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Development of five-finger hand-type robotic forceps for laparoscopic gastrointestinal surgery

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***Abstract*— In laparoscopic surgery, large organs are difficult to handle with one forceps, resulting in low surgical efficiency. In this study, to improve surgical efficiency, we developed a five-fingered robotic forceps that can be inserted through small incisions and has multiple degrees of freedom to handle large organs. The results of an experiment simulating sigmoidectomy showed that the proposed robotic forceps could shorten the surgical time. In addition, we confirmed that the physical burden while using the instrument was comparable to that of conventional forceps.**

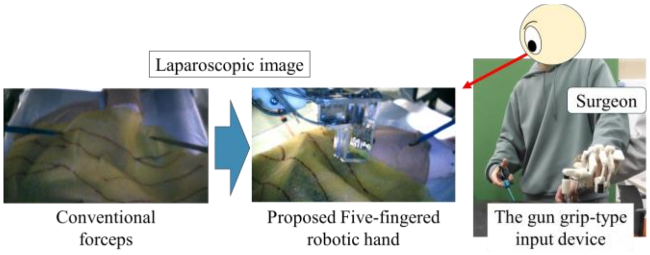

Figure 1. Posture of the surgeon when using surgical instrument

I. INTRODUCTION

Surgical methods targeting the digestive organ include open surgery and laparoscopic surgery. In open surgery, an incision of approximately 100 to 200 mm is made and the surgery is performed while directly observing the inside of the abdominal cavity. This surgical method allows surgeons to easily acquire the necessary skills and respond quickly to emergencies. However, the large incision size of open surgery poses invasiveness and cosmetic concerns. On the other hand, in laparoscopic surgery, five incisions of approximately 5 to 12 mm are made, and the surgeon performs the surgery by viewing the camera image displayed on a monitor. Compared to open surgery, this surgical method, with its smaller incisions, is superior in terms of less invasiveness, appearance, and postoperative hospital stay [1]. However, the forceps used in laparoscopic surgery have small end effectors, making it difficult to manipulate large organs with just one forceps. When handling large organs, the need arises to use two or more forceps, requiring coordination between the surgeon and his assistant, which increases operative time. Instruments with multiple contact points, like retractors, are used when performing exclusion small intestine. However, the issue arises due to the time required for instrument exchange. Therefore, Abe developed a forceps with Least-incision transformable end-effector (LITE) mechanism [2]. The LITE forceps can be used as two different-sized graspers, with diameters of 5 mm and 10 mm, achieved through transformation of their end-effector. However, it is considered that the LITE forceps cannot grasp large organs like the colon with just one instrument, similar to conventional forceps.

In addressing these issues, Hand-Assisted Laparoscopic Surgery (HALS) involves using hands, which allow the handling of large organs without causing damage thanks to the significant surface area of the hands [3] . Surgery time can be shortened in this surgical method because the surgeon handles large organs alone. However, HALS requires an approximate 60-mm incision, making it more invasive. Furthermore, a drawback of this surgical method is the risk of the surgeon getting burns from instruments such as electrocautery. Research is being conducted to replace the hands in HALS with robotic hands that can be inserted through smaller incisions to overcome these drawbacks. First, Oshima proposed a robotic hand with three fingers and five degrees of freedom [4]. This robotic hand can be inserted through a 12-mm incision, allowing organ grasping and exclusion. However, parts are likely to slip during assembly inside the abdominal cavity. Furthermore, it has not been possible to achieve both the holding and operation of the robotic hand with just one hand. Next, Nagase proposed a robotic hand with five fingers and eight degrees of freedom [5]. The robotic hand has a folding mechanism and can be inserted through a 20-mm incision. The robotic hand can be controlled intuitively by using an exoskeleton interface. The robotic hand is held by attaching a socket to the forearm to enable one-handed operation. However, with this holding method, the elbow position is fixed in one place relative to the fingertips of the robotic hand, which puts great physical strain on the surgeon. Here we introduce RULA, an evaluation index of physical burden. Postural strain during work is evaluated based on the angles of the upper arm, forearm, wrist, trunk, neck, and feet. When the physical burden of the posture with using the instrument proposed by Nagase was evaluated using RULA [6], it was determined to be AL=3 (GS=5), a burden that requires "investigation and changes are required soon."

