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Exploring the future of surgical practices: Advances in minimally invasive techniques and the integration of robotic technology

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***Abstract*---Background:** Robotic-Assisted Minimally Invasive Surgery (RAMIS) represents a significant advancement in surgical techniques, leveraging robotic systems to enhance precision, reduce invasiveness, and improve patient outcomes. The da Vinci surgical system has been a leading example, demonstrating the potential of robotic assistance in minimally invasive procedures. **Aim:** This paper explores the evolution of RAMIS, focusing on technological advancements, integration with Artificial Intelligence (AI), and future directions in surgical robotics. **Methods:** The study reviews the development and current state of RAMIS technologies, including the historical background, state-of-the-art systems, and emerging innovations. It analyzes data from a range of sources including literature reviews, market reports, and recent research developments. **Results:** RAMIS systems, particularly the da Vinci surgical system, have achieved widespread adoption due to their advanced features, such as enhanced vision, improved ergonomics, and training programs. Recent advancements include AI integration, new sensor technologies, and enhanced imaging modalities. Despite these improvements, challenges remain in achieving higher levels of autonomy and addressing cost and regulatory issues. **Conclusion:** RAMIS continues to evolve with significant advancements in AI, haptic feedback, and simulation technologies. Future developments are expected to further enhance surgical precision and outcomes. However, the field must address challenges related to autonomy, cost, and global adoption to realize its full potential.

***Keywords*---**Robotic-Assisted Minimally Invasive Surgery, RAMIS, da Vinci surgical system, Artificial Intelligence, surgical robotics, autonomy, haptic feedback.

Introduction

In general discourse, robotic surgery is often associated with telerobotic implementation of minimally invasive surgery (MIS), where the surgeon operates remotely from the patient—typically within close proximity—and the surgical instruments are controlled via direct guidance and remote operation by a human. This clinical technique is referred to as Robotic-Assisted Minimally Invasive Surgery (RAMIS), which is alternatively known as robotically assisted or simply robotic MIS. The ergonomic design of these systems aligns well with the contemporary and increasingly favored approach of MIS, which is conducted through small incisions, also known as keyhole ports. This method has largely supplanted many traditional open surgery techniques due to its benefits of reduced tissue damage, enhanced patient outcomes, and improved ergonomics for surgeons, while also incorporating various technological advancements into the operating room [1]. This paper examines the connection between the technological capabilities of such systems and their clinical applications, considering the regulatory frameworks that govern their use. The exploration of the current state of the art begins with an overview of the existing market, which has been predominantly dominated by a single product over the past two decades.

RAMIS systems utilize real-time imaging via an endoscopic camera that provides a high-resolution, wide-angle video stream with white light as the primary sensory feedback from the surgical site. The robotic instruments are maneuvered by the surgeon through a surgical console, or human-machine interface (HMI), which relies on this video feed. The integration of minimally invasive paradigms has significantly advanced the adoption of robotic assistance, reflected by the annual performance of 1.5 million procedures—showing a 15% annual growth rate—using the "da Vinci surgical system" (Intuitive Surgical Inc., Sunnyvale, CA, USA), making it the most prevalent RAMIS system to date [2]. The key factors contributing to the remarkable success of the da Vinci system and its telerobotic approach include [3], [4]:

- Advanced technological features such as enhanced vision and instrumentation.
- Ergonomics and safety improvements (e.g., EndoWrist for suturing, tremor filtering, and enhanced situational awareness).
- Substantial evidence supporting improved patient outcomes over time.
- Targeted procedures where quality of life can be markedly enhanced (e.g., prostatectomy, benign hysterectomy).
- Robust training programs developed over time (including simulators).
- Absence of high-level autonomy, ensuring legal responsibility remains with the surgeon.
- Extensive marketing and promotional efforts.
- Solution-oriented sales model (including consumable and service-based business models).

