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REVIEW

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The impact of surgical simulation and training technologies on general surgery education

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Abstract

The landscape of general surgery education has undergone a significant transformation over the past few years, driven in large part by the advent of surgical simulation and training technologies. These innovative tools have revolutionized the way surgeons are trained, allowing for a more immersive, interactive, and effective learning experience. In this review, we will explore the impact of surgical simulation and training technologies on general surgery education, highlighting their benefits, challenges, and future directions. Enhancing the technical proficiency of surgical residents is one of the main benefits of surgical simulation and training technologies. By providing a realistic and controlled environment, With the use of simulations, residents may hone their surgical skills without compromising patient safety. Research has consistently demonstrated that training with simulations enhances surgical skills., reduces errors, and enhances overall performance. Furthermore, simulators can be programmed to mimic a wide range of surgical scenarios, enabling residents to cultivate the essential critical thinking and decision-making abilities required to manage intricate surgical cases. Another area of development is incorporating simulation-based training into the wider surgical curriculum. As simulation technologies become more widespread, they will need to be incorporated into the fabric of surgical education, rather than simply serving as an adjunct to traditional training methods. This will require a fundamental shift in the way surgical education is delivered, with a greater emphasis on simulation-based training and assessment.

Highlights

- Surgical simulation and training technologies have revolutionized general surgery education, enhancing technical skills and critical thinking abilities of surgical residents.
- Integration of simulation-based training into the broader surgical curriculum is necessary for its widespread adoption and effectiveness.
- With the support of educational agendas led by national neurosurgical committees, industry and new technology, simulators will become readily available, translatable, affordable, and effective.
- As specialized, well-organized curricula are developed that integrate simulations into daily resident training, these simulated procedures will enhance the surgeon's skills, lower hospital costs, and lead to better patient outcomes.

Keywords Surgical simulation, General surgery education, Training technologies, Simulation-based curriculum

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Introduction

The field of general surgery has seen significant progress in recent decades, significantly transforming surgical education and practice [1]. Traditional surgical training, which primarily relied on the apprenticeship model, has faced numerous challenges, including variability in training experiences, limited opportunities for hands-on practice, and concerns over patient safety [2]. These challenges have highlighted the pressing need for new educational approaches to adequately prepare surgeons for the demands of contemporary surgical practice.

Surgical simulation and training technologies have become pivotal in addressing these challenges [3]. From virtual reality (VR) and augmented reality (AR) to physical simulators and computer-based platforms, these technologies offer diverse training modalities that enhance learning experiences, improve technical proficiency, and elevate patient care [4]. Simulation technologies provide a safe environment for trainees to connect theoretical knowledge with practical clinical skills, allowing for the refinement of critical skills without compromising patient safety [5, 6].

This review aims to assess the current state of simulation technologies used in surgical education, with a specific focus on residency training programs in general surgery. By narrowing the scope to residency-level training, this review will examine how simulation technologies are integrated into surgical curricula and how they impact the development of surgical competencies. Furthermore, the review will define "simulation technology" in the context of surgical training, focusing on tools like VR, AR, mixed reality (MR), and physical simulators.

The central research question guiding this review is: What is the impact of specific simulation technologies on enhancing technical skills and knowledge in general surgery residency programs? This review will explore the types of simulation technologies employed in residency training, evaluate the evidence supporting their effectiveness, and identify the challenges and limitations that may hinder broader adoption. Future directions in simulation-based education, including the potential role of artificial intelligence (AI) and machine learning (ML), will also be explored.

The subsequent sections are organized as follows: an overview of surgical simulation technologies; the integration of these technologies into surgical training programs; a review of the evidence on their educational and clinical effectiveness; an examination of challenges and limitations; and a discussion of future directions and innovations. By providing a focused analysis, this review seeks to offer practical insights for educators, institutions, and policymakers to improve surgical training and, ultimately, patient outcomes.

Overview of surgical simulation technologies

Surgical simulation has seen rapid advancements in recent years, offering tools that enhance training experiences, improve surgical skills, and ultimately optimize patient outcomes [7]. This section provides an overview of different simulation technologies relevant to surgical residency training, including descriptions, uses, and recent innovations.

Types of simulation technologies

This section discusses four key types of simulation technologies: Virtual Reality (VR), Augmented Reality (AR), Physical Simulators, and Computer-Based Simulations. While VR simulations are indeed computer-based, they stand out due to their immersive 3D environments, whereas computer-based simulations generally involve less immersive, software-driven training platforms accessible on standard devices.

Virtual Reality (VR): A fully immersive digital environment where users interact with 3D models and scenarios, often using headsets and motion-tracking devices. In surgery, VR is used to simulate procedural environments, enabling trainees to perform virtual surgeries in a risk-free setting [8].