Therefore, in this study, we aim to develop a surgical instrument that minimizes the physical strain on the operating surgeon, allowing insertion through small incisions and handling large organs.

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II. DESIGN OF THE ROBOTIC HAND

A. *Requirement for the surgical system*

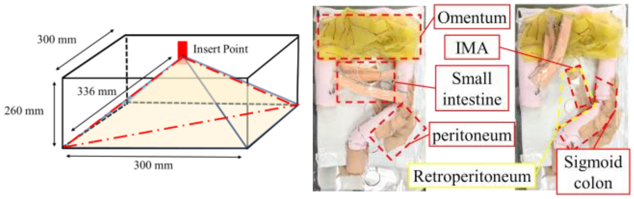
Referencing HALS, we determine the requirements for the end effector. We deemed it necessary for the end effector to have five fingers and a wide surface area like a human hand to handle large organs.

First, we determine the size of the end effector. In laparoscopic surgery, incisions are extended for 20 to 40 mm to take organs out of the abdominal cavity. Therefore, we determined that the incision required to insert the end effector should be 20-mm or less. In addition, the workspace inside the abdominal cavity is approximated as a rectangular prism. When inserting a rod-like instrument from the center of the top surface and considering that the organs are placed on the bottom surface, the operational range of the instrument is represented by a square pyramid (Fig.2(a)). Therefore, the length of the end effector must be 260-mm or less. Furthermore, the surgical instrument needs to be inserted at least 336-mm to access all ranges in the abdominal cavity. We referenced the human hand and surgical gloves to obtain a large surface for handling organs. Then, we decided it was desirable for the length of the end effector to be approximately 130 to 180 mm and the width to be around 70 to 80 mm[7].

Next, we determine the necessary degrees of freedom for the end effector. We took up sigmoidectomy as an example of gastrointestinal surgery and classified the movements required for the surgery. The tasks of sigmoidectomy can be divided into five based on the target organs (Fig.2(b)). When handling thin membranes such as the omentum and retroperitoneum in HALS, the surgeon uses the thumb, index finger, and middle finger to pinch them. (Fig. 3(a)). When handling large organs such as the colon, a grasp is achieved using all five fingers. (Fig. 3(b)). For organs that are challenging to grasp, such as the small intestine, exclusion is achieved using the freedom of the wrist and the broad surfaces of the palm or back of the hand (Fig. 3(c)). Therefore, among the degrees of freedom in hand, the necessary ones are opposing the thumb, flexing the index and middle fingers, flexing the ring and little fingers, and palm-flexing and dorsiflexing the wrist.