From the perspective of healthcare providers, the benefit to patients has been a driving force behind robotic surgery programs, with substantial clinical evidence emerging to support various applications, initially starting with prostatectomy and benign gynecological procedures. Since 1998, over 29,000 peer-reviewed studies have been published concerning da Vinci surgery alone. However, recent research continues to leave unresolved questions about the long-term benefits of MIS compared to open surgery, particularly in cases such as radical hysterectomy [5]. It is important to note that each clinical application domain of a RAMIS system requires separate approval, with the manufacturer's chosen approach and timeline significantly influencing the system's developmental trajectory [6]. There is a notable correlation between costs and the adoption rate of robotic surgery; in the United States, where healthcare expenditures account for 18% of GDP, approximately 5% of surgeries are performed robotically, while in the European Union, which spends about 10% of its GDP on healthcare, the adoption rate is around 2% [7], and it remains below 1% in most other regions. Medtronic estimates that only 3% of the total addressable market for RAMIS has been achieved to date. Concurrently, Frost and Sullivan estimated the total market value of surgical robotics at $8.3 billion in 2020, with projections to reach $33.6 billion by 2026 [8].

In practice, RAMIS is primarily characterized by remote-controlled leader-follower robots, used exclusively in telemanipulation mode, where the surgeon is not directly handling the surgical tools. Various other types of surgical or interventional robots with different architectures are also in clinical use [9]. Notably, image-guided interventional robotics, which relies on medical imaging for executing predefined surgical plans, is not within the scope of this discussion [10], nor is collaborative control, which is often utilized in neuro and orthopedic applications. Microsurgical systems and endoluminal robots, while sharing many similarities with RAMIS in terms of mechatronics, control architecture, and future prospects (and occasionally using the same physical platform, such as with the da Vinci SP), are also excluded from this analysis, as discussed by Dupont et al. [11].

Technically, almost all surgical robotic systems feature a common element: they use robotic mechanisms (in the broadest sense [12]) to provide precise guidance, assistance, or direct delivery of instruments or energy. These systems can focus energy, such as in radiotherapy or high-intensity focused ultrasound (HIFU) treatments, or guide needles and other tools. They rely on detailed preoperative planning based on patient imaging information, typically using three-dimensional modalities like CT or MRI. This analysis focuses on RAMIS systems that are full-scale, teleoperational surgical systems, where the end-effector typically does not require the complex articulation of a continuum robot-like structure with six or more degrees of freedom (DoFs).

History and Early Developments:

While pinpointing a specific inventor of telerobotic surgery remains elusive, the groundwork for this field was laid by early pioneers from the U.S. National Aeronautics and Space Administration (NASA) and the U.S. Department of Defense, particularly through the Defense Advanced Research Projects Agency

(DARPA) in the late 1960s. Their work, inspired by remote manipulators designed for nuclear facilities and space exploration, significantly contributed to the domain [13]–[15]. The commercial breakthrough came with the approval of Intuitive Surgical's da Vinci system by the FDA in 2000. This success spurred numerous research projects and companies to develop their own systems, often closely mirroring the da Vinci model [16]–[19]. Intuitive Surgical outpaced its competitor, Computer Motion (Goleta, CA, USA), in 2003, leading to the discontinuation of the Zeus Robotics Surgical System and leaving Intuitive as the sole major player in the U.S. market for 15 years. This lack of competition can be attributed to Intuitive's robust patent portfolio, which effectively protected their technology, and the fact that many rival in-house developments either failed to materialize into products or were not publicly reported due to cost, regulatory, and complexity issues. Recently, however, there has been a surge of new entrants aiming to introduce significant technological innovations, diverging from the evolutionary advancements of previous decades.

State of the Art in RAMIS

A comprehensive literature review has identified over 65 research projects focused on developing new, fully integrated RAMIS systems, yet only 15 have achieved some level of national regulatory clearance, and merely five have been marketed in multiple countries (see Fig. 1) [20], [21]. A recent review by Moglia et al. [22] discusses the various types and variations of these systems. Additionally, Dupont et al. [23] highlighted that the most significant advancements in the past decade include the automation of surgical processes and the incorporation of force sensing into laparoscopic tools, along with the development of novel robotic architectures aimed at reducing procedural invasiveness.