Augmented Reality (AR): A technology that overlays digital elements, such as images or data, onto the real world. AR is often used in surgical settings to project anatomical models or procedural guides directly onto the patient's body, providing real-time assistance during operations [9].

Mixed Reality (MR): Combines elements of both VR and AR, allowing users to interact with both digital and physical objects simultaneously in a mixed environment. In surgical training, MR can be used to blend virtual simulations with the physical operating room for enhanced learning [10].

Virtual reality (VR)

With the use of virtual reality (VR) technology, users may experience realistic environments that mimic actual surgical situations [8]. Using VR headsets and motion-tracking devices, trainees can interact with 3D models of human anatomy and perform virtual surgeries in a controlled, risk-free setting [8]. VR applications in surgical training, such as laparoscopic and robotic simulations, often rely on feedback mechanisms to replicate real-world conditions [8]. While motorized haptics are used, there is increasing consensus that natural haptics, which better mimic the physical properties of tissue and instruments, provide a more realistic and immersive experience, enhancing surgical skills [8]. These VR systems facilitate repetitive practice, allowing trainees to refine their skills and build confidence before operating on actual patients [11].

Augmented reality (AR)

By superimposing digital content over the actual environment, augmented reality (AR) improves training by offering interactive features and contextual information [12]. In surgical training, AR applications can project anatomical structures, procedural guides, and real-time data onto the operative field, assisting surgeons during live procedures [13]. For instance, AR can be used to superimpose a 3D model of a patient's anatomy onto their body during surgery, aiding in precise incision planning and navigation [14]. This amalgamation of virtual and physical components facilitates the convergence between theoretical understanding and practical implementation, not only in skill acquisition but also in specialist selection, retraining, and returning to practice [15]. This convergence enhances spatial cognition and optimizes decision-making processes, making simulation a critical tool for ongoing professional development [15].

Physical simulators

Physical simulators, including mannequins, haptic feedback devices, task trainers, tissue-based simulations, and cadaver-based simulations, offer diverse means for developing and honing procedural skills [16]. Mannequins equipped with sensors and programmable scenarios are widely utilized in surgical skills labs for practicing procedures such as intubation, suturing, and trauma management [16]. Haptic feedback technologies, including both motorized systems and natural haptics, deliver lifelike tactile responses. These technologies enable trainees to experience the resistance, texture, and physical properties of tissues during virtual dissections or needle insertion exercises, enhancing the realism of medical simulations [17].

Task trainers, which focus on specific procedures like endoscopy or catheterization, provide opportunities for repeated practice and skill refinement in controlled settings [18]. Furthermore, tissue-based simulation, using animal or synthetic tissue, and cadaver-based simulation offer the highest fidelity to human anatomy, allowing learners to practice complex dissections, suturing, and other invasive techniques in a realistic environment. While tissue and cadaver simulations offer unparalleled anatomical accuracy, low-fidelity task trainers remain valuable for early-stage learners, enabling them to build foundational skills before transitioning to higher-fidelity models [19].

Computer-based simulations

Computer-based simulations utilize software platforms to create interactive training modules accessible via personal computers or mobile devices [20]. These simulations can range from basic anatomical quizzes to complex procedural simulations that require critical thinking and decision-making [21]. Online platforms often include comprehensive surgical curricula, enabling trainees to study theoretical concepts, watch instructional videos, and test their knowledge through virtual simulations [22]. The flexibility and accessibility of computer-based simulations make them an invaluable tool for continuous learning and self-assessment [23].

Technological advancements

Recent years have seen significant advancements in surgical simulation technologies, driven by innovations in computing power, graphics, and artificial intelligence [24]. High-fidelity simulations now offer unprecedented realism, with detailed anatomical models, sophisticated physics engines, and real-time feedback mechanisms [25]. Advances in VR and AR have enabled more immersive and interactive training experiences, while developments in haptic technology have improved the tactile realism of physical simulators [26].

The integration of AI and ML is playing an increasingly important role in enhancing surgical simulation methodologies, with ongoing research and development demonstrating their potential to improve accuracy and outcomes [27]. AI algorithms can analyze performance data, provide personalized feedback, and adapt training scenarios to individual learning curves, enhancing the effectiveness of simulation-based education [28]. Additionally, AI-driven analytics can identify patterns in trainee performance, helping educators to tailor training programs and address common deficiencies [29].

The future of surgical simulation promises even greater integration of these technologies, with potential applications including remote training via tele-simulation, collaborative virtual environments for team-based learning, and advanced predictive analytics for personalized education pathways [30]. As these technologies advance, they have the capability to revolutionize surgical education by enhancing its efficiency, efficacy, and accessibility.

