Bending Forceps Manipulator with Offset Distance for Single-port Laparoscopy

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Abstract By integrating locally operated, small surgical robots and devices, a surgeon can perform, robotically assisted laparoscopic surgery safely and accurately. However, no locally operated robotic forceps functioning as the third arm can provide the wide field of view and the large working area required for single-incision laparoscopic surgery (SILS). For SILS using a locally operated third arm, the pivot point should be placed far from the other three instruments inserted through the single port, and the pivot axes should be bending. Size reduction of the differential geared mechanism is difficult. Designing bending pivot axes for the flexible worm mechanism is also difficult. Bending pivot axes are also difficult to achieve in the crank-curved manipulator that we proposed previously as the second arm. The crank distance is short because of the high-step cylinders. The curved forceps have low accuracy because of rubber deformation. In the present study, we modified the crank-curved manipulator and designed a new manipulator for use as the third arm in a sterile environment, which provides offset distance using low-step cylinders in the pivot point placed far from the other instruments, as well as bending forceps mechanisms using ball joints in the bending pivot axes. We succeeded to develop a bending forceps manipulator with offset distance as a locally operated, end-effector manipulator (offset LODEM) for use as the third arm. The operating range was 60 mm for the offset, 32° for the pitch and yaw axes, and 24 mm for the insertion/extraction axis. Positional accuracy was evaluated while performing a simulated surgical procedure. The accuracy was 0.5 mm, which is sufficient for handling organs. The manipulator successfully handled the target in the simulated surgical procedures to provide a wide field of view and a large working area. The offset LODEM was designed to allow minimally invasive, robotically assisted surgery performed by a doctor working near the patient. This device may be used for such applications.

Keywords: single incision laparoscopic surgery, manipulator, local operation, bending forceps with offset distance.

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1. Introduction

Single-port laparoscopy (SLS) or single-incision laparoscopic surgery (SILS) that leaves only a small scar on the navel has become widely used [1]. The single, indiscernible scar after SILS is a cosmetic benefit compared to the small scars resulting from conventional laparoscopic surgery (LS). When performing surgery through the single incision, a surgeon must manipulate tools with limited degrees of freedom (DOFs) to minimize the effects of hand tremors and to cooperate with assistants using an endoscope or forceps. Furthermore, doctors must manipulate tools in a limited field of view blocked by the long rod-like shape of the

tool, and within a narrow working area, while the arms of the doctors collide with these tools [2].

Many master-slave remote-controlled manipulators [3] have been developed to resolve these issues. Surgical robots such as the da Vinci [4] systems in current clinical use provide high positional accuracy because they use four arms attached to a tool with 7 DOFs, motion scaling, and low-pass filtering to counteract tremors. However, systems developed for conventional LS are difficult to adapt to SILS because they are so large. Thus, small surgical robots such as SPRINT with a differential geared mechanism [5] and IREP with a flexible worm mechanism [6] have been developed.

Because of possible emergencies, local operation in a sterilized area is safer than remote operation in a non-sterilized area. By integrating locally operated, small surgical robots and devices, a surgeon can perform robotically assisted endoscopic surgery safely and accurately, holding mechanical forceps with hands stabilized by intelligent armrests, while controlling an endoscope-holding robot and a forceps robot. A large number of locally operated small surgical robots and devices have been developed for LS. Radius [7] and Autonomy [8] are manually controlled mechanical forceps with multiple DOFs. EXPERT [9–10] is a brake-controlled intelligent armrest enabling tremor elimination. Viki [11] and Naviot [12] are endoscope-holding robots with view stabilization. In addition, we developed a locally operated, end-effector manipulator (LODEM) for use as a third arm based on a selective compliance assembly robot arm (SCARA) as well as a mobile LODEM [13–15], which are robotic forceps used to grasp organs and provide traction in LS. However, no locally op-

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erated robotic forceps used as the third arm for SILS can provide the wide field of view and the large working area necessary for the surgeon. Our goal is to achieve robotically assisted surgery performed by a single surgeon working in a sterile area near the patient.