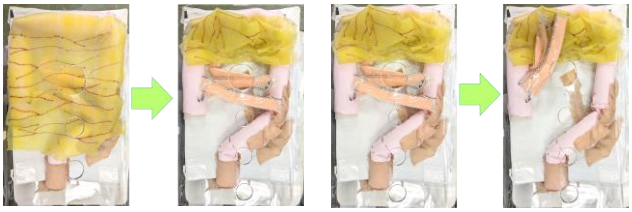
B. *The five-fingered robotic hand*

The five-fingered robotic hand must achieve three actions and be insertable through an incision of less than 20-mm. Furthermore, to eliminate the risk of electrical leakage, placing the actuators outside the body is necessary. Therefore, we adopted mechanism of the five-fingered robotic hand proposed by Nagase [5] (Fig. 4). The four fingers each have three joints like a human hand and are driven by traction, with one wire each for flexion and extension. Because it is an under-actuator that drives three joints with one actuator, the posture of the fingertips is different every time. Therefore, we designed a structure in which the robotic hand always takes a pinch position by restricting the range of motion of the finger joints. The thumb mechanism includes one joint for opposition and one joint each for abduction and adduction. Abduction, adduction, opposition, and apposition are each driven by traction with a single wire. A single motor is used for each movement for the thumb abduction and adduction. Opposition and apposition of the thumb are achieved by the traction of two wires with a single motor. The large intestine has a diameter of 60 to 90 mm and we need to encase it to handle[8]. Therefore, it is thought that a hand length of approximately 140 mm is necessary. However, end effectors with a surface that is too wide obstruct the laparoscopic view. Therefore, it is advisable to make it smaller, and its size has been determined as 136-mm in length and 70-mm in width. The palm is divided into four parts, like the four fingers, and connected by hinges (Fig.5). By tractioning the wires attached for folding, the four fingers can be brought together in a palm-to-palm or back-to-back configuration, allowing them to fold like bellows. The thumb is L-shaped, with the palm and fingers connected at right angles, and the pads of the thumb are folded so that they touch the sides of the four folded fingers. When folded, the thickness is the sum of the five finger thicknesses. So, the thickness of the fingers was determined to be 4-mm.



(a) Workspace inside the abdominal cavity

(b) The target organs



(c) Moving the omentum (Task 1)

(d) Moving the small intestine (Task2)

(e) Cutting the IMA (Task 3)

(f) Cutting the peritoneum (Task 4)

(g) Cutting the retroperitoneum (Task 5)

Figure 2. Workspace inside the abdominal cavity

(a) Pinch

(b) Grasp

(c) Exclusion

Figure 3. Hand action of HALS

In addition to the degrees of freedom of the palmar flexion and dorsiflexion of the wrist, degrees of freedom of radial and ulnar flexion should be implemented to enable approaches to various organs. The cross-section of the wrist part is a circle with a diameter of 14-mm, which is needed to insert through a 20-mm incision (Fig.6). In addition, the length of the wrist is approximately 70-mm, and the length after assembling with the five-fingered robot hand is approximately 230-mm, which satisfies the design requirements. Each action of the wrist is driven by traction with one wire, and one motor is used for each wire.

C. *The gun grip-type input device*

We propose a gun grip-type input device to enable one-handed hold and operation (Fig.7). The angle of the surgeon's fingers is used for control input for the three degrees of freedom of the fingers of the robot hand to enable intuitive operation. The surgeon holds the instrument by grasping the grip part with the ring finger and little finger and operating the robotic hand with the thumb, index finger, and middle finger. In addition, the surgeon uses his arm to manipulate the wrist part by changing the angle of the joint of the input device. The finger angle is measured using a 4-joint, 4-link closed-loop structure that includes the surgeon's finger as a link (Fig.8). The wrist angle is measured at the joint connection between the grip and the robotic hand's axis. The above joint angles are measured using a rotary potentiometer.

