AI-Enhanced Pediatric Robotic and Image-Guided Surgery: Integrating Surgical Data Science and Oncology-Driven Bioinformatics

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Abstract

Artificial intelligence has rapidly entered pediatric perioperative care, spanning diagnostics, surgical planning, robotic-assisted procedures, and postoperative surveillance, yet translation into routine practice remains fragmented compared with adult surgery –. This narrative review synthesizes current evidence on AI-enabled pediatric robotic and image-guided surgery, integrating developments from surgical data science, computer vision, and oncology-focused bioinformatics –,. We highlight clinical use-cases, including AI-assisted preoperative risk stratification, intraoperative navigation, automated pathology, and precision oncology decision support, and contrast them with non-AI robotic programs that rely predominantly on human expertise and ergonomics. While early outcome data suggest at least comparable safety and efficiency, the field faces pediatric-specific barriers such as small, heterogeneous datasets, regulatory constraints, and limited pediatric robotic platforms. Future work must prioritize multi-institutional data sharing, explainable models, and pragmatic trials embedded in pediatric surgical pathways to move from proof-of-concept tools toward trustworthy hybrid human–AI systems.

Keywords: pediatric, artificial intelligence, robotic-surgery, surgical-data-science, computer-vision, oncology, bioinformatics

Introduction

Pediatric surgery has historically lagged behind adult practice in adopting complex technologies, largely due to smaller case volumes, anatomical variability, and device size limitations. Recent years have witnessed a surge of interest in artificial intelligence across pediatric diagnostics, perioperative planning, and robotic-assisted surgery, with several narrative and systematic reviews beginning to map this emerging landscape –. In pediatric oncology, AI-enabled radiomics, digital pathology, and multi-omics integration are actively explored to improve risk stratification and treatment selection, underscoring the feasibility of sophisticated computational pipelines even in rare childhood cancers. Robotic-assisted surgery has also expanded in children, with multicenter cohorts and single-center learning-curve studies demonstrating safety and efficiency gains, thereby providing an ideal substrate on which AI-driven decision support and automation might be layered. This review aims to integrate these parallel streams by focusing on AI-enhanced pediatric robotic and image-guided surgery, contrasting them with conventional robotic workflows and identifying translational

gaps, particularly relevant for clinician–scientists working at the interface of surgery and bioinformatics.

Methods

This narrative review targeted peer-reviewed literature on artificial intelligence in pediatric surgery, pediatric oncology, and robotic-assisted pediatric procedures published predominantly between 2020 and 2025. We focused on studies involving children or mixed-age cohorts with extractable pediatric data that applied machine learning, deep learning, computer vision, or other AI approaches to diagnostics, perioperative planning, intraoperative support, or postoperative care –,. Reference lists of key reviews in pediatric AI surgery, pediatric oncology AI, and robotic-assisted pediatric surgery were manually screened to identify additional relevant primary studies and methodological articles –. Given the heterogeneity of designs and endpoints, we synthesized findings qualitatively, emphasizing clinical use-cases, data characteristics, and outcome trends rather than formal meta-analysis –.

Results

Landscape of AI in pediatric surgical care

Recent narrative syntheses confirm that AI applications in pediatric surgery cluster around four domains: diagnostics, preoperative planning and risk stratification, intraoperative support and error prevention, and postoperative outcome prediction,. Diagnostic imaging represents the most mature area, with deep learning models reaching near-expert performance for tasks such as fracture detection and bone age assessment, although external validation in diverse pediatric populations remains scarce. Preoperative planning increasingly leverages AI for organ and tumor segmentation, 3D reconstruction, and virtual reality simulation, leading to modified surgical strategies in a subset of complex cases, particularly in pediatric oncology,. Intraoperative support via computer vision and surgical data science is still predominantly experimental in pediatrics, constrained by the limited availability of annotated endoscopic videos and lack of pediatric-specific datasets,.

In pediatric surgical pathology, AI has shown promise in automating labor-intensive tasks such as slide triage, tumor region detection, and quantification of histologic features, thereby reducing workload for pathologists and standardizing assessments. These tools mirror trends in adult digital pathology but must contend with the rarity and histologic diversity of pediatric tumors, which challenge robust training and validation,. Across domains, the literature consistently emphasizes that the main value of AI lies not in replacing clinical judgment but in augmenting decision-making speed and consistency in settings where data volumes exceed what humans can efficiently process.

