Between Technology and Healthcare

The evolution of VR applications in surgical education is rapidly advancing from basic design to immersive environments. Two years ago, the idea of shifting surgical training to an interactive VR setup seemed daunting. However, after engaging discussions and developments, this vision has become a reality. Key design meetings emphasized the need for a VR platform to address rising injury predictions and educational dissemination challenges. A collaboration was formed between an academic medical center and a special effects design company experienced in VR applications. Mutual respect's skills allowed productive teamwork, featuring weekly meetings and iterative designs. The concept of creating an interactive VR environment for object-oriented training was thrilling but also overwhelming. Questions arose about template creation, establishing low-fidelity models as milestones, measuring training efficacy, and developing feedback loops between designers and experts. Establishing a structured template ensured responsibilities remained clear, while refining the initial milestone to create a minimalist VR animation of a surgical skill allowed both parties to showcase innovation and easily evaluate content. This facilitated clear communication and assistance in preparing a surgical training manuscript [27, 28].

Training the Trainers: Educating Instructors

Virtual reality (VR) is rapidly becoming a valuable educational tool, providing immersive, computer-generated 3D environments that mimic real-world situations. A growing array of applications is available for various disciplines, including engineering, biology, and computer science. In medical education specifically, simulations allow practice without risking patient safety or disrupting clinical workflows, especially in high-stakes scenarios where errors can lead to significant consequences. VR offers a cost-effective and flexible method for replicating clinical situations anywhere, boasting numerous benefits over traditional desktop simulation software. The economics of the VR industry, encompassing both hardware and software, are becoming more accessible and affordable. Successful VR training requires creating an engaging environment that fulfills educational goals. Educators worldwide must develop and implement VR medical simulations, often with a limited VR background. This paper briefly outlines the essential components for a successful VR training experience and provides recommendations following the BUILD REALITY framework. Establishing a VR-based medical simulation demands a collaborative approach involving computer programmers, 3D artists, and educational experts. However, as industry economics improve, it is increasingly feasible for medical or educational professionals with sufficient VR knowledge to create effective environments with little programmer support. It is crucial to recognize that successful learning experiences cannot depend solely on computer programmers [29-33].

CONCLUSION

Virtual reality represents a pivotal advancement in the evolution of medical education. It addresses many of the logistical and pedagogical shortcomings of traditional training methods by offering scalable, immersive, and interactive simulation experiences. The introduction of the **build reality** framework provides educators and developers with a comprehensive, practical guide to designing and implementing VR-based training sessions. Despite technical challenges, such as system compatibility and spatial fidelity, VR's capacity for realism, repetition, and engagement makes it a highly effective educational tool. Case studies demonstrate tangible improvements in learner performance and engagement, while ongoing advancements in computing and 3D visualization promise even broader applications in the future. As medical training increasingly demands innovation, VR stands out as a promising solution capable of delivering high-quality, accessible, and consistent education across the globe.

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CITE AS: Tom Robert (2025). Virtual Reality for Medical Training: Engineering Realistic Simulations. RESEARCH INVENTION JOURNAL OF RESEARCH IN MEDICAL SCIENCES 4(2):80-87. https://doi.org/10.59298/RIJRMS/2025/428087

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