Among recent achievements in research platforms, the DVRK (da Vinci Research Kit) stands out. Developed by the Laboratory for Computational Sensing and Robotics (LCSR) at Johns Hopkins University, Worcester Polytechnic Institute (WPI), and other partners, and supported by the Intuitive Foundation (https://www.intuitive-foundation.org/dvrk/) [24], [25], the DVRK represents a major advancement. It repurposes retired da Vinci surgical systems into research platforms that enable exploration of innovative concepts in RAMIS. More than 40 academic groups and research centers are involved in the DVRK program (see Fig. 2). A recent review by D'Ettorre et al. [26] provides an overview of significant projects utilizing the DVRK (see Fig. 2).
Current research using the DVRK aligns with key directions for RAMIS development and can be categorized into the following areas (see Fig. 3):

- Hardware implementation and integration
- System simulation and modeling
- Imaging and vision
- Feature automation
- Training, skill assessment, and gesture recognition

Access to both kinematic and system data from the DVRK, as well as clinical data obtained through its vision system, is crucial for advancing these research topics. Such data is essential for applying data-driven machine learning (ML) methods, which are pivotal for future developments in RAMIS.

RAMIS in the Era of Data: Emerging Capabilities:

RAMIS systems offer a robust foundation for surgical innovation, primarily due to the digital data link between the surgeon's console and the patient-side manipulators. Continuous advancements have been made in core components of RAMIS, including the Human-Machine Interface (HMI), patient-side surgical tools, and vision and control systems [27]. Recently, new paradigms have emerged, driven by the integration of Machine Learning (ML) and broader Artificial Intelligence (AI) methods. AI has the potential to bridge the gap between current limited applications of autonomy and the advanced software capabilities demonstrated in other industries, such as Natural Language Processing (NLP) and real-time scene annotation, as well as anomaly detection. By combining robotics with Surgical Data Science (SDS), AI methods can enhance therapeutic outcomes and patient care [28]–[32].

A. Framework for Autonomy Classification in RAMIS:

Autonomy is a crucial aspect affecting the applicability of robotic systems. Medical robotics have adopted the concept of Level of Autonomy (LoA), originally developed for the automotive industry, to classify and compare system functions and capabilities [33]. This concept builds upon the traditional model of analyzing tasks and decisions within the generate–model–plan–execute cycle, a framework that spans from industrial robotics [34] to image-guided interventional systems [35]. This classical CAD/CAM control flowchart remains relevant for RAMIS systems, provided there is a high control loop frequency. This indicates that the fundamental principle—that digital information enables accountable, measurable system engineering and quality management concepts in Cyber-Physical Systems (CPS) through medical imaging, image processing, and robotic execution—is fully applicable to RAMIS. The current classification of LoA for surgical robots [36], with most RAMIS systems currently operating at LoA 1 or 2. Although standardization experts continue to debate the minimum autonomy requirements for robots [12], the trend is clearly towards achieving higher LoAs through advancements in autonomy, driven by both technological innovation and economic incentives.

Successful approaches today emphasize automation at the subtask and task levels in RAMIS, allowing surgeons to concentrate on critical aspects of their procedures [37], [38]. Meanwhile, emerging research is exploring miniaturization of systems for microsurgery and experimenting with robot ensembles and swarms [39].