2. Purpose

For conventional manipulation at a pivot point on the abdominal wall, 5 DOFs are required: the roll, pitch and yaw axes; the insertion/extraction axis; and the opening/closing axis. The robotic forceps for SILS should have 5 DOFs. We previously proposed a locally operated master-slave robot system for SILS [16]. The master-slave manipulator can act as a second arm for the surgeon's left hand. The master manipulator is positioned at the conventional laparoscopic pivot point on the abdominal wall. A commercial tool operated by the surgeon's right hand, the slave manipulator, and an endoscope are inserted through a single port into the abdomen. The slave arm is approached far from the other two instruments for manipulation in a wide field of view. The slave arm consists of a crank distance segment with step cylinders and a curved forceps segment made of silicone rubber. The crank distance from the single port to the forceps tip was 40 mm, and the positional accuracy of the curved forceps was about 1 mm for the pitch and yaw axes. Furthermore, we also constructed a manipulator with actuator interchangeability for feed-forward control using stepper motors and master-slave control using DC motors [17], as well as a hands-free interface based on foot movement patterns [18].

For SILS using a locally operated third arm, the mechanical tools operated by the surgeon's two hands, the third arm, and the endoscope are inserted through a single port into the abdomen. To achieve the objective of locally operated manipulation in a wide field of view and in a large working area as the surgeon's third arm, the pivot point should be placed far from the other three instruments and the pivot axes should be able to bend. Although the differential geared mechanism in SPRINT [5] provides bending pivot axes far from the single port, reducing the diameter of the geared manipulator is difficult. The flexible worm mechanism in IREP [6] provides a small arm far from the single port, but designing bending pivot axes is difficult. The crank-curved manipulator [16] also provides a small arm, but it is difficult to design bending pivot axes far from the single port. The crank distance is short because of the high-step cylinder. The curved forceps has low accuracy because of rubber deformation.

To overcome these difficulties, the manipulator in the present study has an offset distance segment using low-step cylinders and a bending forceps segment using ball joints. The surgeon controls the robotic forceps with 5 DOFs to grasp and pull the organ. We propose a bending forceps manipulator with offset distance (offset LODEM) for SILS that acts as the third arm for the surgeon in the sterile environment of an operating room. The present report introduces the design details of the new offset-bending manipulator, which is a modified design based on the crank-curved manipulator. In addition, we report the positional accuracy of the new manipulator evaluated while performing simulated surgery.

3. Materials and Methods

3.1 Concept

The concept of robotically assisted SILS performed by a single

Fig. 1 Concept of robotically assisted SILS supported by an offset LODEM. (a) Top view. (b) Sagittal plane view.

Fig. 2 Mechanical design of the crank-curved manipulator.

surgeon is illustrated in **Fig. 1** (a: top view, b: sagittal plane view). Carbon dioxide gas is used for abdominal insufflation. An endoscope, the offset LODEM, and two conventional tools are inserted through the navel into the abdomen to remove the target gallbladder. The fixed-angle unit for the offset is placed above the abdominal wall. The actuator unit for the forceps is connected to the bed rail. The offset with 2 DOFs (two radial shapes independently) is controlled manually, and the forceps with 5 DOFs (pitch, yaw, insertion/extraction, roll, opening/closing) is motor controlled by the surgeon. The manipulator can be removed from the surgical table as required, and the sterilized mechanism can be separated and the motors draped with a sterile cover.

3.2 Manipulator

3.2.1 Crank – curved manipulator

Figures 2 through 4 present the design and photographs of the crank-curved manipulator. The outer diameter of the wire-driven manipulator is 10 mm. The crank distance segment consists of three polyetheretherketone (PEEK) step cylinders and a 0.7-mm-diameter super elastic alloy (SEA) linear spring, with a maximum angle of 90°. The maximum length of the crank distance is 40 mm, and the distance from the crank to the manipula-

Fig. 3 Mechanical design of the fixed-angle unit and actuator unit for the crank-curved manipulator.

Fig. 4 Prototype of the crank-curved manipulator prototype.

