Development of a robotic platform for natural orifice transluminal endoscopic surgery
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Abstract
Natural orifice transluminal endoscopic surgery (NOTES) is a novel surgical technique that is widely anticipated to define the next paradigm shift in surgery. Besides leaving no external scar on the patient, the natural orifice approach is envisaged to reduce postoperation morbidity and improve surgical outcomes. However, performing NOTES is technically more demanding than conventional surgery, as the surgical procedure is performed entirely within the small confines of the peritoneal cavity. Current endoscopic systems are not equipped with sufficient dexterity for the intricate maneuvers required in the performance of NOTES. Hence, advanced innovations in endoscopy are called for to circumvent the technical issues commonly encountered in endoscopic surgery. Herein, we describe the development of a robotic NOTES platform that could potentially make the performance of complex endoscopic surgical procedures such as NOTES safer and easier. By applying robotic technology and separating control of instrumental motion from that of endoscopic movement, the robotic system increases dexterity of surgical maneuvers, such as triangulation of instruments, retraction, grasping, approximation, and cutting of tissue, and allows these tasks to be performed with relative ease and precision. The novel robotic NOTES platform discussed herein is nonoperator dependent, is intuitively operated, and comes with force and tactile feedback capability to provide surgeons not just the ease of use, but also a sense of touch while manipulating the tissues. Preliminary evaluations of the platform in animal survival studies and human trials have demonstrated that the system is easy and safe to use. With further development, it may be adapted for highly intricate NOTES, which may otherwise be very difficult to perform using currently available endoscopic tools.

Keywords: Natural orifice transluminal endoscopic surgery, Robotics, Technology

Introduction
NOTES-possibilities and technical requirements
NOTES leaves no external scar on the patient and is potentially more appealing than conventional surgery. It is also expected to shorten hospital stay, reduce morbidity and mortality associated with surgery, and improve overall surgical outcomes. But performing NOTES requires high surgical skills and, preferably, dedicated surgical tools.1 Current endoscopic surgical systems are not designed for NOTES; they are unstable and lack dexterity. Coaxial endoscopic deployment of surgical tools does not permit much articulation to facilitate triangulation of the tools to manipulate the surgical targets. The field of visualization is also limited. Performing NOTES using conventional endoscopy platform is thus daunting and risky. As a compromise, hybrid NOTES has been introduced to reduce technical challenges and ensure safety of the patients undergoing the procedure.1,2 In hybrid NOTES procedures, one or two additional ports of entry are created, most commonly

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laparoscopically, to assist in providing better illumination and visual feedback, or to close the transvisceral perforation site at the end of the procedure. To perform NOTES efficiently and safely without laparoscopic assistance, endosurgical instrumentations with the stability and capabilities of current laparoscopic equipment are required. Ideally, the NOTES platform should come with the ability to deploy and position flexible surgical tools stably at a vantage point within the abdominal cavity, be able to provide a certain degree of triangulation of the surgical tools, and transmit necessary force efficiently to the point of action to facilitate surgery.

Development of a robotic NOTES platform

For the development of a NOTES platform, three basic requirements need to be considered: (1) effective transmission of force to the tools deployed at the tip of the flexible endoscope; (2) sufficient degrees of freedom (DOFs) to provide ample articulation of surgical arms, while maintaining enough stability for precise positioning and triangulation of surgical tools; and (3) adequate visualization of the surgical field. These can only be realized through the incorporation of robotics technology to the endosurgical platform. One such pioneering innovation is the MASTER (Master and Slave Transluminal Endoscopic Robot) designed and built through a collaboration between the National University of Singapore and Nanyang Technological University, Singapore. To the best of our knowledge, this is the only robotics-enhanced endosurgical system of its kind, the pilot trials of which had been published, although innovations of several hand-driven prototypes with less dexterity had been reported.3

The MASTER introduces robotic control of surgical tools through an ergonomic human–machine interface. It separates control of instrumental motion from that of endoscopic movement. Endoscopically deployed instruments are thus independently controlled, allowing bimanual coordination of effector instruments to facilitate surgical tasks such as triangulation of instruments, retraction, grasping, approximation, and dissection of tissue. Furthermore, with the cable-driven joint master–slave system, significant force may be exerted to the point of action, allowing the end effectors to manipulate and dissect the tissue effectively.

