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The Next-Generation Surgical Robots

Zheng Wang, Sicong Liu, Jing Peng and
Michael Zhiqiang Chen

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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 (cumulatively) 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.

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 multifold. 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 conservatism 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.

Author details

Zheng Wang^{1,2*}, Sicong Liu³, Jing Peng¹ and Michael Zhiqiang Chen^{1,2}

*Address all correspondence to: zwangski@hku.hk

1 Department of Mechanical Engineering, The University of Hong Kong, Hong Kong

2 HKU Shenzhen Institute of Research and Innovation (SIRI), Shenzhen, China

3 School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

References

- [1] Stoianovici D. Robotic surgery. *World Journal of Urology*. 2000;**18**(4):289-295
- [2] Camarillo D B, Krummel T M, Salisbury J K. Robotic technology in surgery: Past, present, and future. *The American Journal of Surgery*. 2004;**188**(4):2-15
- [3] Gomes P. Surgical robotics: Reviewing the past, analysing the present, imagining the future. *Robotics and Computer-Integrated Manufacturing*. 2011;**27**(2):261-266
- [4] Kavoussi L R, Moore R G, Adams J B, et al. Comparison of robotic versus human laparoscopic camera control. *The Journal of Urology*. 1995;**154**(6):2134-2136
- [5] Partin A W, Adams J B, Moore R G, et al. Complete robot-assisted laparoscopic urologic surgery: A preliminary report. *Journal of the American College of Surgeons*. 1995;**181**(6):552-557
- [6] Mettler L, Ibrahim M, Jonat W. One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynaecological endoscopic surgery. *Human Reproduction*. 1998;**13**(10):2748-2750
- [7] Alessandrini M, De Padova A, Napolitano B, et al. The AESOP robot system for video-assisted rigid endoscopic laryngosurgery. *European Archives of Oto-Rhino-Laryngology*. 2008;**265**(9):1121-1123
- [8] Sim H G, Yip S K H, Cheng C W S. Equipment and technology in surgical robotics. *World Journal of Urology*. 2006;**24**(2):128-135
- [9] Sung G T, Gill I S. Robotic laparoscopic surgery: A comparison of the da Vinci and Zeus systems. *Urology*. 2001;**58**(6):893-898
- [10] Wedmid A, Llukani E, Lee D I. Future perspectives in robotic surgery. *BJU International*. 2011;**108**(6b):1028-1036
- [11] Intuitive Surgical Inc. Annual Report 2010, Intuitive Surgical, www.intuitivesurgical.com

