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Assemblable Three Fingered Five-DOF Hand for Laparoscopic Surgery

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Abstract— **In laparoscopic surgery, surgeons perform surgery in the abdominal cavity by using only slender instruments that can be inserted through small diameter trocars. When it is difficult to perform surgery by using only instruments for laparoscopic surgery, they often make a 7-8 cm incision through which their hand can be inserted. Clearly this is invasive compared with complete laparoscopic surgery. This paper proposes an assemblable mechanical hand like a human hand that can be inserted through trocars. We already developed a three-fingered three-degree of freedom assemblable hand. The purpose of this paper is to develop an assemblable hand with more degrees of freedom that can grasp/push aside large internal organs and open membranes. The developed hand has three fingers with a total of five degrees of freedom. Its power transmission mechanisms and assembling method are completely different from those of the previous hand. The hand is assembled from body and finger units with an installation tool. The finger unit is fixed to the body unit with only one screw by using the installation tool. To drive the fingers, power is transmitted with cables, gears and shafts. Experimental results verify that the hand can be assembled in a closed space and that it can grasp and push aside various objects.**

I. INTRODUCTION

In laparoscopic surgery, the abdominal cavity is inflated by gas to make a space for surgery. Surgeons perform surgery by using slender instruments inserted through small diameter trocars placed on the abdominal wall. Laparoscopic surgery is minimally invasive by making only small incisions. While it can reduce physical and mental pain of patients, it requires skills and tolerance of surgeons. There have been lots of studies to improve the dexterity of forceps for laparoscopic surgery [1]–[5]. The surgical robots in [2]–[4] are remotely operated master and slave systems with multi-degree of freedom forceps. That in [5] is an integrated master and slave system that can reduce setting time and space. However, such dexterous forces are too small to manipulate large internal organs

As for usual instruments for laparoscopic surgery, grasping forceps that have relatively large grippers are available [7]. They are still too small for large internal organs. Retractors such as a fan retractor, a liver retractor, etc. are also available. The former spreads out plates in a fan-like form. However, spread plates often catch organs between them. The latter cannot necessarily form shapes suited to internal organs.

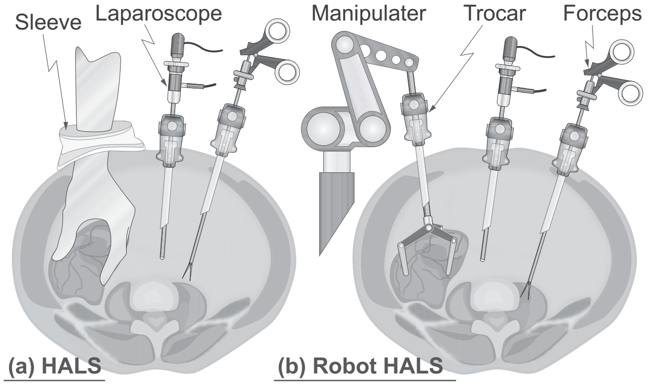

Fig. 1. Proposal of Robot HALS

When it is difficult to perform surgery by using these instruments, surgeons often apply HALS (Hand Assisted Laparoscopic Surgery) and make a 7-8 cm incision through which their hand can be inserted (Fig. 1 (a)). Clearly this is invasive compared with complete laparoscopic surgery.

The purpose of this paper is to develop a mechanical hand like a human hand that can be inserted through trocars and can perform grasping, manipulating, and pushing aside large internal organs. The hand is assemblable, that is, its parts can be inserted through trocars and can be assembled in the abdominal cavity. We already presented our first prototype of a three-fingered three-degree of freedom assemblable hand [8]. Unlike the modular laparoscopic grasper in [6], the hand is assemblable inside a human body.

This paper presents our second prototype of an assemblable hand with more degrees of freedom, that is, a three-fingered five-degree of freedom hand with completely different power transmission mechanisms that can be assembled in a completely different way. There are two directions in this study. One is to develop simple and small degree of freedom hands specialized for a single task such as grasping or pushing aside. The other is to develop large degree of freedom hands that can perform multiple functions aiming at replacement of a human hand as shown in Fig. 1 (b). The assemblable hand in this paper is in the latter direction.

This paper is organized as follows. Section II shows the design concept of the proposed assemblable hand and section III describes its mechanisms. Section IV shows experimental results and section V discusses subjects for future work.

