The Next-Generation Surgical Robots

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Abstract

The chronicle of surgical robots is short but remarkable. Within 20 years since the regulatory approval of the first surgical robot, more than 3,000 units were installed worldwide, and more than half a million robotic surgical procedures were carried out in the past year alone. The exceptionally high speeds of market penetration and expansion to new surgical areas had raised technical, clinical, and ethical concerns. However, from a technological perspective, surgical robots today are far from perfect, with a list of improvements expected for the next-generation systems. On the other hand, robotic technologies are flourishing at ever-faster paces. Without the inherent conservation and safety requirements in medicine, general robotic research could be substantially more agile and explorative. As a result, various technical innovations in robotics developed in recent years could potentially be grafted into surgical applications and ignite the next major advancement in robotic surgery. In this article, the current generation of surgical robots is reviewed from a technological point of view, including three of possibly the most debated technical topics in surgical robotics: vision, haptics, and accessibility. Further to that, several emerging robotic technologies are highlighted for their potential applications in next-generation robotic surgery.

Keywords: surgical robot, review, soft robotics, origami

1. Surgical robots today

Two decades since the American Food and Drug Administration (FDA) approved the first robotic device for surgical application, the establishments and achievements for robotic-assisted surgery are remarkable [1–3]. A brief skim through the history of surgical robotics would reveal the mileage covered in this very short period comparing with the history of surgery. The first FDA-approved surgical robot, the automated endoscopic system for optimal positioning (AESOP, Computer Motion Inc.), was a teleoperated robotic endoscopic camera that followed the commands of the surgeon via either pedals or voices. The AESOP system was successfully used in laparoscopic surgical procedures in areas such as urology, gynecology, etc., [4–7]. The subsequent ZEUS robotic system (Computer Motion Inc.) complemented an AESOP camera with two teleoperated robotic manipulators that were also continuously controlled by the surgeon through motion or voice commands [1, 8]. Despite its clinical success, the ZEUS was rivaled by the da Vinci Surgical System (Intuitive Surgical Inc.) and was discontinued two years after clearing FDA due to company merger [9, 10]. The da Vinci, on the other hand, has been the class leader for robotic-assisted surgery ever since. General laparoscopic surgery was among the first group of FDA-approved procedures for the da Vinci system in 2000, followed by radical prostatectomy in 2001, and urological surgical procedures in 2005 [11]. The list of FDA-approved procedures kept expanding, until the recent one for benign hysterectomy and salpingo-oophorectomy procedures for the latest version of the da Vinci system in 2013 and 2014 [12].

Besides expanding to new surgical areas, surgical robots have also made remarkable success in market penetration. The total number of da Vinci surgical systems installed (accumulatively) by December 2014 was 3,266 (2,223 in the US), with 570,000 procedures performed in the year 2014 [12]. Both the clinical and commercial successes have stimulated global research attention in surgical robotics. For physicians, there are various aspects of robotic-surgery–related research being investigated, ranging from efficacy [13–16] to benefits for patients [16, 17], as well as risks [18–20] and ethics [20, 21]. Another major aspect of research is surgical training, where surgical robots are generally believed to shorten the learning curve for laparoscopic surgery for young surgeons [22–25], while some variations were reported on skilled open surgeons transferring to robotic procedures [26]. Surgical training was also investigated by scientists and engineers, but via a different approach. Utilizing the complete mechanical separation between the surgeon and the patient, it was possible to generate computer signals in virtual reality (VR) and present to the surgeon using exactly the same surgeon's interface console used in real surgeries. Virtual reality surgical simulations could easily be programmed to emulate cases difficult or rare in the real world with high resemblance, hence saving animal and patient models, while significantly reducing the surgical training cost [27–29]. The VR-based surgical training was reported to be efficient in training new surgeons to robotic surgery [30, 31].

2. Technical innovations for surgical robotics

While surgeons kept innovating in robotic surgery by developing new procedures and training programs for the commercially available surgical robots, scientists and engineers have strived to innovate for robotic surgery outside the operational theater. One major direction was to develop new functionalities for the existing surgical robots. Among the various research directions, the most successfully implemented functions are vision, haptics, and accessibility.

