Minimally Invasive Therapy. 2014;Early Online: 1–10

ORIGINAL ARTICLE

Surgical robots for SPL and NOTES: a review

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Abstract

Introduction:Single port laparoscopy (SPL) and natural orifice transluminal endoscopic surgery (NOTES) are next-generation minimally invasive surgery (MIS) procedures which could further reduce patient trauma. Robotic assistance shows great potential in providing augmented motion precision and manipulation dexterity. This article reviews the robotic systems recently developed for SPL and NOTES. **Material and methods**: A literature search was conducted based on Science Citation Index, Engineering Index, Medline, and PubMed databases. **Results**:Eleven robotic systems for SPL and six robotic systems for NOTES were identified. Structures and performances of these systems were reported. Special attention was directed to the systems using continuum mechanisms. ***Discussion and conclusion:*** Regarding the structure aspect, the reviewed systems for SPL and NOTES all deploy a vision unit and at least two manipulation arms for surgical interventions through an access channel. To date, the smallest diameter of such a channel is so far 12 mm. Regarding the functionality aspect, only a few systems demonstrated results promising enough for animal or clinical studies in the near future. Surgical robots using dual continuum mechanisms achieved both design compactness and functional versatility. The characteristics suggest that the use of continuum mechanisms is worth exploring through future developments of surgical robots.

Key words: *continuum mechanism, NOTES, SPL, surgical robots*

Introduction

Benefiting patients with reduced trauma and improved recovery, multi-port laparoscopy has prevailed since its introduction (1). On the other hand it also brings difficulties to surgeons, such as reduced distal dexterity, reversed hand-eye coordination, limited visualization, affected tactile sensing, etc. Many surgical robots were hence developed to enhance surgeons with these hindered capabilities (2). Among the existing systems for multi-port laparoscopy, the da Vinci robot (Intuitive Surgical Inc., Sunnyvale, CA, USA) is currently applied clinically to a wide spectrum of procedures. The Intuitive Surgical, Inc. has built its dominance via its solid intellectual holdings (3).

On the way to less invasiveness, new surgical paradigms such as single port laparoscopy (SPL) and natural orifice transluminal endoscopic surgery (NOTES) have been introduced. NOTES uses only natural orifices to access surgical sites through a long and curved endoscope (4). But its adoption is limited due to the challenges in tool instrumentation (5). On the other hand, SPL uses one skin incision for surgical interventions, generating better surgical outcomes than traditional multi-port laparoscopy (6) as well as receiving fair adoption enabled by the newly developed manual tools. However, substantial training is necessary for surgeons to master the manipulation skills due to the mirrored and crossed hand-eye coordination.

To address the challenges associated with manual operations, quite a few robotic systems were developed for SPL and NOTES. These robots follow different design topology and possess various features and functionalities. But they also share some similar characteristics. Most of the robots can be deployed inside a sheath through a single channel (a laparoscopic access port or

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ISSN 1364-5706 print/ISSN 1365-2931 online
DOI: 10.3109/13645706.2014.999687

an endoscope) to surgical sites (Figure 1). A vision unit and two manipulation arms can then be inserted for visualization and surgical interventions. Key specifications of the robots for SPL and NOTES include the diameter of the access port and performance of their manipulation arms.

A surgical robot with a smaller sheath could lead to less invasiveness. A smaller sheath could also ease the system's deployment through the narrow and curved natural orifices during NOTES. On the other hand, the performance of the manipulation arms of a surgical robot could be characterized by the distal dexterity and payload capability of the arm. Although the definition of distal dexterity of a surgical manipulation arm has not been well established, roughly speaking it refers to the capability of the arm to move and orient a surgical end effector. The degree of freedom (DoF) configuration and dimensions of the arm directly affect its distal dexterity. It could be very difficult to miniaturize a manipulation arm with high distal dexterity and high payload capability. Hence it is always a challenge for the designer to minimize the diameter of the system sheath and to maximize the performance of the manipulation arm.

This study reviews the development statuses of the state-of-the-art surgical robots for SPL and NOTES. By listing and comparing the system configurations, key specifications and major milestones of these surgical robots, this study attempts to summarize the characteristics, point out the specific design advantages, and provide technical suggestions for the future development of surgical robots for SPL and NOTES.

Material and methods

A literature search based on Science Citation Index, Engineering Index, Medline, and PubMed databases for English language publications from 2004 to 2014 was carried out. Conference proceedings and web pages of medical product suppliers were also consulted. Key words used for the search include single port/incision/site, robot, laparoscopy, NOTES, natural orifice, endoscopy, etc.