AI in pediatric oncology and its perioperative relevance

Pediatric oncology has emerged as a leading testbed for high-dimensional AI, driven by the availability of imaging, genomic, and clinical data, and the critical need for precise risk stratification. Recent reviews describe AI models capable of integrating

radiomics, genomics, proteomics, and metabolomics to discover novel biomarkers, predict therapy response, and personalize treatment protocols for childhood cancers,. In imaging, AI applications include low-dose reconstruction, automated lesion segmentation, and metric-based response assessment in modalities such as MRI and CT, although translation into routine pediatric oncology imaging remains limited by nonstandardized protocols and small datasets. Digital pathology approaches have achieved high diagnostic accuracy in classifying hematologic malignancies and discriminating overlapping brain tumor subtypes, occasionally outperforming expert hematologists and providing low-cost decision support in resource-constrained environments,.

These oncologic advances have direct implications for pediatric surgical practice, particularly in tumor surgery and transplant oncology. AI-assisted segmentation and 3D modeling can improve preoperative understanding of tumor–organ relationships, potentially altering operative plans in complex hepatobiliary or thoracic oncology cases, as has been observed in adult series and emerging pediatric reports,. Multi-omics models that predict treatment toxicities and long-term sequelae may also influence surgical timing, reconstruction choices, and perioperative risk discussions with families,. However, systematic integration of such predictive models into perioperative pathways is rarely reported, with most work still limited to retrospective analyses and prototype decision-support tools.

Current status of pediatric robotic-assisted surgery

Robotic-assisted surgery in pediatrics has grown steadily, with multicenter series and recent seven-year single-center experiences demonstrating feasibility across urologic, gastrointestinal, thoracic, and oncologic procedures. A large multicenter cohort reported major postoperative complications in approximately 7% of robotic cases, despite a substantial proportion of patients presenting with high anesthetic risk scores, supporting the safety of robotic platforms in complex pediatric populations when centralized in specialized centers,. Single-center longitudinal analyses show significant learning curves, with median docking times decreasing from around 45 to 15 minutes and operative times falling significantly as teams gain experience, while maintaining low conversion and complication rates,. These efficiency gains, coupled with shorter hospital stays and faster recovery, suggest potential long-term cost offsets even though the upfront investment in robotic systems remains substantial,.

Despite these advances, several pediatric-specific barriers persist. Robotic instruments and platforms are mostly designed for adults, imposing constraints when operating in small body cavities and requiring careful case selection in infants and younger children,. Economic considerations are particularly acute in pediatrics because case volumes are lower and indications narrower compared with adult programs, making volume consolidation and regionalization critical for sustainability. Importantly, current pediatric robotic workflows are largely “non-AI,” relying on improved ergonomics, tremor filtration, and 3D visualization rather than genuine autonomy or

algorithmic decision support,. This gap highlights an opportunity for AI to augment robotic pediatric surgery with smarter guidance, automation of routine tasks, and data-driven performance feedback.

AI-enhanced versus non-AI pediatric robotic surgery

While few clinical studies directly compare AI-enhanced robotic platforms with conventional robotic systems in children, existing reviews outline conceptual and early practical differences in how these paradigms might operate. AI-augmented workflows can incorporate preoperative predictive models for risk stratification, in-silico rehearsal using patient-specific simulations, intraoperative computer vision for landmark recognition, and postoperative analytics for performance assessment, whereas traditional robotic programs rely primarily on surgeon experience and qualitative teaching. Initial pediatric reports of AI use in robotic-assisted surgery are mostly confined to feasibility phases, such as automated instrument tracking, context-aware video annotation, and semi-autonomous suturing tasks, often extrapolated from adult surgical data due to limited pediatric case volumes,.

The table below contrasts key dimensions of contemporary pediatric robotic-assisted surgery programs with envisioned AI-augmented counterparts, based on current literature on pediatric AI surgery, robotic surgery, and surgical data science –.

Comparison of pediatric robotic programs

Dimension	Conventional pediatric RAS	AI-augmented pediatric RAS
Preoperative planning	Surgeon-driven interpretation of imaging; occasional 3D reconstructions ,	AI-based segmentation, virtual rehearsal, and risk prediction integrating imaging and clinical data , ,
Intraoperative guidance	Enhanced 3D visualization, tremor filtering; no automated recognition ,	Computer-vision landmark recognition, anatomy tracking, and context-aware alerts for potential errors , ,
Surgical autonomy	Fully human-controlled robotic arms; standardized instrument motions ,	Shared-control autonomy for subtasks (e.g suturing, camera steering) with safety constraints ,
Training and feedback	Proctoring, simulation-based training, and subjective assessments ,	AI-driven metrics from video and kinematics enabling objective learning curves and personalized feedback ,
Outcome prediction	Traditional risk scores, expert judgment ,	Dynamic prediction of complications and length of stay using perioperative data streams ,
Data usage	Limited structured capture; variable video archiving ,	Systematic data capture for continuous model retraining and quality improvement , ,

Data, regulatory, and ethical constraints

Several recurring barriers limit the translation of AI into pediatric robotic and image-guided surgery. First, pediatric datasets are inherently small and heterogeneous due to the rarity and diversity of conditions, making it difficult to train complex deep learning models without overfitting or bias. Second, interoperability and standardization challenges—nonuniform imaging protocols, inconsistent labeling, and variable video

quality—impede multi-institutional data sharing and external validation, issues particularly acute in pediatrics where collaboration is essential. Third, regulatory pathways for AI-based surgical support systems, especially those that modify intraoperative behavior, remain underdeveloped, and existing frameworks are predominantly informed by adult applications,.