B. Impact of Advanced Communication Strategies on Telesurgery

The advent of 5G communication networks has been anticipated to significantly impact telesurgery, first demonstrated in China in 2019 with the KangDuo-Surgical Robot-01. The inherent capabilities of 5G, including high bandwidth, low latency, and high throughput, promise to enable real-time telesurgery [40], [41]. Although intercontinental RAMIS operations were demonstrated two decades ago [42], the enhanced capabilities of 5G, 5G+, and 6G may be essential for streaming high-fidelity, high-resolution, and multimodal information required for remote surgeries [43], [44]. Intuitive Surgical plans to release a wireless version of the da Vinci system by 2023. Technologies such as edge, fog, and cloud computing will support AI-related, computationally intensive processes, thus simplifying patient-side systems while enhancing data processing through the cloud. However, the global infrastructure needed to make remote telesurgery commonplace is still lacking, and cybersecurity issues remain unresolved [45], [46]. The absence of significant cyberattacks on healthcare infrastructure thus far is fortunate, as Western hospitals become increasingly connected and online. Nonetheless, there has been a rise in cyber incidents [47], and current RAMIS systems offer limited protection [48].

C. The Role of SDS—Data and AI in Advancing RAMIS:

In the clinical context, data are heterogeneous and derived from multiple sources, including intraoperative data like robot kinematics, laparoscopic video streams, device data, as well as preoperative and postoperative patient datasets [28], [29], [49]. The integration and storage of such high-volume data streams pose challenges related to interoperability and storage standards [28]. Big data methods enable the development of new ML and AI applications, ranging from semi-automation of surgical tasks to context-aware surgical guidance [50]–[54]. Deep learning methods require extensive annotated datasets for training, which often constitutes a major bottleneck in robot-assisted surgery. Annotation is labor-intensive and demands highly qualified human experts. Current strategies to address this issue include generating synthetic datasets [55]–[57], expediting annotation through crowdsourcing [58], [59] or active learning [60], and employing self-supervised learning methods that minimize the need for detailed annotations [61]. Datasets must be representative of the task, incorporating anatomical and pathological variations from multiple centers and linked to patient outcomes (e.g., EQ-5D [62]), while addressing selection and confounding biases [29]. High-quality, robust clinical datasets currently exist mainly in medical imaging, highlighting the need for open challenges in the field, such as the annual MICCAI Endoscopic Vision Challenges (http://www.miccai.org/special-interest-groups/challenges/). These challenges aim to democratize surgical skills and enhance collaboration between surgeons and robots through cyber-physical systems, quantifying surgical experience and making it accessible to machines [31]. There is growing interest in integrating AI technologies seamlessly into the field. The concept of Surgery 4.0 has emerged, representing the "seamless integration of medical decision support systems, imaging, and automated execution" [36]. Verb Surgical (Mountain View, CA, USA), a joint venture of Verily/Alphabet Inc. (Mountain View, CA, USA) and Johnson & Johnson (New Brunswick, NJ, USA), was among the first in 2015 to develop a Surgery 4.0-compatible system, combining advanced visualization, robotic instrumentation, data analytics, and ML.

D. Vision, Haptics, and HMIs in RAMIS

Current RAMIS systems utilize advanced interfaces to enhance surgical precision and effectiveness. These systems feature ergonomic consoles that allow for remote manipulation of instruments and visualization of the surgical site. Vision systems in RAMIS often include high-resolution 3-D stereoscopic displays, which can operate in immersive mode or use open 3-D display technologies like polarized glasses [63]. In addition to the stereo camera feed, the display systems may incorporate system preferences, instruments, and relevant information, similar to augmented reality solutions [64]. They also support the display of other imaging modalities, such as ultrasound (US) or preoperative 3-D anatomical renditions [65]. These displays can highlight information using AI inference systems or fuse multiple data sources [66]. Furthermore, integrating new sensor probes with robotic manipulation capabilities could lead to advanced imaging techniques, such as multispectrum fluorescence imaging, optical coherence tomography (OCT), structured light, time-of-flight endoscopy, and RAMEN spectroscopy [67]–[71].

