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Reimagining surgery in a world powered by intelligence, connectivity, and code

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Surgery is undergoing a profound digital transformation, driven by advances in artificial intelligence, computer vision, sensor technologies, and cloud connectivity. These innovations are redefining the operating room as a dynamic, data-native environment where multimodal information streams support real-time decision-making, predictive modeling, and personalized workflows. From digital twins and autonomous task execution to global tele-mentoring and remote postoperative care, the emerging ecosystem of "intelligence, connectivity, and code" is reshaping surgical practice. Ensuring transparency and patient-centered implementation will be critical as surgery accelerates into its digital future.

The operating room has entered a new epoch—defined not solely by the surgeon's hand, but by an ecosystem of intelligent technologies, real-time data flows, and computational insight. We are now operating at the speed of data. For much of the 20th century, surgical innovation advanced through anatomical mastery and technical skills refinement. Milestones such as the introduction of laparoscopy and robotics redefined precision and access but still relied on human interpretation. Today, surgery is evolving into a data-native discipline. Advances in computing, sensor technology, machine learning, and cloud infrastructure have created an environment where digital tools learn, adapt, and interact. Digital surgery[1] now encompasses an integrated ecosystem: Artificial Intelligence (AI) that analyzes video and suggests intraoperative actions[2]; computer vision that identifies anatomical landmarks and procedural phases[3]; digital twins that simulate entire operations from patient-specific anatomy and live feedback[4]; augmented and mixed reality overlays for enhanced situational awareness[5]; and cloud-connected operating rooms (ORs) enabling remote collaboration, performance monitoring, telesurgery, and global learning[6]. These technologies communicate, integrate, and co-evolve—transforming the surgeon from sole procedural expert into a node in a high-frequency network of computation and care. The transformative potential of these tools was underscored by the awarding of two Nobel Prizes to artificial intelligence in 2024 for its medical applications[7]. Every movement becomes a data point; every outcome, a feedback loop. Crucially, this transformation is not confined to elite centers. Mobile networks, modular imaging platforms, and wearable devices are extending digital capacity to low- and middle-income countries[8], enabling a global, equitable evolution in surgical care. To reimagine surgery in this world is to move from a craft defined by isolated brilliance to a practice driven by shared intelligence, continuous learning, and precision at scale[9].

From data acquisition to intelligent action

The digitization of surgery begins with perception. Multimodal data—from 3D video, robotic kinematics, tissue interaction forces, physiologic signals, and intraoperative imaging—now streams continuously throughout procedures[3]. What was once tacit knowledge is measurable, archivable, and computationally learnable. Sensor technologies extend beyond robotics, embedding into handheld instruments, sutures, implants, and the operative environment[10]. Smart instruments equipped with microelectromechanical systems, fiber-optic strain gauges, and pressure sensors quantify grasping force, torque, tension, and compliance—providing objective feedback and real-time safety alerts[11]. Sensorized implants can monitor strain, biochemical changes, perfusion, inflammation, and oxygenation[10]. Integrated into meshes, stents, orthopedic hardware, or skin-adherent devices, they track wound healing, hydration, mobility, pH, and temperature—shifting postoperative care from episodic follow-up to continuous, data-driven recovery with earlier detection of complications[12]. These vast data streams feed advanced machine learning models trained on large-scale, multimodal datasets[3]. Computer vision algorithms perform real-time scene analysis—semantic segmentation, landmark recognition, and procedural phase classification—with growing accuracy[13]. Voice-based AI coaching systems under development aim to provide hands-free, context-aware guidance[14], reducing cognitive load and enhancing decision-making. Instrument telemetry and haptic analytics now enable precise skill assessment—measuring motion smoothness, economy of movement, applied force, and instrument trajectory[3]. Such metrics outperform traditional human-observed assessments in reliability and objectivity, informing training, credentialing, and ongoing development[9]. These perceptual and analytic systems are advancing semi-autonomous surgical functions[2]. Defined tasks such as suturing, camera control, or orthopedic drilling can now be executed autonomously under supervision[11], integrating real-time sensor feedback with predictive algorithms. The trajectory is clear: sensing, computer vision, AI, and robotic actuation are converging toward embodied surgical cognition[15]—where safety is augmented by embedded intelligence, and the surgeon is amplified, not replaced.

Predictive models and personalized operations

The most promising frontier is outcomes prediction. AI models trained on multimodal datasets—including electronic health records, imaging, pathology, and intraoperative recordings—are now forecasting complications, length of stay, and reintervention risks with high accuracy[16]. Transformer-based architectures have outperformed traditional risk scores in predicting events such as anastomotic leaks[3]. Preoperative imaging, AI segmentation, and 3D modeling now integrate with augmented or mixed reality to provide personalized intraoperative overlays for anatomical mapping, vascular assessment, and tumor localization[5]. The concept of the surgical digital twin—a dynamic, real-time computational model of a patient—has moved from theory to early implementation[4]. Digital twins support procedural rehearsal, intraoperative simulation, and adaptive surgical

planning[4]. Live data from endoscopic cameras and instruments can update the twin in real time, allowing AI agents to simulate and suggest optimal next steps in parallel with the surgeon[15]. This marks a shift from reactive care to anticipatory, continuously optimized operations[10].

The new surgical contract

Modern ORs are becoming smart, integrated ecosystems, where seamless interoperability, cloud-based synchronization, and secure remote access enable global collaboration and benchmarking[6]. Real-time tele-mentoring and remote assistance are now feasible across continents[11]. These capabilities extend beyond the hospital. Digital home services link the OR to patients' homes via telehealth, wearable biosensors, and remote nursing[8,12], enabling hospital-level monitoring, wound assessment, and rehabilitation without prolonged inpatient stays. This continuous care pathway accelerates recovery, improves satisfaction, and optimizes system resources[12]. Industrial innovation in surgical robotics is facilitating important improvements in the performance and digital understanding of surgery[6]. Surgeons must, however, remain aware of the potential for nascent surgical ecosystems to be leveraged disproportionately in favor of controlling companies, as illustrated by the monopolization allegations currently faced by Apple in the consumer technology sector. While surgical robotics companies are entitled to protect their intellectual property and pursue profit, the commercial attractiveness of their platforms is intrinsically linked to how well their ecosystems reflect and serve the wider biome of surgical practice[6]. The surgical community has a responsibility to use its agency to ensure that operative data—and the insights derived from it—remain accessible and actionable for the benefit of patients, rather than locked within proprietary systems. With connectivity comes responsibility. Data privacy, informed consent, and transparency of decision-support tools must be safeguarded[15]. Without this, AI risks amplifying disparities[6]. Ownership and value of surgical data remain contentious: while industry builds products from clinical datasets[7], hospitals and surgeons often relinquish this information without compensation. The challenge ahead is to establish governance and value-sharing models that ensure data serves collective benefit rather than private commodification[6,17].

Conclusion

The digital transformation of surgery is active, accelerating, and redefining the craft[7]. Operating at the speed of data means moving beyond mere intuition toward measurable, shareable, improvable knowledge[9]. Surgeons will be both operators and orchestrators—fluent in anatomy, technology, and information flow. Above all, the aim must be to center these advances on the patient, ensuring that intelligence, connectivity, and code serve to further humanize, not mechanize, the surgical experience[7].

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Author Contributions

O.Y.K. wrote the first draft of the manuscript. J.L.L and A.J.H. made revisions. All authors have read and approved the final manuscript.

Competing interests

O.Y.K. is the editor-in-chief of npj Digital Medicine, J.L.L. is an associate editor and A.J.H. is on the editorial board.

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