SIMULATION, VIRTUAL REALITY, AND ARTIFICIAL INTELLIGENCE IN PEDIATRIC SURGICAL TRAINING: CURRENT GAPS AND FUTURE DIRECTIONS

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Abstract:

Training in pediatric surgery presents unique challenges due to small patient populations, anatomical variability, ethical constraints, and the high level of technical precision required. Traditional apprenticeship-based training models, while historically effective, are increasingly insufficient to meet modern educational and patient safety demands. In recent years, simulation, virtual reality (VR), and artificial intelligence (AI) have emerged as promising tools to supplement surgical education. However, most existing technologies are developed for adult surgery and lack pediatric-specific design, validation, and outcome correlation. This article reviews the current role of simulation, VR, and AI in pediatric surgical training, critically examines existing gaps in their development and implementation, and outlines future directions for research and integration. Emphasis is placed on the need for child-specific anatomical modeling, standardized curricula, objective assessment tools, and equitable access to training technologies. Addressing these gaps is essential to ensure that technological innovation translates into meaningful improvements in pediatric surgical competence and patient outcomes.

Keywords: Pediatric surgery, Simulation, Virtual reality (VR), Artificial Intelligence (AI), child-specific anatomical modelling, technological innovation.

Introduction:

Pediatric surgery is fundamentally different from adult surgical practice. Surgeons must operate on patients ranging from premature neonates to adolescents, each with distinct anatomical, physiological, and developmental considerations. In addition, many pediatric surgical conditions are rare, limiting clinical exposure during training. Ethical imperatives further restrict hands-on experience, particularly in neonates and infants, where tolerance for error is minimal. The traditional apprenticeship model of surgical education, often summarized as "see one, do one, teach one," is increasingly strained by reduced working hours, heightened patient safety expectations, and medicolegal concerns. As a result, there is growing interest in alternative educational strategies that allow trainees to develop technical and non-technical skills without compromising patient care.

Simulation, virtual reality (VR), and artificial intelligence (AI) have gained prominence as potential solutions. While these technologies have been widely explored in adult surgical training, their application in pediatric surgery remains limited and fragmented. This article examines the current landscape of these technologies in pediatric surgical education, identifies critical gaps, and proposes future directions for meaningful innovation.

Unique Challenges in Pediatric Surgical Training

Several factors distinguish pediatric surgical training from adult surgical education:

1.Small and delicate anatomy, requiring exceptional precision and fine motor control.

2.Low case volumes for many congenital anomalies, limiting repetition and mastery.

3.Wide anatomical variability, particularly in congenital conditions.

4.Ethical constraints, reducing trainee autonomy in high-risk cases.

5.Non-technical demands, including communication with parents and caregivers and complex consent processes.

These challenges highlight the need for training tools specifically designed for pediatric surgery rather than scaled-down versions of adult models.

Simulation in Pediatric Surgical Training

Current Applications

Simulation has become an integral component of surgical education, encompassing low-fidelity task trainers, high-fidelity mannequins, animal models, and cadaveric laboratories. In pediatric surgery, simulation is commonly used for basic procedural skills, neonatal resuscitation, and laparoscopic techniques.

Strengths

Simulation allows:

1.Repetitive practice without patient risk

2.Skill acquisition in a controlled environment

3.Team training and crisis management exercises

4.These benefits are particularly valuable in pediatric surgery, where real-life exposure may be limited.

Limitations and Gaps

Despite its advantages, pediatric surgical simulation faces several limitations:

1.Many simulators are adapted from adult designs and fail to accurately represent pediatric anatomy or tissue properties.

2.Rare congenital anomalies are poorly represented in existing models.

3.There is limited evidence linking simulation performance to real operative outcomes.

4.High-fidelity simulators are often cost-prohibitive, especially in resource-limited settings.

5.The lack of standardized, validated pediatric simulation curricula remains a major barrier to widespread adoption.