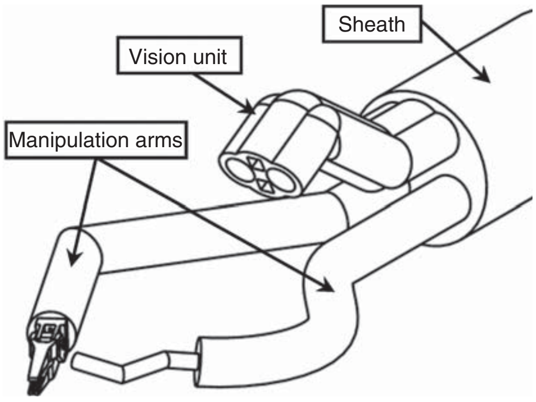

Figure 1. A common configuration adapted by most of the SPL/NOTES robots

After screening more than 3000 hits that showed up, about 80 papers were identified to be relevant. These papers deal with the development of eleven robotic systems for SPL and six robotic systems for NOTES. Since many papers only report incremental developments of these systems, only one or two representative or conclusive papers were cited for each system in this study.

This review is limited to completed robotic systems for SPL and NOTES. There are many papers about the development of an individual module or a single enabling technology which could be applied in a SPL/NOTES robot. These papers are not included.

Results

Eleven robotic systems for SPL and six robotic systems for NOTES are reviewed. The system configurations, key specifications and major milestones are listed and compared. Particularly, the system performances, including the DoF arrangement, distal dexterity and payload capabilities, are emphasized. With a high distal dexterity, the system's manipulation arms can move and orient different surgical end effectors freely. With a high payload capability, the arms can generate enough forces for different surgical tasks such as organ lifting, tissue peeling, suturing, or knot-tying.

The diameter of the system sheath is a critical parameter. With a bigger diameter, more dexterous and more powerful manipulation arms and a better vision unit (e.g., with HD camera chips) could be integrated. The SPL/NOTES robots are hence reviewed in a sequence with descending sheath diameters (Table 1).

Specific attention is directed to a SPL robot and a NOTES robot using continuum mechanisms. The diameters are among the smallest while the functionalities of the system are well demonstrated. In order to reveal why such systems could achieve both functional versatility and design compactness, the dual continuum mechanism, which was used in both systems, is also described.

Robotic systems for SPL

SAIT (Samsung Advanced Institute of Technology, Gyeonggi-do, Korea) developed a surgical robot for single-incision laparoscopic surgery (SILS) (7,8). The robot could be deployed through a single incision less than 50 mm. It is composed of two $\emptyset 8$ mm manipulation

Table 1. Existing state-of-the-art SPL/NOTES robots

Procedure	System or developer	Year	Main mechanism in the arms	Arm size (mm)	Port size (mm)	Arm DoFs	Payload
SPL	SAIT (Samsung Advanced Institute of Technology) (7,8)	2014	Articulated elbow pitch structure with RCM	∅8	<∅50	9	> 10N
SPL	The VeSPA instruments (9)	2010	da Vinci Si EndoWrist instruments with semi-rigid shafts	-	∅35	-	-
SPL	The SPRINT robot (10,11)	2013	Embedded motors with gears	∅18	∅30	6	5N
SPL	Sekiguchi et al. (12)	2010	Double screw drive mechanism	∅8	∅30	5	-
SPL	Kobayashi et al. (14)	2014	Double screw drive mechanism	∅8	∅25	6	
SPL	Lee, Choi and Yi (15)	2012	Stackable 4-bar linkage	-	∅25	5	-
SPL	The SPORT system (16)	2013	-	-	∅25	8	> 3.25N
SPL	The da Vinci SP System (17)	2014	-	-	∅25	7	-
SPL	Shin and Kwon (18)	2013	Cable driven revolute joints and links	∅8	≫ ∅16	6	> 7.5N
SPL	The IREP robot (19,20)	2013	Continuum structure	∅6.4	∅15	7	-
SPL	The SURS robot (21,22)	2014	Dual continuum mechanism	∅6.35	∅12	6	2N
NOTES	Phee et al. (23,24)	2008	Revolute joints and links	∅7	∅22	4	3N
NOTES	The ViaCath system (25)	2007	Cable driven joints and links	∅7.2	∅19	6	0.5 N
NOTES	Lehman et al. (26)	2009	Embedded motors and linkages	14×17	14×17	3	-
NOTES	Harada et al. (27)	2009	Motor embedded modules	∅15.4	∅15.4	-	-
NOTES	Tortora *et al.* (28,29)	2013	Embedded motors and gears	∅12	∅14	4	0.65N
NOTES	Zhao *et al.* (30)	2013	Dual continuum mechanism	About ∅5	∅12	5	2N

arms and one ∅15 mm laparoscope. The articulated arm adopts an elbow-pitch structure and has six DoFs (Figure 2a). Each arm is attached to a 3-DoF conically shaped Remote Center of Motion (RCM) mechanism and the arm can be exchanged during a surgery. Peg transfer, suturing and knot-tying were successfully performed. A payload test showed that the arm is able to lift a 1-kg weight. *In-vivo* animal trials were also mentioned.

