2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Development of a Smart Surgical Robot with Bended Forceps for Infant Congenital Esophageal Atresia Surgery

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***Abstract*—Minimally invasive surgery (MIS) is commonly used in pediatric operations. This method greatly benefits patients because of the reduced surgical trauma. To perform such surgery smoothly, doctors must be highly skilled. To reduce operating difficulties, a great deal of research on surgical systems have been carried out. However, in some cases, smaller workspaces limit the application of MIS. For example, the workspace of infant congenital esophageal atresia (ICEA) surgery is only around 30×30×30 mm. Until now, most ICEA surgeries have been manually performed with traditional instruments. This paper presents a smart surgical robot (SSR) for ICEA surgery. The robot is composed of two slave arms, each consisting of a positioning manipulator and a surgical tool manipulator. The positioning manipulator uses a selective compliance assembly robot arm (SCARA) and a screw-pair mechanism to achieve translational movement in 3D space, and the surgical tool manipulator uses a "double screw drive + universal joint" structure to allow an omni directional bending motion. During surgery, the surgeon first creates the workspace manually to explore the target esophagus. The SSR system is then applied to perform operation. The configuration of the SSR means it can perform tissue manipulation under endoscopic view in a small workspace. Experimental results show that the endoscopic view permits the SSR system to be operated intuitively and accurately in the target workspace.**

I. Introduction

Minimally invasive surgery (MIS) has become a common choice in pediatric operations [1]. It provides patients with beneficial results by taking advantage of reduced surgical incisions, lower risk of infection, and shorter hospital stays.

However, compared with adult patients, the pediatric patient poses additional challenges, such as smaller operative fields and more delicate tissue. Therefore, use of the MIS system in pediatric surgery is still restrained by the requirement of instrument dexterity, miniaturization, and operability [2].

Generally, surgical instruments approach the surgical site through the primary trocar during MIS [3]. For example, Rothenberg *et al.* reported the thoracoscopic repair of a tracheoesophageal fistula in a neonate by manually operating instruments through several holes [4], [5]. Zee *et al.* presented the thoracoscopic repair of esophageal atresia with distal fistula [6], [7]. The surgical platforms offered by Anubis (Karl Storz, Germany) and EndoSAMURAI (Olympus, Japan) use a multichannel sheath to guide flexible instruments and the endoscope. These instruments are manually operated via bimanual handles [8]. However, this method of operation requires doctors to have a high level of operating skill.

Robotic assistant systems aim to reduce the complexity of operations and improve the operating precision. The da Vinci system (Intuitive Surgical Inc., Sunnyvale, CA) offers surgical manipulation through multiple keyholes [9]. This system is usually applied in abdominal surgery, but, when manipulation is required in a smaller workspace, it is very difficult to attain dexterous operation.

Many studies have considered the development of robotic systems to enhance surgical operability. Single port surgery (SPS) is a current tread in MIS. Petroni *et al.* presented a robotic system for single port laparoscopic surgery, composed of two multi-DOF (degree of freedom) arms and a stereoscopic camera [10]. Kobayashi *et al.* developed a

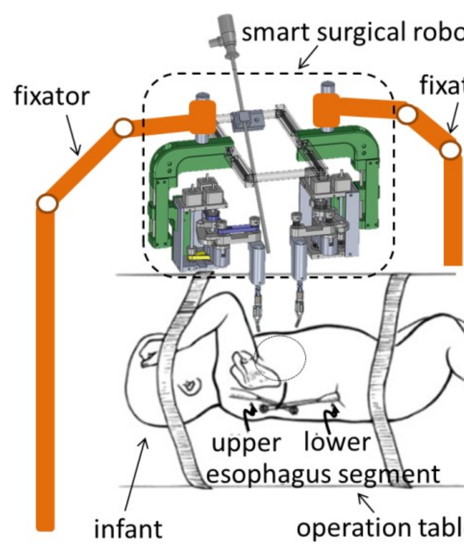

Figure 1. Overview of infant congenital esophageal atresia (ICEA) surgery with the smart surgical robot (SSR).

This work was supported in part by Global COE (Centers of Excellence) program "Global Robot Academia", from the Ministry of Education, Culture, Sports, Science and Technology of Japan, in part by Grant Scientific Research (A) (90198664), in part by a Waseda University Grant for Special Research Project (2009B-207).