- [12] Intuitive Surgical Inc. Annual Report 2014, Intuitive Surgical, www.intuitivesurgical.com
- [13] Wexner S D, Bergamaschi R, Lacy A, et al. The current status of robotic pelvic surgery: Results of a multinational interdisciplinary consensus conference. *Surgical Endoscopy*. 2009;**23**(2):438-443
- [14] Joyce D, Morris-Stiff G, Falk G A, et al. Robotic surgery of the pancreas. *World Journal of Gastroenterology: WJG*. 2014;**20**(40):14726
- [15] Pai A, Melich G, Marecik S J, et al. Current status of robotic surgery for rectal cancer: A bird's eye view. *Journal of Minimal Access Surgery*. 2015;**11**(1):29
- [16] Araujo S E A, Seid V E, Klajner S. Robotic surgery for rectal cancer: Current immediate clinical and oncological outcomes. *World Journal of Gastroenterology: WJG*. 2014;**20**(39):14359
- [17] Kaye D R, Mullins J K, Carter H B, et al. Robotic surgery in urological oncology: Patient care or market share?. *Nature Reviews Urology*. 2015;**12**(1):55-60
- [18] Zorn K C, Gautam G, Shalhav A L, et al. Training, credentialing, proctoring and medicolegal risks of robotic urological surgery: Recommendations of the society of urologic robotic surgeons. *The Journal of Urology*. 2009;**182**(3):1126-1132
- [19] Weinstein G S, O'Malley Jr B W, Desai S C, et al. Transoral robotic surgery: does the ends justify the means?. *Current Opinion in Otolaryngology & Head and Neck Surgery*. 2009;**17**(2):126-131
- [20] Sarlos D, Kots L V, Stevanovic N, et al. Robotic hysterectomy versus conventional laparoscopic hysterectomy: Outcome and cost analyses of a matched case-control study. *European Journal of Obstetrics & Gynecology and Reproductive Biology*. 2010;**150**(1):92-96
- [21] Larson J A, Johnson M H, Bhayani S B. Application of surgical safety standards to robotic surgery: Five principles of ethics for nonmaleficence. *Journal of the American College of Surgeons*. 2014;**218**(2):290-293
- [22] Schreuder H W R, Wolswijk R, Zweemer R P, et al. Training and learning robotic surgery, time for a more structured approach: A systematic review. *BJOG: An International Journal of Obstetrics & Gynaecology*. 2012;**119**(2):137-149
- [23] Brinkman W M, Schout B M A, Rietbergen J B, et al. Training robotic surgery in urology: experience and opinions of robot urologists. *The International Journal of Medical Robotics and Computer Assisted Surgery*. 2015;**11**(3):308-318
- [24] Buffi N, Van Der Poel H, Guazzoni G, et al. Methods and priorities of robotic surgery training program. *European Urology*. 2014;**65**(1):1
- [25] Honaker M D, Paton B L, Stefanidis D, et al. Can robotic surgery be done efficiently while training residents?. *Journal of surgical education*. 2015;**72**(3):377-380
- [26] Doumerc N, Yuen C, Savdie R, et al. Should experienced open prostatic surgeons convert to robotic surgery? The real learning curve for one surgeon over 3 years. *BJU International*. 2010;**106**(3):378-384

- [27] Van der Meijden O A J, Schijven M P. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surgical Endoscopy*. 2009;**23**(6):1180-1190
- [28] Gallagher A G, Ritter E M, Champion H, et al. Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. *Annals of Surgery*. 2005;**241**(2):364
- [29] Aggarwal R, Ward J, Balasundaram I, et al. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. *Annals of Surgery*. 2007;**246**(5):771-779
- [30] Lerner M A, Ayalew M, Peine W J, et al. Does Training on a Virtual Reality Robotic Simulator Improve Performance on the da Vinci® Surgical System? *Journal of Endourology*. 2010;**24**(3):467-472
- [31] Kenney P A, Wszolek M F, Gould J J, et al. Face, content, and construct validity of dV-trainer, a novel virtual reality simulator for robotic surgery. *Urology*. 2009;**73**(6):1288-1292
- [32] Volonté F, Pugin F, Bucher P, et al. Augmented reality and image overlay navigation with OsiriX in laparoscopic and robotic surgery: not only a matter of fashion. *Journal of Hepato-biliary-pancreatic Sciences*. 2011;**18**(4):506-509
- [33] Ukimura O, Gill I S. Image-fusion, augmented reality, and predictive surgical navigation. *Urologic Clinics of North America*. 2009;**36**(2):115-123
- [34] Tan G Y, Goel R K, Kaouk J H, et al. Technological advances in robotic-assisted laparoscopic surgery. *Urologic Clinics of North America*. 2009;**36**(2):237-249
- [35] Gill I S, Ukimura O. Thermal energy-free laparoscopic nerve-sparing radical prostatectomy: one-year potency outcomes. *Urology*. 2007;**70**(2):309-314
- [36] Bos J, Steinbuch M, Kunst HPM. Design of a new image-guided surgical robot for precision bone drilling in the lateral skull base. *Journal of Neurological Surgery B*. 2016;**77**(S 02):FP-20-04
- [37] Bowthorpe M, Tavakoli M. Generalized predictive control of a surgical robot for beating-heart surgery under delayed and slowly-sampled ultrasound image data. *IEEE Robotics and Automation Letters*, 2016;**1**(2):892-899
- [38] Okamura A M. Haptic feedback in robot-assisted minimally invasive surgery. *Current Opinion in Urology*. 2009;**19**(1):102
- [39] Whitney D E. Force feedback control of manipulator fine motions. *Journal of Dynamic Systems, Measurement, and Control*. 1977;**99**(2):91-97
- [40] Patarinski S P, Botev R G. Robot force control: a review. *Mechatronics*. 1993;**3**(4):377-398
- [41] Craig J J, Raibert M H. A systematic method of hybrid position/force control of a manipulator. *Computer Software and Applications Conference, 1979. Proceedings. COMPSAC 79. The IEEE Computer Society's Third International*. 1979:446-451