Integration of simulation in surgical training

The incorporation of simulation technologies into surgical training marks a fundamental transformation in medical education, introducing novel methodologies for developing educational curricula, enhanced training programs, and robust certification processes [31]. This section provides an in-depth analysis of the integration of simulation technologies within medical and surgical education, evaluates case studies pertaining to simulation-based training programs, and investigates the impact of simulation on certification and accreditation processes [32].

Curriculum development

The integration of simulation technologies into medical and surgical education has resulted in substantial modifications to the structure and content of curricula [33]. Traditional surgical training, which heavily relied on didactic lectures and observation, is increasingly being supplemented or replaced by simulation-based learning [34]. This transition facilitates the acquisition of practical experience by trainees within a structured and secure setting, thereby augmenting their technical proficiency and decision-making capabilities before they engage with real patients [35].

Simulation-based curricula often include a blend of theoretical instruction, practical skills training, and assessment [36]. For instance, Simulations utilizing VR and AR technologies are employed to facilitate the instruction of intricate anatomical structures and procedural methodologies, providing immersive and interactive experiences that enhance understanding [37]. Physical simulators and task trainers offer tactile feedback, allowing trainees to practice procedures such as suturing, laparoscopic surgery, and endoscopy with realistic sensations [38].

To ensure comprehensive training, curricula may incorporate a variety of simulation modalities, each targeting different aspects of surgical competence [39]. For example, VR simulations might be used for initial familiarization with surgical anatomy and procedures, while physical simulators are employed for practicing manual dexterity and technique [40]. This multi-faceted approach ensures that trainees develop a well-rounded skill set, encompassing both cognitive and technical competencies [41].

Training programs

Several pioneering institutions have developed and implemented simulation-based training programs that serve as models for effective integration [42]. These programs often span different surgical specialties and are tailored to address specific training needs.

One notable example is the Fundamentals of Laparoscopic Surgery (FLS) program, which utilizes a combination of online didactic materials, VR simulations, and physical task trainers to teach and assess essential laparoscopic skills [43]. The program is widely recognized for its structured curriculum and objective assessment methods, which have been shown to improve trainees' proficiency and confidence in laparoscopic surgery [44].

Another exemplary program is the American College of Surgeons (ACS) Accredited Education Institutes (AEI) network, which provides a platform for surgical education and training through high-fidelity simulation [45]. The AEI network emphasizes a competency-based approach, offering standardized curricula across various surgical disciplines [46]. Training modules cover a range of skills, from basic surgical techniques to advanced procedures, and include both individual and team-based simulations [47].

In addition, the application of AR in surgical education has been empirically validated. in programs like the Stanford School of Medicine's AR-enhanced surgical education, where trainees use AR glasses to visualize patient-specific anatomy and procedural steps during practice sessions [48]. This novel methodology facilitates the integration of theoretical knowledge with practical application, enhancing the comprehension of surgical techniques.

Certification and accreditation

Simulation technologies play a crucial role in the certification and accreditation processes for surgeons. By providing objective, standardized assessments of surgical skills, simulations help ensure that trainees meet the required competencies before they are certified to practice independently [49].

Board certification bodies, such as the American Board of Surgery (ABS), have increasingly incorporated simulation-based assessments into their certification exams [50]. The ABS, for example, includes simulation components in its qualifying exams to evaluate candidates' proficiency in critical procedures and decision-making under pressure [50]. These simulation-based assessments provide a reliable measure of technical competence and readiness for clinical practice [51].

Continuing Medical Education (CME) programs also leverage simulation technologies to facilitate ongoing professional development [52]. Surgeons are required to maintain their skills and remain informed about the most recent developments and innovations within their area of expertise, and simulation-based CME modules offer an effective means to achieve this [53]. CME programs often include advanced procedural simulations, scenario-based training, and team-based exercises, enabling experienced surgeons to enhance their proficiency and acquire novel techniques within a controlled, risk-free setting [54].

Moreover, simulation-based training is increasingly being recognized by accreditation organizations as a standard for quality surgical education [55]. Institutions that incorporate high-fidelity simulations into their training programs are often awarded accreditation by bodies such as the ACS AEI, which sets rigorous standards for educational excellence [56, 57].

Evidence of effectiveness

This review was conducted following a structured and systematic approach to ensure a comprehensive evaluation of the impact of surgical simulation and training technologies on general surgery education. The methodology was designed to provide a thorough assessment of the current evidence available in the field.

A comprehensive literature search was performed using three primary databases: PubMed, Scopus, and Web of Science. These databases were selected for their extensive coverage of peer-reviewed publications in the medical and educational fields. The search strategy included a combination of keywords and Medical Subject Headings (MeSH) terms related to "surgical simulation," "surgical training technologies," "general surgery education," and "simulation-based learning." To focus on the most relevant and up-to-date studies, articles published in the last two decades (2013–2023) were included.