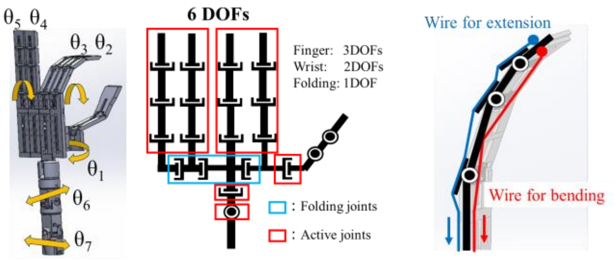


Figure 4. Mechanism of the end effector

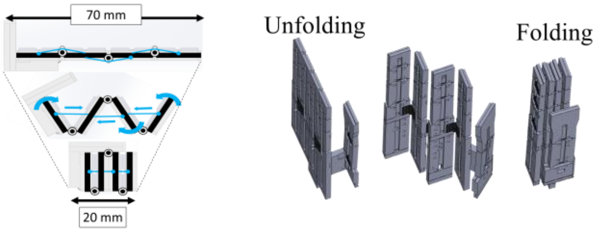


Figure 5. Mechanism of folding

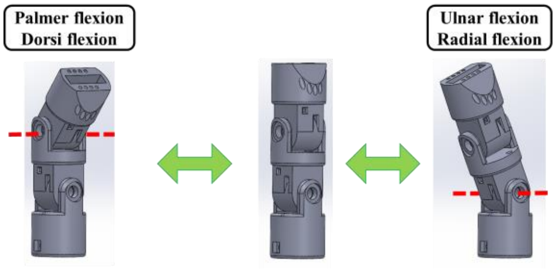


Figure 6. Mechanism of the wrist

Leader-follower control is performed using a gun grip-type input device as the leader and a five-fingered robotic hand as the follower. The joint angle measured with the input device is used as the input 5-dimensional vector $\boldsymbol{\theta}$, and a 7-dimensional vector $\boldsymbol{\theta}_{\mathrm{M}}$ of the target value is output using a linear regression model. θ_1 means the angle of opposing the thumb. θ_2 to θ_5 means the angle of flexing fingers. θ_6 means the angle of palm-flexing and dorsiflexing the wrist. θ_7 means the angle of radial and ulnar flexing. $\boldsymbol{b}$ is a 7-dimensional vector indicating the minimum angle of each joint.

The adduction and abduction motor angles $\boldsymbol{\theta}_{\mathrm{MT}}$ of the thumb are set in three values according to the index finger flexion motor angle $\boldsymbol{\theta}_2$. Each parameter is expressed as in equations (1), (2) and (3).

$$\boldsymbol{\theta_M} = \boldsymbol{A\theta} + \boldsymbol{b} \tag{1}$$

$$\boldsymbol{A} = \begin{pmatrix} a_1 & 0 & 0 & 0 & 0 \\ 0 & a_2 & 0 & 0 & 0 \\ 0 & a_3 & 0 & 0 & 0 \\ 0 & 0 & a_4 & 0 & 0 \\ 0 & 0 & a_5 & 0 & 0 \\ 0 & 0 & 0 & a_6 & 0 \\ 0 & 0 & 0 & 0 & a_7 \end{pmatrix} \tag{2}$$

$$\boldsymbol{\theta_{MT}} = \begin{cases} \boldsymbol{\theta_{MT1}} & \theta_2 < \theta_a \\ \boldsymbol{\theta_{MT2}} & \theta_a \le \theta_2 < \theta_b \\ \boldsymbol{\theta_{MT3}} & \theta_b \le \theta_2 \end{cases} \tag{3}$$

