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REVIEW ARTICLE

Innovations in surgical training: from simulation to AI-enabled competency-based education: a narrative review

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Abstract

There has been a proliferation of innovations for surgical training, but there remains a critical lack of integrative synthesis that places innovation within a coherent educational framework. As a result, surgical educators face an abundance of tools but limited guidance on how to integrate them into effective, scalable, and globally applicable training systems. In this narrative review, the authors synthesized contemporary literature (2010–2025) identified through structured searches of PubMed/MEDLINE, Scopus, and Google Scholar, focusing on simulation-based education, competency-based medical education, immersive and digital technologies, and emerging applications of artificial intelligence. Eligible empirical studies and high-quality syntheses were analyzed thematically, with descriptive appraisal of evidence maturity aligned to established educational frameworks. The educational foundations and translational evidence of current innovations were critically appraised, and future directions that prioritize measurable learning outcomes, patient safety, implementation feasibility, and equity over technological enthusiasm alone are suggested.

Keywords: *surgical training; innovations; narrative review; simulation-based education; competency-based; learning outcomes*

Introduction

Early surgical education was grounded in the Halstedian apprenticeship model, often summarized as "see one, do one, teach one."[1] While this paradigm was instrumental in shaping early generations of surgeons, it was predicated on assumptions that are no longer tenable in contemporary practice: unlimited operative exposure, prolonged training time, and tolerance for trainee-related variability in patient outcomes. Increasing complexity of procedures, heightened public expectations of safety, medico-legal scrutiny, and ethical imperatives to minimize avoidable harm have collectively exposed the limitations of unstructured experiential learning. Multiple studies have demonstrated wide inter-trainee variability in skill acquisition when operative exposure alone is relied upon, with little assurance of competence at the point of independent practice.[2,3]

Simultaneously, surgical training environments have undergone profound structural constraints. Duty-hour restrictions, reduced case volumes in certain index procedures, increasing subspecializations, and rapid technological evolution have significantly curtailed traditional learning opportunities in the operating room.[4–6] These pressures have driven a global shift toward competency-based medical education (CBME), emphasizing demonstrable performance over time-based progression. However, CBME mandates reliable, valid, and scalable methods for training and assessment, requirements that the operating room alone cannot consistently fulfill. Simulation-based education, structured assessment tools such as Objective Structured Assessment of Technical Skills (OSATS), and Proficiency-based Progression (PBP) models have, therefore, emerged not as adjuncts but as necessities to ensure patient safety while maintaining educational rigor.[7–9]

Despite the proliferation of studies and technologies, there remains a critical lack of integrative synthesis that places innovation within a coherent educational framework. Moreover, innovation is frequently equated with technology adoption, overlooking the central role of curriculum design, deliberate practice, feedback, and competency-aligned assessment. As a result, surgical educators face an abundance of tools but limited guidance on how to integrate them into effective, scalable, and globally applicable training systems. In this narrative review we have synthesized contemporary innovations in surgical training, critically appraised their educational foundations and evidence maturity, and articulate future directions that prioritize learning outcomes, patient safety, and equity over technological enthusiasm alone.

Methods

Study design

This article was conducted as a narrative review of the contemporary literature on innovations in surgical training, with a specific focus on simulation-based education, CBME, digital and immersive technologies, and emerging applications of artificial intelligence (AI). A narrative approach was chosen to allow critical synthesis across diverse educational frameworks, technologies, and global contexts that are not readily amenable to formal systematic review or meta-analysis.

Literature search strategy

A comprehensive literature search was performed using the electronic databases PubMed/MEDLINE, Scopus, and Google Scholar. Searches were conducted for English-language publications from January 2010 to December 2025, reflecting the period during which modern simulation, CBME, and digital innovations in surgical training have evolved.

Search terms and combinations included:

("education, medical"[mesh] OR "internship and residency"[mesh] OR "surgical procedures, operative/education"[mesh] OR surgical education[tiab] OR surgical training[tiab])

AND

(innovation*[tiab] OR technolog*[tiab] OR digital[tiab] OR platform*[tiab] OR competency-based[tiab] OR "competency based" [tiab] OR EPA[tiab] OR entrustable[tiab])

AND

(surg*[tiab])

Reference lists of key articles and relevant reviews were also manually screened to identify additional pertinent studies.