- [42] Mason M T. Compliance and force control for computer controlled manipulators. *IEEE Transactions on Systems, Man and Cybernetics*. 1981;**11**(6):418-432
- [43] Hogan N. Impedance control: An approach to manipulation: Part II—Implementation. *Journal of Dynamic Systems, Measurement, and Control*. 1985;**107**(1):8-16
- [44] Anderson R, Spong M W. Hybrid impedance control of robotic manipulators. *IEEE Journal of Robotics and Automation*. 1988;**4**(5):549-556
- [45] Buchli J, Stulp F, Theodorou E, et al. Learning variable impedance control. *The International Journal of Robotics Research*. 2011;**30**(7):820-833
- [46] Lawrence D A. Stability and transparency in bilateral teleoperation. *IEEE Transactions on Robotics and Automation*. 1993;**9**(5):624-637
- [47] Yokokohji Y, Yoshikawa T. Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment. *IEEE Transactions on Robotics and Automation*. 1994;**10**(5):605-620
- [48] Okamura A M. Methods for haptic feedback in teleoperated robot-assisted surgery. *Industrial Robot: An International Journal*. 2004;**31**(6):499-508
- [49] Van der Meijden O A J, Schijven M P. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surgical Endoscopy*. 2009;**23**(6):1180-1190
- [50] Panchulidze I, Berner S, Mantovani G, et al. Is haptic feedback necessary to microsurgical suturing? Comparative study of 9/0 and 10/0 knot tying operated by 24 surgeons. *Hand Surgery*. 2011;**16**(01):1-3
- [51] Lanfranco A R, Castellanos A E, Desai J P, et al. Robotic surgery: a current perspective. *Annals of Surgery*. 2004;**239**(1):14
- [52] Yamamoto T, Abolhassani N, Jung S, et al. Augmented reality and haptic interfaces for robot-assisted surgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*. 2012;**8**(1):45-56
- [53] Wang Z, Sun Z, Phee S J. Haptic feedback and control of a flexible surgical endoscopic robot. *Computer Methods and Programs in Biomedicine*. 2013;**112**(2):260-271
- [54] Zhou M, Tse S, Derevianko A, et al. Effect of haptic feedback in laparoscopic surgery skill acquisition. *Surgical Endoscopy*. 2012;**26**(4):1128-1134
- [55] Koehn J K, Kuchenbecker K J. Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery. *Surgical endoscopy*. 2015;**29**(10):2970-2983
- [56] Kranzfelder M, Schneider A, Fiolka A, et al. What Do We Really Need? Visions of an Ideal Human–Machine Interface for NOTES Mechatronic Support Systems From the View of Surgeons, Gastroenterologists, and Medical Engineers. *Surgical Innovation*. 2015;**22**(4):432-440

