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Development of a Robotic Colonoscopic Manipulation System, Using Haptic Feedback Algorithm

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Purpose: Colonoscopy is one of the most effective diagnostic and therapeutic tools for colorectal diseases. We aim to propose a master-slave robotic colonoscopy that is controllable in remote site using conventional colonoscopy.
Materials and Methods: The master and slave robot were developed to use conventional flexible colonoscopy. The robotic colonoscopic procedure was performed using a colonoscope training model by one expert endoscopist and two unexperienced engineers. To provide the haptic sensation, the insertion force and the rotating torque were measured and sent to the master robot.
Results: A slave robot was developed to hold the colonoscopy and its knob, and perform insertion, rotation, and two tilting motions of colonoscope. A master robot was designed to teach motions of the slave robot. These measured force and torque were scaled down by one tenth to provide the operator with some reflection force and torque at the haptic device. The haptic sensation and feedback system was successful and helpful to feel the constrained force or torque in colon. The insertion time using robotic system decreased with repeated procedures.
Conclusion: This work proposed a robotic approach for colonoscopy using haptic feedback algorithm, and this robotic device would effectively perform colonoscopy with reduced burden and comparable safety for patients in remote site.

Key Words: Colonoscopy, endoscopy, haptic, robotics

INTRODUCTION

Colonoscopy, which is based on analysis of real-time imaging and examination of pathological samples, is one of the most effective diagnostic and therapeutic tools for colorectal diseases. Colonoscopy also enables early colorectal cancer to be treated successfully and even cured completely through endoscopic resection. The examination is commonly performed using a conventional flexible colonoscope that can interrogate the interior of the colon through a digital camera and allow various procedures by passing miniature therapeutic tools through the channel of the endoscope. However, with advances in therapeutic devices and endoscopic techniques, advanced endoscopic procedures increase the burden on the endoscopists. Recently, a variety of innovations have improved the colonoscopy procedure, resulting in greater comfort and safety for the patient and less physical burden for the endoscopist.[1-4]

The master-slave robotic system using a telesurgical unit has proven to be very effective for reducing the burden and overcoming physiological constraints on the surgical field. The well-known locomotive mechanism units such as the da Vinci system and other robots[5-7] have been successfully employed for diverse types of surgery in the abdominal cavity, thoracic cavity, pelvic cavity, and head and neck area.

Current robotic endoscopy systems are designed to use a rigid scope in the surgical field. However, robotic systems using a conventional flexible endoscope are new. In the master-slave robotic colonoscopy, a flexible endoscope is used, but a slave

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robot rather than an endoscopist holds and operates the endoscope. The motion of the slave robot is controlled by using a master robot. However, due to the complex or abnormal anatomy of the colon, it is sometimes difficult to insert the flexible endoscope into the cecum. Moreover, since excessive tension can cause severe pain and perforation of the colon, an endoscopist is needed to carefully control the colonoscope.[8] Thus, the robotic system should be designed in such a way as to ensure safety as well as provide a convenient user interface for the endoscopist.[8] The robotic system should also provide the endoscopist with haptic sensations such as insertion force and torque during colonoscopy, in order to prevent damage to the colon.

To manage such requirements, we developed a new master-slave robotic system that facilitates the insertion motion of the endoscope in a safe manner and expends less power by providing the endoscopist with scaled-down haptic force and moment feedback.

MATERIALS AND METHODS

System development

We initially determined the degrees of freedom required for the colonoscopy. There are four degrees of freedom for the tip-end of the flexible endoscope: insertion motion, rotation motion, and two tilting motions (up-down and right-left). The front part of the slave robot grips the distal end of the flexible endoscope body and the rear part holds the knob of the endoscope body. The slave robot (Fig. 1) was designed to have the same range of motion as the flexible endoscope when manipulated by the endoscopist (i.e., maximum insertion length: 1.5 m; maximum rotation angle: 360°; maximum tilting angles: +/- 180°). Two torque sensors were installed between the motors and power transmission lines to sense the insertion force and moment while the endoscope is being inserted into the colon. This information is sent to the master robot to provide the endoscopist with some haptic feeling of the constrained force or torque against the colon wall. A haptic interface is a kinesthetic link between the human operator and a virtual environment; the haptic interaction allows the robotic colonoscope to have greater stability.[9]