SAIT might just be a recent player in the field of surgical robots. The dominating one is still Intuitive Surgical Inc. The company introduced the VeSPA instrument to be used with the da Vinci surgical robot (9). The typical setup involves a ∅35 mm multichannel port, one laparoscope, one assistant instrument and two VeSPA instruments. Compatibility with a standard da Vinci robot limits the capabilities of the VeSPA tool. The company later announced the da Vinci SP system that is described later in this chapter.

Among the research prototypes, Picciagallo *et al.* (10,11) constructed the SPRINT (Single-Port lapaRoscopy bImaNual roboT) robot for SPL (Figure 2b). The robot comprises two 6-DoF arms that can be individually inserted and removed through a ∅30 mm port. Within each ∅18 mm arm, four DoFs are actuated by onboard servomotors with bevel gears and two proximal DoFs actuated by external motors. A payload capability of 5N is achieved for each arm. The robot was able to perform surgical tasks such as pick-and-place, or suturing.

Research for SPL robots takes place not only in Europe but also in Asia. Sekiguchi *et al.* (12) developed a robotic system for SPL. The sheath has an outer diameter of 30 mm. A flexible endoscope, a ∅6 mm 3-DoF manipulation arm for cautery, and a ∅8 mm 5-DoF manipulation arm for gripping are integrated. A double-screw-drive mechanism (13), which consists of parallel screws and universal joints,

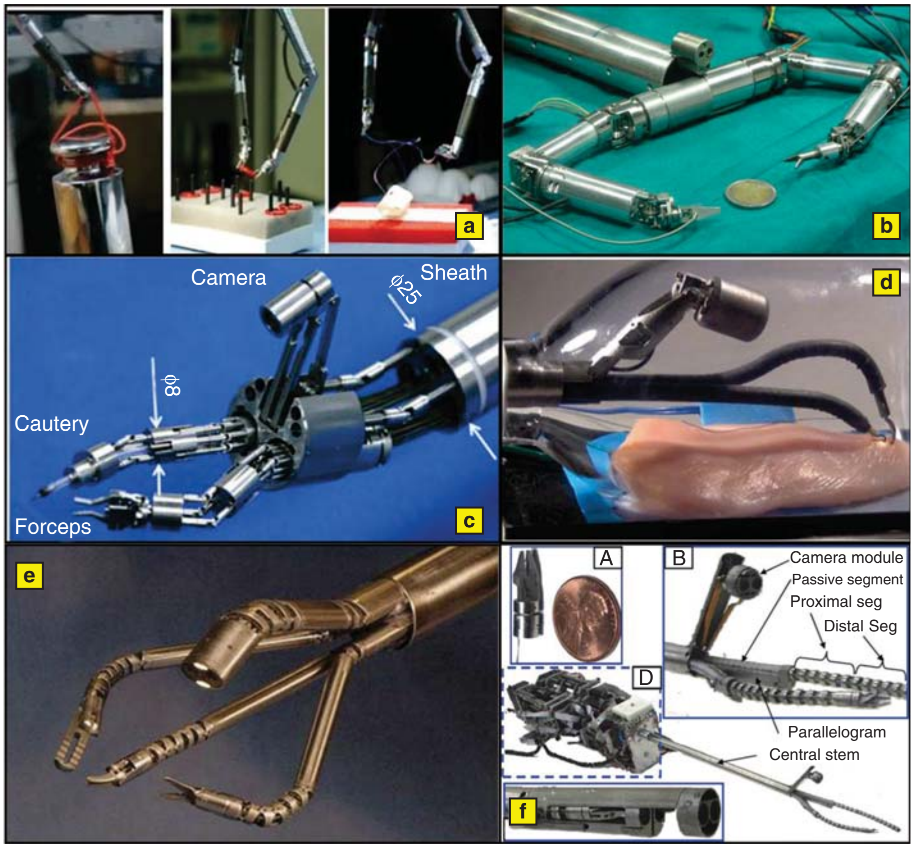

Figure 2. Robotic systems for SPL: (**A**) The robot developed by Choi et al., (**B**) the SPRINT robot, (**C**) the robot developed by Kobayashi et al., (**D**) The SPORT system, (**E**) the da Vince SP system, (**F**) the IREP robot

was applied in the arm designs. Flexible shafts were used to transmit the motion from the servomotors to the distal joints. Kobayashi et al. advanced this research by developing an updated version of this robot (14). The diameter of the sheath was reduced to 25 mm and both manipulation arms possess six DoFs and a diameter of 8 mm (Figure 2c). The entire system can also be positioned by an external manipulator that serves as a RCM mechanism. Functionality of the robot was validated through target approaching and tissue resection under *in-vitro* and *in-vivo* conditions. Some problems were identified during the *in-vivo* tests, such as limited field of view, poor imaging quality, insufficient arm motion ranges, etc. Lee *et al.* also developed a research-oriented SPL robot using stackable four-bar linkages (15). The prototype with two 5-DoF manipulation arms could be inserted through a ∅25 mm port.