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2.1. Innovations for vision

In robotic laparoscopic surgeries, the surgeon no longer has a direct view of the surgical site, but must rely on camera images displayed on computer screens. Before the age of high-definition video, this used to be a significant limiting factor such that the surgeon did not have a view of the surgical site with sufficient resolution. This concern was soon overcome by high-definition high-quality live video streaming, even three-dimensional (3D), which are already standard specifications for many available surgical robots [12]. The benefit of using cameras did not end with stereo vision. Making use of advanced lens systems, the surgeon could have an artificial view of the surgical site beyond the capability of the naked eye, for instance, the ultra-wide angle fisheye view from an endoscope or a super macro enlarged view of a tiny area otherwise not visible to a human. Moreover, since the video presented to the surgeon was in fact a computerized image sequence, it was possible to overlay a variety of information and other images [32, 33]. The resulting augmented vision has already been successfully implemented in surgical robots for the surgeon's maximum benefits [34]. Furthermore, overlaying preoperative imaging results and even live imaging data such as ultrasound or magnetic resonance imaging (MRI) could potentially solve the navigation challenge for laparoscopic surgery. Pioneering systems have already been reported for both preoperative and intraoperative imaging augmentation [33, 35–37].

2.2. Innovations for haptics

Another major and yet still ongoing debate is on whether haptics is a necessity for robotic surgery [34]. The term haptics has been used to refer to the sense of touch in general, while in this context, it only refers to providing force feedback signal to the surgeon on the surgeon's console, so that the surgeon could feel how much force is being applied even without direct view over the contact point, for better and safer handling of tissues [38]. Haptics of the same narrow sense had been investigated for a much longer period of time in general robotics research. Controlling forces at the interaction point had been studied in the 1970s [39, 40], with hybrid force/position control algorithms proposed in the late 1970s and the early 1980s [41, 42]. Soon afterwards, the concept of impedance control was formulated in the mid-1980s, where the virtual stiffness of a robotic manipulator could be controlled instead of position or force individually, to cope with any unpredicted interaction status [43, 44]. This concept quickly became one of the most popular and well-established control approaches in robotics until today [45]. By the time of the first-ever FDA approval on surgical robots (the AESOP), roboticists proposed the concept of transparency: that an ideal teleoperation system should be transparent to the user, such that every command could be faithfully executed and every event in the remote environment could be fed back to the user [46, 47]. All of the above concepts were built on available and high-quality real-time force feedback signals, which roboticists took for granted. Unfortunately for surgical robots, it was not the case. Due to strict spatial constraints, there was no force sensor available at that time that could fit into the instruments, hence the first generation of surgical robots was not equipped with force sensors, and naturally there was no force feedback [34, 38].

While engineers could not get over the fact that the state-of-the-art surgical robots were still utilizing the pre-1980 technology without proper force sensing, surgeons were starting to be trained to use the haptic-less surgical robots and estimate interacting forces by visual information [48, 49]. After the remarkable clinical achievements of haptic-less surgical robots, the addition of haptics to existing surgical robots became a radical move, in the eyes of the very group of surgeons who were radical enough to adopt robotic surgery earlier. In fact, this makes the underlying argument for the majority of literature against haptics in robotic surgery: since the current robots are already so good without it, if the additional complexity, unknown risks, and added costs could still be justified [49–51]. This hesitation was caused, at least partially, by technical reasons: in early surgical robotic systems, haptic feedback was either patched on or estimated/simulated, the performance of which was rather limited, hence surgeons were less in favor of the outcomes [48]. However, with the fast developments in robotic technology, recent surgical systems with haptic feedback are equipped with new force sensors and very well implemented control [52, 53], and as a result, more and more studies showed that haptic feedback became one of the most wanted features for the next generation of surgical robots [54–59].