The master robot was designed to reflect the ergonomics of the user. Usually, the endoscopist employs one hand to manipulate the shaft of the endoscope for insertion, retraction, and rotation, and the other hand to grip the rear part to control the up-down and right-left angulation of the endoscopic tip using two endoscopic knobs. Thus, the master robot was designed to have two components, a tilting device and an insertion/rotation device with a grip similar to the conventional colonoscope (Fig. 2). For detailed control, a two-channel haptic algorithm[9] was employed for the master-slave robot system. In the slave device, we installed two torque sensors to measure the force for insertion and torque for twisting the endoscope tube. First of all, the position command by the master robot is sent to the slave robot. Next, the measured force and torque information are transferred to the master device to generate a reflecting force and moment by activating actuators of the master device. Here, it is necessary to apply lower scaling factor to the master device. This is because the size of the master robot

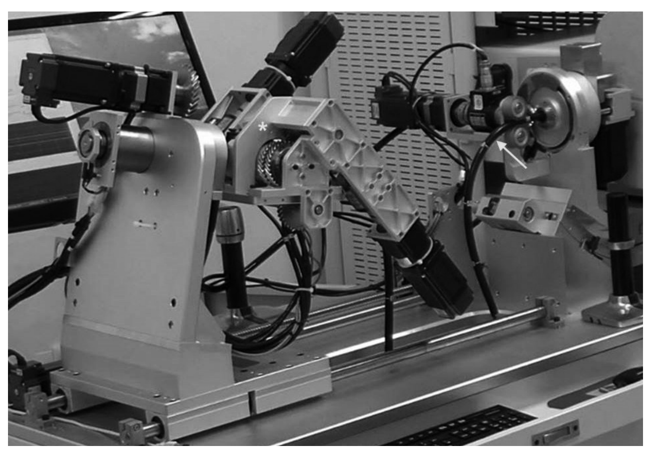

Fig. 1. The slave robot mounted on conventional colonoscope (arrow), and robotic arm (*) holding control body of colonoscope.

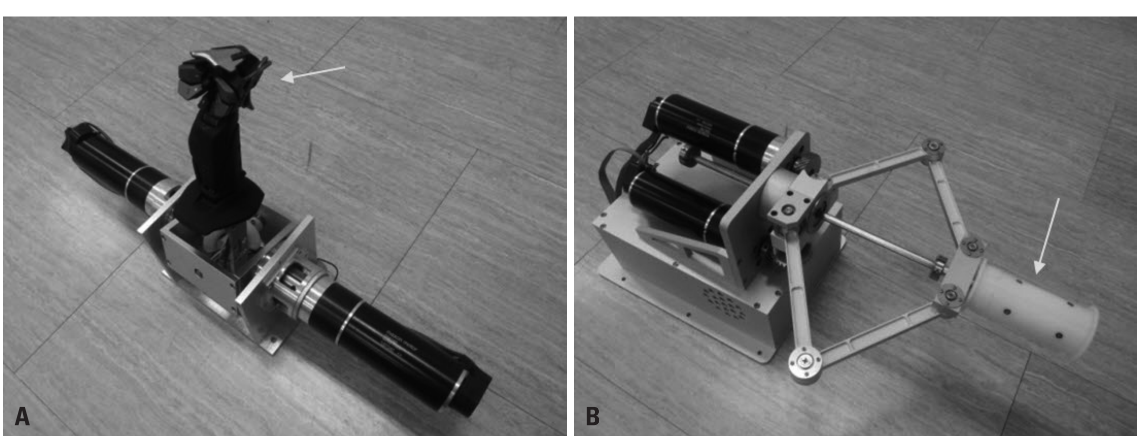

Fig. 2. The devices of master robot. (A) Tilting device, which is comparable to a joystick, for controlling up-down and right-left angulation of endoscopic tip. (B) Insertion and rotation device for controlling insertion, retraction, and rotation of endoscope. The arrow presents handgrip for controlling endoscope.

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gets bigger to create the same amount of force/moment measured at the slave side. Even though the amounts of force/moment reflected to the operator are lower than the measured ones, the operator is able to get the sense of insertion and twisting motion with less energy expenditure. When sensing too much insertion force and torque, the operator would pull out the tube to release the damage given to the wall of the colon. A personal computer is employed as a controller of the slave robot as well as a means to display all data.