The sheath diameter of 25 mm seems to reach a balance point between the acceptable incision size suggested by surgeons and the challenges of system integration and realization. Not only the aforementioned research prototypes but also the commercial prototypes described below adopt this sheath size. The SPORT$^{\mathrm{TM}}$ (Single Port Orifice Robotic Technology) surgical system was developed by Titan Medical Inc. (Toronto, Ontario, Canada) (16). The system can be deployed through a ∅25 mm incision with a 3D vision system and two multi-articulating instruments (Figure 2d). Each manipulation arm has seven DoFs with a payload capability > 3.25N. Functionality of the system was demonstrated by several tasks including resecting tissue, peeling a grape, threading a needle and passing small beads. Intuitive Surgical Inc. also introduced the da Vinci SP Surgical System for Urology (17). The robot delivers a 3D camera and three EndoWrist SP instruments through its 25 mm sheath (Figure 2e). Each of the EndoWrist SP instruments has seven DoFs.

In academia, researchers keep trying to reduce the required port diameter while maintaining good performance. Shin and Kwon developed a ∅8 mm 6-DoF surgical manipulation arm with a payload capability of >7.5N (18). The arm consists of cable actuation and revolute joints. However, an access port with a diameter much bigger than 16 mm might be needed to form a SPL robot using this arm.

Considerable reduction in the sheath diameter was only achieved when continuum mechanisms were used in the robot design. The examples include the

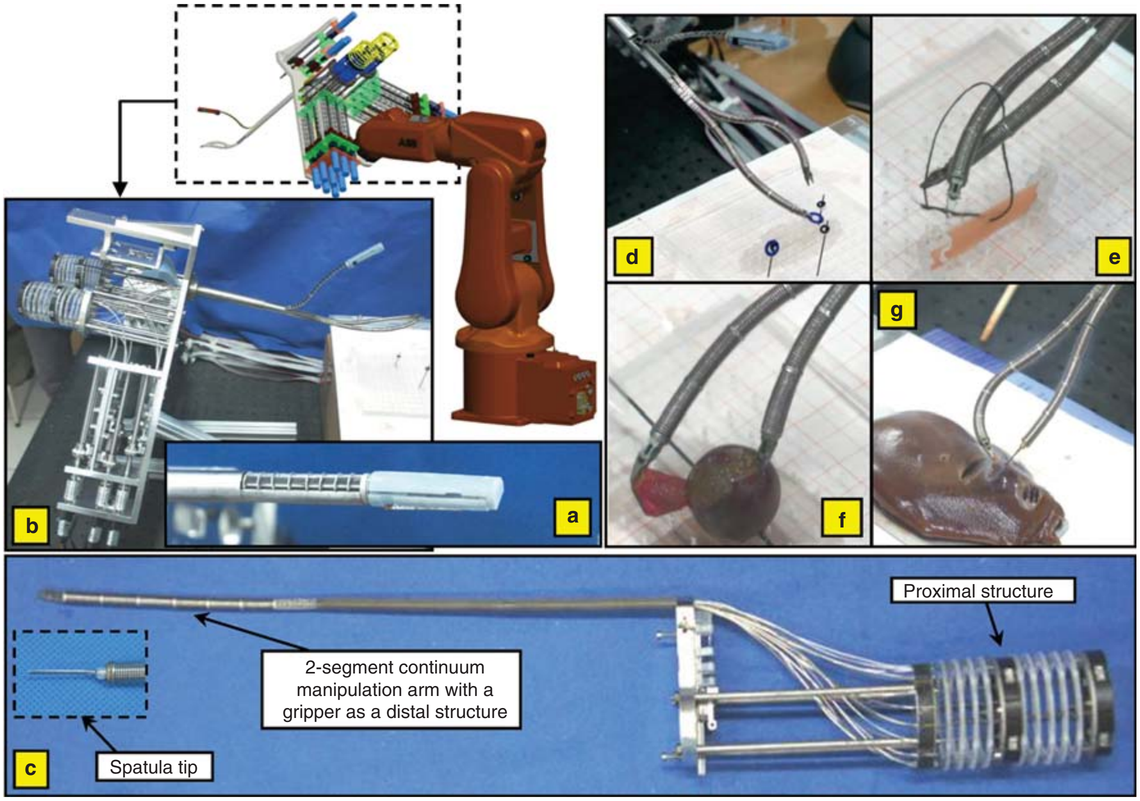

Figure 3. System descriptions of the SURS robot: (**A**) The folded configuration, (**B**) the unfolded working configuration, (**C**) the manipulation arm, (**D**) pick-and-place, (**E**) knot-tying, (**F**) grape skin peeling, and (**G**) tissue resection.