Study selection and inclusion criteria

- Inclusion: empirical studies (randomized controlled trials, quasi-experimental, cohort/comparative, validation studies of assessment/technology, implementation studies, and mixed methods), and high-quality syntheses/consensus relevant to training innovation.
- Exclusion: non-surgical disciplines (unless directly generalizable to surgical skill training), purely opinion pieces without data (can be used only in "future directions" if clearly labeled), and studies not about training/education.
- Timeframe: 2010 to current
- Language: English

Particular emphasis was placed on studies that addressed educational design, assessment validity, skills transfer to the operating room, patient outcomes, and implementation considerations in both high-resource and low- and middle-income country (LMIC) settings.

Data extraction and synthesis

Data were extracted narratively and thematically rather than quantitatively. Key domains of interest included:

1. Educational frameworks underpinning modern surgical training
2. Simulation modalities and evidence for skills acquisition and transfer
3. Immersive technologies [virtual reality (VR), augmented reality (AR), and mixed reality (MR)] and 3D printing
4. Digital and distributed training models
5. AI-enabled assessment and coaching
6. Implementation challenges, scalability, and global applicability.

The strength and maturity of evidence were appraised descriptively, with attention to outcome levels aligned with Miller's Pyramid, Kirkpatrick's framework, and principles of validity as described by Messick. Rather than formal quality scoring, emphasis was placed on consistency of findings, translational relevance, and alignment with competency-based educational principles (Fig. 1).

Ethical considerations

As this study was based exclusively on published literature, ethical approval was not required. No primary data involving human participants were collected.

Frameworks of modern surgical training

Contemporary innovations in surgical training are grounded in well-established educational frameworks that define how competence is developed, measured, and translated into clinical practice. Miller's Pyramid provides a hierarchical model of assessment, progressing from knowledge ("knows") and application ("knows how") to performance ("shows how") and real-world clinical practice ("does"), emphasizing that true competence must ultimately be demonstrated in authentic settings rather than inferred from surrogate

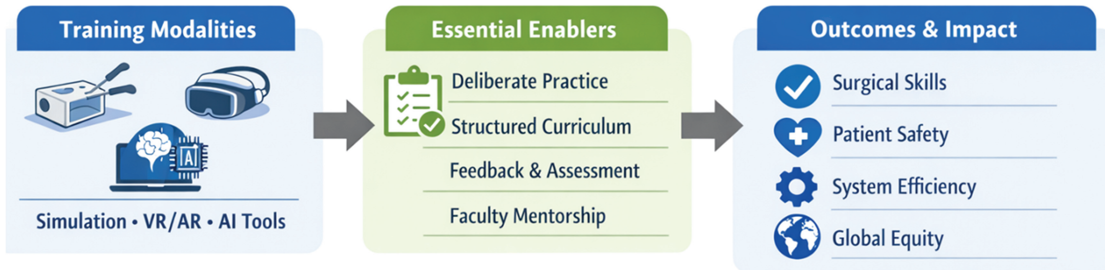

Figure 1. Overview of how innovations in surgical training can achieve meaningful impact when integrated with deliberate practice, structured curricula, feedback, and faculty mentorship, ultimately translating into improved surgical skills, patient safety, system efficiency, and global equity. AR: augmented reality; VR: virtual reality.

measures alone.[10] Complementing this, the Kirkpatrick framework categorizes educational outcomes from learner reaction and knowledge acquisition to behavioral change and patient or system-level impact, highlighting the persistent gap between skill acquisition in simulated environments and demonstrable improvements in operative performance or patient safety.[11] These frameworks underpin the shift toward CBME, which prioritizes outcome-defined training, explicit performance standards, and progression based on demonstrated ability rather than time spent in training.[12,13] Within CBME, PBP and mastery learning models operationalize competence by requiring trainees to achieve predefined, validated benchmarks before advancing, thereby reducing performance variability and enhancing skill transfer to the operating room.[14] Central to all these approaches is the requirement for robust assessment systems, best conceptualized through Messick's unified validity framework, which integrates content, response process, internal structure, relations to other variables, and consequences of testing into a single construct of validity.[15] Together, these frameworks provide the theoretical foundation for evaluating surgical training innovations, ensuring that technological advances are aligned with meaningful learning outcomes, reliable assessment, and ultimately, improved patient care.