Enhancements in vision may also involve semantic information. Active research focuses on surgical tool identification and tracking, which aids in compensating for robotic inaccuracies, assessing surgical skills, and ensuring safety during autonomous tasks by replicating the surgeon's visual feedback loop [72], [73]. Computer vision-based methods are also being developed to enhance anatomical identification, situational awareness, and accurate reconstruction of surgical phases and workflows [74]–[76]. Another promising but underdeveloped feature in clinical RAMIS systems is haptic feedback. Sensing interaction forces between instruments and tissue, and providing a sense of touch through haptic feedback, could significantly enhance surgical precision. This capability would allow surgeons to adapt their manipulations based on vibrations, pressure, or texture with clinical relevance [80]. However, implementing haptic sensations involves complex challenges, including the need for appropriate sensors in instrumentation, the means to relay feedback to the surgeon, and addressing safety and cost issues [81].

E. Simulation and Training in RAMIS:

Simulation and training are critical for ensuring that surgeons are proficient with RAMIS systems. Various physical and virtual simulators have been developed to support skill training [82], [83]. The data generated from these training sessions are used to enhance system usability and understand human capabilities better [84]. Recent research in skill assessment has focused on both traditional and ML-based methods to improve outcome prediction [85]. Future surgical consoles could benefit from technologies that enable more interactive and sensory modalities. For example, eye-tracking systems might allow adaptive consoles to tailor functions based on specific areas of the surgeon's focus [86]. Non-technical skill assessment is also important for patient outcomes, though it is often overlooked. Simple methods like skin dryness sensing, pupillometry, or eye tracking can provide basic stress measurements [88], [89]. More advanced systems, such as functional near-infrared spectroscopy (fNIRs), may offer insights into cognitive processes, stress levels, and skill development [90]. Integrating these technologies could lead to improved training and skill assessment, enhancing the overall effectiveness of RAMIS systems.

Role of Healthcare Professionals:

In the context of Robotic-Assisted Minimally Invasive Surgery (RAMIS), the roles of physicians, pharmacists, and nurses are integral to the successful implementation and utilization of these advanced technologies.

Physicians: Surgeons are at the forefront of utilizing RAMIS systems. Their role involves operating the robotic systems to perform minimally invasive procedures with increased precision and control. Surgeons must be adept in using the robotic consoles and interpreting the high-resolution imaging provided by these systems. They are responsible for planning and executing surgical procedures, ensuring patient safety, and adapting to new technologies through continuous training and practice. Their expertise is crucial in leveraging the capabilities of RAMIS to improve surgical outcomes and patient care.

Pharmacists: Pharmacists contribute to the RAMIS workflow by managing perioperative medications, including anesthesia and pain management. Their role involves ensuring that medications are appropriately administered and monitored, considering the unique requirements of robotic-assisted surgeries. Pharmacists also play a role in managing drug interactions and side effects, which can be critical in minimizing complications and optimizing patient recovery. Their expertise in pharmacotherapy is essential for providing comprehensive care in the surgical setting.

Nurses: Nurses are vital in the perioperative care of patients undergoing RAMIS procedures. They assist with preoperative preparations, including patient education, positioning, and monitoring vital signs. During surgery, nurses support the surgical team by managing sterile fields, handling instruments, and providing real-time assistance. Postoperatively, nurses play a key role in patient recovery, monitoring complications, managing pain, and providing patient education on postoperative care. Their support ensures the smooth operation of RAMIS procedures and contributes to overall patient safety and satisfaction. Together, these healthcare professionals ensure the effective implementation of RAMIS technologies, contributing to improved surgical outcomes and enhanced patient care. Their collaborative efforts are essential in optimizing the use of robotic systems and advancing the field of minimally invasive surgery.