2.3. Innovations for accessibility: SIL and NOTES

Another important area of technical innovation is accessibility. One of the main improvements laparoscopy had over open surgery was the significantly reduced size of incisions; hence, the alias "minimally invasive surgery" became more familiar to the general public. Reducing the incisions resulted not only in cosmetic improvements but also in a spectrum of procedural and postoperative benefits to both the surgeon and the patient [60–62]. However, surgeons had to undergo specific training with a steep learning curve to accommodate the compromised vision and maneuverability [63, 64]. This was precisely what the first generation of surgical robots took on manual laparoscopy, removing the burden of maneuverability from the surgeon by automatic control programs and electric motors, such that the surgeon no longer needed to think about the small incisions or apply fatiguing excessive forces, but focus on the surgical procedure [23, 65]. As a result, the learning curve for robotic laparoscopic surgery is much shorter [22–25]. While manual laparoscopy is still a required training, there have been studies in comparing the use of surgical robots by surgeons experience or inexperience with manual laparoscopy [26, 66, 67].

With the clinical and general adoption for laparoscopic surgical robots, roboticists tackled the more challenging single-incision surgery (SIL), where the multiple small incisions in laparoscopic surgery were further merged into one. The idea of SIL was first proposed as a manual procedure, and grew into a daily surgical routine for general surgery in particular, especially for transoral, transanal, and transvaginal interventions [68–70]. The majority of manual SIL procedures were carried out using a single instrument for intervention, as laparoscopic SIL was found with compromised practicality, where the surgeon had to either reverse the motion of the instrument tips or cross his/her own hands to accommodate the immobilizing incision point, being a very counterintuitive exhaustive motoring task to add to the mental burden for the surgeon [71]. However, various studies have pointed out that, after proper training, the efficacy for laparoscopic SIL is at least as good as standard laparoscopy [72–74]. Robotic technology bares every potential to overcome the primary limiting factor for SIL: constant and high mental burden of motoring control for the surgeon. Assuming sufficient instrumental rigidity and maneuverability, the automatic control program could drive the robotic instruments around one incision in the same way as driving them around multiple incisions. This, however, requires redesigning the hardware to provide the necessary kinematic structures for the additional complexity in motion mapping. Single site surgical robotic system has already been released, and will be accumulating clinical results in the near future [12, 75–78].

In parallel with laparoscopic SIL, another approach to increasing accessibility is by introducing robotic technology to flexible endoscopy. Endoscopic interventions are slowly growing popular after the introduction of endoscopic submucosal dissection (ESD) by Japanese physicians [79]. ESD was first targeted at endoscopic removal of neoplasia or early-stage gastric cancer [80, 81]. The technique could potentially unify the imaging, diagnostic, and treatment procedures, and find the basis for natural orifice transluminal endoscopic surgery (NOTES) [82–84]. However, in practice, manual ESD required extensive training and experience, and remained technically challenging to execute for both surgeons and endoscopists [85–87]. Overcoming the technical hurdle, the first endoscopic surgical robot was introduced by enabling multiple degrees-of-freedom (DOF) triangulated instrumentation on a standard endoscope platform [88]. The robot adopted the master-slave design similar to laparoscopic surgical robots [89, 90], and was enabled with haptic feedback [91, 92]. Robotic ESD was the first targeted procedure, with a series of porcine model [93, 94] and human trials [95], followed by a preclinical trial on full-thickness mucosa removal [96]. Behind the clinical success, significant engineering efforts were spent overcoming the cable transmission issues under very tight spatial constraints for the endoscopic instrument channels, where mechanical transmission [97, 98], static [99, 100] and dynamic [101, 102] friction attenuations were investigated thoroughly to improve the performance of the robot under the harsh working environments of the endoscope for both ESD and NOTES [103].

2.4. Global attention and trends in surgical robots

The success of laparoscopic and endoscopic surgical robots had stimulated worldwide attentions in surgical robot research, for instance, the laparoscopic telesurgical RAVEN robot [104, 105], the Magellan endovascular robot [106], snake-like surgical robots [107, 108], MRI-compatible surgical robots [109, 110], single-incision laparoscopic robots [111–116], and endoscopic robots [117–121].