Colonoscopic procedure using the robotic system

For the robotic colonoscopy, the colonoscope training model (M40, Kyoto Kagaku Co., Ltd., Kyoto, Japan) was used. The colonoscope (Olympus CFQ-260 AI, Olympus Co., Ltd., Tokyo, Japan) was mounted on the slave robot. The tip of the flexible colonoscope was inserted manually into the anal region of the model, and the operator controlled the colonoscope using the two devices (tilting, and insertion/rotation) of the master robot.

The robotic colonoscopies were performed by the authors at beginner's grade of colonoscope training model: an experienced endoscopist who has completed over 7000 total colonoscopies and two engineers (inexperienced participants), and insertion times were compared. Insertion time was defined as the length of time it took for the tip of the colonoscope to proceed from the anus to the cecum of the training model.

RESULTS

Because a vacuum pressure above 0.4 bar can damage the intestinal tissue, it is necessary to sense the actual feeling of insertion and rolling motion.[10] During the colonoscopy, maximum measured insertion force and the torque were about 10N in the insertion motion (range 0–10N) and 0.2Nm in the rotation motion (range 0–2Nm), respectively. Conducting 10 times measurement, we found that the average recorded force and moment were 4N and 0.1Nm, respectively. And the measured insertion forces were largest (between rows 3N and 5N) in the part of the instrument where most of the looping occur, which corresponds to 28–40 cm from the tip of the instrument. This result is similar to that of earlier publications.[11,12] However, it was difficult to design the motor system by reflecting those specifications; thus, a 10-to-1 scaling factor was applied to design the haptic system. Then, the amount of force and moment feedback was scaled-down as compared to the measured force and moment at the slave robot. In our setting, the force/moment feedback helped the endoscopist sense the actual feeling of the insertion and rolling motion. In addition, the endoscopist could manipulate the master-slave robotic colonoscope without time delay because the bandwidth for the motion control was set to 200 Hz.

Using the colonoscope training model, the endoscopist performed the master-slave robotic colonoscopy. The expert endoscopist finished the robotic endoscope insertion within 15 to 20 minutes (17.4±2.1 min; mean±SD) with 100% of success rate. On the other hand, the two engineers (unexperienced participants) finished the insertion within 30 to 45 minutes (39.0±5.3 min; mean±SD) with 70% of success rate. The expert repeated the procedure 5 times, and the first and the last insertion time was 20 min and 15 min, respectively. The engineers repeated the procedure 10 times, and the first and the last insertion time was 45 min and 30 min, respectively. Both the endoscopist and the engineers were able to shorten the procedure time with repetition. Fig. 3 shows the endoscopist performing the colonoscopy using the whole robotic system. Fig. 3 includes two video images of the procedure; the luminal video image of colon during the procedure, and the video image of master/slave robot and endoscopist during the procedure.

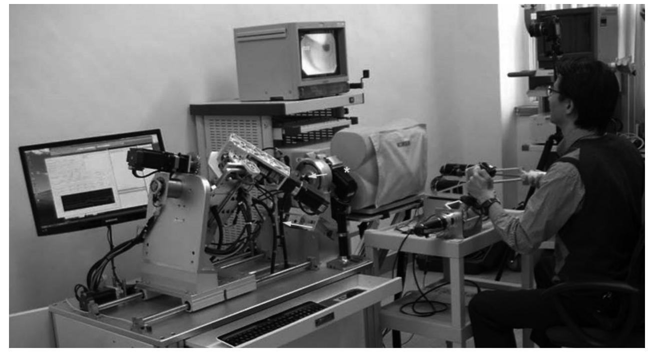

Fig. 3. Performing the colonoscopy using the whole master slave robotic system by a endoscopist (Dr. Tae Il Kim). Mounted colonoscope (arrow) and artificial anus (*) of colonoscope training model.

DISCUSSION

Robotic systems are widely used in the medical field for diagnosis, surgical procedures, and rehabilitation.[13] In particular, there have been many prototypes of micro robots for use in colon, such as the self-propelled type, inchworm type, paddling-based locomotion type, and earthworm-like type.[1-3,14-16] However, they typically do not supply enough driving force to move through the intestine, and are not advanced enough to be used for active interventions such as biopsy and polypectomy.

