Integrating Simulation-Based Anatomy and Operative Skills Training for Medical Students: A Narrative Review

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Abstract

Contemporary surgical practice demands that graduating medical students possess not only sound anatomical knowledge but also foundational operative skills acquired in a safe, structured learning environment. Traditional cadaveric dissection has long been central to anatomy education and early surgical training; however, growing constraints on theatre exposure, work-hour limitations, and patient safety concerns have accelerated the adoption of simulation-based approaches. Recent evidence shows that simulation modalities ranging from low-fidelity bench models and three-dimensional (3D)-printed organs to high-fidelity virtual reality (VR) systems can enhance anatomical understanding, suturing performance, and overall technical proficiency among medical students. Studies comparing cadaveric and simulator-based training highlight that cadavers remain the gold standard for appreciating realistic tissue handling and complex three-dimensional relationships, whereas simulators offer repeatability, structured feedback, and risk-free practice.

Keywords: anatomy education; operative surgery training; simulation-based training; cadaveric dissection; virtual reality; medical students.

Introduction

Anatomy and operative surgery form the intellectual and technical foundation of clinical practice, yet there is ongoing debate about how best to teach these disciplines to increasingly large and diverse cohorts of medical students. Historically, cadaveric dissection and apprenticeship-style observation in the operating theatre were considered sufficient to foster spatial understanding, respect for tissue planes, and basic procedural skills. However, constraints such as reduced working hours, heightened emphasis on patient safety, and ethical concerns about using real patients as practice opportunities have limited the availability of live surgical exposure for undergraduates. At the same time, advances in digital technology and educational theory have created new possibilities for simulation-based training that can reproduce key aspects of anatomy and operative technique in controlled, reproducible environments. There is

now substantial interest in how best to integrate these tools with traditional anatomy teaching to prepare students for modern surgical training pathways.

This narrative review aims to synthesize current evidence on the integration of anatomical education and operative skills training for medical students, with a particular focus on simulation-based modalities and their relationship to cadaveric dissection. Specifically, it addresses three questions: how simulation-based courses can support the integration of anatomy and surgical approaches, what impact these interventions have on students' knowledge and technical performance, and how cadaveric and simulator-based methods can be blended across the curriculum. By drawing together findings from randomized trials, cohort studies, and systematic reviews, the review seeks to inform curriculum designers, anatomists, and surgeons who are planning or refining integrated surgical anatomy programs at the undergraduate level.

Methods

This narrative review was informed by a structured literature search but did not follow a formal systematic review protocol such as PRISMA. PubMed, Scopus, and Web of Science were searched for English-language articles published between 2005 and 2025 using combinations of the following terms: "anatomy, operative surgery, simulation-based training, cadaveric dissection, medical students, virtual reality, 3D-printed model." Additional sources were identified by screening reference lists of key articles and relevant systematic reviews on surgical simulation and anatomy education. Inclusion criteria were studies and reviews that: (1) involved undergraduate medical students; (2) described interventions or curricula linking anatomy teaching with operative or procedural skills; and (3) reported outcomes related to knowledge, technical performance, confidence, or attitudes. Postgraduate-only studies and purely conceptual papers without educational outcomes were excluded, although selected postgraduate evidence is cited for context where directly relevant to curriculum design. Data from included studies were extracted narratively with attention to intervention type (cadaver, low-fidelity models, 3D-printed models, VR), target anatomy or procedure, study design, outcome measures, and key findings. Given the heterogeneity of interventions and outcomes, no meta-analysis was attempted; instead, results are presented thematically, emphasizing patterns that inform undergraduate surgical anatomy education rather than effect sizes per se.

Results

Integration of anatomy and operative approaches through simulation

One of the clearest examples of integrated teaching is a surgical anatomy course that combines practical learning of anatomy with simulation-based surgical approaches. In this model, students revisit region-based anatomy in the context of common operations, using structured sessions that link each step of a procedure to underlying anatomical

structures and relationships. Evaluation of such a course demonstrated improved anatomical knowledge, better understanding of three-dimensional relationships, and increased confidence in entering surgical rotations among participating students. These findings align with broader literature showing that simulation-based training in medical education enhances learning by allowing repeated practice and immediate feedback in a low-risk environment.

