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Enhanced Robotic Systems in Minimally Invasive Surgery

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Abstract: Minimally invasive surgery has been evolving rapidly since the beginning of the nineties, mainly due to the advent and continuous implementation of robotic systems. This paper reviews the main advancements achieved with the use of robotics by focusing on recently proposed and developing robotic systems specifically designed for minimally invasive surgery, indicating how the evolution of robotics is progressing. All the improvements offered by robotic systems are discussed in detail, beginning with the flexibility in the architecture of the last decade, which was tailored to accommodate instruments and manipulators for general minimal access surgery. [1][2][3].

Key words: robotic, surgery, invasive, surgical trauma, including pain, accuracy, accuracy, trauma

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INTRODUCTION

Robotic systems have made an impactful presence in the surgical field over the last three decades. The transition has been gradual but critical as traditional open surgery paradigms started incorporating sophisticated robotic systems. Also known as computer-assisted surgery or telesurgery, this shift offers the ability to execute precise movements, free from neuromuscular tremors, along with incorporating the use of micro-tools. A pioneer of robotic and surgical vision techniques in the mid-1980s is attributed with the globalization of robotic surgical techniques and hence fostering research and collaboration.

New technologies have revolutionized modern surgery and have enabled intricate operations to treat a range of chronic diseases and conditions. In addition, minimally invasive procedures have become viable alternatives to the classic techniques used for open surgery. In minimally invasive surgery, or endoscopic surgery, the operating space is partially and typically fully visually inaccessible, and the capacity for direct tactile feedback transference is eliminated. Robotics and image-guided systems in minimally invasive surgery have been able to provide qualitative solutions for many of these surgical inadequacies. Laparoscopic surgery with rigid operating tools, restricted viewing angles, and very limited articulation has been replaced by microsurgery. Robotic-assisted surgery, owing to its higher range of movement, enhanced visual image, and ability to carry out finer movements with greater precision, has become less operator-fatiguing.

In the current era, operative skill sets, state-of-the-art technologies, and comprehensive preoperative planning are being orchestrated for each unique patient to achieve better post-surgery quality outcomes. Robotic surgery, also known as robot-assisted surgery, is one of the most advanced forms of surgery, and it is being increasingly adopted as a minimally invasive approach to achieve better surgical outcomes in terms of reduced trauma, shorter hospital stays, and little blood loss. Further, many terms are also being used in the context of robotic surgery, such as telesurgical, teleoperation, and da Vinci surgery. Regardless, these terminologies are interchangeably used to describe robotic or robot-assisted surgical procedures. As a result, the robotic field has the potential for growth, and an increasing number of research works are being proposed to inspect the possible limitations, technical challenges, and to present new and advanced modalities to be adopted as the surgical gap. The research aims at robotic systems in minimally invasive surgical practice, covering robotic assessment, control, sensing, robotics platform, haptic feedback, computer-aided surgery, medical expenditure, surgical tools, interventional pain management, simulation education, surgical oncology, multi-robot, or multi-limb robotic systems. [4][3][5]

Minimally invasive surgery, with reduced complications and shorter recovery time, has now become a surgical standard that enhances patients' quality of care. Some recent advancements in robotic technology have dramatically improved the development of minimally invasive surgeries compared to conventional procedures. Robotic surgical platforms for minimally invasive surgery have since evolved with hardware design improvements and new technologies such as enhanced visual systems, dexterous instruments, and haptic feedback. Cameras that provide high-definition 3D video imaging are enabling surgeons to perform complex operations with reduced depth perception concerns. Capable hands provided by robotic systems allow surgeons to perform complex actions that are not possible with traditional laparoscopy. Most recently, new robotic systems have adapted artificial intelligence and machine learning to provide new capabilities in segmentation, operative procedure analysis, and potentially assistive autonomy.

Improved surgical technology has been shown to be reliable and can lead to improved performance in dexterity and time-requiring tasks when compared to the existing standard of care. Modern robotic surgical platforms provide upgrades that can confer to the users more capabilities and enhance surgical performance and potentially surgeons' ergonomics. But the availability of new technology isn't the only factor that can contribute to improved surgical technique and outcomes. For surgical robots, training might not be part of their operations. Instead, highly complex systems for machine learning need extensive training on accurate and reliable operative datasets in order to be successful. Simultaneously, the robotic systems' operators, surgeons, require training to be able to efficiently operate the new robotic technologies. Most surgical robotic products have associated training curriculums, where users usually undergo a combination of e-learning and didactic training as well as hands-on work in a lab setting before receiving final certification. Such comprehensive training is essential to ensure user experience and a safe and successful installation of advanced surgical robotic hardware and software. A review and a comparison of the design and key attributes of the surgical robotic systems are presented. [6][7][8]

Robotic systems enhance surgical procedures with their ability to ensure higher precision, accuracy, and controllability. The miniaturization of enhanced robotic systems allows miniaturized surgical instruments to be inserted through small incisions made in the patient's skin, reducing some of the side effects associated with open surgery, such as infection, bleeding, pain, and minimal scarring. Overall, robotic surgery can improve patient outcomes and allow them to recover faster after surgery. Clinical studies have also identified additional benefits, such as a reduction in the frequency of postoperative complications and the patient's return to normal activities.