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surgical robot for single port endoscopic surgery. This consists of two serpentine arms and a flexible endoscope, which is fixed on the sheath [11]. Yang *et al.* described a multitasking robotic platform with an articulated head and two flexible arms. The articulated head is a multichannel sheath, through which flexible instruments and an endoscope can be inserted and steered by a surgeon [12]. Xu *et al.* presented an insertable robotic effectors platform for single port access surgery [13]. This robot can raise its stereoscopic camera after being inserted through an incision port. These systems take advantage of dexterous manipulators to achieve good operability. However, they require space to extend their manipulator and vision mechanisms. Therefore, they are not directly applicable in pediatric surgery because of the limited workspace.

To arrange the instruments and vision module at the surgical site, an artificial pneumoperitoneum is usually needed at the beginning of the MIS [14]-[16]. However, the cavity pressure caused by the pneumoperitoneum, increase the higher likelihood of injury to an infant's fragile organs.

In this paper, we present the design and construction of a smart surgical robot (SSR) that works in open surgery. It can be operated in small workspace by utilizing two dexterous arms. An overview of the robotic system is shown in Fig. 1.

II. Brief Introduction to Infant Congenital Esophageal Atresia Surgery

A. Clinical Target

Infant congenital esophageal atresia (ICEA) is a congenital medical condition (birth defect) that affects the alimentary tract. It occurs in approximately 1 in 4400 live births [17]-[18]. ICEA takes several different forms, often involving one or more fistulas connecting the trachea to the esophagus. In approximately 85% of cases, the esophagus ends in a blind-ended pouch, rather than connecting normally to the stomach. Saliva and food will accumulate in the upper pouch, as it cannot drain into the stomach. Without treatment, the infant will soon die due to malnutrition. Currently, the most immediate and effective treatment in the majority of ICEAs is a surgical repair to close the fistulas and reconnect the two ends of the esophagus to each other. However, there are several factors affecting the surgical procedure, such as the state of the patient's health [19] and the size of the esophageal gap [20]. In this study, we consider the neonate to have been

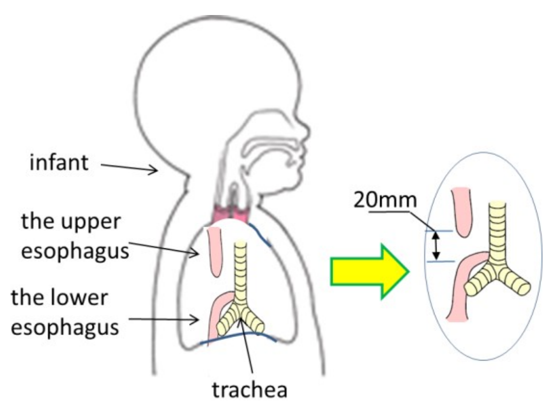

Figure 2. General case of congenital esophageal atresia (CEA).

admitted to the neonatal intensive care center and fulfill the surgical conditions. Generally, neonates are suffering from the CEA symptoms shown in Fig. 2. The mean gap between the upper esophagus and the lower esophagus is typically about 20mm [21], and the average chest measurement of the neonate is about 31 cm [22].

B. Robotic Assistant System for ICEA Surgery

The traditional operation in ICEA surgery includes several steps: exploration of operative field, stripping esophagus, ligation of tracheoesophageal fistula, and esophageal anastomosis. Compared with the thoracoscopic surgical method, open surgery with small incision can avoid the side effect of pneumoperitoneum. In our study, the surgeon manually explores the esophagus segments, then, performs esophagus anastomosis via robotic assistant system.

The semi-prone position is recommended during ICEA surgery, with the right side elevated at 45° and the right arm placed over the head [23] (Fig.1). Because the mean gap between the separated esophagus is 20 mm and the chest measurement is 31 cm, arranging a surgical forceps to manipulate the esophagus, requires a 30×30 ×30 mm space to be created near the fourth intercostal of the right side.

Our objective is to develop a compact, simple SSR for ICEA surgery. The proposed SSR is composed of two slave arms that approach the target esophagus through a 30×30 mm incision on the right side of the infant. Bended forceps located at the distal of the slave arm are designed to improve the operative intuitiveness.