Inclusion and exclusion criteria

The inclusion criteria for selecting studies were: (1) Peer-reviewed articles. (2) Studies published in the English language. (3) Research focusing on the use of simulation technologies in surgical education. (4) Articles evaluating the impact of simulation on surgical competence, educational outcomes, clinical outcomes, and skill transferability.

Studies were excluded if they: (1) Focused on non-surgical specialties. (2) Were not published within the specified timeframe. (3) Were editorial pieces, commentaries, or anecdotal reports without empirical data.

Data extraction and analysis

After the initial screening of titles and abstracts, full-text reviews were conducted to assess the relevance of each study based on the inclusion and exclusion criteria. Key data extracted from each study included the type of simulation technology used, target population (surgical residents, fellows, etc.), study design, outcome measures, and key findings related to surgical competence, patient outcomes, and skill retention. The results of these studies were synthesized to provide a comprehensive overview of the evidence supporting the integration of simulation technologies into surgical education.

Quality assessment

The quality of the studies was evaluated using standardized tools for assessing the risk of bias and methodological rigor in educational research. Studies with robust methodologies, including randomized controlled trials (RCTs) and longitudinal studies, were prioritized in the analysis.

Educational outcomes

Impact on Knowledge Acquisition, Technical skills, and procedural competence

Paraphrased with scientific terminology A substantial body of research has established that training through simulation markedly improves both the acquisition of knowledge and the development of technical competencies within surgical education [58, 59]. For instance, a meta-analysis by McGaghie et al. (2011) revealed that simulation-based medical education is associated with large, statistically significant effects on learning outcomes, particularly in procedural and technical skills [60]. This phenomenon can be ascribed to the immersive and iterative characteristics of simulation-based training, which facilitates skill acquisition and refinement by enabling trainees to repeatedly engage in practice within a controlled setting [61].

Specifically, Studies have indicated that simulations using VR and AR are effective in improving the understanding of anatomical features and procedural knowledge [62]. A study by Nagendran et al. (2013) found that trainees who used VR simulators for laparoscopic surgery performed better in terms of speed and accuracy compared to those who received traditional training [63]. The immersive experience provided by VR helps trainees visualize complex anatomical structures and procedural steps, leading to better retention and understanding [64].

Physical simulators and task trainers also contribute significantly to the development of technical skills. For example, a randomized controlled trial by Tellez et al. (2021) demonstrated that surgical residents who trained with physical simulators showed improved performance in suturing and knot-tying skills compared to those who trained using conventional methods [65]. These findings suggest that hands-on practice with realistic models enhances procedural competence and confidence [66].

Clinical outcomes

Correlation between simulation training and patient safety, reduction in surgical errors, and improvement in surgical outcomes

The impact of simulation-based training on clinical outcomes is a critical area of study, with existing research suggesting an association with enhanced patient safety and a reduction in surgical errors. For instance, Zendejas et al. (2013) demonstrated that simulation-based interventions contributed to a significant reduction in surgical difficulties and errors [67], likely due to improved surgeon preparedness and proficiency.

Simulation training has also shown positive results in specific procedures. Humm et al. (2022) reported that surgeons trained with virtual reality (VR) performed laparoscopic cholecystectomies with fewer errors and faster completion times compared to traditionally trained surgeons [68], suggesting that the skills acquired through simulation can positively influence clinical performance.

Furthermore, team-based simulation exercises, particularly in trauma and emergency surgeries, have been linked to enhanced team communication and coordination. Roberts et al. (2013) found that high-fidelity team simulations significantly improved both team performance and patient outcomes in critical care settings [69]. These findings underscore the importance of simulation in preparing surgical teams for complex, high-stakes procedures.

While these studies provide strong evidence for the effectiveness of simulation training in improving surgical performance and team dynamics, the direct translatability of these outcomes to broader patient-centered clinical outcomes remains a limitation. Current evidence predominantly highlights intermediate outcomes—such as error reduction, procedural efficiency, and improved technical skills—but further research, particularly large-scale and longitudinal studies, is required to conclusively demonstrate a consistent and measurable improvement in overall patient outcomes such as morbidity and mortality.

Skills retention and transfer

Long-term retention of skills and transferability of training from simulation to clinical practice

Investigations into the prolonged retention of competencies developed via simulation-based training reveal that these skills are retained over extended periods and are transferable to clinical practice [70]. A study by Kahol et al. (2010) found that surgical residents who underwent simulation-based training retained their skills for at least six months, outperforming their peers who received traditional training [71]. This suggests that the repetitive and immersive nature of simulation fosters durable learning.

The effective translation of competencies acquired in simulated environments to practical application in real-life surgical settings represents a critical determinant of the efficacy of surgical training programs [72]. A systematic review by Dawe et al. (2014) concluded that simulation-based training is highly effective in transferring technical skills to the operating room [73]. The review highlighted those trainees who practiced on high-fidelity simulators demonstrated better performance in actual surgeries, confirming the practical value of simulation-based education [73].