IREP (Insertable Robotic Effector Platform) robot developed by Ding et al. (19,20) and the SURS (SJTU Unfoldable Robotic System) robot developed by Xu et al. (21,22) for SPL. The IREP robot with a stereo vision unit and two manipulation arms can be deployed into the abdomen through a ∅15 mm port (Figure 2f). The ∅6.4 mm 7-DoF arm is comprised of a 4-DoF two-segment continuum structure, a 2-DoF parallelogram mechanism, a 1-DoF distal wrist, and a gripper. Peg transfer and knot tying were successfully carried out using the IREP robot.

The SUSR robot needs an even smaller access port (∅12 mm) for its deployment. After being positioned by a 6-DoF industrial robot as a RCM mechanism, it can be inserted into the abdomen in its folded configuration (Figure 3a). Then it can unfold itself into a working configuration with a stereo vision unit and two manipulation arms (Figure 3b). The vision unit consists of a camera head and a two-segment continuum camera arm with ten light-emitting diodes (LEDs) integrated for illumination.

Each of the 6-DoF exchangeable manipulation arms is comprised of a distal structure and a proximal structure (Figure 3c). The distal structure consists of a two-segment continuum structure and a gripper. The gripper can also be replaced by a unipolar electrical cautery spatula to achieve tissue resection. Each continuum segment has a 2-DoF bending and 1-DoF extension/compression. The proximal structure is actuated to mobilize the distal structure. Here a specific type of continuum mechanism, the dual continuum mechanism (DCM), is applied in the design. The DCM improves the mechanical properties of the structure but maintains its actuation simplicity. A detailed description of the DCM is presented later. The arm can lift a weight of 200 grams. The SURS was teleoperated to accomplish various surgical tasks, such as pick-and place (Figure 3d), knot-tying (Figure 3e), grape skin peeling (Figure 3f) and tissue resection (Figure 3g).

Robotic system for NOTES

Unlike the SPL robots among which commercial prototypes have emerged, the NOTES robots are still all research prototypes.

In an early development Phee et al. presented a dual-arm endoscopic robot for polypectomy on the gastric wall (23,24). Two prototypes were constructed in this effort. The second one has an endoscopic sheath with a diameter of 22 mm (Figure 4a). Each manipulation arm has four DoFs. By reducing the

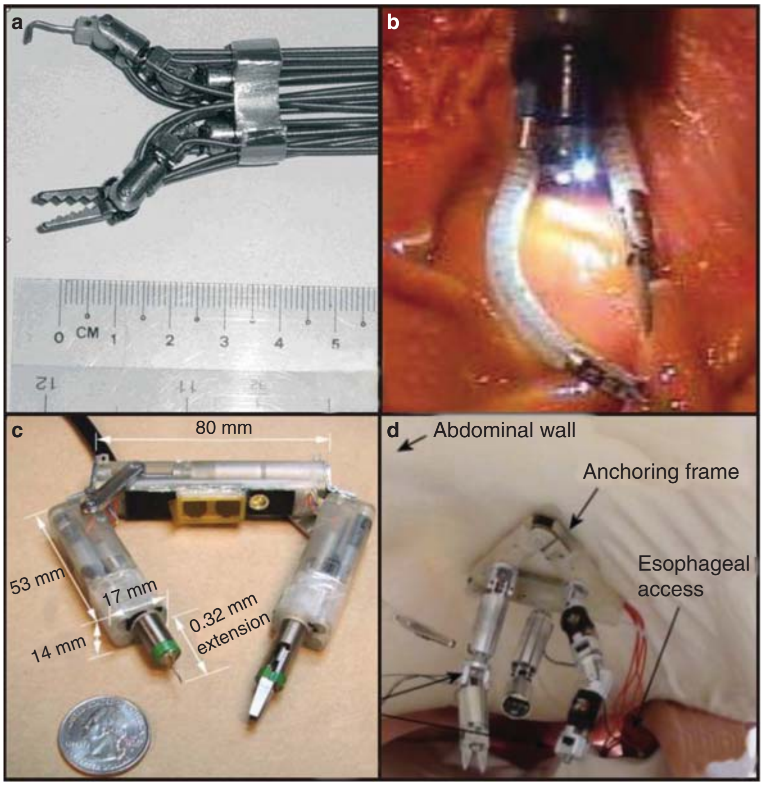

Figure 4. Robotic systems for NOTES: (**A**) The robot developed by Phee et al., (**B**) the ViaCath tsystem, (**C**) the robot developed by Leman et al., (**D**) the robot developed by Tortora et al.

length of the arm (from 60 mm to 41.7 mm) and the number of DoFs (from 6 to 4), the maximal force output of the arm was improved from 1N to 3N. Dissection of stomach mucosa on a porcine model was performed.