II. DESIGN CONCEPT

A. Number of fingers and degrees of freedom

We designed an assemblable hand while considering what it could perform. An assemblable hand with only two fingers

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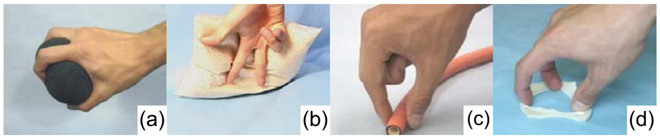

Fig. 2. Surgical manipulations

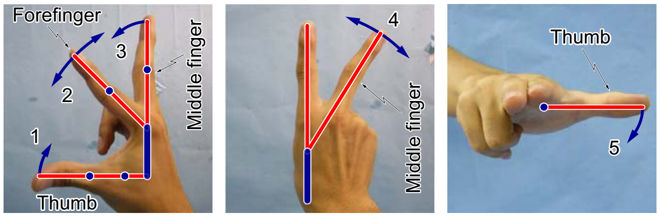

Fig. 3. Motion degrees of freedom for the manipulations

cannot envelop/push aside a large internal organ, whereas it is hard to develop a four-fingered assemblable hand. Therefore we decided to develop a three-finered assemblable hand and concluded that we could develop an assemblable hand that could perform manipulations shown in Figs. 2 (a) through (d). (a) and (b) are grasping/pushing aside soft and large internal organs to make a space, respectively. (c) and (d) are pinching tubular organs and opening membranes, respectively. These manipulations are difficult to perform with traditional instruments for laparoscopic surgery, which require the motion degrees of freedom shown in Fig. 3. To perform the grasping, pinching, and opening, the motion degrees of freedom 1, 2, and 3 of the thumb, forefinger and middle finger, respectively, are necessary. To perform the pushing aside, motion degrees of freedom 4 and 5 of the middle finger and the thumb, respectively, are necessary. The fingers also need to be able to exert fingertip forces in both the closing and opening directions, whereas the fingers of the previous hand can exert a fingertip force only in the closing direction [8].

B. Three fingerd five-DOF hand

Figure 4 shows the developed three fingered five degree of freedom hand (3f5d-hand). This hand has nine joints. The joint set 1a, 1b and 1c are dependently driven with a shape-fitting mechanism. So are the joint sets 2a and 2b, and 3a and 3b. Each joint can rotate 90 degrees from the configuration in which the fingers are in full extension. The assembled hand is one size smaller than author's hand in consideration of using with other instruments. Its dimensions are shown in Fig. 4

The 3f5d-hand is assembled by connecting the cylindrical body unit and the finger unit with the installation tool shown in Fig. 5. The body unit has the two degree of freedom middle finger, and the finger unit has the two degree of freedom thumb and single degree of freedom forefinger. The body unit has an operation part at its back end to operate the five degrees of freedom manually. Currently the 3f5d-hand has no actuators. Master-slave control with actuators is our future work. The dimension of each unit is 12 mm in diameter so that it can be inserted through trocars. The next section presents the proposed assembling method.

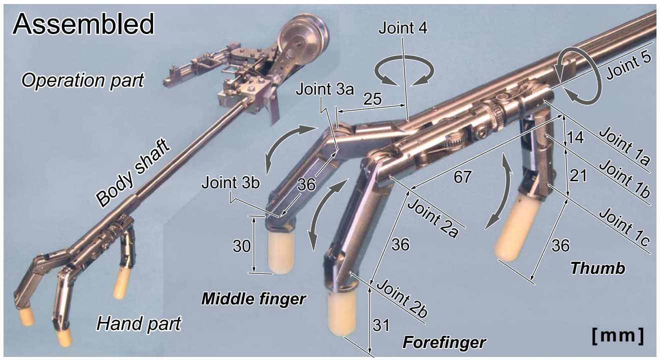

Fig. 4. Assemblable three-fingered five-DOF hand

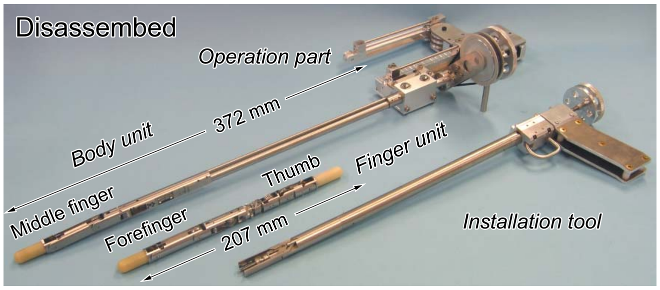

Fig. 5. Units of the assemblable three-fingered five-DOF hand

C. Assembling method

In laparoscopic surgery, typically three to five ports are made on the abdominal wall. Two of them are used for assembling and disassembling the 3f5d-hand. The 3f5d-hand uses only one port after assembled. We propose an assembling procedure that uses one hex socket head screw for fixing the finger unit to the body unit. Figure 6 illustrates the proposed assembling procedure.

Step 1: Insert the installation tool and the finger unit through trocars 1 and 2, respectively.

Step 2: Grasp the finger unit with the gripper equipped at the front end of the installation tool.

Step 3: Insert the body unit through trocar 2 while the installation tool grasps the finger unit.

