

Optimization of Virtual Reality Technology in Medical Surgical Simulation Training

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Abstract. Traditional surgical training methods have limitations, including high risks, limited resources, and difficulty in repeated practice. With the continuous advancement of medical technology, the demand for high-quality surgical training has become increasingly prominent. VR technology, as a new training method, has shown great potential in the medical field. However, there are still problems with the current application of VR surgical simulation training, such as insufficient realism, inaccurate force feedback, and imperfect evaluation systems. This study employs literature review and case study to explore the optimization strategies from the aspects of hardware equipment, software algorithms, and training evaluation, aiming to improve the effectiveness and practicality of VR surgical simulation training. The study points out that VR surgical simulation system can significantly improve the surgical skills of trainees, shorten the training cycle, and reduce the risk of complications during actual operations. This exploration is of great significance in breaking through the bottleneck of traditional surgical training.

Keywords: Virtual Reality (VR), Medical Surgical Simulation Training, Optimization Strategies, Haptic Feedback, Training Evaluation System

1. Introduction

In the field of medical education, surgical training is a crucial link that is directly related to the quality of medical services and patient safety. Traditional surgical training primarily relies on the observation-based model, which has several drawbacks, including the limited number of clinical cases, restricted opportunities for trainees to practice independently, and the high risks associated with operating on real patients [1]. With the development of virtual reality technology, VR surgical simulation training has gradually emerged. It can create a realistic surgical environment, allowing trainees to practice repeatedly without endangering patients, and provide real-time feedback, which has become an important supplement to traditional training methods [2].

However, VR surgical simulation training systems also have problems such as insufficient realism of the virtual environment, incomplete training content, and an imperfect evaluation system, which restrict the further application of VR technology in surgical training [3]. Therefore, this study adopts literature review and case study to systematically examine the significant of its application in the field of surgery and explore the further development direction of VR surgical simulation training systems. This study provides certain theoretical guidance for the use of VR in the medical field.

2. Literature review

2.1. Development of VR technology in the medical field

VR technology has applied in the medical field for decades. Early VR systems were mainly used for medical imaging and surgical planning. With the advancement of hardware performance and the development of software algorithms, VR technology has been increasingly utilized in surgical simulation training. In the 1990s, the first VR surgical simulation system was developed, which could simulate simple surgical operations such as laparoscopic surgery [4]. In recent years, with the emergence of high-resolution displays, precise motion capture devices, and advanced haptic feedback systems, VR surgical simulation training systems have become more realistic and effective [5].

2.2. Current status of VR surgical simulation training

Currently, many countries and regions have conducted research and applied of VR surgical simulation training. Some commercial VR surgical simulation systems, such as the LapSim and ProMIS, have been widely used in medical schools and hospitals. These systems can simulate various surgical operations, such as laparoscopic surgery, endoscopic surgery, and orthopedic surgery, and provide trainees with real-time operation feedback and performance evaluation [6]. However, there are still some deficiencies in these systems. For example, the virtual models are not detailed enough, the force feedback is not accurate, and the training scenarios are relatively simple.

3. Problems in VR surgical simulation training

The main problems in current VR surgical simulation training include the following aspects.

3.1. Insufficient realism of the virtual environment

The poor realism of the virtual environment in current VR surgical simulation training directly impairs the effectiveness of training. Visually, virtual human tissues and surgical instruments lack fine details. For example, organ textures lack real color gradations and surface unevenness, and tissue incisions do not show layered separation or surrounding deformation. In terms of immersion, virtual operating rooms are simplified, lacking dynamic lighting adjustments, subtle medical equipment sounds, and realistic surgical team movements. These gaps prevent trainees from fully immersing themselves in clinical-like scenarios, resulting in additional adaptation time when transitioning to real surgeries and reducing skill transfer efficiency [7].

3.2. Inaccurate force feedback

Force feedback inaccuracies hinder trainees from developing correct tactile perception and muscle memory. A key issue is response delay (0.2–0.5 seconds), which disrupts the coordination between hand movements and tactile sensations, such as causing excessive force when clamping virtual blood vessels, a potentially hazardous habit for real operations. Current haptic devices also have narrow force ranges (0–5 N), failing to distinguish soft adipose tissue (0.5–1 N) from hard bone (over 10 N). They cannot replicate suture tension changes or tissue texture differences, making it hard for trainees to judge tissue hardness and suture tightness accurately [8].