Almost during the same period of time, Abbott et al. developed the ViaCath system for NOTES (25). The ViaCath uses a ∅19 mm overtube for its insertion through the GI tract. Two ∅7.2 mm wire-actuated manipulation arms were included (Figure 4b). Each arm has eight DoFs with an end effector. The payload of the arm is only 0.5N with a tool stiffness of 1.15 deg/mNm. Lehman et al. developed an *in-vivo* robot which can be magnetically anchored to the abdominal wall (26) to perform cholecystectomy (Figure 4c). The robot consists of a central "body" and two 3-DoF arms. The cross section of the robot is 14 × 17 mm. Non-survivable animal studies demonstrated the feasibility of performing a NOTES cholecystectomy. However, problems were encountered using the robot, such as inefficient magnetic holding forces and mechanical failures of the joints.

Harada et al. introduced a reconfigurable modular robot for NOTES (27), which consists of 12 structural modules. Each module has a diameter of 15.4 mm and two DoFs. The modules could be assembled *in-vivo* for surgical intervention. A more compact and completed version of this robot was recently constructed (28,29). A ∅14 mm trans-abdominal anchoring frame with embedded magnets shall be deployed first as a base. And then the ∅12 mm modules could be inserted trans-orally and reconfigured to form a 2-DoF imaging unit, a 4-DoF manipulation arm and a 2-DoF gripper unit (Figure 4d). The 4-DoF manipulation arm could generate 0.65N tip force.

Continuum mechanisms are also applied in the design of a NOTES robot. Zhao et al. developed a continuum robotic testbed to characterize enabling features for NOTES (30). The surgical testbed has an endoscopic sheath with an outer diameter of 12 mm (Figure 5a). Two exchangeable continuum manipulation arms and a vision unit can be deployed to form a working configuration (Figure 5b). The cross section of the sheath (Figure 5c) is fully used by the non-circular cross sections of the camera unit and the manipulation arms. Each arm consists of a distal structure and a proximal structure (Figure 5d). The distal structure consists of a 5-DoF continuum manipulation arm and a gripper. The proximal structure is actuated so as to actuate the distal structure. The arm is exchangeable with a maximal payload capability of 200 grams. Particularly, the arm is equipped with a pre-curved suture made from super-elastic nitinol. While housed

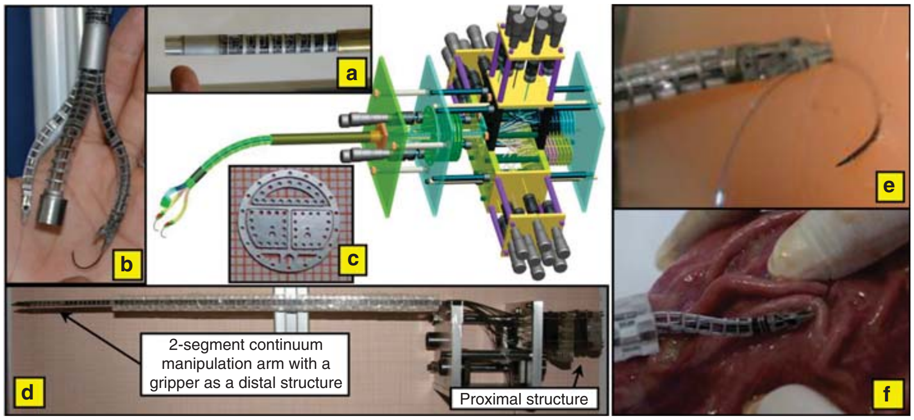

Figure 5. System description of the NOTES robot developed by Zhao et al: (**A**) The folded configuration, (**B**) the working configuration, (**C**) layout of the cross section, (**D**) the manipulation arm, (**E**) tissue penetration on a silicone phantom, and (**F**) tissue penetration on a porcine model

inside the arm, the suture is forced straight. Once pushed out, the suture bends back to its original circular shape and creates a circular penetrating path in the tissue. Tissue penetration experiments were carried out on a silicon phantom (Figure 5e), then on a porcine stomach (Figure 5f) to verify this idea. The results showed that the use of a pre-curved suture could achieve tissue penetration without incorporating a distal rotary wrist for the manipulation arm.

The existing state-of-the-art SPL/NOTES robots are summarized in Table 1.

Dual continuum mechanism

Among the reviewed robotic systems, the SURS robot for SPL (21,22) and the endoscopic robotic testbed for NOTES (30) possess the smallest sheath diameter. Versatile functionalities are also well demonstrated by the two systems. Both systems used the dual continuum mechanisms (DCM) to form their manipulation arms.