- [57] Kume K, Sakai N, Goto T. Development of a novel endoscopic manipulation system: the Endoscopic Operation Robot ver. 3. *Endoscopy*. 2015;**47**(09):815-819
- [58] Kim U, Seok DY, Kim YB, Lee DH, Choi HR. Development of a grasping force-feedback user interface for surgical robot system. 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems. 2016;845-850
- [59] Munawar A, Fischer G. A Surgical robot teleoperation framework for providing haptic feedback incorporating virtual environment-based guidance. *Front Robot AI*. 2016;**3**:47
- [60] Zhu J H, Li W, Yu K, et al. New strategy during complicated open appendectomy: Convert open operation to laparoscopy. *World Journal of Gastroenterology: WJG*. 2014;**20**(31):10938
- [61] Gaillard M, Tranchart H, Dagher I. Laparoscopic liver resections for hepatocellular carcinoma: current role and limitations. *World Journal of Gastroenterology: WJG*. 2014;**20**(17):4892
- [62] Limongelli P, Vitiello C, Belli A, et al. Costs of laparoscopic and open liver and pancreatic resection: A systematic review. *World Journal of Gastroenterology: WJG*. 2014;**20**(46):17595
- [63] Cadeddu J A, Wolfe J S, Nakada S, et al. Complications of laparoscopic procedures after concentrated training in urological laparoscopy. *The Journal of Urology*. 2001;**166**(6):2109-2111
- [64] Kaiser A M. Evolution and future of laparoscopic colorectal surgery. *World Journal of Gastroenterology: WJG*. 2014;**20**(41):15119
- [65] Sarle R, Tewari A, Shrivastava A, et al. Surgical robotics and laparoscopic training drills. *Journal of Endourology*. 2004;**18**(1):63-67
- [66] Ugarte D A, Etzioni D A, Gracia C, et al. Robotic surgery and resident training. *Surgical Endoscopy*. 2003;**17**(6):960-963
- [67] Schreuder H W R, Persson J E U, Wolswijk R G H, et al. Validation of a novel virtual reality simulator for robotic surgery. *The Scientific World Journal*. 2014;**2014**:1-10
- [68] Maggiori L, Gaujoux S, Tribillon E, et al. Single-incision laparoscopy for colorectal resection: a systematic review and meta-analysis of more than a thousand procedures. *Colorectal Disease*. 2012;**14**(10):e643-e654
- [69] Mittermair C, Schirnhofner J, Brunner E, et al. Single port laparoscopy in gastroenterology and hepatology: A fine step forward. *World Journal of Gastroenterology: WJG*. 2014;**20**(42):15599
- [70] Cianchi F, Staderini F, Badii B. Single-incision laparoscopic colorectal surgery for cancer: State of art. *World Journal of Gastroenterology: WJG*. 2014;**20**(20):6073