Moreover, studies have shown that simulation training enhances not only technical skills but also critical decision-making and problem-solving abilities [74]. For example, a study by Kantamaneni et al. (2021) revealed that VR training improved the decision-making skills of surgeons during laparoscopic procedures, leading to fewer intraoperative errors [75]. This indicates that simulation provides a comprehensive training experience that prepares surgeons for the complexities of clinical practice [75].

Challenges and limitations

While the integration of simulation technologies into surgical training has shown significant benefits, numerous challenges and constraints must be overcome to fully harness their potential [76]. This section discusses the financial barriers, standardization and validation issues, and resistance to change that currently hinder the widespread adoption and effectiveness of simulation-based training.

Cost and accessibility

A significant obstacle in the adoption of simulation technologies for surgical training is the substantial financial investment required [77]. Developing and maintaining high-fidelity simulators, virtual reality (VR) and augmented reality (AR) systems, as well as comprehensive simulation centers, requires significant financial investment [78]. It is important to note that the concept of 'fidelity' in simulation, as defined by the Society for Simulation in Healthcare (SSH), encompasses more than just technological accuracy—it also refers to the degree to which the simulation replicates real-world environments, which can include physical, psychological, and environmental elements [78]. it is essential to further explore and quantify the Return on Investment (ROI) in these advanced technologies to ensure that the financial outlay translates into measurable educational and clinical outcomes [78]. Future research should focus on identifying key performance indicators (KPIs) and cost-benefit analyses that justify the continued allocation of resources to such technologies [78]. For instance, sophisticated VR systems can cost several hundred thousand dollars, while physical simulators and haptic feedback devices also entail significant expenditure [79]. Additionally, ongoing costs such as software updates, maintenance, and the need for specialized personnel to operate and manage these technologies further escalate the financial burden [80].

Disparity in access

The high cost of simulation technologies creates a disparity in access, particularly between well-funded institutions and those with limited resources [81]. Academic medical centers and large teaching hospitals in developed regions are more likely to afford and implement advanced simulation tools, whereas smaller hospitals and institutions in developing regions may struggle to provide such opportunities for their trainees [82]. This disparity can lead to unequal training experiences and potentially widen the gap in surgical competence and patient care quality between different regions and institutions [83].

The disparity in access to advanced simulation technologies is particularly pronounced between well-funded institutions in developed countries and those in low- and middle-income countries (LMICs) [81]. High costs and infrastructure requirements can limit the ability of institutions in LMICs to implement these technologies, resulting in uneven access to high-quality training tools for healthcare professionals [81]. This gap may contribute to disparities in medical education, potentially affecting the competence of healthcare providers and the quality of patient care in resource-constrained settings [82].

Despite these challenges, simulation technologies hold significant potential for improving surgical training in LMICs [83]. Emerging efforts to develop low-cost, portable, and scalable simulation models tailored to the needs of these regions could offer promising solutions [83]. Leveraging advancements in virtual reality (VR), augmented reality (AR), and mobile platforms, initiatives have begun exploring ways to make simulation-based training more accessible and affordable [84]. Such innovations could play a crucial role in addressing disparities by democratizing access to high-quality training tools, ultimately improving surgical outcomes and reducing the gap in healthcare quality between high-income and low-income settings [84]. Future efforts should focus on the sustainable integration of these technologies in LMICs, considering cost-effective approaches, local infrastructure, and potential collaborations with global health organizations and educational institutions [84].

Standardization and validation

The lack of standardization in simulation technologies poses a significant challenge to their effective integration into surgical training [49]. Various simulators and training programs may use different models, metrics, and assessment tools, making it difficult to compare outcomes and ensure consistent training quality across different settings [85]. For example, VR simulations for laparoscopic surgery may vary in terms of anatomical accuracy, realism, and feedback mechanisms, leading to variability in the training experience [85].

Validation of training outcomes

Another critical issue is the validation of simulation-based training outcomes [86]. Numerous studies have substantiated the efficacy of simulation-based training in enhancing surgical proficiency, there remains a critical need for the development and implementation of rigorous, standardized validation methodologies to ensure that competencies gained through simulation are reliably transferable to clinical practice [86]. Currently, validation studies often employ varied methodologies and metrics, which can lead to inconsistent conclusions [87]. Establishing standardized validation protocols and assessment criteria is essential to ensure the reliability and credibility of simulation-based training [88].

Resistance to change

Resistance to change within the surgical education community presents a notable barrier to the adoption of simulation technologies [89]. Traditional surgical training methods, such as apprenticeship models and hands-on learning in the operating room, have been deeply ingrained in medical education for centuries [90]. Transitioning to simulation-based training requires a cultural shift and acceptance of new pedagogical approaches, which can be challenging for educators and trainees accustomed to conventional methods [91].