tor tip is 160 mm. The crank angle can be changed independently to pull a polyethylene (PE) wire with a diameter of 0.3 mm (255 N maximum tension force, Ultra Dyneema WX8, YGK YOZ-AMI, Naruto, Japan). The curved pitch and yaw axes of the forceps consist of silicone rubber with a hardness of 30. The operating ranges of the prototype are 18° for the pitch and yaw axes, 0 to 36 mm for the insertion/extraction axis (consisting of two embedded pipes), 90° for the roll axis, and 0 to 75° for the opening/closing axis made from conventional grasping forceps with 3-mm diameter (K30310KS, KARL STORZ, Tuttlingen, Germany). The inner rod of the forceps is connected to a 1.2-mm-diameter wire rod. The design operating ranges are 60° for the pitch and yaw axes and 0 to 50 mm for the insertion/extraction axis. The performance of the prototype is approximately 30% compared to the design because of mechanical friction and low rigidity of the rubber. Crank driven wires are connected to the fixed-angle unit; forceps-driven wires in the polytetrafluoroethylene (PTFE) sheath are connected through the center of the step cylinders in the offset; and a coiled steel tube cable (2.2×5 -mm-diameter, SLR, SHIMANO, Sakai, Japan) is connected to the actuator unit. The fixed-angle unit for the crank is a ratchet gear mechanism that can be locked to prevent motion. The manipulator mechanism weighs 0.4 kg. The actuator unit for the stepper mo-

Fig. 5 Mechanical design of the offset-bending manipulator.

Fig. 6 Mechanical design of the fixed-angle unit and actuator unit for the offset-bending manipulator.

tors is $445 \times 192 \times 95$ mm and weighs 6.0 kg.

3.2.2 Offset – bending manipulator

Figures 5 through 7 present the design and photographs of the new offset-bending manipulator which is a modified design based on the crank-curved manipulator. The offset consists of eight step cylinders and a 0.6-mm-diameter SEA linear spring, with a maximum angle of 120° . The maximum length of the offset is 60 mm, and the distance from the offset to the manipulator tip is 150 mm, pulling a wire with a diameter of 0.4 mm (314 N maximum tension force, Ultra Dyneema WX8, YGK YOZ-AMI). The bending pitch and yaw axes of the forceps consists of a PEEK ball joint. The operating ranges of the prototype are 32° for the pitch and yaw axes, and 0 to 24 mm for the insertion/extraction axis consisting of three telescopic pipes. The operating ranges of the prototype for the roll axis and for the opening/closing axis are the same as those of the crank-curved manipulator. The design operating ranges are 60° for the pitch and yaw axes, and 0 to 50 mm for the insertion/extraction axis. The performance of the prototype is approximately 50% compared to the design because of mechanical friction. The fixed-angle unit for the offset is a worm

Fig. 7 Prototype of the offset-bending manipulator prototype.

gear mechanism that can self-lock to prevent motion. The grasping forceps, the inner rod, the sheath, and the tube cable are the same as the crank-curved manipulator. The manipulator mechanism weighs 0.6 kg. The actuator unit for the stepper motors is $350 \times 190 \times 120$ mm and weighs 3.4 kg.

3.2.3 Drive system

The actuator unit consists of the same two stepper motors (3 Nm maximum torque, CRK543BPB-PS50, Oriental Motor Co., Ltd, Tokyo, Japan) and a spur gear with a 2:1 gear ratio for the pitch and yaw axes; a stepper motor (0.24 Nm maximum torque, CRK545BPB, Oriental Motor Co., Ltd) and a ball screw with 10-mm lead length for the insertion/extraction axis; and two stepper motors (0.5 Nm maximum torque, CRK523BPB-T30, Oriental Motor Co., Ltd) for the roll and opening/closing axes.

The forceps are feed-forward controlled by a handheld interface of ten button switches attached to the surgeon's forceps, the same as SCARA-LODEM [13]. The interface has different shaped switches and a symmetric layout ($53 \times 36 \times 11$ mm, 20 g). Commands to control the five individual axes are input by pressing the appropriate buttons, and they are processed by a motion control board (PCI-7414V, 8 μ s digital input, 6.5 M pulse/s pulse rate, Interface, Hiroshima, Japan) installed in a PC, which then outputs the appropriate signals to the manipulator. The manipulator is feed-forward controlled by a PC system.

3.3 Experimental Methods

An object-moving task and *ex vivo* cholecystectomy using the crank-curved manipulator were performed to evaluate the feasibility of the manipulator as the second arm for the surgeon's left hand. The manipulator is master-slave controlled by the master manipulator placed on the abdominal wall and operated by the surgeon's left hand. The commercial tool operated by the surgeon's right hand, the slave manipulator, and the endoscope were inserted through a single port. In a previous study, the slave crank-curved manipulator could be approached far from the other two instruments for manipulation in a wide field of view [16], but the motion trajectories for the manipulator was not shown. To evaluate the new offset-bending manipulator, the manipulator was used in the following experiments. Experiment 1 was performed to

confirm the improvement in accuracy. Experiment 2 was designed to confirm the feasibility of using the manipulator as the surgeon's third arm.