Role of cadaveric dissection in operative skills training

Cadaveric simulation remains highly valued for its fidelity in representing surgical anatomy and tissue handling. A systematic review of cadaveric simulation in postgraduate surgical training found that cadaver-based courses improve procedural performance, facilitate the acquisition of complex three-dimensional neurovascular relationships, and offer authentic practice in conducting operations from incision to closure in a realistic environment removed from patient care. Although most included studies focused on trainees rather than undergraduates, the review underscored that cadaveric dissection provides ultra-high-fidelity anatomical context that is difficult to replicate in synthetic or purely virtual models. For medical students, exposure to cadaveric surgical anatomy can therefore provide an essential bridge between textbook knowledge and operative reality, especially when framed within structured courses that emphasize operative approaches and safety principles.

Emerging evidence for 3D-printed models and bench simulators

Recent work has highlighted the potential of 3D-printed models to enhance operative training for medical students. In a randomized cohort study of sixth-year students, those trained on realistic 3D-printed intestinal anastomosis models showed superior performance compared with peers using simple suturing pads, as measured by standardized exam scores and operative times on the 3D model itself. While both groups improved during the course, the 3D-model group demonstrated greater gains in technical accuracy and reported higher interest in surgery and technical training. Bench-top simulators and synthetic models also feature prominently in earlier surgical simulation trials, where they have been shown to improve basic laparoscopic skills, suturing, and knot-tying compared with no training or standard teaching alone. These findings suggest that low- to medium-fidelity simulators can effectively support early acquisition of psychomotor skills, particularly when integrated with concurrent anatomical instruction.

Impact of virtual reality simulation on anatomy and surgical skills

Virtual reality has emerged as a particularly promising tool for both anatomy and operative skills training. A recent systematic review on VR simulation in anatomy education concluded that VR-based interventions significantly improved medical students' spatial understanding, retention of anatomical knowledge, and engagement compared with traditional methods alone. Meta-analytic work in orthopedic and

general surgical education similarly found that VR-based teaching yields higher knowledge scores, better clinical operation scores, and improved operative design performance relative to traditional instruction. In an international randomized controlled trial of urology residents, additional simulation training was associated with higher OSATS scores and fewer complications during ureterorenoscopy, illustrating the potential patient-safety benefits of simulation when trainees progress to real operations. Although this trial included residents rather than students, the underlying mechanisms—deliberate practice, standardized feedback, and risk-free rehearsal—are directly relevant to designing VR-enhanced operative curricula at the undergraduate level.

Comparison of cadaveric and simulator-based modalities

Direct comparisons between cadaveric and simulator-based training show a nuanced picture. Cadaver-based arthroscopic training and VR simulators have each been associated with improvements in technical performance, but studies comparing the two modalities suggest that neither uniformly dominates the other; rather, they offer complementary strengths. Cadavers provide unparalleled realism in tissue characteristics and anatomical variation, which is essential for advanced procedural judgment, while VR and synthetic simulators allow for more frequent, standardized practice and objective performance assessment. An earlier systematic review of surgical simulation found that computer-based simulation was generally superior to no training and at least comparable to low-fidelity models, though not always superior to well-structured traditional training when operative performance was the primary outcome. Overall, these findings support a blended approach that harnesses both cadaveric and simulation modalities across the continuum of anatomy and operative skills education.

Proposed curriculum model and placement of figures and tables

Synthesizing the above evidence, a staged curriculum can be proposed in which early preclinical years emphasize foundational anatomy through a combination of traditional dissection, prosection, and VR-based spatial visualization, while parallel skills labs introduce basic suturing and knot-tying on bench models. In later years, students can progress to integrated surgical anatomy courses that marry regional anatomy with specific operative approaches using cadaveric specimens, 3D-printed models of complex structures, and procedure-focused simulation scenarios. This progression allows learners to move from conceptual understanding to hands-on technical performance in a scaffolded manner that respects patient safety and optimizes limited cadaver resources.