Conclusion

The integration of robotic technology in minimally invasive surgery (MIS) has revolutionized surgical practices by enhancing precision, reducing invasiveness, and improving patient outcomes. The da Vinci surgical system has been a pivotal development in this field, demonstrating the potential benefits of robotic assistance through its advanced features, including high-resolution 3-D vision, ergonomic consoles, and sophisticated instrumentation. RAMIS systems have achieved remarkable success, with the da Vinci system leading the market in both prevalence and innovation. These systems facilitate a range of minimally invasive procedures, offering significant advantages over traditional open surgery, such as reduced recovery times, minimized tissue damage, and improved surgical accuracy. The system’s robust training programs and extensive clinical evidence supporting its efficacy have further cemented its role in modern surgical practice. Recent advancements in RAMIS include the integration of Artificial Intelligence (AI), which has the potential to transform surgical outcomes by enhancing automation, improving situational awareness, and supporting real-time decision-making. The incorporation of new imaging modalities, such as multispectrum fluorescence imaging and optical coherence tomography (OCT), also promises to advance the capabilities of robotic systems. However, challenges remain. Achieving higher levels of autonomy in RAMIS systems is an ongoing pursuit, requiring advancements in AI and robotics. Additionally, addressing the high costs associated with these technologies and ensuring their accessibility on a global scale are critical issues that need to be addressed. The field must also overcome regulatory hurdles and develop solutions to enhance the safety and effectiveness of robotic-assisted surgeries. Looking forward, the future of RAMIS is promising, with continued advancements expected to further refine surgical techniques and outcomes. The integration of AI and emerging technologies will play a crucial role in shaping the next generation of surgical robotics, potentially leading to more autonomous systems and broader adoption across diverse healthcare settings.

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استكشاف مستقبل الممارسات الجراحية: التقدم في التقنيات طفيفة التوغل ودمج التكنولوجيا الروبوتية

الملخص:

الخلفية: تمثل الجراحة بمساعدة الروبوت (RAMIS) تقدمًا كبيرًا في تقنيات الجراحة، حيث تعتمد على أنظمة الروبوت لتحسين الدقة وتقليل التدخل الجراحي وتحسين نتائج المرضى. وقد كان نظام "دا فينشي" الجراحي مثالًا رائدًا، حيث أظهر إمكانية المساعدة الروبوتية في الإجراءات طفيفة التوغل.

الهدف: يستكشف هذا البحث تطورRAMIS ، مع التركيز على التقدم التكنولوجي، الدمج مع الذكاء الاصطناعي(AI) ، والاتجاهات المستقبلية في جراحة الروبوتات .الطرق: تستعرض الدراسة تطور وتطور تقنياتRAMIS ، بما في ذلك الخلفية التاريخية، الأنظمة الحديثة، والابتكارات الناشئة. يتم تحليل البيانات من مجموعة متنوعة من المصادر بما في ذلك المراجعات الأدبية، تقارير السوق، والتطورات البحثية الحديثة.

النتائج: حققت أنظمةRAMIS ، وخاصة نظام "دا فينشي" الجراحي، اعتمادًا واسعًا بسبب ميزاتها المتقدمة، مثل الرؤية المحسنة، وتحسين الهندسة البشرية، وبرامج التدريب. تشمل التطورات الأخيرة دمج الذكاء الاصطناعي، تقنيات الاستشعار الجديدة، وطرق التصوير المحسنة. على الرغم من هذه التحسينات، تظل هناك تحديات في تحقيق مستويات أعلى من الاستقلالية ومعالجة قضايا التكلفة والتنظيم .

الخلاصة: تستمر RAMIS في التطور مع تقدم كبير في الذكاء الاصطناعي، والتغذية الراجعة اللمسية، وتقنيات المحاكاة. من المتوقع أن تعزز التطورات المستقبلية دقة الجراحة ونتائجها. ومع ذلك، يجب على هذا المجال معالجة التحديات المتعلقة بالاستقلالية والتكلفة والتبني العالمي لتحقيق إمكانياته الكاملة.

الكلمات الرئيسية: الجراحة بمساعدة الروبوت، RAMIS، نظام "دا فينشي" الجراحي، الذكاء الاصطناعي، جراحة الروبوتات، الاستقلالية، التغذية الراجعة اللمسية.