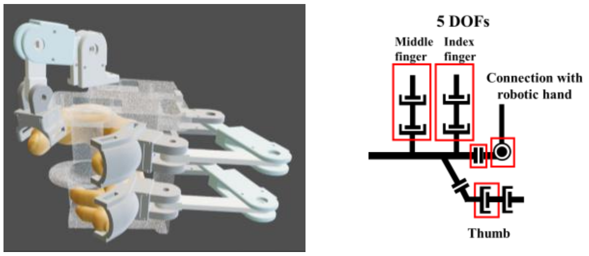


Figure 7. Gun grip-type input device

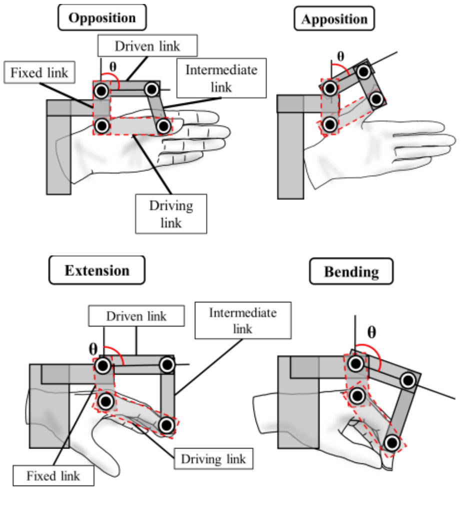


Figure 8. Mechanism of measuring joint angles

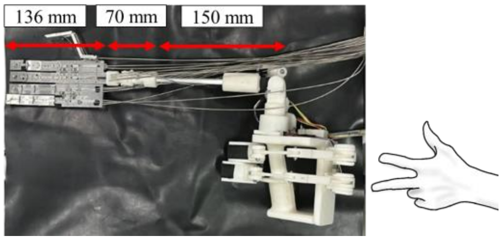


Figure 9. Overview of the proposed robotic forceps

TABLE I. DEMONSTRATION FORCE OF THE PROPOSED ROBOTIC FORCEPS

	Design requirements	Actual value
Pinch [N]	2.8	5.1±0.15
Grasp [N]	5.5	22.2±1.39
Torque of wrist [N・m]	0.451	0.51±0.01

D. Production of the proposed robotic forceps

Figure 9 shows the five-fingered robotic forceps that we created. Figure 10 also shows the input device and the corresponding action of the robotic hand. Next, we investigated whether the force of the instrument for three surgical actions satisfied the design requirements. The results are shown in TABLE I. This result confirmed that the design requirements were satisfied in all operations. The design requirements for the force of surgical actions were determined from the weight of the target organ and the friction between the organ and the glove[9].

III. EXPERIMENTS

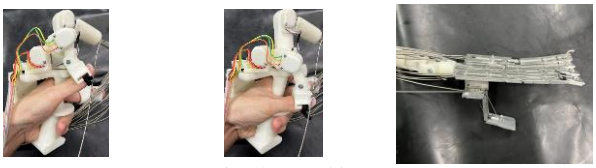
We conducted a comparative experiment between the proposed robotic forceps and conventional forceps for sigmoidectomy, a typical surgery targeting the digestive organ. In this experiment, we verified whether the method with the proposed robotic forceps would shorten the surgical time and investigated the degree of burden on the posture when using the proposed robotic forceps.

A model reproducing the abdominal cavity and organs was created (Fig.11). The large and small intestines were simulated with a silicone membrane and cloth. The membranous tissue to be cut, such as the retroperitoneum and the cut portion of the IMA, was simulated with stockings (76% nylon, 24% polyurethane). In addition, a simulated organ manufactured by Applied Medical was used for the omentum.

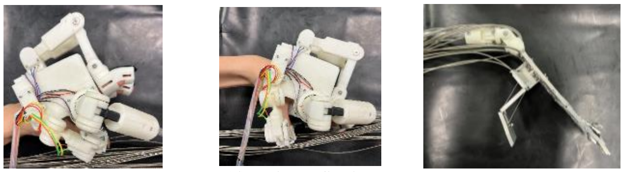
Figure 12 shows the port arrangement with conventional forceps and the proposed robotic forceps. During the experiment, a simulated abdominal cavity was placed on a 60-cm-high table and covered with a black rubber membrane to recreate the surgical environment. Subjects watched intraperitoneal images taken with a fiberscope and performed the task. The conventional method was performed by three people: the surgeon, an assistant, and a camera assistant, while the proposed method was performed by the surgeon and a camera assistant. The surgeon and camera assistant were the same person in both methods: a male non-medical worker in his 20s. For each method, one trial was performed after two practice sessions. Figure 13 shows the task in the conventional method, and Figure 14 shows the task in the proposed method.