- [71] Santos B F, Reif T J, Soper N J, et al. Effect of training and instrument type on performance in single-incision laparoscopy: results of a randomized comparison using a surgical simulator. *Surgical Endoscopy*. 2011;**25**(12):3798-3804
- [72] Farach S M, Danielson P D, Chandler N M. Impact of experience on quality outcomes in single-incision laparoscopy for simple and complex appendicitis in children. *Journal of pediatric surgery*. 2015;**50**(8):1364-1367
- [73] Weiss H G, Brunner W, Biebl M O, et al. Wound complications in 1145 consecutive transumbilical single-incision laparoscopic procedures. *Annals of Surgery*. 2014;**259**(1):89-95
- [74] Yun J A, Yun S H, Park Y A, et al. Single-incision laparoscopic right colectomy compared with conventional laparoscopy for malignancy: assessment of perioperative and short-term oncologic outcomes. *Surgical Endoscopy*. 2013;**27**(6):2122-2130
- [75] Kaouk J H, Goel R K, Haber G P, et al. Robotic single-port transumbilical surgery in humans: initial report. *BJU International*. 2009;**103**(3):366-369
- [76] Canes D, Desai M M, Aron M, et al. Transumbilical single-port surgery: evolution and current status. *European Urology*. 2008;**54**(5):1020-1030
- [77] Kaouk JH, Haber GP, Autorino R, et al. A novel robotic system for single-port urologic surgery: First clinical investigation. *European Urology*. 2014;**66**(6):1033-1043
- [78] Holsinger FC. A flexible, single-arm robotic surgical system for transoral resection of the tonsil and lateral pharyngeal wall: Next-generation robotic head and neck surgery. *Laryngoscope*. 2016;**126**(4):864-869
- [79] Yahagi N, Fujishiro M, Kakushima N, et al. Endoscopic submucosal dissection for early gastric cancer using the tip of an electrosurgical snare (thin type). *Digestive Endoscopy*. 2004;**16**(1):34-38
- [80] Gotoda T, Yamamoto H, Soetikno R M. Endoscopic submucosal dissection of early gastric cancer. *Journal of Gastroenterology*. 2006;**41**(10):929-942
- [81] Tanaka S, Oka S, Kaneko I, et al. Endoscopic submucosal dissection for colorectal neoplasia: possibility of standardization. *Gastrointestinal Endoscopy*. 2007;**66**(1):100-107
- [82] Sebastian G, DeMaria E J, Reynolds J D, et al. New developments in surgery: natural orifice transluminal endoscopic surgery (NOTES). *Archives of Surgery*. 2007;**142**(3):295-297
- [83] McGee M F, Rosen M J, Marks J, et al. A primer on natural orifice transluminal endoscopic surgery: building a new paradigm. *Surgical Innovation*. 2006;**13**(2):86-93
- [84] Rao G V, Reddy D N, Banerjee R. NOTES: human experience. *Gastrointestinal Endoscopy Clinics of North America*. 2008;**18**(2):361-370
- [85] Deprez P H, Bergman J J, Meisner S, et al. Current practice with endoscopic submucosal dissection in Europe: position statement from a panel of experts. *Endoscopy*. 2010;**42**(10):853-858

- [86] Teoh A Y B, Chiu P W Y, Wong S K H, et al. Difficulties and outcomes in starting endoscopic submucosal dissection. *Surgical Endoscopy*. 2010;**24**(5):1049-1054
- [87] Berr F, Ponchon T, Neureiter D, et al. Experimental endoscopic submucosal dissection training in a porcine model: learning experience of skilled Western endoscopists. *Digestive Endoscopy*. 2011;**23**(4):281-289
- [88] Phee S J, Low S C, Sun Z L, et al. Robotic system for no-scar gastrointestinal surgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*. 2008;**4**(1):15-22
- [89] Phee S J, Low S C, Huynh V A, et al. Master and slave transluminal endoscopic robot (MASTER) for natural orifice transluminal endoscopic surgery (NOTES). *Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE. IEEE*. 2009:1192-1195
- [90] Phee S J, Sun Z, Wang Z, et al. The future of transluminal surgery. *Expert review of medical devices*. 2011;**8**(6):669-671
- [91] Sun Z, Wang Z, Phee S J. Towards haptics enabled surgical robotic system for NOTES. 2011 IEEE Conference on Robotics, Automation and Mechatronics (RAM), IEEE, 2011:229-233
- [92] Wang Z, Sun Z, Phee S J. Haptic feedback and control of a flexible surgical endoscopic robot. *Computer Methods and Programs in Biomedicine*. 2013;**112**(2):260-271
- [93] Ho K Y, Phee S J, Shabbir A, et al. Endoscopic submucosal dissection of gastric lesions by using a Master and Slave Transluminal Endoscopic Robot (MASTER). *Gastrointestinal Endoscopy*. 2010;**72**(3):593-599
- [94] Wang Z, Phee S J, Lomanto D, et al. Endoscopic submucosal dissection of gastric lesions by using a master and slave transluminal endoscopic robot: an animal survival study. *Endoscopy*. 2012;**44**(7):690-694
- [95] Phee S J, Reddy N, Chiu P W Y, et al. Robot-assisted endoscopic submucosal dissection is effective in treating patients with early-stage gastric neoplasia. *Clinical Gastroenterology and Hepatology*. 2012;**10**(10):1117-1121
- [96] Chiu P W Y, Phee S J, Wang Z, et al. Feasibility of full-thickness gastric resection using master and slave transluminal endoscopic robot and closure by over stitch: a preclinical study. *Surgical Endoscopy*. 2014;**28**(1):319-324
- [97] Wang Z, Sun Z, Phee S J. Modeling tendon-sheath mechanism with flexible configurations for robot control. *Robotica*. 2013;**31**(07):1131-1142
- [98] Sun Z, Wang Z, Phee S J. Elongation modeling and compensation for the flexible tendon-sheath system. *IEEE/ASME Transactions on Mechatronics*. 2014;**19**(4):1243-1250
- [99] Sun Z, Wang Z, Phee S J. Modeling and motion compensation of a bidirectional tendon-sheath actuated system for robotic endoscopic surgery. *Computer Methods and Programs in Biomedicine*. 2015;**119**(2):77-87