The current prototype of the MASTER features an anthropomorphic design in which the slave robot arm resembles the human upper limb4 and allows intuitive operation by the surgeon. It has a nonexoskeleton design for its master arm. The slave design, as shown in Fig. 1, has 5 DOFs, allowing movements that mimic flexion, hyperextension, supination, opening/closing, and translation of the human arm. The first four movements correspond to the upper limb DOFs that are essential to endoscopic dissection, while the last translational DOF improves the maneuverability by allowing reach-and-retract actions without introducing mechanical redundancy. The slave arm is actuated by tendon-sheath mechanisms driven from outside the patient. The master arm follows the same DOF and mechanical configuration as the slave arm (Fig. 2). The latest prototype of the MASTER is also equipped with a motorized master interface that provides haptic feedback to the surgeon.

Preclinical and clinical evaluations of the MASTER endosurgical platform

Prototypes of the MASTER endosurgical system have been tested in a series of animal trials, including studies on explanted pig organs and live pigs. Both nonsurvival and survival animal studies had been conducted.5–10 Experimental evaluations of the robotic endosurgical system showed that it increases the dexterity of surgical maneuvers and enables tasks such as triangulation of instruments, retraction, grasping, approximation, and cutting of tissue to be carried out with relative ease and precision. In the live animal survival study, the surgeon had successfully dissected simulated submucosal lesions of diameter ranging from 25 to 104.6 mm in five pigs. The mean time taken to complete the endoscopic submucosal dissection (ESD) procedures was 21.8 minutes (range, 6–39 minutes). All animals operated survived the 2-week experimental survival time period.

Intuitiveness and anthropomorphic design of the MASTER endosurgical system enable the surgeon to perform ESD with much more dexterity than in conventional endoscopy system (5 + 4 DOFs in comparison with 1 DOF for traditional endoscopy instrument). Following the successful animal survival studies, a multicenter human trial was carried out using the prototype shown in Fig. 3. A total number of five patients with gastric neoplasia (three in Hyderabad, India, and two in Hong Kong, China) underwent ESD successfully.11 Average submucosal dissection time was 18.6 minutes (3–50 minutes), and no late complications were observed in the 30-day follow-up period. The follow-up endoscopy also revealed no residual or recurrent tumor in all patients.

The MASTER endosurgical system is currently being tested in the performance of NOTES. In the first nonsurvival animal trial
conducted, a NOTES transgastric endoscopic wedge hepatic resection in an animal model was successfully completed. Further studies and experiments are planned to obtain more knowledge on the requirements of NOTES on the robotic MASTER endosurgical system. Further modifications and refinements such as provision of additional DOF, higher payload, and better navigation should enhance MASTER’s performance in NOTES procedures.

Conclusion

A robotics-enhanced endosurgical system such as the MASTER presents a viable platform for the performance of intricate endoscopic surgeries such as NOTES. By incorporating intelligent robotic control, it enables endoscopic performance of bimanual surgical tasks, which is currently not possible with conventional endoscopy system. The MASTER endosurgical system provides stable positioning and dual-arm triangulation of the surgical arms, additional DOF for enhanced dexterity in surgical maneuvers, efficient force transmission, haptic feedback, and full visualization of surgical field. Although still rudimentary for full NOTES application at this stage, we believe that further development of the current basic system, including provision of a range of easily deployable and exchangeable surgical end effectors dedicated for specialized surgical tasks, should make the system completely compatible with NOTES.

Conflict of interest

Soo Jay Phee and Khek-Yu Ho co-invented the MASTER. The other authors declare no conflict of interest.

References