Acceptance and integration of new technologies

Integrating new technologies into established training programs often encounters resistance due to concerns over their efficacy, the time required for implementation, and the potential disruption of existing curricula [92]. Educators and institutions may be hesitant to adopt simulation-based training if they perceive it as an unproven or supplementary method rather than a core component of surgical education [76]. Furthermore, the learning curve associated with new technologies can be a deterrent, as both educators and trainees need to invest time and effort to become proficient in using simulation tools effectively [93].

Addressing the challenges

Funding and Resource Allocation: Securing funding from government bodies, educational grants, and private sector partnerships can help alleviate the financial burden associated with simulation technologies [94]. Additionally, creating shared simulation centers accessible to multiple institutions can optimize resource utilization and improve accessibility [95].

Standardization Efforts: Developing standardized guidelines for the creation, application, and evaluation of training based on simulation can help ensure consistency and reliability [96]. Collaborative efforts among professional organizations, accrediting bodies, and educational institutions are essential to establish these standards [97].

Validation Research: Conducting large-scale, multicenter validation studies using standardized protocols can provide robust evidence of the efficacy of instruction through simulation [98]. This will enhance the credibility of simulation technologies and encourage their adoption in surgical education [99].

Cultural Shift and Education: Promoting a cultural shift within the surgical education community through workshops, seminars, and training programs can facilitate acceptance of simulation technologies [100]. Highlighting the proven benefits of simulation and providing support for educators to integrate these tools into their curricula can drive the adoption of innovative training methods [101].

Future directions

As surgical simulation and training technologies continue to evolve, several promising avenues for future development and research emerge. The focus of these guidelines is on the incorporation of advanced technologies such as AI and ML, addressing existing research gaps, and establishing robust policies and guidelines to support the global adoption of simulation-based education.

Emerging technologies

Artificial Intelligence (AI) and machine learning (ML)

AI and ML are poised to transform surgeon training by providing sophisticated tools for analyzing vast amounts of data generated from simulation sessions. One critical area where AI can contribute is the precise calculation and optimization of learning curves [102[. Learning curve analysis traditionally focuses on how quickly trainees acquire proficiency in specific skills. In surgical education, the key parameters of learning curves—such as time to competence, error reduction, and skill retention—are vital for both trainees and educators to understand progress [102].

AI can be employed to track the progression of surgical residents by identifying inflection points where significant improvements occur and areas where progress plateaus [103]. For example, AI-based systems can analyze trainee performance over time to calculate the number of repetitions required to reach proficiency in particular procedures, factoring in variables such as task complexity, prior experience, and cognitive workload [104]. By continuously monitoring and adjusting these parameters, AI models can personalize training schedules and offer targeted interventions, ensuring more efficient and effective learning [104].

AI-driven virtual tutors and coaches simulate real-time interactions with trainees, providing guidance, answering questions, and assessing performance [105]. They enhance cognitive skills, such as analytical reasoning and complex problem-solving, which are crucial for surgical practice [106].

ML algorithms also allow for dynamic prediction of performance trajectories. By identifying patterns in a trainee's development, educators can implement timely and individualized feedback [107]. This not only optimizes the time spent on mastering specific skills but also ensures that learning curves are shortened, leading to faster and more accurate attainment of clinical competencies [107].

Advanced haptics

The development of advanced haptic technologies has the potential to significantly improve the realism of physical simulators, particularly by using real instruments on models that replicate both the physical and visual properties of tissue. This approach aligns with the concept of natural haptics, where the fidelity of tactile feedback closely mirrors interactions with actual human tissue. By integrating such haptic technology, the tactile feedback in training environments will better mimic the nuanced textures and resistance of human tissue, contributing to more effective skill acquisition for procedures that require fine motor control and precise manipulation, such as microsurgery and robotic-assisted surgery [108].

It is important to acknowledge the unique challenges posed by haptics in robotic simulation. Current limitations in simulating the complexities of tactile sensations—such as tissue compliance, texture, and response to manipulation—highlight the need for further advancements. Future haptic devices may offer multi-modal feedback, combining tactile, auditory, and visual cues to create an immersive and comprehensive training experience. Such improvements could enhance the simulation's accuracy and effectiveness, particularly in procedures where precision is critical [109]. Addressing these challenges will be crucial to furthering the effectiveness of robotic and physical simulation training in medical education.

Tele-simulation and remote training

Tele-simulation leverages internet connectivity to provide remote training and assessment, making high-quality surgical education accessible to trainees worldwide, Disregarding geographical boundaries [110]. This strategy is especially beneficial for regions with limited access to advanced simulation centers [111]. Tele-simulation platforms can facilitate collaborative training sessions, where trainees and mentors from different parts of the world interact in a virtual environment. This can foster a global exchange of knowledge and best practices, enhancing the overall quality of surgical education.