(a) Pinch

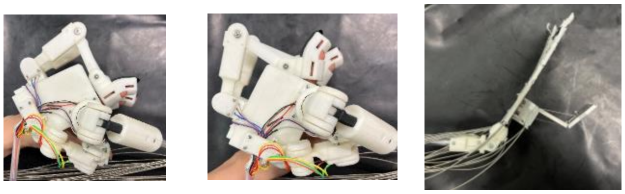
(b) Grasp



(c) Thumb opposition

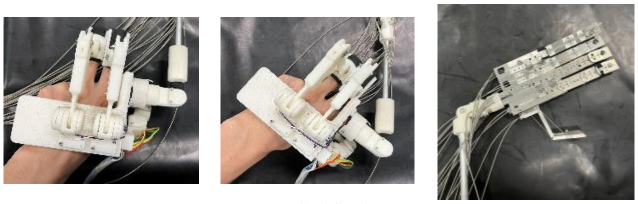


(d) Palmar flexion



(e) Dorsi flexion

(f) Ulnar flexion



(g) Radial flexion

Figure 10. The action of the end effector

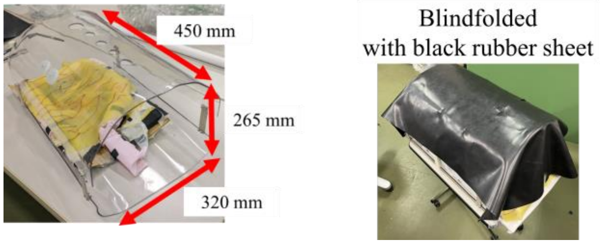
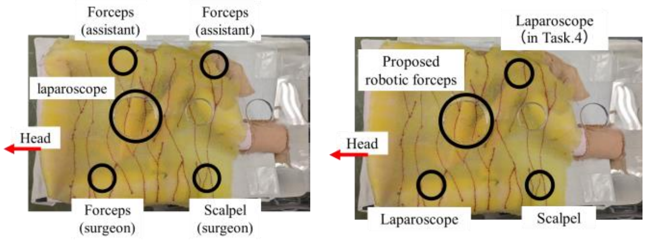


Figure 11. Simulated abdominal cavity

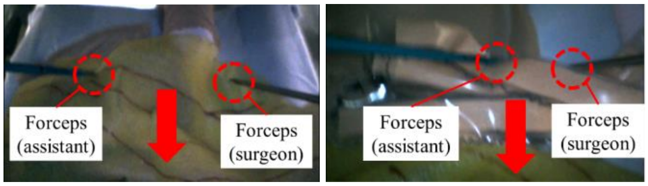


(a) Conventional forceps (b) Proposed robotic forceps

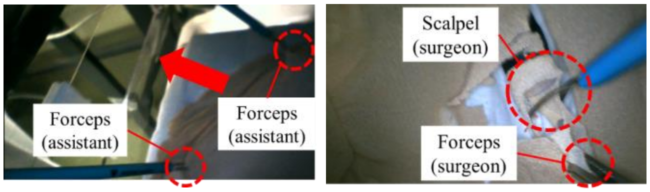
Figure 12. Port placement

The result of the task completion time is shown in Fig.15. The results showed that time was reduced for all tasks. The overall task completion time was reduced by 144 s. In task 1, the task completion time was reduced by 22 s. The reduced working time is likely because there is no longer a need to give instructions to the assistant or cooperate with the assistant. In task 2, a reduction of 31 s was observed. This may have been shortened for the same reason as task 1. The result of task 3 is significantly reduced by 59 s, but that of task 4 is reduced by 6 s, and no significant shortening can be seen. This is related to the difference in the content of tasks 3 and 4 in each method. Focusing on the content of task 3, in the conventional method, the assistant grasps and pulls the large intestine, and then the surgeon approaches the IMA, while in the proposed method, the surgeon approaches the IMA without grasping the large intestine. Focusing on the content of task 4, in the conventional method, the assistant only changes the direction of traction the colon held in task 3, whereas, in the proposed method, the surgeon had to control the instrument to approach, grasp, and retract the large intestine. We focused on grasping and pulling the large intestine. The task completion time for these actions is shown in Fig. 16. From Fig. 16, in the proposed method, the task completion time is reduced by 12 s because of not giving instructions to the assistant. In addition, the task completion time for moving the instrument and grasping was also reduced by about half. When grasping and pulling the large intestine and applying tension to the membrane tissue, it must be grasped with contact at multiple points. However, since conventional forceps can only grasp one point, it is necessary to use two forceps, and the movement of the instrument and the grasping action must be performed twice. On the other hand, since the proposed robotic forceps has a large surface and multiple fingers, achieving multi-point contact with a single movement is possible, and may have reduced the task completion time.