Virtual Reality and Augmented Reality
Potential Advantages

Virtual reality (VR) and augmented reality (AR) offer immersive, reproducible training environments. These technologies allow trainees to visualize complex anatomy, rehearse procedures, and make intraoperative decisions without patient risk. VR is particularly promising for rare pediatric conditions, where clinical exposure is inherently limited.

Current State

Most VR platforms in surgical education focus on basic laparoscopic skills or adult procedures. Pediatric-specific modules are scarce, and those that exist often lack rigorous validation. AR has been explored for intraoperative guidance, but its role in structured pediatric training remains underdeveloped.

Research Gaps

Key gaps include:

1.Lack of child-specific anatomical modeling

2.Minimal incorporation of tissue deformation and haptic feedback

3.Insufficient studies comparing VR-based training with traditional methods

4.Limited assessment of long-term skill retention

5.Without addressing these gaps, VR risks becoming a novelty rather than a transformative educational tool.

Artificial Intelligence in Pediatric Surgical Training

Emerging Applications

1.AI introduces the possibility of objective, data-driven assessment in surgical education. Potential applications include:

2.Automated evaluation of technical skills using motion tracking

3.Error detection and performance benchmarking

4.Personalized learning pathways based on trainee performance

5.Relevance to Pediatric Surgery

AI has particular relevance in pediatric surgery, where limited case numbers and subjective assessments hinder consistent evaluation. AI-driven systems could supplement faculty feedback and help standardize training across institutions.

Current Limitations

The application of AI in pediatric surgical training remains in its infancy. Major challenges include:

1/Lack of large, high-quality pediatric surgical datasets

2/Minimal pediatric-specific validation studies

3/Ethical concerns related to data privacy and algorithmic bias

4/Without intentional pediatric-focused development, AI tools risk perpetuating adult-centric training models.

5/Cross-Cutting Barriers to Implementation

Despite technological promise, several systemic barriers limit adoption:

1.Cost and infrastructure requirements

2.Need for collaboration between surgeons, engineers, and educators

3.Resistance to curricular change

4.Limited access in low- and middle-income regions

5.Equity must be a central consideration to prevent widening disparities in surgical training quality.

Future Directions

To realize the full potential of simulation, VR, and AI in pediatric surgical training, future efforts should focus on:

1.Pediatric-specific design of all training technologies

2.Standardized curricula aligned with competency-based education

3.Multicenter studies linking training outcomes to clinical performance

4.Hybrid models combining physical simulation with VR and AI feedback

5.Scalable and affordable solutions for global training environments

6.Investment in collaborative research and open-access platforms may accelerate progress and ensure broader impact.

Conclusion

Simulation, virtual reality, and artificial intelligence represent powerful tools with the potential to reshape pediatric surgical education. However, their current application remains limited by adult-centric design, insufficient validation, and unequal access. Meaningful progress will require a deliberate shift toward pediatric-specific innovation, robust outcome research, and inclusive implementation strategies. By addressing these gaps, the pediatric surgical community can ensure that technological advancement translates into safer surgery and better outcomes for children.

Literature:

1.Laspro, M., Groysman, L. et al. (2023). "The Use of Virtual Reality in Surgical Training: Implications for Education, Patient Safety, and Global Health Equity." Surgeries.

2.Exploring the use of virtual reality in surgical education — PMC (2023).

3.Surgical Simulation: Virtual Reality to Artificial Intelligence (на ScienceDirect).

4.Transforming Surgical Training With AI Techniques for Training, Assessment, and Evaluation (JMIR, 2025).

Advances in Pediatric Surgery Simulation-Based Training — PMC (обзор).

6.Impact of Extended Reality on Robot-Assisted Surgery Training (arXiv, 2025).

7/Augmented Reality and Simulation-Based Training in Pediatric Laparoscopic Surgery (SSIH/PLS study).

7.Artificial intelligence systems in surgery: A review of opportunities, limitations, and prospects — Russian Journal of Pediatric Surgery, Anesthesia and Intensive Care (2023).