Research needs

Identifying gaps in current research

Despite substantial advancements in simulation-based surgical education, there remain significant gaps in evidence, particularly concerning the translation of simulation training into improved clinical outcomes—commonly referred to as Level 3 outcomes. A critical area of investigation is the impact of simulation-based training on long-term clinical performance and patient safety outcomes [112]. To address this, longitudinal studies that follow trainees from simulation environments through their professional careers are essential to demonstrate the sustained benefits of simulation-based education and its relevance to real-world clinical practice.

Furthermore, the development and validation of standardized evaluation tools is another pressing research need [113]. The establishment of consistent, reliable metrics for assessing trainee performance across different simulation platforms is crucial for enabling accurate benchmarking and cross-platform comparisons [114]. In addition, the cost-effectiveness of simulation technologies must be rigorously evaluated. Providing robust data in this area will not only justify the financial investments in simulation tools but also help identify the most efficient strategies for integrating these technologies into comprehensive, structured training programs [115].

Suggestions for future studies

Future research should focus on exploring how to effectively integrate simulation training across multiple disciplines, where surgical trainees collaborate with other healthcare professionals, such as anesthesiologists, nurses, and radiologists [116]. This approach can improve team dynamics, communication, and coordination, which are critical for successful surgical outcomes [116]. Additionally, there is a growing need to direct research efforts toward exploring how cutting-edge technologies like AI and advanced haptics are shaping learning experiences and trainee satisfaction. Understanding the role these innovations play in education will provide valuable insights into their potential to improve training outcomes [117].

Exploring the role of virtual and augmented reality in continuing medical education (CME) for practicing surgeons is another valuable research avenue. These technologies can provide ongoing training and skill refinement, ensuring that surgeons stay updated with the latest techniques and best practices throughout their careers [118].

Policy and guidelines

Developing policies and guidelines

To support the integration of simulation in surgical education globally, comprehensive policies and guidelines are necessary [119]. These should be developed by international surgical and educational organizations in collaboration with accreditation bodies and healthcare institutions [119]. Key elements of these policies should include:

Standardization of Simulation Curricula: Establishing standardized curricula that outline the core competencies and skills to be developed through simulation training [120]. This includes defining the minimum requirements for simulation-based training programs and ensuring consistency in training quality across institutions.

Accreditation and certification Implementing accreditation processes for simulation centers and certification programs for simulation-based training [121]. This ensures that training facilities meet high standards of quality and that trainees achieve recognized competencies.

Funding and resource allocation Advocating for funding from governments, educational grants, and private partnerships to support the development and maintenance of simulation centers [122]. Policies should promote equitable access to simulation technologies, particularly in under-resourced regions.

Research and evaluation Encouraging ongoing research and evaluation of simulation-based training programs to continuously improve their effectiveness [123]. This includes funding for longitudinal studies, validation of assessment tools, and cost-effectiveness analyses.

Ethical considerations Addressing ethical considerations related to simulation training, using patient data to train AI models and protecting the privacy and confidentiality of data related to trainees' performance are crucial ethical issues in the development of modern healthcare technologies [124].

Case studies and best practices

The integration of simulation into surgical training programs has been transformative for several institutions, resulting in enhanced learning outcomes and improved surgical skills [125]. A prime example is the Stanford Medicine Center for Immersive and Simulation-Based Learning, recognized for its pioneering use of immersive technology and simulation techniques in advancing medical education and training. Stanford's program is widely recognized for its comprehensive use of high-fidelity simulations, which include VR, AR, and mannequin-based scenarios [126]. The center has reported significant improvements in surgical residents' competency and confidence, particularly in complex procedures such as laparoscopic surgeries and emergency response protocols [127].

The University of Toronto's Surgical Skills Centre is another exemplary case [128]. Their program emphasizes a structured curriculum that integrates simulation-based training (SBT) from the early stages of medical education [129]. The use of cadaveric simulations, coupled with sophisticated VR platforms, has been shown to enhance the tactile and spatial skills of residents [130]. A longitudinal study conducted at the center demonstrated a marked reduction in intraoperative errors and a faster transition to independent practice among residents who underwent extensive simulation training [131].

Innovative approaches

Innovative technologies and approaches in surgical simulation are continuously evolving, offering new dimensions to medical education. One such approach is the use of haptic feedback systems in VR environments, which provide realistic tactile sensations, enabling trainees to develop fine motor skills critical for delicate surgical procedures. A study by Azher et al. (2023) highlighted the effectiveness of haptic VR simulators in improving residents' proficiency in microvascular surgeries, a field that demands high precision [132].