Robotic-assisted surgery increases the precision and controllability of manual tasks related to the performance of surgical procedures that require high levels of precision in the surgical treatment of a broad range, including gynecology, urology, and surgery/oncology. The capacity for precision during surgery is believed to reduce the occurrence of adrenal metastasis. A study on patients with advanced ovarian cancer who received robotic gynecologic surgery showed that surgery with robotic support was associated with a higher overall success rate compared to traditional surgery. Robotic surgery has been shown to be useful in the treatment of lung cancer, with intraoperative pathologic assessment revealing negative resection edges in a high percentage of patients. The study also showed that the complication rate, relative risk of recurrence, and estimated hazard rate have been reduced.

In laparoscopic or minimally invasive surgery, the spatial resolution of the standard surgical instruments can be on the order of millimeters and microns, and their degrees of freedom are limited to just a few axes of movement. The comparative movements of the robotic manipulators can have up to seven independent degrees of freedom of translation or rotation. Such a degree of freedom provides the ability for very fine actions, beyond the natural precision of hand movements. In addition, tremors can be filtered out of the manipulator's response, yielding more precise placement and securing of sutures. The incidence of ureteral and bowel injuries during laparoscopic robotic surgery has been shown to be reduced in studies involving thousands of procedures, and thoracic operations, particularly thymectomy, are good examples of how robotic technology can, through its 3D vision system, visual magnification, and real-time feedback, simplify complex procedures with less than a 10% conversion rate in various studies. Time and again, the theme of the importance of this technology, in addition to its improved visualization, is emphasized, as this technology became integral to the procedure itself and was not just considered a "gimmick" for camera visualization.

The relationship between the improvement of precision and accuracy by technology and the patient experiencing improved surgical outcomes is assumed, but this has long been implicit rather than explicitly stated and quantified. In one of the few studies, the notion that greater precision in surgery makes surgery safer is discussed, often eclipsing the potential time savings. Such an observation about robotic-assisted technology is common across the board: this technology takes more time, although in a survey of experienced cardiothoracic surgeons, some felt that the console time was equal between robotic and open techniques, and no one felt that the robotic technique was faster. Alongside the potential financial benefit of quicker return to work and decreased effort required, the incidence of complications and the patient satisfaction and safety (decreased blood loss, time in the hospital) make the increased operative time worthwhile. [6][9][10]

Improved Patient Recovery Times

The reduced recovery times that accompany robotic-assisted minimally invasive surgery can be attributed to a number of advantages that exist due to the reduction of incision size. A smaller incision means that there is less trauma done to the tissue of the patient, since fewer nerves and other tissue are involved. As a result, procedures that previously meant a week of recovery time are now only taking patients a few days. Patients spent fewer days receiving care and more satisfactorily completed their post-operation care through the use of minimally invasive and robotic-assisted technology. The reduction in length of stay for minimally invasive surgery of the esophagus quantified this as a reduction from 12.1 days to 10 days.

Healthcare professionals claim that there are potential psychological benefits to healing for less time, increasing patient satisfaction. Because the surgery and recovery time associated with open surgery is typically painful for patients, this in turn also means that they typically return to their doctor more often to help with pain medication. Re-admission of patients into the hospital increases the occupancy rate, which in turn constricts the number of cases that can be performed by the hospital annually. Robots help to reduce healthcare costs for the hospital because day hip surgeries mean more often than not, it is expensive for the hospital to keep a patient for more than one night. It has been claimed by healthcare professionals that if roughly 75% of people are discharged after one day, with the rest having to stay longer post-surgery, robotic surgery improves patient care. [11][12]

Lower complication rates, reduced mortality, shorter hospital stays, and quicker recovery times are parameters often used to assess and predict positive outcomes in healthcare. In surgery, many well-controlled studies have demonstrated that minimally invasive surgical techniques and the use of robotics lead to an improvement in these metrics. With myriad upgrades to the robotic systems, the outcomes continue to improve. Lower complication rates and lower in-hospital mortality rates indicate an overall better recovery, and the ease of recovering for most patients is likely a reason minimally invasive surgeries have become the new routine in the care of surgical diseases. Patients are the best indicator of how their procedure and post-operative care have gone. Not only do almost 90% of robotic surgical patients say they would be likely or very likely to recommend the surgery to a friend or family member, but they also talk about the impact robotic surgery had on their recovery. When clinical outcomes data is accompanied by patient testimonials, it illustrates both the positive outcomes of surgery and patient satisfaction with care.