- [100] Sun Z, Wang Z, Phee S J. Haptic modeling of stomach for real-time property and force estimation. *Journal of Mechanics in Medicine and Biology*. 2013;**13**(03):1-25
- [101] Do T N, Tjahjowidodo T, Lau M W S, et al. Dynamic friction-based force feedback for tendon-sheath mechanism in notes system. *International Journal of Computer and Electrical Engineering*. 2014;**6**(3):252-258
- [102] Do T N, Tjahjowidodo T, Lau M W S, et al. An investigation of friction-based tendon sheath model appropriate for control purposes. *Mechanical Systems and Signal Processing*. 2014;**42**(1):97-114
- [103] Wang Z, Phee S J, Wong J, et al. Development of a robotic platform for natural orifice transluminal endoscopic surgery. *Gastrointestinal Intervention*. 2012;**1**(1):40-42
- [104] Lum M J H, Friedman D C W, Sankaranarayanan G, et al. The RAVEN: Design and validation of a telesurgery system. *The International Journal of Robotics Research*. 2009;**28**(9):1183-1197
- [105] Rosen J, Lum M, Sinanan M, et al. Raven: Developing a surgical robot from a concept to a transatlantic teleoperation experiment. *Surgical Robotics*. Springer US, 2011:159-197
- [106] Hemmerling T M, Taddei R, Wehbe M, et al. First robotic ultrasound-guided nerve blocks in humans using the Magellan system. *Anesthesia & Analgesia*. 2013;**116**(2):491-494
- [107] Webster R J, Okamura A M, Cowan N J. Toward active cannulas: Miniature snake-like surgical robots. 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2006:2857-2863
- [108] Shang J, Noonan D P, Payne C, et al. An articulated universal joint based flexible access robot for minimally invasive surgery. 2011 IEEE International Conference on Robotics and Automation (ICRA). IEEE. 2011:1147-1152
- [109] Hempel E, Fischer H, Gumb L, et al. An MRI-compatible surgical robot for precise radiological interventions. *Computer Aided Surgery*. 2003;**8**(4):180-191
- [110] Sutherland G R, Latour I, Greer A D, et al. An image-guided magnetic resonance-compatible surgical robot. *Neurosurgery*. 2008;**62**(2):286-293
- [111] Xu K, Zhao J, Fu M. Development of the SJTU unfoldable robotic system (SURS) for single port laparoscopy. *IEEE/ASME Transactions on Mechatronics*. 2015;**20**(5):2133-2145
- [112] Lee J, Kim J, Lee K K, et al. Modeling and control of robotic surgical platform for single-port access surgery. 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014). IEEE, 2014:3489-3495
- [113] Horise Y, Matsumoto T, Ikeda H, et al. A novel locally operated master-slave robot system for single-incision laparoscopic surgery. *Minimally Invasive Therapy & Allied Technologies*. 2014;**23**(6):326-332
- [114] Choi H, Kwak H, Kim H, et al. Surgical robot for single-incision laparoscopic surgery. *IEEE Transactions on Biomedical Engineering*. 2014;**61**(9):2458-2466