The first observation is the global flourish of surgical robot research. The non-exhaustive country list includes the US, the UK, Germany, Italy, China, Japan, Korea, and Singapore. The cited works here did not include literature published in non-English format, or industrial developments, which could be expected considering the strong application orientation for this field. The second trend is the clear convergence of targeted surgical procedures for the various, independently developed surgical robotic systems. While earlier systems such as the RAVEN [104, 105] was still designed for laparoscopic surgery with multiple incisions, later laparoscopic robots were all aimed for single-incision procedures [107–116]. For endoscopic alternatives, nearly all systems were aimed fully or partially at NOTES [118–122]. General surgery and urologic surgery were the most common two surgical areas mentioned in the system development goals. The third observation is the technology used in the new systems. All of the cited systems used cable transmission to remotely drive the robotic end-effector except one design that utilized a screw-drive [117]. To create the cable-pulling motion, various techniques were employed; the majority used electric motor [103, 106–109, 113–115, 119–121], while others used shape-memory alloy [116, 118], pneumatics [109], piezoelectric actuator [110], and magnetics [117]. The final observation is on the manipulator structure. Both SIL- and NOTES-oriented surgical robots are attempted to integrate multiple (three to six) DOF mechanisms under a very tight spatial constraint, while required to deliver high gripping force for tissue handling and suturing tasks. While conventional revolute joints were still employed in some designs [122], articulated and continuum mechanisms were the clear trend for their better integration potential, stronger structure, and higher force capabilities [123]. The kinematic designs of typical surgical robots were reviewed in Ref. [124].

3. Emerging technologies for future surgical robotic applications

Robotic research in general is also moving at remarkable speeds. There are constantly new developments and discoveries that could potentially be translated into surgical robotic applications. Here, two of the emerging new technologies are highlighted: origami and soft robotics. Both directions are quickly picking up momentum in recent years, with the potential to tackle on one of the fundamental challenges in surgical robotics, and both already had pioneering systems being reported for related applications.

3.1. Origami in surgical robots

Origami is the art of intricately folding a sheet of paper into elaborate 3D sculptures and objects [125]. The essential elements of an origami pattern are the facets and crease lines (mountain and valley folds) that formed flat facets, i.e., quadrilaterals or triangles, and fold lines which are considered as revolute hinges connecting the facets. As a result, origami mechanisms could be folded from 2D states to 3D structures, such as the Miura-ori patterned sheet [126] and deployable structures [127, 128]. By implementing actuation in the hinges, self-folding origami composed of shape-memory polymer [129] and print-and-self-fold miniature electric devices could be obtained [130].

Origami mechanisms have the potential to tackle two crucial challenges faced by surgical robots: fabrication and assembly. A micro-fabrication technique known as Pop-Up Book MEMS [131] could create 3D, multi-material, and monolithic meso- and microstructures using purely 2D planar manufacturing and origami folding techniques [132]. The Pop-Up technology allows for the fabrication of complex, multifunctional electromechanical devices on the 0.1–10 mm scale, significantly below the size limitation for traditional machining techniques. It consists of flexible (polyimide), structural (carbon fiber or metal), and adhesive layers. To overcome planar limitations inherent to MEMS, surface-machined pin-and-staple hinges [132] and polymer flexures [133] are used to create folding linkages.

In addition to the fabrication scale advantages, origami mechanisms also allow for novel assembly possibilities. As the boundary of miniature surgical instruments keeps being pushed, the difficulty for the assembly, bonding, and packaging processes would increase in multifolds. Self-folding (self-assembly/self-deployable) origami-inspired miniature devices have been demonstrated to effectively solve the assembly challenge [132]. A series of self-folding grippers have been demonstrated in Refs. [134–136] with a variety of materials, shapes, and sizes, mostly targeted at single-cell manipulation. Techniques such as photolithography, electron-beam lithography, and soft lithography have been used to precisely pattern two-dimensional sheets of materials, namely metals, semiconductors, and polymeric films. Actuations derived from surface tension, residual stress, thermal or PH stimuli are used to fold patterned sheets into three-dimensional structures [137]. Instruments of an SIL surgical robot have a much larger scale than the cell manipulators above, while also requiring much higher forces. A Pop-Up-based surgical robot grasper was developed as given in Ref. [138]. Besides easy assembly, a novel feature was the integrated force sensing during the same fabrication and assembling procedure.