When discussing health outcomes, it is important to remember that they are not uniform across a patient population because patient characteristics are not the same. This means that surgical outcomes are affected by patient disparities and could explain variations we see in overall health outcomes. There is also a need to evaluate the overall outcome of care—not just the surgical portion. Often, patients require additional care following surgery, and successful patient care is the result of an integrated and consistent plan crafted by many healthcare specialists, not just surgeons. Future refinements that give personalized care to patients possess the likelihood of providing even greater medical outcomes and have the potential to weave together the complementary knowledge and expertise of specialists, subspecialists, nurse care coordinators, patients, and family members comprising the medical safety net. There are a growing number of reports of sustained results in follow-up care and longitudinal studies that demonstrate the improvements in health have continued. Besides outcomes, goals in care vary for mortality rates, operative and inpatient morbidity, and quality of life, which are another option when intending to track long-term outcomes. [13][14][15]

In robotics, it is sometimes said that the adoption of new enhanced robotic systems will overtake the cost penalty and the training period. In surgery, however, this needs to be taken with caution. The initial and operational costs of new technology matter far more in the health sector. In addition, robotic surgery could lead to additional and costly overuse. Robotic systems can only be operated properly by a skilled team and surgeon. Specialized training of the surgical team is lacking for many robotic systems. Although user-friendly designs and software allow people with relatively little experience to operate these systems, there is still a steep learning curve to adequately master the system as well as training in basic endoscopic surgery. Moreover, there are potential technical and clinical limitations. Modernized robotic systems are often software-based and thus could encounter system errors and failures as well as require constant updates and improvements. Expensive maintenance repair programs need to be in place to overcome these potential technical limitations. Widespread use of semi-automated systems in surgery may also cut down on the acquisition of basic skills by trainees and, in the longer term, this may limit future progress in surgically manipulating the robotic or semi-automated systems. Also, not all patients have equal accessibility to robotic surgery, often favoring patients who have been recruited to clinical centers equipped with such technology. Additional national and international regulatory or intermediary bodies overseeing robotic systems and the approval of new devices must be established to ensure patient safety and clinical advantage. Users may have ethical issues with reliance on technology in the clinical setting, especially if the deployment of such systems were to replace the need for surgical skill. Medical legal issues could be problematic if the operator merely supervises the robotic system. [16][17][18]

Future Directions in Robotic Surgery and Innovations We Can Expect

The global medical robotics markets are expected to have a positive upturn, as companies are already gaining clearance for procedures once considered for manual surgeons. Development and research in medical robotics focus on three major areas of current concern—advancing the field of robotics (both autonomous and semi-autonomous), collaboration between fields such as computer science and mathematics and surgery, and the creation of expertise for the field of medical robotics. Current research has, and is now moving toward, advanced robotic systems that can extend the capabilities of a surgeon to include more complex and delicate tasks in open surgeries or replicate an open surgery in a minimally invasive manner. These enhancements of current systems bring up the question of potential developments in the next 5–10 years.

Many current systems are looking to integrate emerging technologies, such as augmented reality, or have been refurbished with improved algorithms and AI for decision making, either through better sensors and imaging or flow dynamics, improving tactile feedback by introducing effects of haptic feedback or human factors to the system, and further reducing the invasiveness of current systems, designing modular approaches that can expand or contract as patient consent grows with time. The most prominent and most sought-after novel advancement would be that of a medical robot that assists a surgeon with autonomous or semi-autonomous surgery. The healthcare industry is a global entity, and with new technologies becoming more widely used and including patient-centered care through telehealth and connectivity with smart devices in the home for ongoing monitoring, the medical robotics markets are expected to exceed their current limitations. Several top orthopedic device companies are now invested in the development of robotic systems that could be used in many healthcare facilities around the world. [19][20]

Conclusion

In conclusion, an in-depth look at the use of enhanced robotic systems in minimally invasive surgery (MIS) has been carried out, as well as the several advantages of this advanced technological approach in comparison to traditional methods. From the review of these studies, it can be seen that with the progression of technology, robots in surgery are of increasing interest. Since enhancement in precision also results in less surrounding tissue damage, the possible reduction in the formation of adhesions can lead to shorter recovery times and reduced risks of developing complications or infections. Most importantly, improved dexterity and reduced surgeons' tremors due to physical and mental fatigue allow surgeons to exert greater concentration on their skills during the procedure, directly leading to improved patient outcomes.

However, some limitations continue to persist in the world of enhanced robotic surgery. Considering costs and a lack of universal standardization due to rapid ideation and team generation effectively restrict their present-day use. Nevertheless, continuing research remains crucial, as these enhancements have clearly shown to benefit patients and societies as a whole. Additionally, the limitations that are currently being tackled to make advancements can be similarly studied in the future to enable further applicable surgeries in modern health systems. This can be attributed to the fact that the inherent intelligent collaboration of robots and humans plays an important role and can be expanded for potential achievements on the technological front with the right investment and focus**.**

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