(1) Motion trajectories were measured to confirm the positional accuracy for each manipulator. The trajectory of the tip of the forceps was measured using an optical displacement sensor (0.1 mm accuracy, OPTOTRAK Certus, NDI, Waterloo, Canada) for movements of the pitch, yaw, and insertion/extraction axes when the offset angle was maximal.

When an organ was pulled up and held by the manipulator, the crank or the offset had to be fixed by the angle. Thus, the traction force of the crank- or the offset-driven wire was measured when the angle became maximal. The maximum force exerted by the manipulator was also measured.

(2) Simulated surgery using the new offset-bending manipulator was performed on a surgically realistic gall bladder model (50128, Limbs and Things, Bristol, UK) in a training box (Endowork-pro II, KARL STORZ) to evaluate the feasibility of using the manipulator as the surgeon's third arm. The manipulator is feed-forward controlled by a handheld interface of ten button switches attached to the surgeon's forceps, as in the SCARA-LODEM [13]. An endoscope (10 mm diameter, Tricam 3D, KARL STORZ) and the manipulator were set in the training box, and two conventional tools were inserted thorough the SILS port (E-Z ACCESS and LAP-PROTECTOR, Hakko, Chikuma, Japan) in the training box. The operator who was an endoscope specialist used the scissors with the right hand and operated the forceps with the button switches interface by the left hand. The experiment was approved by the ethics committee of Osaka Institute of Technology.

4. Results

The results of the two experiments are as follows.

(1) **Figure 8** presents the results of the forceps tip trajectory measurements. In this experiment, positional accuracy was defined as the maximum error between the hysteresis for the pitch and yaw axes, and as the maximum vibrational displacement for the insertion or extraction axis. For the crank-curved manipulator, the positional accuracy was 1.1 mm for the pitch axis (**Fig. 8a**), 1.0 mm for the yaw axis (**Fig. 8b**), and 3.3 mm for the insertion/extraction axis (**Fig. 8c**). The traction force of the crank-driven wire when the angle reached its maximum (90°) was 32 N. The range was 13% based on the maximum wire tension force. The maximum force exerted by the manipulator for the pitch and yaw axes was 1.2 N.

For the new offset-bending manipulator, the positional accuracy was 0.3 mm for the pitch axis (**Fig. 8d**), 0.4 mm for the yaw axis (**Fig. 8e**), and 0.5 mm for the insertion/extraction axis (**Fig. 8f**). The horizontal distance at the switching pipe for the insertion/extraction axis ranged from 10 to 30 mm. The traction force of the offset driven wire when the angle reached its maximum (120°) was 25 N. The range was 8% based on the maximum wire tension force. The maximum force exerted by the manipulator for the pitch and yaw axes was 0.5 N.

(2) The experimental setup is presented in **Fig. 9a**. The organ model could be handled in various directions using the manipulator controlled by button switches operated by the left hand (**Fig. 9b**). The surgeon was also able to pull the model organ in opposite directions using the forceps with the left hand and dis-

Fig. 8 Results of trajectory measurements of the forceps tip: (a) pitch axis, (b) yaw axis, (c) insertion/extraction axis for the crank-curved manipulator, (d) pitch axis, (e) yaw axis, (f) insertion/extraction axis for the offset-bending manipulator.

Fig. 9 Experiment of simulated surgery performed by a specialist using the feed-forward, offset-bending manipulator. (a) Operator with two forceps. (b) Handling a surgical model in the training box.

sect it using scissors with the right hand. The specialist smoothly dissected the target organ. The new offset-bending manipulator could be approached far from the other three instruments for manipulation in a wide field of view and in a large working area as the surgeon's third arm.

5. Discussion

Surgical robots SPRINT [5] and IREP [6] have been developed for SILS. SPRINT consists of a camera arm and two tool arms. The diameter of the tool arm is 18 mm, and the maximum force exerted is 5 N. The SPRINT arm provides a large working area because of the differential geared mechanism, but the diameter of the arm is not small compared to commercial tools. IREP also consists of a camera arm and two tool arms. The diameter of the tool arm is 6.4 mm, and the working load is 2 N. The IREP arm has characteristics opposite to SPRINT. The arm is small, but does not provide a large working area because of the flexible worm mechanism. The offset-bending manipulator has an offset distance segment using low-step cylinders for the pivot point

placed far from the other three instruments inserted through the single port. Furthermore, the manipulator has a bending forceps segment using ball joints for the bending pivot axes, and the diameter is 10 mm. Our offset-bending manipulator has the structural advantages of providing a wide field of view and a large working area.