Therefore, the master-slave robotic system using a conventional flexible endoscope would be a very useful option for remote manipulation, providing potential advantages and benefits over current conventional colonoscopy modalities. First, the master-slave robotic approach for colonoscopy will be useful for care of patients located in remote sites. To control the locomotion of the robotic colonoscopy, the endoscopist can operate the joystick while sitting in a console positioned remotely from the operating area, even miles away.

Second, endoscopists will perceive less physical fatigue using the robotic approach because they do not handle the endoscope under the force of gravity. The increasing need for colonoscopies increase the physical burden on endoscopists. In addition, advanced therapeutic endoscopic techniques, such as endoscopic submucosal dissection, reduce the burden on the patient, but increase physical fatigue of the endoscopist. Various ways to reduce physical fatigue of the endoscopist through the use of locomotive mechanisms have been developed. Furthermore, robotic system reduces physiological limitations common in conventional colonoscopy manipulation, which are due to the limited range of motion of the endoscopist's joints. Our new robotic colonoscope, which is based on an ergonomically designed manipulation system, can be controlled easily while sitting at a comfortable console, and it could be developed into a more comfortable automated type with advanced technology in the future.

Third, endoscopists performing the procedure require less physical exertion to manipulate the robotic endoscope, which increases the safety of the procedure. However, for less physical exertion and increased safety, compared to conventional colonoscopy, scaled-down haptic sensation and feedback system should be applied to robotic system. During the development of our robotic system, we found that a similar system using a master-slave robot had also been developed by another group.[17] While their system showed the possibility of the clinical application of an endoscopic robot with the mechanization and standardization of endoscopic manipulation, it showed limitations due to the lack of a haptic feedback system. However, during the time when we were developing advanced robot colonoscopic system using haptic feedback algorithm, they also developed the Endoscopic Operation Robot ver.3, which incorporates haptic feedback.[18] Presentation of force and tactile sensation are critical for easy and precise manipulation and safety of the endoscopic procedure, because unintended application of force could cause severe pain and result in complications like perforation. In our system, we also applied a kinesthetic and haptic algorithm and demonstrated the usefulness of including a haptic feedback function. It should be noted here that there are some differences between our system and the system developed by Kume, et al.[18] The system by Kume, et al.[18] requires more space for slave unit compared to our system, because the colonoscope is mounted on a slave unit in a fully straightened shape, whereas our system can load and manipulate the scope in a flexed shape. Another difference is that our system is more user-friendly, because our system uses both hands, as with the usual colonoscopy procedure, while the system by Kume, et al.[18] uses one hand in a relatively complicated manner. In addition, Kume, et al.[18] equipped more accessory systems like inflation/suction functions, which are more similar to those in real colonoscopy procedure. This difference of accessory systems might explain the shorter insertion time of their system than ours because the inflation/suction of air would be important function for insertion of colonoscope.

As for the limitation of this study, the time constraint from system maintenance limited testing of some detailed factors, such as measurement of learning curve and detailed mechanical factors. In addition, as a prototype of master-slave robotic colonoscopic system focusing on haptic feedback algorithm, the current system was not fully equipped with all accessory systems for real endoscopy procedure including inflation/suction functions. In the next development, these limitations would be overcome. In order for our system to be used in clinical setting, advances for high levels of precision control are necessary, and the validity of robotic colonoscopy should be confirmed in extensive studies using animal models.

In conclusion, we describe the efficacy of robotic colonoscopy with haptic feedback based on an ergonomically-designed manipulation system that does not require direct contact with the endoscope. Robotic endoscopy is a promising next-generation endoscopic system that is expected to bring a fundamental revolution to endoscopic manipulation.

SUPPLEMENTARY DATA

Video 1. The luminal video image of colon during the procedure.
Video 2. Video image of master/slave robot and endoscope (Dr. Tae Il Kim) during the procedure using colonoscope training model. The endoscopist is using a joystick in left hand to control angulation of endoscopic tip and insertion/rotation device in right hand to insert, retract, and rotate the endoscope.

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