III. Mechatronic Configuration

A. System Overview

Fig. 3 depicts an overview of the SSR. The SSR has 16 actuators that drive its two slave arms. Each slave arm consists of: 1) a positioning manipulator (four DOFs); and, 2) a surgical tool manipulator (four DOFs). The positioning manipulator works in a coordinated manner to position the tool manipulator. The surgical tool manipulator is attached to the front of the positioning manipulator. The dual slave arms

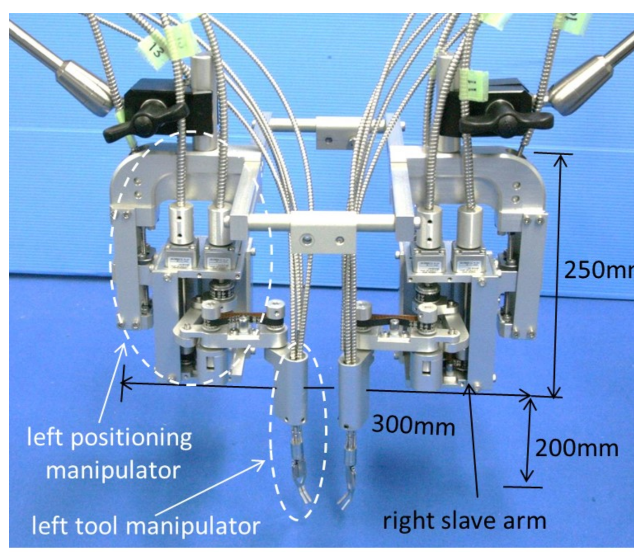

Figure 3. Overview of the SSR.

are used for surgical intervention.

The geometric dimensions of the SSR are approximately 300×200×250 mm. The tool manipulator has a diameter of 8 mm. Because the dual slave arms are analogous, only the mechanism of the left slave arm is presented.

B. Positioning Manipulator

1) Objective: The positioning manipulator was designed to control the translational displacement of the tool manipulator. Fig. 4 shows an overview of the positioning manipulator.

2) Required DOFs: Generally, three DOFs are required to determine a point in space. Redundant DOFs can be used to improve operative dexterity. The designed positioning manipulator includes four DOFs: vertical translational joint of the surgical tool manipulator (one DOF), horizontal translational joint of the surgical tool manipulator (three DOFs). One DOF of the horizontal translational joint is used to set the initial posture of the tool manipulator.

3) Mechanism: The positioning manipulator consists of a SCARA (Selective Compliance Assembly Robot Arm) and a screw-pair mechanism. This can achieve three translational movements in 3D space. The tool manipulator is held at the distal of the SCARA mechanism, which is fixed on the screw nut (shown in Fig. 4). Because the SCARA mechanism and the tool manipulator are lightweight, they can easily achieve translational movement along the screw rotational axis. In the SCARA mechanism, timing belts are employed to transmit power from the base coordinate frame to the corresponding link, because the power transmission path of each link is independent (shown in Fig. 5), Therefore, link 1, link 2, or link 3 could maintain its original pose in the base coordinate system, even though other links have moved. This configuration means the positioning manipulator can be easily deployed to adjust the position of the tool manipulator. Flexible shafts are used for the power transmission elements, reducing the overall weight of the robot by separating the motor and end-effector, and simplifying the assembly process.

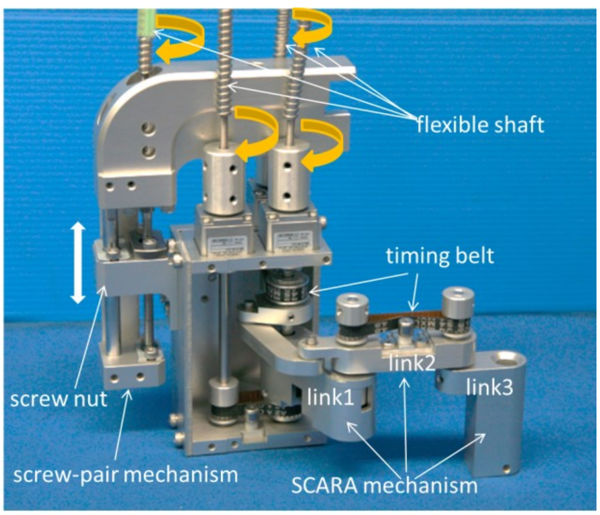

Figure 4. Overview of the positioning manipulator.