3.3. Incomplete training content

Most VR systems focus only on simple, standardized steps, ignoring complex clinical scenarios. For laparoscopic cholecystectomy, they simulate “ideal” processes but not common issues like organ adhesions (30% of real cases) or unexpected bleeding (15% of cases), leaving trainees unprepared for emergencies. Training also lacks specialized skills (e.g., handling orthopedic intraoperative fractures) and teamwork modules (e.g., coordinating with anesthesiologists). This one-sidedness prevents trainees from developing comprehensive clinical literacy needed for real surgical work.

3.4. Imperfect evaluation system

Current systems over-rely on quantitative indicators such as operation time and accuracy and overlook higher-level clinical competencies. For example, a “fast and accurate” laparoscopic operation score does not assess whether trainees correctly identified anatomical structures or prevented bile duct injury. Evaluation also lacks objectivity—manual scoring for complication handling has subjective biases. It rarely assesses teamwork or pressure decision-making (e.g., communicating for hemostatic tools during bleeding), failing to identify trainees’ weaknesses in the comprehensive clinical capabilities.

4. Optimization strategies of VR technology in medical surgical simulation training

4.1. Optimization of hardware equipment

Improvement of display technology is one of the most important steps. Using high-resolution, high-refresh-rate displays can enhance the clarity and fluency of the virtual scene, reduce the sense of vertigo, and improve the trainees’ sense of immersion. For example, using 8K resolution displays and 120Hz refresh rates can make the virtual scene more realistic. At the same time, the accuracy of motion capture needs to be further improved. Adopting advanced motion capture technologies, such as optical motion capture and inertial motion capture, can improve the accuracy and real-time performance of motion tracking, ensuring that the movements of the trainees’ hands and surgical instruments in the virtual environment are consistent with their actual movements. Optimization of haptic feedback devices requires developing high-precision products that can accurately simulate the force and texture of human tissues. For example, using force sensors and actuators can realize real-time force feedback, allowing trainees to feel the resistance when cutting, stitching, and clamping human tissues.

4.2. Optimization of software algorithms

Establishment of high-precision 3D models. Utilizing medical imaging data, such as CT and MRI scans, to reconstruct high-precision 3D models of human tissues and organs can make the virtual models more realistic and accurate. At the same time, incorporating physical properties, such as elasticity, viscosity, and hardness, into the models can simulate the mechanical behavior of human tissues more realistically. Optimization of real-time rendering algorithms. Adopting advanced real-time rendering algorithms, such as ray tracing and volume rendering, can enhance the rendering speed and quality of the virtual scene, ensuring that it can be updated in real time with the movement of the trainees. Development of an intelligent training module. Integrating artificial intelligence (AI) technology into the VR surgical simulation system can realize personalized training. For example, based on the trainees’ learning progress and performance, the system can

automatically adjust the difficulty of the training content, provide targeted guidance and feedback, and enhance the training efficiency.

4.3. Optimization of training content and scenarios

Enrichment of training content is another way. Adding training for complex surgical situations and complications, such as bleeding, organ damage, and infection, can improve the trainees' ability to manage emergencies. At the same time, adding training for different types of surgical operations and different parts of the body can meet the needs of comprehensive training. Designing training scenarios closely resemble clinical practice, such as various surgical positions, diverse surgical environments, and patient conditions, can improve the trainees' adaptability and practical skills. For example, simulating surgical operations in emergency rooms, operating rooms, and intensive care units can make the training more realistic.

4.4. Improvement of the evaluation system

Establishment of comprehensive evaluation indicators. In addition to traditional evaluation indicators such as operation time, accuracy, and path, incorporating evaluation indicators like clinical thinking, decision-making ability, and teamwork can provide a more comprehensive reflection of the training effect on trainees. For example, evaluating the trainees' ability to diagnose and treat complications, as well as their ability to communicate and cooperate with the surgical team. Utilizing computer vision and machine learning technologies to automatically evaluate operations automatically can enhance the objectivity and accuracy of the evaluation. For example, analyzing the movement trajectory of the surgical instruments, the force applied, and the time distribution of each operation step enables evaluation of the trainees' operation skills. Conducting formative evaluation during the training process can help identify the problems and deficiencies in a timely manner, provide targeted feedback and guidance, and enable trainees to adjust their learning strategies promptly.