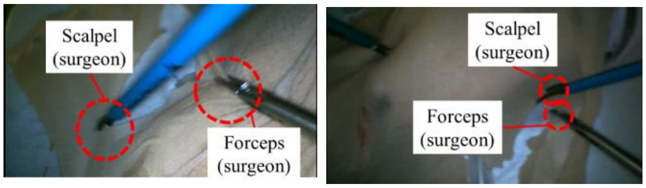
The physical strain during the task was evaluated using RULA [6]. Figure 17(a) shows the posture when the task was judged to be the most burdensome while performing the surgical task using conventional forceps. The score at this posture was determined to be AL=2 (GS=3). Figure 17(b) shows the posture determined to be the most burdensome while performing the surgery task using the proposed robotic forceps. The score at this posture was determined to be AL=2 (GS=3). Therefore, the physical strain required when using the proposed robotic forceps is comparable to that of the conventional forceps, which is an acceptable strain.



(a) Moving the omentum (Task 1) (b) Moving the small intestine (Task 2)

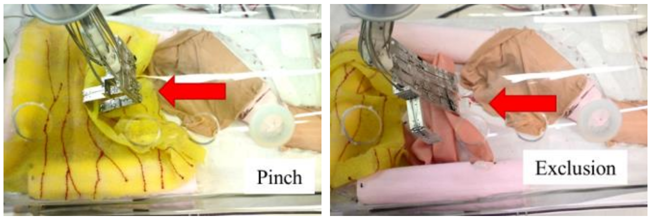


(c) Traction on the large intestine (Task 3-1) (d) Cutting the IMA (Task 3-2)

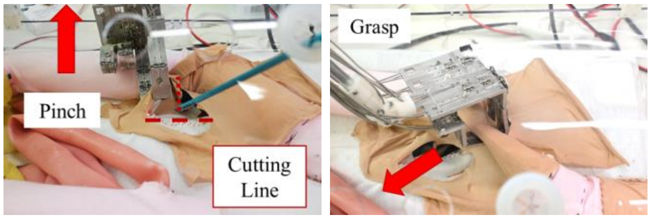


(e) Cutting the peritoneum (Task 4) (f) Cutting the retroperitoneum (Task 5)

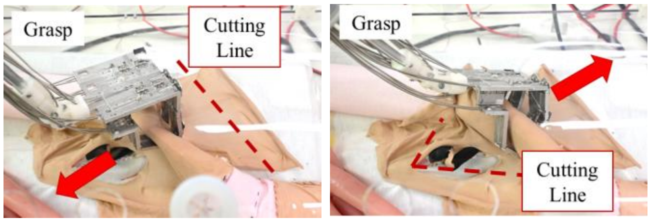
Figure 13. The surgery processes with conventional forceps



(a) Moving the omentum (Task 1) (b) Moving the small intestine (Task 2)

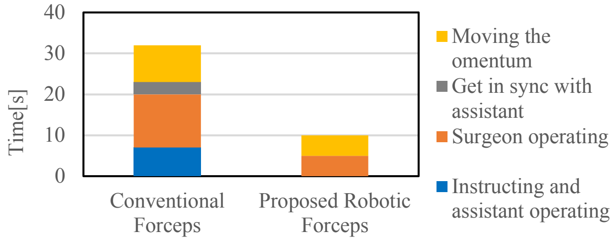


(c) Cutting the IMA (Task 3) (d) Traction on the large intestine (Task 4-1)