- [115] Yuan X, Liu D, Gong M. Design and research on a shape memory alloy-actuated single-port laparoscopic surgical robot. 2014 IEEE International Conference on Mechatronics and Automation (ICMA). IEEE. 2014:1654-1658
- [116] Yi B, Wang G, Li J, et al. The first clinical use of domestically produced Chinese minimally invasive surgical robot system "Micro Hand S". Surgical endoscopy. 2016;**30**(6):2649-2655
- [117] Kobayashi Y, Sekiguchi Y, Noguchi T, et al. Development of a robotic system with six-degrees-of-freedom robotic tool manipulators for single-port surgery. The International Journal of Medical Robotics and Computer Assisted Surgery. 2015;**11**(2):235-246
- [118] Tognarelli S, Salerno M, Tortora G, et al. A miniaturized robotic platform for natural orifice transluminal endoscopic surgery: in vivo validation[J]. Surgical endoscopy. 2015;**29**(12):3477-3484
- [119] Poon C C Y, Yang H, Lau K C, et al. A bio-inspired flexible robot with hybrid actuation mechanisms for endoscopic surgery[C]//The Hamlyn Symposium on Medical Robotics. 2014: p.81
- [120] Son J, Cho C N, Kim K G, et al. A novel semi-automatic snake robot for natural orifice transluminal endoscopic surgery: preclinical tests in animal and human cadaver models (with video)[J]. Surgical endoscopy. 2015;**29**(6):1643-1647
- [121] Thakkar S, Awad M, Gurram K C, et al. A novel, new robotic platform for natural orifice distal pancreatectomy. Surgical innovation. 2015;**22**(3):274-282
- [122] Lomanto D, Wijerathne S, Ho L K Y, et al. Flexible endoscopic robot. Minimally Invasive Therapy & Allied Technologies. 2014;**24**(1):37-44
- [123] Xu K, Fu M, Zhao J. An experimental kinestatic comparison between continuum manipulators with structural variations. 2014 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2014:3258-3264
- [124] Arkenbout E A, Henselmans P W J, Jelínek F, et al. A state of the art review and categorization of multi-branched instruments for NOTES and SILS. Surgical endoscopy. 2015;**29**(6):1281-1296
- [125] You Z. Folding structures out of flat materials. Science. 2014;**345**(6197):623-624
- [126] Liu S, Lu G, Chen Y, et al. Deformation of the Miura-ori patterned sheet. International Journal of Mechanical Sciences. 2015;**99**:130-142
- [127] Liu S, Chen Y, Lu G. The rigid origami patterns for flat surface, ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers. 2013;**6B**: p.1-7
- [128] Liu S, Lv W, Chen Y, et al. Deployable prismatic structures with origami patterns, ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers. 2014;**5B**:1-8