Besides the Pop-Up-based grasper in Ref. [138], another grasper design based on origami mechanism was reported in Ref. [139] with four DOF and was actuated by shape memory alloy (SMA). Origami could eventually revolutionize surgical instrument design and manufacturing, with self-assembling micro-scale robotic end-effectors integrated with sensors and actuators. Moreover, the actuator could be delivered into the surgical site in 2D form and self-assemble into 3D working form afterwards.

3.2. Soft robotics for surgical applications

Soft robotics is another rapidly emerging research field. Soft robots are commonly fabricated with flexible and elastomeric materials to achieve complex motions with simple mechanical structures [140, 141]. Generating motions without relying on rigid structures or components, these systems are ideal for bio-mimicking [142, 143] and manipulating delicate objects [144, 145]. Soft robots could be actuated with electrical charges [146], chemical reactions [147], and most commonly pressurized fluids [143, 144, 148, 149]. When pneumatic/hydraulic soft robots are pressurized, the internal fluid chambers would expand and deform the actuator. By selectively controlling and redirecting the deformation, multiple forms of motions could be created or even combined, such as contraction/extension [150], bending [143, 144, 148, 151–153], and twisting [142, 154]. Soft robots have a long list of desirable features, such as low weight, high power-to-weight ratio, low material cost, and ease of fabrication [141, 142].

For surgical robotic applications, soft robots have one clear advantage: inherent compliance. Without any rigid component, the entire robot is soft and compliant at rest. Even after pressurization, its soft structure and fluidic actuation media would still allow some level of compliance and back-drivability under extreme conditions [142]. This inherent compliance translates to safe and atraumatic tissue handling and manipulation during surgical procedures. With the vast majority of the current instruments for surgical robots made from metal or other high-stiffness materials, soft robots bear the potential to offer soft alternatives for specific situations. A soft robotic grasper was developed for atraumatic tissue handling in robotic surgery, as a safe interface between the rigid surgical instrument and the delicate human organ [155]. The preliminary results were very promising for the future application of soft robotics into surgical systems.

4. Conclusions

Technology had once again brought a paradigm shift into operational theaters toward robotic surgery. Robotic surgery has been and will continue to be one of the fastest growing fields in medicine in the foreseeable future. On the other hand, as elaborated in this article, the current generation of surgical robots is far from perfect in the sense of robotic technology, neither are they providing the surgeons with the ideal user experience. This is in part due to the inherent conservation in medical innovation, such that only the well-matured and proven technologies could penetrate the regulatory barrier into implementation. Another important reason not to be overlooked is the exploration and make-do spirits of visionary surgeons: it is not unusual that surgical robots are experimented in new procedures or even surgical areas it was not originally designed for. Regulatory would also put efficacy and safety over the surgeon's user experience as the main considerations, as they are directly related to the benefits of the patient, the regarded real end user for surgical robots. Therefore, as long as the (previously approved) surgical robot could be used in a new procedure effectively and safely, it could potentially be approved for clinical practice.

Built on the remarkable success of current surgical robots, in the near future, there will be a spectrum of new surgical robots, developed by both robotic laboratories and companies all around the globe, and employing a wide range of novel technologies, including the ones introduced in this article. The majority of such new systems will strive to reduce both the footprint of the robot and the size of the incision, for better suitability for SIL and/or NOTES. Automated surgery would still be a challenging area as, until now, the judgments of the surgeon remained the core of the entire surgical procedure. Shifting the role of robots from assistive instruments and operational interfaces to decision makers, even partially, would require a much greater effort, both in research/development and in the mentality of surgery, than technically improving surgical robots within their current range of responsibility. However, both the acquisition cost of the robotic system and the maintenance and procedural costs will be lowered, even if this means compromising the generalizability and introducing new robots more specialized in certain surgical areas or procedures. This would help in promoting robotic surgery into regional and specialized clinics. On the other hand, given the complexity of the design iteration and the time required for the regulatory approval procedure, the development of new surgical robot systems would hardly catch up with the speed of pushing new surgical boundaries. For this, surgeons and roboticists will continue to innovate based on the current generation of surgical robots, add new functions, develop evolutionary updates, apply modifications to fit new procedures, as well as compose new training protocols and programs to fully cultivate the potentials of surgeons.

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