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Review Article

Robotics in gastrointestinal endoscopy

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Abstract The application of robotics in gastrointestinal endoscopy is a much anticipated technological advancement that is attracting an enormous amount of interest from innovators and end-users alike. Emerging robotics-enhanced endoscopy platforms for performance of various endoscopic interventional procedures are already in development and some are expected to be in the pipeline for commercialization in another few years' time. In particular, the Master And Slave Transluminal Endoscopic Robot (MASTER) developed by a collaboration between the National University of Singapore and the Nanyang Technological University, Singapore is already in human trials for an endoluminal procedure, endoscopic submucosal dissection (ESD). The results on trials performed on five patients with early gastric neoplasia have demonstrated the feasibility and safety of using the system for such procedure, while also shortening the procedure time. This article will highlight the advantages of robotics innovations in gastrointestinal endoscopy, with the MASTER as an example, and explore some of the many possibilities for future applications of robotics-enhanced endoscopy.

Key words Endoscopic submucosal dissection, master and slave transluminal endoscopic robot, MASTER, natural orifice transluminal endoscopic surgery

Introduction

The application of robotics in gastrointestinal endoscopy is a much anticipated technological advancement that is attracting an enormous amount of interest from innovators and end-users alike. Emerging robotics-enhanced endoscopy platforms for performance of various endoscopic interventional procedures are already in development and some are expected to be in the pipeline for commercialization in another few years' time. In particular, the Master and Slave Transluminal Endoscopic Robot (MASTER) developed by a collaboration between the National University of Singapore and the Nanyang Technological University, Singapore is already in human trials for an endoluminal procedure, endoscopic submucosal dissection (ESD). The results on trials performed on five patients with early gastric neoplasia have demonstrated the feasibility and safety of using the system for such procedure, while also shortening the procedure time. This article will highlight the advantages of robotics innovations in gastrointestinal endoscopy, with the MASTER as an example, and explore some of the many possibilities for future applications of robotics-enhanced endoscopy.

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Why Robotics in Gastrointestinal Endoscopy?

In gastrointestinal endoscopy, access to target of interest often has to go through a tortuous path and interventional procedures must be performed within the limited space of the gastrointestinal lumen. Both space and instrumental constraints pose limitations on what surgery the interventional endoscopists could perform. In today's operation of endoscopic surgeries, the surgical tools used are deployed through the working channel of the endoscope. But due to the parallelism of standard endoscopic fixtures, the degree of freedom for surgical maneuvers is limited, and so is the field of visualization. Furthermore, the lack of instrumental dexterity makes triangulation of endoscopically deployed instruments to approach the surgical target extremely difficult. Instrumental manueverity is, at best, sub-optimal. With

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robotics enhancement, multiple degrees of freedom at the effector end could be made possible, and technical challenges in instrumental manueverity could be mitigated, making performance of intricate interventional procedures in the gastrointestinal tract easier.

The Master and Slave Transluminal Endoscopic Robot

MASTER, a novel robotics-enhanced endoscopy platform was developed to provide today's endoscopists the technological means to mitigate many of the technical limitations they face with conventional endoscopy platforms. Designed to be applicable for both intraluminal and transluminal surgeries, the MASTER consists of three parts: a master console as the human-machine interface, a flexible endoscope together with slave end-effectors as the flexible instrument, and a tele-surgical workstation in between as the controller.[1,2] MASTER represents a reconfiguration of the endoscopy platform, by introducing robotic control of surgical tools and tasks through an ergonomic human-machine interface built around the original endoscopic paradigm. The master controller is the human-machine interface that controls the slave manipulator, a unilateral electromechanical device which responds to operator's input and drives the end-effectors – a grasper and a monopolar electrocautery hook. The slave manipulator, with its end-effectors, is connected to the master controller by electrical cables that route through the operating channels of the endoscope. Surgical manipulation is executed by the master controller through a joint-control system.

Operation of the MASTER Endosurgical System

For operation, the MASTER is adapted to a standard dual-channel therapeutic endoscope connected to a standard endoscopy platform with high-definition visual display and real-time video recording functions. An attached electrical surgical generator regulates and monitors the power output used for the monopolar resection (cutting and coagulation). Surgical operation is conducted through the ergonomically designed steerable motion sensing exoskeleton with two articulating arms. The exoskeleton is embedded with an array of linear and rotary encoders. To operate, the operator simply fits his/her wrists and fingers into the two articulating arms and moves them in the same way he/she would to manipulate the end-effectors directly. Motions are detected by the array of sensors and actuated into force signals to drive the manipulator and end-effectors via a tendon-sheath mechanism. This allows the operator to intuitively control the operation remotely. The master control exoskeleton and the slave manipulator are both equipped with nine rotational degrees of freedom (DOF).