Simulation-based training: foundation of modern surgical education

Simulation-based training (SBT) has become the cornerstone of contemporary surgical education by providing a controlled, reproducible environment for deliberate practice without risk to patients. Foundational modalities such as box trainers, cadaveric dissection, and wet laboratories remain highly relevant, particularly for developing psychomotor skills, anatomical understanding, and procedural sequencing. Evidence suggests that generic skills training (e.g. hand–eye coordination, depth perception, bimanual dexterity) effectively prepares novices for early technical development, while procedure-specific simulation offers greater educational value for advanced trainees approaching independent practice.[3,16,17] Multiple randomized and comparative studies have demonstrated that SBT improves technical performance metrics and, importantly, facilitates transfer of skills to the operating room, with reductions in operative time, errors, and intraoperative complications for selected procedures.[7,18,19] Newer ideas like robot-assisted surgical training (RAST) offer high-certainty improvements in technical performance and show encouraging, although more variable, benefits for efficiency, error reduction, workload, and retention.[20] It bears repetition that the effectiveness of simulation is not universal and is influenced by curriculum design, feedback quality, and alignment with competency benchmarks rather than simulator fidelity alone. High-cost, high-fidelity platforms have not consistently shown superiority over well-designed low-fidelity models, challenging the assumption that realism equates to educational impact.[21,22] Practical limitations including financial cost, faculty time requirements, and sustainability remain significant barriers to widespread implementation, underscoring the need for evidence-informed, context-sensitive adoption of simulation rather than indiscriminate technology-driven expansion. While SBT improves technical performance, further Kirkpatrick Level 4 evidence is needed to clarify how these gains translate into measurable patient-centered outcomes, reflecting the complexity of this relationship.[23]

Immersive learning technologies

Immersive learning technologies, encompassing VR, AR, and MR extended reality, have expanded the scope of simulation by enabling interactive, three-dimensional learning environments that support repetitive practice, procedural rehearsal, and real-time feedback.[24] VR platforms are particularly effective for developing visuospatial skills and procedural flow, while AR and MR offer the advantage of overlaying digital guidance onto physical models or live operative fields, facilitating contextual learning. Evidence consistently demonstrates that immersive technologies improve technical skill acquisition and short-term performance metrics in simulated settings; earlier doubts about translation of these gains to sustained operating-room performance are now giving way to evidence for enhanced surgical performance and precision.[25,26] It must be noted that indiscriminate adoption driven by novelty alone cannot be reliably translated into superior learning outcomes. VR/AR/MR is most effective when integrated into structured curricula with defined proficiency targets, particularly for minimally invasive and endoscopic procedures, whereas its benefits are less clear for complex open surgery, non-technical skills, or advanced decision-making.

3D printing

3D printed models add substantial value in both surgical training and anatomical education. These are effective in the enhancement of anatomical education with both common and rare scenarios and are associated with a high degree of trainee satisfaction, thereby strengthening future surgical curricula. Use of immersive VR environments combined with 3D printed models allows trainees to manipulate and interact with anatomical structures in ways that would not be possible with traditional methods. Such experience significantly improves a trainee's ability to replicate these procedures in real clinical settings.[27]

Digital surgical training

Digital and distributed training models, including telementoring, tele-simulation, and remote proctoring, have emerged as important extensions of surgical education beyond the physical confines of the operating room and simulation laboratory.[28–32] Telementoring enables real-time expert guidance across geographic boundaries, while tele-simulation facilitates structured skills training and feedback using digital platforms, expanding access to expertise and standardizing instruction. The COVID-19 pandemic accelerated adoption of these models, demonstrating that remote training and supervision can preserve educational continuity during periods of restricted operative exposure and travel limitations. Importantly, these approaches have significant implications for global surgery, offering scalable solutions to address workforce shortages, inequitable access to specialist training, and faculty scarcity in low- and middle-income countries (LMICs).[32,33] However, challenges related to connectivity, medico-legal accountability, credentialing, and sustainability remain, underscoring that distributed training is most effective when embedded within collaborative frameworks rather than used as a substitute for comprehensive local capacity building.