A generic DCM (Figure 6a) consists of the DS-1 (distal segment #1), the DS-2 (distal segment #2) (Figure 6b), the PS-1 (proximal segment #1), the

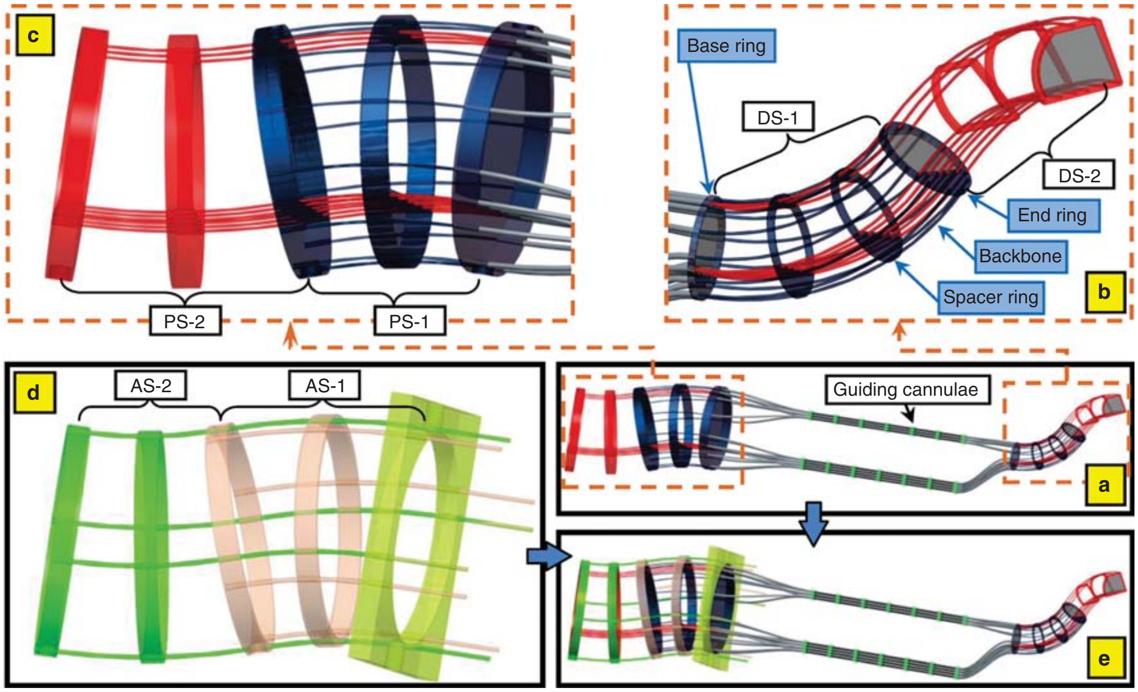

Figure 6. (**A**) The dual continuum mechanism with (**B**) the distal segments and (**C**) the proximal segments; (**D**) the actuation structure, (**E**) the dual continuum mechanism assembled into the actuation structure

PS-2 (proximal segment #2) (Figure 6c) and a set of rigid guiding cannulae (31). The DS-1 consists of a base ring, a few spacer rings, an end ring, and several backbones that are super-elastic nitinol rods. The DS-1, the DS-2, the PS-1 and the PS-2 are structurally similar. A backbone of the DS-1 is connected to the end ring, routed through the guiding cannulae, and connected to the end ring of the PS-1. The backbone arrangement in the DS-1 is similar and scaled to that in the PS-1 so that bending of the PS-1 would bend the DS-1 in the opposite direction; a length change of the PS-1 leads to the opposite length change of the DS-1. The PS-2 drives the DS-2 in a similar way.

Arrangement of the guiding cannulae doesn't have to be similar to that of the backbones, as long as the cannulae could provide rigid and smooth channels for the backbones. This feature enables the compact integration of the DCMs in the surgical robotic systems in which thin, long and even curved channels are usually used for deployment of surgical tools.

The DCM can be assembled into an actuation structure (Figure 6d and Figure 6e) that consists of the AS-1 (actuation segment #1) and the AS-2 (actuation segment #2). The AS-1 and the AS-2 are bent, extended and compressed by simultaneous push-pull actuation of its backbones. Actuation of the AS-1 and the AS-2 drives the PS-1 and the PS-2 so as to drive the DS-1 and the DS-2.

The DCM introduces a nice feature of actuation modularity. The DS-1 and the DS-2 could be designed for different lengths, different sizes, and/or with different end effectors attached. As long as the matching PS-1 and PS-2 could be fitted to the actuation structure, the DCM can always be actuated. What's more, the DCM is a purely mechanical structure which could be easily sterilized after being disassembled from the actuation structure. The DCM's mechanical properties can also be adjusted freely for different procedures by adjusting the number and arrangement of the backbones. The actuation always remains the same due to its actuation modularity.

Discussion and conclusion

This study reviews the development statuses and the clinical readiness of the state-of-the-art surgical robots for SPL and NOTES.