MASTER Trials in Animals and Humans

The feasibility and safety of using the MASTER to perform technically demanding endoscopic endoluminal and translumenal procedures had been evaluated in animal survival studies. In procedures involving (i) the endoscopic submucosal dissection (ESD) of simulated gastric lesions, and (ii) transgastric endoscopic wedge hepatic resection, we demonstrated that the MASTER could effectively mitigate the technical constraints normally encountered in operations conducted using conventional endoscopy platform.[3-5] With MASTER, the triangulation of surgical tools and the manipulation of tissue became an ease, and surgical resection could be accomplished without the need for assistance using laparoscopic instruments. The MASTER made its debut clinical trial in human in July 2011 at the Asian Institute of Gastroenterology, Hyderabad, India, where surgeons successfully performed ESD of early gastric tumor on three patients. This was followed by two other successful operations performed at the Prince of Wales Hospital in Hong Kong in December 2011, in which patients with gastric neoplasia had pre-cancerous lesions removed via ESD (in press). In all the trial procedures conducted, control of the slave manipulators was successfully achieved by the surgeon steering the ergonomically designed motion sensing exoskeleton. Execution of surgical tasks was intuitively done and robotic coordination of the end-effectors was precise, allowing efficient enbloc resection of all lesions. Compared with conventional endoscopy platforms, the robotic-enhanced endoscopic surgery substantially reduced both the operation and patient's recovery time.

Advantages of the Robotics-Enhanced Endosurgical System

There are many advantages in using a robotics-enhanced endosurgical system such as the MASTER, and one important advantage is having the operator gain full control in the maneuverity and movements of the surgical tools. The design of the MASTER separates control of instrumental motion from that of endoscopic movement. Endoscopically deployed instruments are thus independently controlled via the human-machine interface, allowing bimanual coordination of slave end-effectors to facilitate actions such as retraction/exposure, traction/countertraction, approximation and dissection of tissue. Robotic technology increases the degrees of freedom for mobility of endoscopic instruments deployed at the distal end of the endoscope. With nine degrees of freedom at the manipulating end of the robotic slave, MASTER allows the operator to position and orient the attached effector instrument at any point in space. This enables triangulation of surgical end-effectors otherwise not possible with standard endoscopy platforms. Through the master-slave system, significant force could be exerted to the point of action, allowing the end-effectors to effectively manipulate and dissect the tissue. Besides, the intuitiveness of the robotic human-machine interface accelerates the surgical learning curve. To operate the MASTER, an intensive training for 1-2 weeks usually suffice, even if the operator has no experience in robotic surgery. This compares well with the years needed to train clinicians to perform the procedure using conventional endoscopic tools.

Further Development and the Future

The success of the first series of human ESD of early gastric neoplasia demonstrated the utility of the MASTER in gastrointestinal endoscopic surgery and its capability to improve the performance of common endoscopic surgical procedures such as removals of tumors and polyps in the gastrointestinal tract. There is potential for further development of the MASTER to adapt it for performance of natural orifice transluminal endoscopic surgery (NOTES). Thus far, the development of the field of NOTES had been much impeded by lack of enabling technologies. Performing transluminal operations using the conventional endoscopy system is extremely challenging due to the spatial constraints of the natural orifices The surgical device needs to have a highly flexible body that can be maneuvered through the natural orifices, while the instruments at the distal end must be compact and yet possess adequate dexterity and be able to form a triangulation for manipulation of target tissue. Mechanical power driving the system needs to be transmitted to the effector end of the surgical equipment for physical operation. A clear vision of the operating field and haptic feedback are needed to assist the operator in performing the procedure. Robotics enhancement of the present endoscopy platform is the foreseeable best solution for NOTES, but to realize that, a range of new function-specific end-effectors and associated auxiliary instruments has to be developed to support various endoscopic surgical tasks. And when the technology meets the requirements for the most important hurdle - proper closure of perforations made for transluminal access to organs in the peritoneum - it will become viable for MASTER to take on NOTES. This is envisaged to open up the field of endoscopic surgery to include a wide range of transluminal operations, currently only performed through laparascopy or open surgery, and push further the boundaries of endoscopic surgeries.

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