Artificial intelligence in surgical training: promise and caution

Artificial intelligence is increasingly being explored in surgical training as a tool for coaching, assessment, and curriculum personalization, leveraging advances in machine learning, computer vision, and natural language processing.[34] AI-driven systems have demonstrated the ability to analyze surgical motion, instrument handling, and video data to generate objective performance metrics, offering scalable and consistent feedback that may complement faculty assessment. More recently, large language models (LLMs) have shown potential in educational applications such as formative feedback, simulation scenario generation, and learner support; however, technical challenges such as data quality issues, inaccuracies, and uncertainties around model interpretability remain barriers to widespread adoption.[35] Moreover, concerns persist regarding data governance, algorithmic bias, transparency, and the interpretability of AI-derived assessments, particularly when training data lack diversity or contextual relevance. Importantly, current evidence supports AI as an augmentative rather than substitutive tool, enhancing feedback, standardization, and efficiency, while the educator's role in judgment, mentorship, and contextual decision-making remains irreplaceable.[36] Responsible integration of AI into surgical education therefore requires rigorous validation, ethical oversight, and alignment with established competency frameworks to ensure that technological advancement serves learning, patient safety, and professional development rather than undermining them.[37] Efficacy and ease of use of commonly available ChatGPT (chat-generative pre-trained transformer) deserve special mention.[38]

Implementation challenges and global applicability

Despite strong evidence supporting simulation, 3D printing, and digital innovation in surgical training, implementation at scale remains constrained by cost, faculty workload, and infrastructural disparities.[39] High upfront investment, ongoing maintenance, and the need for trained faculty time can limit sustainability, particularly in resource-constrained settings, where educational priorities often compete with service delivery demands. Importantly, innovation in surgical education should not be equated with high-cost technology; evidence increasingly supports the effectiveness of low-cost, context-adapted simulation models when embedded within structured curricula and deliberate practice frameworks. Frugal simulation approaches, including locally fabricated trainers, tele-simulation, and shared digital resources, have demonstrated feasibility and educational impact in LMICs, addressing workforce shortages while minimizing financial barriers.[40] However, inequities in digital access, connectivity, and institutional support risk widening existing gaps if innovation is adopted without attention to inclusivity and context. Achieving global applicability therefore requires a shift from infrastructure-driven adoption to an innovation mindset focused on scalability, equity, and alignment with local training needs, ensuring that advances in surgical education enhance access rather than reinforce disparities.[41] It is heartening to note that user-friendly ChatGPT can be a surgical assistant, offering real-time, context-specific clinical support and tailored practical recommendations to surgeons in LMICs who need to navigate resource constraints and require affordable, evidence-based solutions.[42]

Table 1 synthesizes the current surgical training innovations by mapping their educational intent against the strength of evidence for skill acquisition, operating room transfer, patient-level outcomes, and implementation constraints, with a particular focus on feasibility and relevance for LMIC settings.

Table 2 contextualizes key implementation challenges across high-resource and LMIC settings and aligns them with evidence-supported, context-sensitive mitigation strategies, highlighting pathways to equitable and scalable adoption of surgical training innovations.

Future directions and research priorities

All these innovations have tremendously helped in surgical training. These are being continuously tweaked and improved, like short video reels, gamification, asynchronous tele-mentoring using smartphones, and video-based self-assessment show promise.[43–46] However, future research in surgical training must move beyond learner satisfaction and short-term skill acquisition toward outcomes that reflect meaningful clinical impact. While simulation and digital innovations consistently demonstrate improvements in technical performance within controlled environments, robust evidence linking these gains to sustained operating-room performance, patient safety, and health system outcomes remains limited.[23] Addressing this gap will require longitudinal study designs, integration of training data with clinical outcomes, and greater emphasis on higher-level educational endpoints. Standardization of outcome measures is equally critical, as heterogeneity in assessment tools and reporting currently limits comparability across studies and undermines evidence synthesis. The development of core outcome sets for surgical education aligned with competency frameworks and validated assessment principles would substantially strengthen the field. Looking ahead, hybrid training ecosystems that combine human expertise with AI offer promising opportunities to enhance feedback, personalize learning trajectories, and improve scalability, provided these systems are rigorously validated and ethically governed. Advancing surgical education will therefore depend not on isolated technological advances but on coordinated efforts to align innovation with patient-centered outcomes, standardized metrics, and thoughtfully integrated human–AI partnerships.[47]