As reported previously, the positional accuracy of the SCARA-LODEM is 0.5 mm, which is sufficient for its use as a third arm for grasping and manipulating organs [13–15]. The positional accuracy of 0.5 mm is sufficient for handling organs based on confirmation by *in vivo* experiments. For the offset-bending manipulator, the positional accuracy was also 0.5 mm from the forceps tip trajectory measurements. When the organ was pulled up by the manipulator, the traction force has to exceed 5 N [19]. It was confirmed that the offset angle was maintained to pull up the model organ because of the allowance for wire tension force based on the experimental results. In the simulated surgical procedures, the manipulator successfully handled the target. From these results, the offset LOEDM used as the third arm for SILS provides wide field of view and large working area necessary for the surgeon.

The positional accuracy of the offset-bending manipulator is superior to that of the crank-curved manipulator. The pitch and yaw axes are constructed of silicone rubber in the crank-curved manipulator, while these axes are moved by PEEK ball joints in the offset-bending manipulator. When the forceps-driven wires are pulled by the motor, the rubber is compressed and deformed because of the compliance, but the ball joints are not deformed because of the rigid connection. Thus, the stability of each motion trajectory is improved. The difference in positional accuracy between the two manipulators is due to the difference in strength of the material used to construct the pitch and yaw axes.

The hysteresis observed at the insertion/extraction axis (Fig. 8c, 8f) is a result of the construction material of the pitch and yaw axes. When the direction of the axis is changed, the crank- or offset-driven wire is changed at the same time to increase the tension. Under this circumstance, deformation occurs due to compression of the rubber in the crank-curved manipulator, or sliding on the contact surface of the ball joint in the offset-bending manipulator. After that, the balance between friction and traction forces is shifted. When the forceps reach the organ and the organ is grasped and lifted, the approach direction is changed because of the hysteresis. A follow-up operation is required when the organ has to be lifted in a strictly defined direction.

Based on these results, further improvements are being planned to develop the offset-bending manipulator for clinical use. First, the grasp and traction force must exceed 5 N [19], and the friction resistance of the transmission mechanisms should be lower. Second, an intuitive interface with 5 DOFs is necessary. Endoscope-holding robots such as Viky [11] and AESOP [20] can be operated by voice control; Naviot [12] is operated by a forceps-mounted button control; and FreeHand [21] is operated by a head-mounted sensor control. These systems have 2 or 3 DOFs. No locally used intuitive interface suitable for a LOEDM with 5 DOFs is available. For easier operability, we have developed an ergonomic forceps-mounted button interface and a hands-free interface that uses foot motion [13, 18]. Third, when the offset of the manipulator is fixed by the angle, it moves out of the field of

view. This leads to a risk of bleeding if the organ and the manipulator collide. To avoid this, the offset part should be covered with tubing. By covering the outer circumferential gap between the step cylinders, jamming with other parts and organs can be prevented. Finally, the offset-bending manipulator must be clean and sterile. To facilitate sterilization of the manipulator, the mechanisms should be easily separable into a mechanical drive part that allows autoclaving and an electric drive part that does not require sterilization. It should be possible to disassemble the manipulator into the wire-driven mechanism, the passive hand controller, and the active motor controller. To realize robotically assisted surgery performed by a single surgeon working in a sterile area near the patient, it is important for some manipulator mechanisms to be detached from the actuators easily. In a surgical robot, actuator interchangeability should be integrated into some mechanisms. Thus, we have developed a manipulator with actuator interchangeability between stepper motors and DC motors [17].

6. Conclusion

We developed a feed-forward controlled, offset LODEM that can be used by a surgeon as the third arm during SILS. The wire-driven offset distance and bending forceps mechanism are designed to facilitate minimally invasive, robotically assisted surgery by a doctor working near the patient. The results of the present study indicate that this device could be used for such applications. Future work will include *ex vivo* and *in vivo* simulated surgery performed by specialists.

Conflict of Interest

We have no conflicts of interest relationship with any companies or commercial organizations based on the definition of Japanese Society of Medical and Biological Engineering.

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