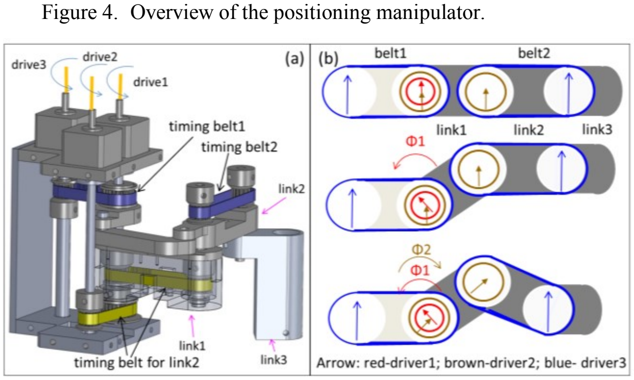

Figure 5. Power transmission in the SCARA. a, configuration of timing belts; b, principle of independent link control.

C. Surgical Tool Manipulator

1) Objective: The surgical tool manipulator is designed for tissue manipulation (Fig. 6). The tool manipulator acts as a surgical slave for surgical intervention. To realize this task, the tool manipulator presented here is equipped with a forceps as an end-effector. The mechanism of the tool manipulator is inspired by previous research in our laboratory [11].

2) Required DOFs: Generally, more DOFs can achieve higher dexterity. In addition, the tool manipulator should have sufficient rigidity for operation in the target organs. Considering the trade-off between dexterity and rigidity, the tool manipulator is designed to resemble a simplified human arm from elbow to finger. The designed tool manipulator comprises a two-DOF bending wrist, a one-DOF rotational elbow, and a forceps for the opening and closing motion of a hand.

3) *Mechanism*: A "double screw drive (DSD) + universal joint" structure is used to realize the bending motion. The combination of a right-handed screw, a left-handed screw and a universal joint is called the "bending linkage", and the

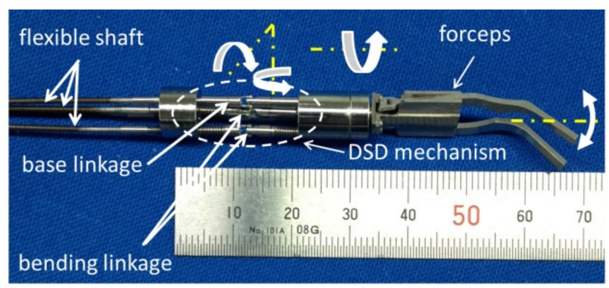

Figure 6. Overview of the tool manipulator.

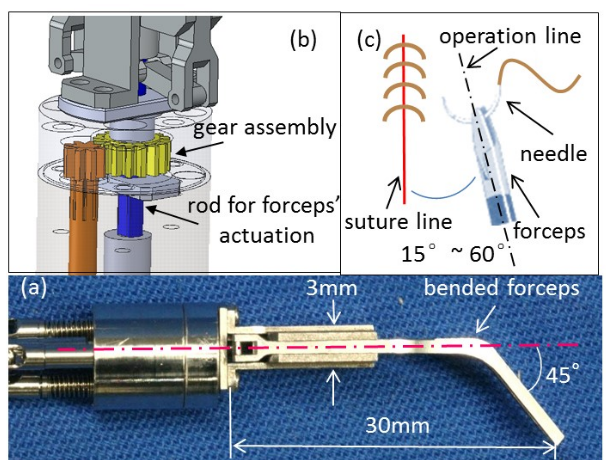

Figure 7. Forceps design. a, geometric dimensions of forceps; b, wrist design indicating major components; c, ideal suture posture.

combination of two support rods and a universal joint is referred to the "base linkage". Because two orthotropic DOFs are located on one universal joint, the forceps of the manipulator can achieve an omni directional bending motion.

The forceps of the manipulator is shown in Fig. 7. This forceps design presents a big challenge for robotic mechanisms of this size. Key factors affecting the forceps performance include the rotational angle, actuation manner, and geometric dimension. As shown in Fig. 7, a geared mechanism is used to realize rotation, while a pull-push rod, passing through the central channel of the gear, is designed to open and close the forceps.

In MIS, the angle between the suture line and the operation line should be in the range 15-60° [24], [25], as shown in Fig.7(c). Therefore, in our project, we select the bending angle of the tip to be 45°. User can achieve a good suture attitude even with the tool manipulator in its straight state. The length of bended forceps is 30 mm, which is consistent with the workspace for ICEA surgery. During surgery, only the bended forceps will be inserted into the body cavity. Because the thickness of the bended forceps is 3 mm, it can be flexibly operated on the target esophagus.