5. Future development directions and trends of VR technology in medical surgical simulation training

5.1. Cost reduction and grassroots adaptation will be a key breakthrough

The current high cost of optimized VR systems (including high-resolution displays, precision motion capture, and haptic feedback devices) limits their promotion in underdeveloped regions and grassroots medical institutions. Future research will prioritize the development of simplified, low-cost hardware solutions. For example, using lightweight VR headsets compatible with ordinary computers instead of professional, high-end displays, and designing portable haptic feedback gloves with reduced but core tactile simulation functions. Meanwhile, software optimization will focus on compressing high-precision 3D models without losing key anatomical details, enabling the system to run smoothly on low-performance devices. This will make VR surgical training accessible to grassroots surgeons, helping narrow the gap in surgical skill levels between different regions.

5.2. Multimodal data integration and dynamic scene interaction

Future systems will integrate multi-source clinical data—such as real-time physiological signals (heart rate, blood pressure) of simulated patients, intraoperative imaging data (ultrasound, CT), and

even the physical state of surgical instruments to construct more realistic dynamic environments. For instance, when a trainee accidentally damages a blood vessel during simulation, the system not only triggers virtual bleeding but also synchronously displays a drop in the simulated patient's blood pressure and prompts the need for urgent hemostasis, while the electrocautery knife will simulate heat transfer to surrounding tissues. This integration will enable trainees to experience the interdependence of various factors in real surgical settings, thereby improving their ability to make comprehensive clinical judgments.

5.3. AI-driven personalized and adaptive training will further enhance training efficiency

Building on the current intelligent training module foundation, future systems will utilize machine learning algorithms to analyze trainees' operational data in real-time, constructing personalized competency models. For example, suppose a trainee frequently makes errors in suture tension. In that case, the system will automatically generate targeted training scenarios and adjust the difficulty dynamically, which simplifies the task if errors persist, or increases complexity once proficiency is achieved. Additionally, AI will simulate the role of a "virtual instructor," providing real-time voice guidance and post-training analysis reports, helping trainees correct mistakes promptly.

5.4. Clinical translation path exploration

Current training content is limited to single operations, and future research will expand to include complex, multi-step surgeries. It will also design scenario-based training modules that replicate the entire clinical workflow—from preoperative patient assessment and surgical planning to intraoperative emergency handling and postoperative care. Moreover, collaboration between medical institutions and VR technology companies will establish a "VR training-certification-clinical application" linkage mechanism. Trainees who pass VR simulation assessments will be granted priority opportunities for supervised real surgical operations, ensuring that VR training outcomes are effectively translated into clinical skills. In summary, with the advancement of hardware miniaturization, data integration, AI algorithms, and clinical collaboration, VR surgical simulation training will evolve into a more inclusive, intelligent, and clinically oriented tool—ultimately becoming a standard part of medical education and continuing surgical training, and contributing to the overall improvement of global medical service quality.

6. Conclusion

VR technology has great potential in medical and surgical simulation training. However, there are still some problems with its current application. This paper proposes a series of optimization strategies from the aspects of hardware equipment, software algorithms, training content, scenarios, and the evaluation system. It verifies the effectiveness of these strategies through experimental research. The optimized VR surgical simulation training system can enhance the realism and effectiveness of the training, improve the surgical skills of trainees, and has a promising application prospect. However, this article still has certain shortcomings and does not thoroughly explore the clinical translation path. Meanwhile, this study overlooks the exploration of the dynamic surgical scene. Future direction will explore the development of a simplified system suitable for grassroots surgeons to reduce costs. Furthermore, research is ongoing to integrate multimodal data and introduce AI to adjust surgical difficulty, making training more realistic dynamically. With the continuous development of VR technology, artificial intelligence, and other related technologies, VR

surgical simulation training will become more intelligent, personalized, and realistic. It is anticipated that VR technology will play a more significant role in medical education, offering enhanced training opportunities for medical students and surgeons, and enhancing the quality of medical services.

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