The reviewed robotic systems have to be deployed to surgical sites inside a sheath through an access port. Hence the diameter of such an access port is a critical specification. A smaller diameter could lead to less invasiveness but increase the difficulty of system integration dramatically. The diameter could only be determined after carefully weighing the feasibility of various component designs. A sheath diameter of 25 mm seems to reach a balance point between the acceptable incision size suggested by surgeons and the challenges of system integration and realization. Many SPL robots adopt this size but of course a smaller size is desirable. The size should be reduced to 12 mm to 15 mm for the NOTES robots to facilitate their deployment through the thin, long and curved natural orifices.

Most of the reviewed robotic systems possess a common configuration of a vision unit and two manipulation arms. The design of the vision unit heavily depends on the availability of miniature imaging sensors. A research lab usually does not have the resources, and the integrated camera chips often only provide a low-quality visualization of a surgical site.

Manipulation arms of the reviewed robotic systems are of various forms. Each arm usually possesses four to eight DoFs so that enough workspace and distal dexterity could be generated. Actuation schemes of the arm joints include cables (7,16–18,23–25), embedded servo motors (10,11,26–29), flexible shafts (12,14), linkages (15), and continuum mechanisms (19–22,30). The characteristics could be summarized as follows.

- For the arms using cable actuation, the design challenge mainly lies on the cable routing from a distal joint to a proximal motor through all the intermediate joints. Maintaining enough cable tension and minimizing the motion coupling among different joints could be difficult. Once properly designed, the arm can generate large output forces since the braided cables can undergo relatively large tensions. Limited by the minimal radius of a pulley, it might also be difficult to miniaturize such an arm with cable actuation.
- Using an embedded servo motor to drive a nearby joint could avoid the troublesome cable routing. These arms usually consist of several joint modules. Each module has one embedded motor for the actuation of one joint. The integration of a servo motor and related control electronics could be really challenging. With the modules built, connecting several modules to form an arm may be straightforward. However, the distal modules become loads of the proximal modules. Hence overall payload capabilities of such an arm might not be very high. The size of a servo motor also limits the miniaturization of such an arm.
- Utilization of the DCM brings a couple of advantages. Actuation at the proximal side of the system can be transferred to the distal side via the DCM. The DCM's backbones are thin super-elastic

nitinol rods and they can inherently transfer pushing and pulling forces. Design compactness of the arms is achieved by the dual roles of these backbones as both the structural components and the motion output members. The smallest diameters of the access port were hence achieved by a SPL robot (21,22) and a NOTES robot (30) using the DCMs. Furthermore, the DCM introduces the feature of actuation modularity. The distal segments can be designed differently with different lengths, different sizes and different backbone arrangements with different mechanical properties. The actuation could always remain the same. An arm using the DCM design can also be easily exchanged during a surgery and sterilized after a procedure. Safe interactions with human anatomy are introduced by the inherent compliance of the DCM. A redundant backbone arrangement also improves the design reliability. Major difficulties introduced by the DCM include modeling, control and motion compensation of the arm since the DCM undergoes large nonlinear deformations while actuated. Overall the DCM has been shown quite promising to be considered as a design alternative to build manipulation arms for SPL and NOTES robots.

Regarding the usability aspect of the reviewed robots, many systems are identified with motion awkwardness and/or missing functions (e.g., cautery or ablation). Some of them also have difficulty in tool exchanging and sterilization. Only a few SPL robots demonstrated enough functionality for possible animal or clinical studies, including the SAIT system (7,8), the SPORT robot (16), the da Vinci SP system (17), and the SURS robot (21,22). Commercial prototypes have emerged and they might enter the market in the near future.

Unlike the SPL robots, all the NOTES robots are still research prototypes. None of the existing systems has demonstrated all of the desired performances, such as a smooth deployment, a large motion range, a high payload capability, enough surgical functions (e.g., clipping, cautery or ablation), etc. Apparently the curved natural orifices with limited diameters introduce paramount challenges to the instrumentation of NOTES robots. None of the existing design approaches have proved themselves effective enough to fully enable robotic NOTES.

Constructing a robot for SPL or NOTES is never an easy task. Promising results have been presented for robotic SPL procedures. But for NOTES robots, the advances are clear but there are still some gaps to close. The surgical robots for SPL and NOTES using the DCMs achieved both design compactness and functional versatility. The results suggest that the use of continuum mechanisms is worth exploring through future developments of surgical robots. With the synergy between academia and industry, it would not be long to realize robotic NOTES or SPL procedures with the desired delicacy and reduced invasiveness.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (Grant No. 51375295), in part by the Shanghai Rising-Star Program (Grant No. 14QA1402100), and in part by the Shanghai Jiao Tong University Interdisciplinary Research Funds (Grant No. YG2013MS26)

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this paper. AQ4

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