Table 3 delineates key evidence gaps across simulation, assessment, AI, and global training while framing priority research questions that define future directions for building robust, scalable, and equitable surgical education systems.

Conclusion

Innovation in surgical training must be reframed as a means to educational and clinical excellence rather than an end

Table 1. Surgical training innovations: educational goals, evidence strength, outcomes, limitations, and LMIC applicability

Innovation domain	Primary educational goal	Evidence for skill acquisition	Evidence for OR transfer	Patient outcome data	Key limitations	LMIC applicability
Low-cost box trainers	Basic technical and procedural skills; anatomical familiarity	High	Moderate	Limited	Faculty time, infrastructure, recurring costs	High
3D modeling and printing	Anatomical understanding and preoperative planning	High	Moderate	Emerging (reduced complications, improved planning)	Cost, need for imaging and printing facilities	Moderate
VR/AR/MR	Visuospatial skills, procedural flow, decision-making in complex surgery	High	Variable	Limited	High cost, hardware requirements, variable validation	Moderate
Tele-simulation	Access to training, mentorship, and standardization	Moderate	Moderate	Limited	Connectivity, time zones, faculty availability	High
AI-based assessment and mentoring	Objective feedback, personalized learning, performance analytics	Emerging	Limited	None	Bias, lack of validation, regulatory concerns	Unclear

AI: artificial intelligence; AR: augmented reality; LMIC: low and middle income countries; MR: mixed reality; VR: virtual reality.

Table 2. Implementation challenges and context-sensitive solutions in surgical training innovation

Challenge	High-resource settings	LMIC settings	Evidence-supported mitigation
Cost	High-fidelity simulators	Budget constraints	Low-cost/frugal simulation
Faculty workload	Competing clinical duties	Severe shortages	Tele-simulation, AI-assisted feedback
Infrastructure	Advanced but siloed	Limited connectivity	Hybrid digital models
Equity	Access gaps	Geographic isolation	Distributed training models

AI: artificial intelligence.

Table 3. Research gaps and future priorities

Domain	Current gap	Priority research question
Simulation	Short-term outcomes	Does simulation reduce complications long-term?
Assessment	Non-standard metrics	Can core outcome sets be developed?
AI	Limited validation	Does AI feedback outperform expert coaching?
Global training	Fragmented models	What scales sustainably in LMICs?

AI: artificial intelligence; LMIC: low- and middle-income countries.

defined by technological adoption. While simulation, 3D printing, digital platforms, and AI have expanded the educational armamentarium, their true impact depends on rigorous alignment with sound pedagogical principles, deliberate practice, feedback, validated assessment frameworks, and patient-centered outcomes. Technology divorced from structured curricula and outcome relevance risks becoming an expensive novelty rather than a transformative force. Realizing the promise of these innovations also demands a concerted, collaborative effort among policymakers, industry developers, and surgical educators, supported by targeted institutional and governmental investment, robust policy frameworks, and clear ethical guardrails. Concrete mechanisms such as international working groups to harmonize standards and public–private partnerships to enable affordable deployment in LMICs are essential to prevent the widening of global disparities and to foster a more inclusive surgical workforce. Ultimately, the central challenge for surgical education is not the pursuit of ever-newer tools but the disciplined integration of evidence-based, competency-driven, and context-sensitive innovations that are effective, equitable, and scalable—ensuring that progress in training translates into safer surgery and better care for patients worldwide.

Conflict of interest

None declared.

Data availability

No new data were generated or analyzed in support of this work.

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