Generally, surgical instruments hold a needle for suturing task. The typical needle driver force applied by *EndoWrist* (used in the da Vinci system) is about 13 N [26]. Our bended forceps uses a "flexible shaft + universal joint" system for power transmission. The flexible shaft has a diameter of 1.4mm, and a length of 1.0 m, and is made up of several bunches of highly elastic twisted steel wires. A motor (EA-1754G-C040-10 SJP 1/6, rated torque 24 mNm, made by Chiba citizen precision Co., Ltd, Japan) is used to rotate the flexible shaft. Power is transmitted through the universal joint to the bended forceps. As shown in Fig. 8, the close movement of the forceps drives the housing unit to press a piezoelectric sensor, from which the gripping force can be calculated. The bending angle of the joint is designed to be ±45°. The gripping force for this and different bending angles is about 25 N. It can fulfill the requirement of the needle driver force.

IV. Control System Scheme

The user controls the robot via a console located in the operating room (OR). The console consists of a monitor and user input. The monitor is used to display the video from the endoscope. The console provides a master-slave mode for controlling the slave robot. The user input to the slave manipulator is through a PHANTOM-Omni (SensAble Technologies Inc.). There are six DOFs to sense the stylus position and posture. The current prototype robot is controlled using a relative position system. The swing pivot of the bendable joint in the slave arm corresponds to the rotation center of the phantom's gimbal, and the two bending DOFs of the gimbal are used to control the bending motions of the surgical tool manipulator. Based on the kinematics of the slave arm, the incremental position of the stylus is initially resolved in an inverted manner, and the computed resolution is sent to the corresponding actuator. Therefore, the slave arm moves with a velocity proportional to the user input movement of the phantom's gimbal displacement.

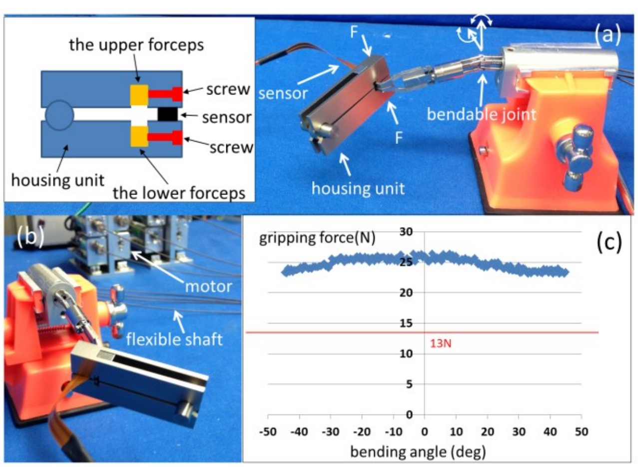

Figure 8. Gripping force of the bended forceps. a, experimental setup of force detection; b, distribution of flexible shaft and motor in the experiment; c, gripping force with different bending angle.

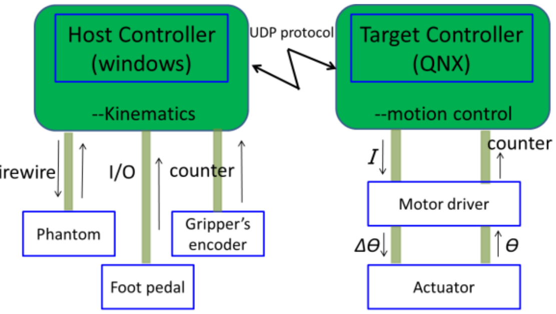

Figure 9. Control system frame.

To facilitate the distribution of devices for clinical application, our system uses two PCs. One is located in the console, and processes the phantom data and kinematics calculations. The other, located beside the slave robot, processes the encoder data and sends out appropriate signals to actuate the motors required for the designed movements. The PC in the console runs a C/C++ program in a Windows environment, and the slave side PC uses QNX software (QNX Software Systems, Ottawa, Ontario) for real-time processing. The PCs communicate by the UDP protocol through the Ethernet. The architecture of the control system is shown in Fig. 9.

V. Experiments

A. Objectives

We performed experiments to evaluate the performance of the SSR system. In the first experiment, the user operated the robot to transfer rings between different nails. This was intended to evaluate the operating intuitiveness and flexibility of the SSR. In the imitative experiment, the probability of clinical application was discussed.