Tele-simulation is another groundbreaking approach that has gained significant traction, especially in remote and underserved areas. Platforms like Proximie have revolutionized remote surgical training by enabling real-time, interactive simulations and collaborations between surgeons across different locations [133]. For instance, the program developed by the University of British Columbia demonstrates how tele-simulation has been successfully utilized to provide comprehensive, high-quality surgical education to trainees in both urban and rural settings [133]. By leveraging such innovative platforms, tele-simulation has played a pivotal role in democratizing access to surgical education, bridging geographic disparities, and enhancing the skills of healthcare professionals irrespective of their location.

Furthermore, the incorporation of AI in simulation training is an emerging trend. AI algorithms can analyze performance data and provide personalized feedback, identifying specific areas for improvement. A case study from the Mayo Clinic demonstrated the efficacy of AI-enhanced simulations in refining surgical techniques and decision-making processes [134]. Trainees who utilized AI-driven feedback showed a 25% increase in technical skill acquisition compared to traditional methods [135].

Another noteworthy innovation in medical education technology is the increasing integration of mixed reality (MR), which blends aspects of virtual reality (VR) and augmented reality (AR) to create immersive and interactive learning environments. This technology has been utilized in platforms such as Hololens, enabling institutions to provide advanced anatomy lessons and surgical planning exercises. For example, Wong et al. (2023) reported that MR significantly enhances spatial awareness and anatomical comprehension, contributing to improved surgical outcomes [136]. Additionally, commercial entities like Inovus Medical and UpSurgeon have leveraged MR to develop highly interactive training tools, further emphasizing its growing impact in medical training and simulation.

Surgical training is being revolutionized by the use of advanced modeling techniques. Three-dimensional (3D) printing, poured, moulded synthetic models, and even grown organic models offer diverse approaches for creating highly accurate and customizable anatomical models. These models enable trainees to practice on patient-specific anatomies, which is particularly advantageous for rare or complex cases [137]. A study by Masada et al. (2023) demonstrated that surgical residents who trained with 3D-printed models exhibited improved precision and reduced operative time in subsequent real-life procedures [137]. Incorporating various modeling techniques, including poured, moulded, and organic models, enhances the realism and diversity of training experiences, further improving skill acquisition and patient outcomes.

Gamification of surgical training is another innovative approach that has garnered attention. By incorporating game design elements into simulation exercises, training programs can enhance engagement and motivation among trainees [138]. For example, the use of competitive scenarios and reward systems has been shown to improve learning outcomes and skill retention [138]. A study by Oussi et al. (2020) reported that gamified simulation training led to a higher frequency of practice and better overall performance in laparoscopic skills [138].

Conclusion

The integration of simulation technologies in general surgery education marks a transformative shift from traditional apprenticeship-based models to innovative, technology-driven approaches. Various simulation modalities, including VR, AR, physical simulators, and computer-based platforms, have demonstrated significant benefits in enhancing surgical training. These technologies provide immersive, risk-free environments where trainees can acquire, practice, and refine their skills, effectively connecting theoretical knowledge with hands-on clinical application. Extensive research has validated the efficacy of simulation-based training in improving educational outcomes such as knowledge acquisition, technical proficiency, and procedural competence. Simulation has also been linked to positive clinical outcomes, including enhanced patient safety, reduced surgical errors, and improved overall surgical performance.

The skills gained from simulation training not only persist over time but also prove highly effective in real-world clinical scenarios. However, several challenges impede the broader adoption of simulation technologies, including high costs, disparities in access, lack of standardization, and resistance to change within the surgical education community. Addressing these barriers is crucial for maximizing the potential of simulation-based training.

Moreover, the retention of healthcare staff is a significant global challenge. Engaging healthcare professionals through continuous learning and the integration of advanced simulation technologies into medical education, especially in surgical training, represents a pivotal strategy. The future of surgical education depends on the effective incorporation of cutting-edge simulation technologies to equip future surgeons with the necessary skills to navigate the complexities of modern healthcare. By fostering a commitment to continuous learning, interdisciplinary collaboration, and strategic investment, the healthcare sector can prepare professionals to meet the evolving demands of patient care.

As these technologies become more widely accepted and integrated into mainstream educational curricula, they are expected to play a crucial role in shaping the future of surgical practices. The widespread adoption of simulation-based training will not only improve surgical outcomes and enhance patient safety but also contribute to standardizing surgical competencies globally. Surgical educators and policymakers must collaborate to ensure that these innovative tools are woven into the fabric of surgical education, providing the next generation of surgeons with the skills and knowledge they need to excel in an increasingly complex healthcare environment.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable. This review article does not include any individual person's data in any form (including individual details, images, or videos) that would require consent for publication.

Competing interests
The authors declare no competing interests.

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