Ethical considerations are amplified in children, where data privacy, consent processes, and potential long-term impacts of algorithmic decisions warrant heightened scrutiny. Explainability is a core concern; clinicians and parents must be able to understand, at least at a conceptual level, the rationale behind AI-generated recommendations in high-stakes surgical contexts,. Emerging work on explainable AI in pediatric oncology imaging and genomics aims to address this gap, for example by visualizing salient regions or feature contributions in predictive models, but similar efforts in intraoperative computer vision and robotic control remain nascent.

Discussion

This review brings together rapidly evolving yet still fragmented lines of research on AI in pediatric surgical care, robotic-assisted procedures, and oncology-driven bioinformatics to outline a roadmap for AI-enhanced pediatric robotic and image-guided surgery –,. Diagnostic imaging and digital pathology currently lead in maturity, with models that achieve near-expert performance in tasks such as bone age assessment, fracture detection, and tumor classification, albeit with limited external validation and clinical embedding. Pediatric oncology has further demonstrated the power of integrating radiomics and multi-omics data to refine risk stratification and treatment personalization, providing templates for perioperative risk models that could inform surgical decisions, staging strategies, and reconstruction choices,. At the same time, pediatric robotic-assisted surgery has established a solid safety and feasibility record, with well-documented learning curves and efficiency gains, but remains largely devoid of true AI-driven automation or decision support.

The convergence of these domains offers a compelling vision: AI could connect preoperative, intraoperative, and postoperative phases into a continuous learning system that personalizes surgical planning, assists with real-time navigation, and anticipates complications to optimize recovery in children. Early experimental work in computer vision, surgical data science, and task-level autonomy suggests that robotic platforms could evolve from advanced telemanipulators into collaborative partners capable of handling routine subtasks and flagging deviations from optimal technique. However, achieving this vision requires addressing structural barriers, including the paucity of shared pediatric datasets, the need for pediatric-specific regulatory guidance for AI in surgery, and the imperative to develop explainable models that clinicians and families can trust. Investments in multi-institutional registries, standardized video and imaging repositories, and embedded clinical trials will be crucial to generating robust evidence, particularly for outcome improvements beyond surrogate technical metrics.

From a practical standpoint, pediatric centers interested in AI-augmented robotic surgery should adopt a staged approach. Initial steps may include systematic capture and annotation of robotic videos; deployment of validated, interpretable prediction models for perioperative risk; and integration of AI-based imaging tools for segmentation and 3D planning in complex oncologic and reconstructive cases. Parallel efforts in clinician education, interdisciplinary collaboration with data scientists, and development of governance frameworks for data sharing and algorithm oversight are essential to prevent ad hoc, uncoordinated adoption. For clinician–scientists with bioinformatics expertise, pediatric oncology offers a fertile ground to pilot AI pipelines that link omics-derived risk scores with surgical decisions, thereby creating demonstrable clinical value and informing frameworks transferrable to other pediatric surgical subspecialties. Ultimately, the field must transition from isolated proof-of-concept tools toward integrated hybrid intelligence systems that enhance, rather than obscure, pediatric surgeons' judgment in high-stakes environments –.

Conclusion

AI-augmented pediatric robotic and image-guided surgery sits at the intersection of three rapidly advancing fields—pediatric robotic surgery, surgical data science, and oncology-driven bioinformatics—and offers a realistic pathway from sophisticated diagnostics to genuinely intelligent perioperative care –. Contemporary evidence suggests that while pediatric robotic-assisted surgery is already safe and efficient in specialized centers, embedding AI for risk prediction, anatomical understanding, intraoperative guidance, and performance feedback could unlock the next level of precision and reliability for complex procedures in children. Realizing this potential will depend on collaborative, multi-institutional data infrastructures, pediatric-focused regulatory and ethical frameworks, and a commitment to explainable, trustworthy models that support shared decision-making with families,. For pediatric surgeons and bioinformaticians, now is a strategically opportune moment to design and test integrated AI workflows, ensuring that future generations of children benefit from surgical systems that are not only more technologically advanced but also safer, fairer, and more responsive to their unique needs.

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