B. Intuitiveness and Flexibility Experiments

In this session, the experimental platform consisted of the SSR system and a square phantom, as shown in Fig. 10. There are four nails located at the vertexes of the 30×30 mm square phantom. The task was to actuate the robot to transfer the rings between the nails.

Two initial ring locations were selected in this task, one horizontal placement and one vertical placement. The different initial locations corresponded to different postures of the robot distal.

For the horizontal placement, the trajectories for transferring the ring were (left arm, trail1) N1->N2->N3->N4->N1; (right arm, trial2) N4->N3->N2->N1->N4. For vertical placement, the trajectories were (left arm, trail3) N5->N1; (right arm, trail4) N5-> N4 (N5 is located in the center of the square phantom).

Five users with no experience of using the robot were selected to complete these four trajectories. Each user had 10 min to familiarize themselves with the operating characteristics of the robot system and the visual feedback from the endoscope before transferring the ring between the nails. Because both arms are analogous, only the transfer process of the right slave arm is shown in Fig. 11. The average time of three attempts by each user to finish the four trails is presented in Fig. 12.

All five operators exhibited a similar trend in their performance of using the robot to complete these trails. The results show the robot can be easy to control. According to the visual feedback from the endoscope, the operators can easily manipulate the bended forceps. Comparing the average time to transfer the horizontal ring with that of transferring the vertical ring, trail3 and trail4 are more time-consuming for a single transfer from one nail to another. To a novice user, the 2D visualization of the horizontal ring is more intuitive than that of the vertical ring in an endoscopic view.

C. Surgical Scenarios Experiment

An imitative surgical site is shown in Fig. 13. An esophagus model is located in a 30×30×30 mm cavity. Only the bended forceps is inserted into the cavity. Because the bended forceps is thin, the area of vision shielded by the surgical tool manipulator is small. This allows the user to operate the manipulator with good visual feedback

The experiment using the robot consisted of two stages.

In the first stage, the robot approached the target esophageal model, as the esophageal model lies in a 30 mm deep cavity (similar to the environment of ICEA surgery).

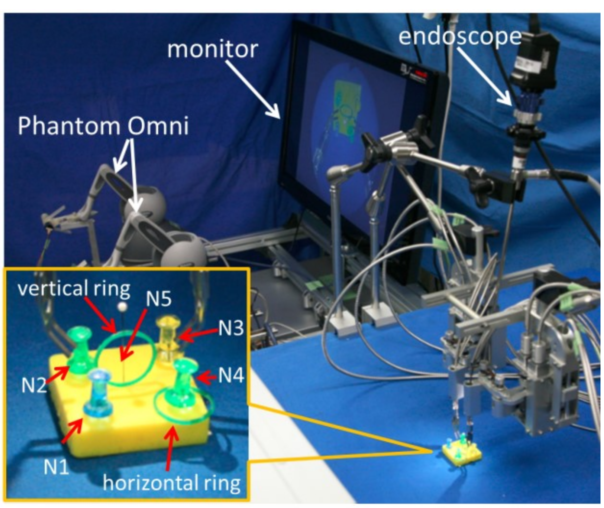

Figure 10. Setup for the intuitiveness and flexibility experiments.

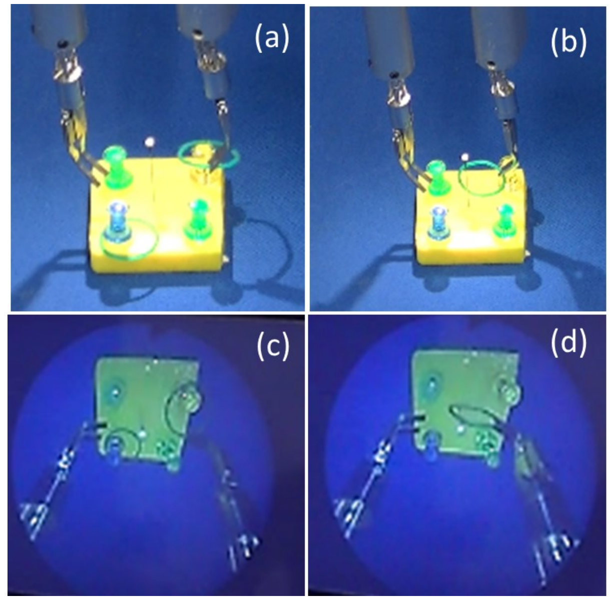

Figure 11. Operating view of the slave arms. a, transfer the ring from point N4 to point N3 in trail2; b, transfer the ring from point N5 to N4 in trail4; c, endoscopic view of (a); d, endoscopic view of (b).