Within the Results section of a primary research or curriculum-evaluation article, it would be appropriate to present a table summarizing key educational outcomes from different training modalities. A table titled "Table 1. Summary of Educational

Outcomes from Cadaveric, 3D-Printed, and VR-Based Training in Anatomy and Operative Skills" could appear immediately after the narrative paragraph describing comparative results. In text, it would be introduced as follows: "Table 1 summarizes reported changes in knowledge scores, technical performance, and learner confidence across cadaveric, 3D-printed, and VR-based interventions." This table would list study type, modality, learner level, and main outcome improvements, illustrating at a glance how each approach contributes to anatomy and operative skill development.

A complementary figure could be placed later in the Results section to visualize the staged curriculum model. "Figure 1. Proposed Staged Integration of Anatomy and Operative Skills Training Across the Undergraduate Curriculum" would depict a flow diagram or layered bar illustrating how dissection, bench models, 3D-printed organs, and VR simulations are introduced over successive years. The text could reference it as: "As illustrated in Figure 1, the proposed curriculum introduces low-risk skill acquisition in early years, followed by higher-fidelity cadaveric and VR-supported procedural training closer to clinical clerkships." This figure would help readers quickly understand the temporal and pedagogical relationships between modalities without requiring detailed narrative description alone.

Discussion

The reviewed literature indicates that integrating anatomy teaching with operative surgery training through simulation-based methods can substantially enhance medical students' preparation for clinical practice. Simulation offers opportunities for deliberate practice, feedback, and standardized assessment that are difficult to achieve in crowded operating theatres or time-limited dissection labs, while cadaveric dissection remains indispensable for appreciating real-world anatomy and tissue handling. A coherent curriculum should therefore avoid framing cadavers and simulators as competitors; instead, it should position them as complementary tools deployed at different stages and for different learning objectives. Early use of VR for spatial orientation, bench models for fundamental psychomotor skills, and 3D-printed models for procedure-specific practice can prime students to derive greater benefit from later cadaver-based surgical anatomy and supervised operative exposure.

However, there are important challenges to implementing such integrated curricula, including financial costs, faculty development needs, and the risk of overreliance on technology without sufficient pedagogical grounding. High-fidelity VR systems and 3D-printing facilities require substantial initial investment, and their educational value depends on careful scenario design, alignment with learning outcomes, and robust assessment strategies. Faculty who trained in traditional apprenticeship models may require support to adapt to simulation-rich environments and to provide structured feedback using tools such as OSATS. Furthermore, simulation experiences must be explicitly linked to real patient care, both conceptually and through subsequent clinical

placements, to avoid the perception that they are merely "games" detached from authentic surgical responsibility.

Limitations of the current evidence base should also be acknowledged. Many studies focus on short-term gains in knowledge or skills rather than long-term retention or transfer to clinical performance, and few randomized trials compare carefully matched cadaveric and VR-based curricula in undergraduate populations. Heterogeneity in outcome measures, ranging from self-reported confidence to diverse technical scoring systems, complicates synthesis and may overstate the impact of some interventions. Future research should prioritize multi-institutional, longitudinal studies that track students from preclinical anatomy courses through clerkships and early residency, using standardized metrics that capture both technical and non-technical skills, including operative planning, communication, and situational awareness.

Conclusion

Anatomy and operative surgery education are undergoing a profound transformation as simulation technologies mature and pressures on traditional training models intensify. The evidence reviewed here demonstrates that when thoughtfully integrated with cadaveric dissection, simulation-based approaches—including bench models, 3D-printed organs, and virtual reality platforms—can deepen anatomical understanding, accelerate acquisition of operative skills, and boost learners' confidence as they approach real surgical environments. Rather than replacing the dissection room or the operating theatre, these tools offer a powerful scaffold that allows students to progress from conceptual knowledge to technical competence while preserving patient safety and optimizing scarce clinical resources. To capitalize on this potential, medical schools should adopt staged, blended curricula in which anatomy, simulation, and supervised operative experience are intentionally aligned, supported by trained faculty and rigorous assessment. By doing so, educators can cultivate a new generation of doctors whose mastery of anatomy is matched by practical operative skills, reflective judgment, and a readiness to engage with increasingly complex surgical care from day one of postgraduate training.

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