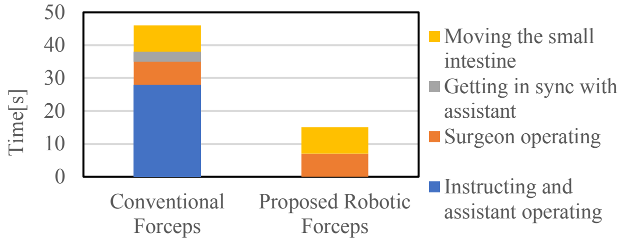


(e) Cutting the peritoneum (Task 4-2) (f) Cutting the retroperitoneum (Task 5)

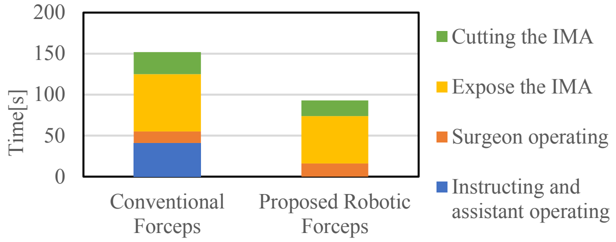
Figure 14. Surgery processes with the proposed robotic forceps



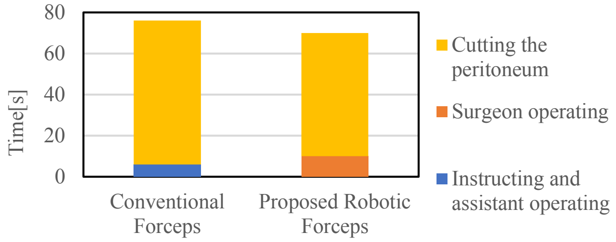
(a) Moving the omentum (Task 1)



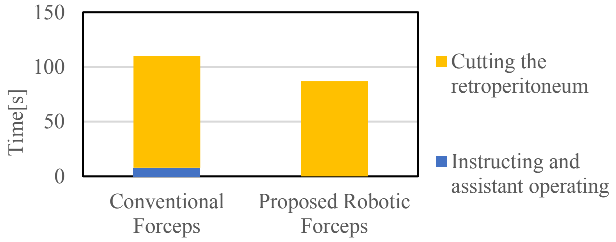
(b) Moving the small intestine (Task 2)



(c) Cutting the IMA (Task 3)



(d) Cutting the peritoneum (Task 4)



(e) Cutting the retroperitoneum (Task 5)

Figure 15. Task completion time

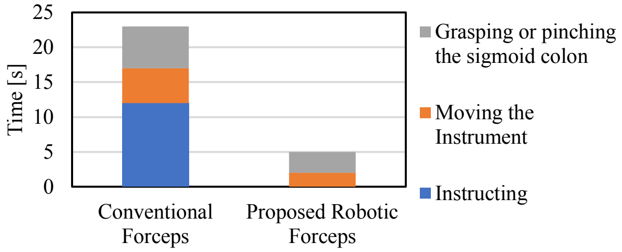


Figure 16. Task completion time of grasping and traction on the large intestine

(a) Conventional forceps (b) Proposed robotic forceps

Figure 17. The posture while performing the tasks of sigmoidectomy

IV. CONCLUSION

In this study, we developed a five-fingered robotic forceps that can be inserted through a 20-mm incision to create a surgical instrument that is easy to operate in gastrointestinal laparoscopic surgery. The proposed robotic forceps can perform three operations on the digestive organs: grasp, pinch, and exclusion. Experiments simulating sigmoidectomy showed that the proposed robotic forceps reduced the surgical time. An evaluation of the physical burden while using the proposed robotic forceps using RULA confirmed that the physical burden was comparable to that of conventional forceps and that it was tolerable. The above showed that the proposed robotic forceps could improve surgical efficiency. In the future, we recommend that doctors conduct experiments and discuss whether the proposed robotic forceps can be used in actual surgery.

ACKNOWLEDGMENT

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