- [129] Tolley M T, Felton S M, Miyashita S, et al. Self-folding origami: shape memory composites activated by uniform heating. *Smart Materials and Structures*. 2014;**23**(9):094006
- [130] Miyashita S, Meeker L, Tolley M T, et al. Self-folding miniature elastic electric devices. *Smart Materials and Structures*. 2014;**23**(9):094005
- [131] Whitney J P, Sreetharan P S, Ma K Y, et al. Pop-up book MEMS. *Journal of Micromechanics and Microengineering*. 2011;**21**(11):115021
- [132] Hui E E, Howe R T, Rodgers M S. Single-step assembly of complex 3-D microstructures. *The Thirteenth Annual International Conference on Micro Electro Mechanical Systems*, 2000. MEMS 2000. IEEE, 2000:602-607
- [133] Cohen A, Zhang G, Tseng F G, et al. EFAB: rapid, low-cost desktop micromachining of high aspect ratio true 3-D MEMS. *Twelfth IEEE International Conference on Micro Electro Mechanical Systems*, 1999. MEMS'99. IEEE. 1999:244-251
- [134] Malachowski K, Jamal M, Jin Q, et al. Self-folding single cell grippers. *Nano letters*. 2014;**14**(7):4164-4170
- [135] Shenoy V B, Gracias D H. Self-folding thin-film materials: From nanopolyhedra to graphene origami. *MRS Bulletin*. 2012;**37**(09):847-854
- [136] Pandey S, Gultepe E, Gracias D H. Origami inspired self-assembly of patterned and reconfigurable particles. *JoVE (Journal of Visualized Experiments)*, 2013(72): e50022-e50022.
- [137] Gracias D H. Stimuli responsive self-folding using thin polymer films. *Current Opinion in Chemical Engineering*. 2013;**2**(1):112-119
- [138] Gafford J B, Kesner S B, Wood R J, et al. Force-sensing surgical grasper enabled by pop-up book MEMS. *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2013:2552-2558
- [139] Salerno M, Zhang K, Menciassi A, et al. A novel 4-DOFs origami enabled, SMA actuated, robotic end-effector for minimally invasive surgery. *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2014:2844-2849
- [140] Majidi C. Soft robotics: a perspective—current trends and prospects for the future. *Soft Robotics*. 2014;**1**(1):5-11
- [141] Wang Z, Chen M Z Q, Yi J. Soft robotics for engineers. *HKIE Transactions*. 2015;**22**(2):88-97
- [142] Shepherd R F, Ilievski F, Choi W, et al. Multigait soft robot. *Proceedings of the National Academy of Sciences*. 2011;**108**(51):20400-20403
- [143] Poon C C Y, Leung B, Chan C K W, Lau J Y W, Chiu P W Y. Design of wormlike automated robotic endoscope: dynamic interaction between endoscopic balloon and surrounding tissues. *Surgical Endoscopy and Other Interventional Techniques*. 2016;**30**(2):772-778
- [144] Laschi C, Cianchetti M, Mazzolai B, et al. Soft robot arm inspired by the octopus. *Advanced Robotics*. 2012;**26**(7):709-727

- [145] Wang H, Zhang R, Chen W, et al. A cable-driven soft robot surgical system for cardiothoracic endoscopic surgery: preclinical tests in animals. *Surgical Endoscopy*. 2016;1-7
- [146] Keplinger C, Kaltenbrunner M, Arnold N, et al. Röntgen's electrode-free elastomer actuators without electromechanical pull-in instability. *Proceedings of the National Academy of Sciences*. 2010;**107**(10):4505-4510
- [147] Onal C D, Rus D. A modular approach to soft robots. 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob). IEEE. 2012:1038-1045
- [148] Suzumori K, Endo S, Kanda T, et al. A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. 2007 IEEE International Conference on Robotics and Automation. IEEE. 2007:4975-4980
- [149] Martinez R V, Branch J L, Fish C R, et al. Robotic tentacles with three-dimensional mobility based on flexible elastomers. *Advanced Materials*. 2013;**25**(2):205-212
- [150] Chou C P, Hannaford B. Measurement and modeling of McKibben pneumatic artificial muscles. *IEEE Transactions on Robotics and Automation*. 1996;**12**(1):90-102
- [151] Polygerinos P, Lyne S, Wang Z, et al. Towards a soft pneumatic glove for hand rehabilitation. 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE. 2013:1512-1517
- [152] Polygerinos P, Wang Z, Galloway K C, et al. Soft robotic glove for combined assistance and at-home rehabilitation. *Robotics and Autonomous Systems*. 2015;**73**:135-143
- [153] Polygerinos P, Wang Z, Overvelde J T B, et al. Modeling of soft fiber-reinforced bending actuators. *IEEE Transactions on Robotics*. 2015;**31**(3):778-789
- [154] Sun Y, Song Y S, Paik J. Characterization of silicone rubber based soft pneumatic actuators. 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE. 2013:4446-4453
- [155] Gafford J, Ding Y, Harris A, et al. Shape deposition manufacturing of a soft, atraumatic, deployable surgical grasper. *Journal of Medical Devices*. 2014;**8**(3):030927