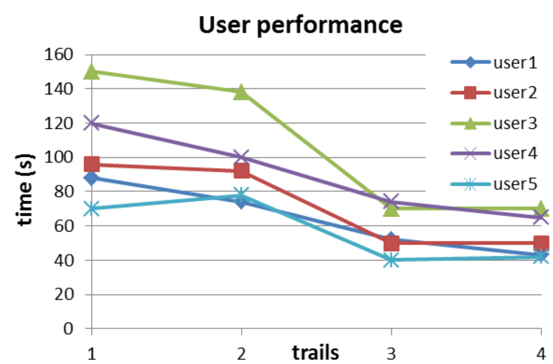

Figure 12. Average time taken by five novice operators to traverse four trails.

Therefore, only the bended forceps of our robot should be inserted into the cavity. In this stage, the positioning manipulators of the robot were mainly manipulated to search the surgical site.

In the second stage, a stitching procedure was carried out on the esophageal model. One gripper grabbed the model while the other held a needle for suturing. This coupled motion of the positioning manipulator and surgical tool manipulator can achieve a good attitude in the surgical scenarios, as shown in Fig.13 (c).

This imitative experiment demonstrates that the bended forceps allow the user operate intuitively. The bended forceps enable easy tissue manipulation.

VI. Conclusion and Future Work

This paper has presented a SSR system for ICEA surgery. This robot system makes use of a bended forceps, which offers intuitive user operation. The prototype robot consists of two slave arms. Each slave arm is composed of a positioning manipulator and a surgical tool manipulator. SCARA and

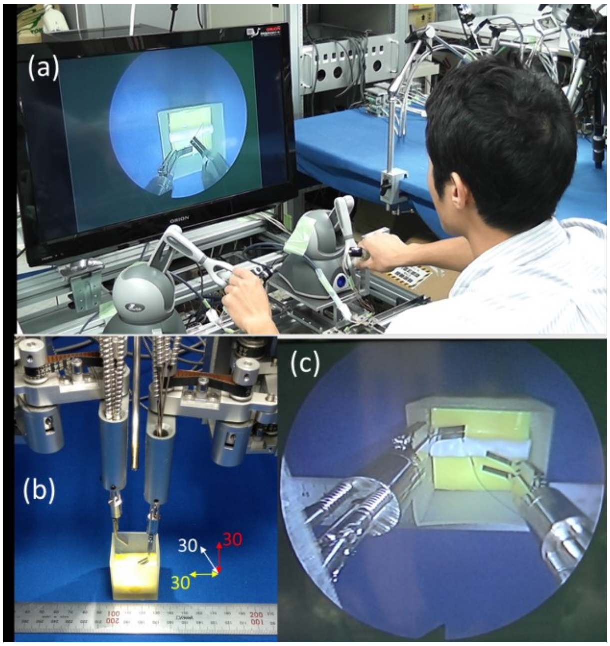

Figure 13. The robot was deployed for stitching an esophagus phantom in a 30×30×30mm workspace. a, overview of configuration; b, robot is approaching the target tissue; c, stitching applied.

screw-pair mechanism are used to achieve translational movement in the positioning manipulator. "DSD + universal joint" structure is used to obtain omni directional bending movement in the surgical tool manipulator. The SSR is lightweight and small. Furthermore, the flexible shaft used for power transmission simplifies the robot assembly. During surgery, the robot will be located above the infant's chest. The bended forceps of the robot, the only part inserted into the pediatric body, can be deployed for tissue manipulation.

The results of intuitiveness and flexibility experiments show that users can easily operate the robot for basic surgical intervention. The imitative surgical scenarios experiment demonstrates that the bended forceps offers intuitive operability to the user. Therefore, we can conclude that the SSR system is competent.

In vivo experiments will be required to conclusively demonstrate these benefits and ensure that this design makes a positive contribution to real ICEA surgery.

ACKNOWLEDGMENT

The authors sincerely thank the help of the subjects for participating in our experiments.

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