Step 4: Place the finger unit to the side of the body unit and screw up the hex socket head screw set up at the tip of the installation tool.

Step 5: After fixing the finger unit to the body unit, detach the installation tool from the finger unit and take it out of the abdominal cavity.

The disassembling procedure is the reverse of this assembling procedure.

The previous hand is assembled by inserting fingers in its body [8]. Such an assembling method does not suit for this hand [8] because the power transmission mechanism of this hand needs to be more densely installed in its body unit.

III. MECHANISM DESIGN

A. Installation tool

Figure 7 shows the schematic diagrams of the installation tool. As shown in (a), the installation tool has two coaxial

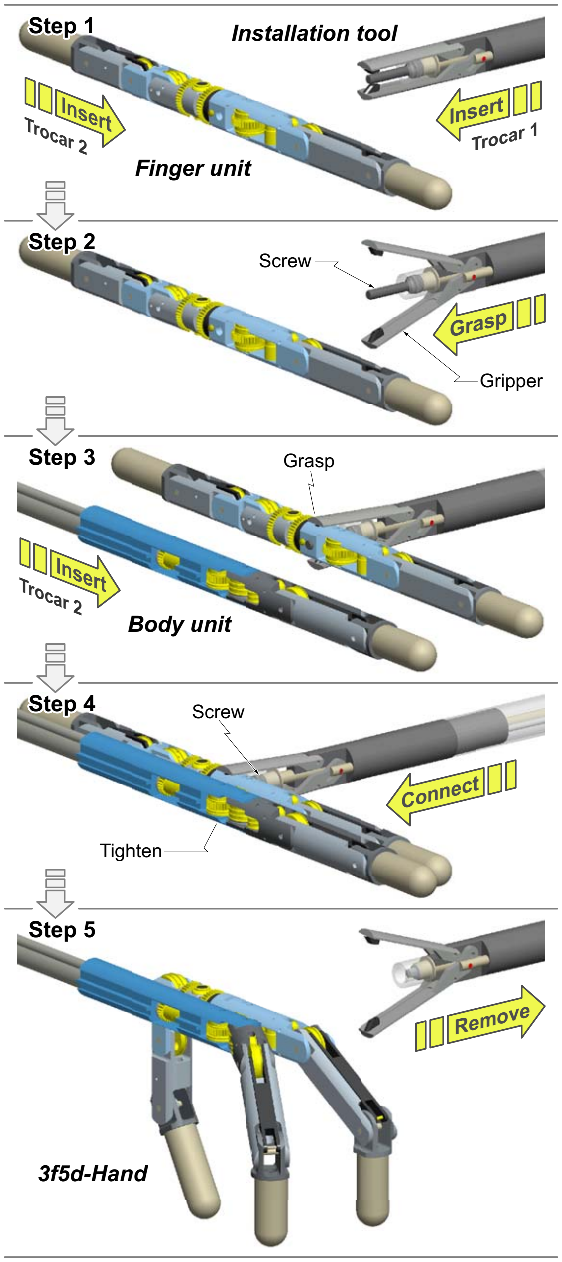

Fig. 6. The proposed assembling procedure

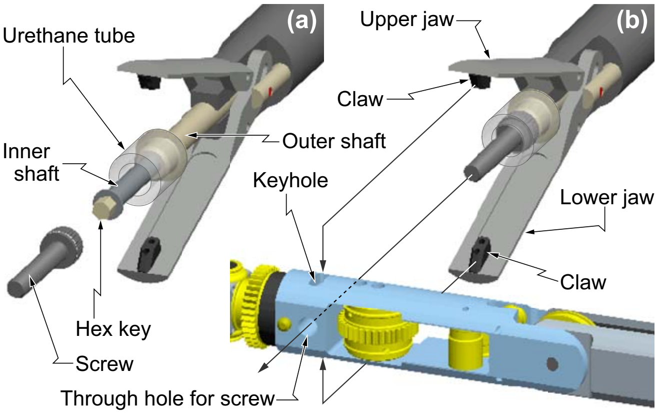

Fig. 7. The mechanism of the installation tool

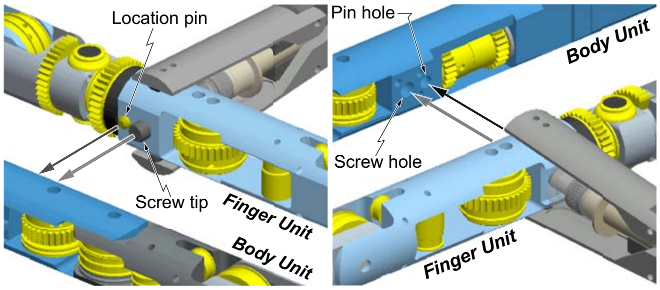

Fig. 8. Connection of the body and finger units

shafts, inner and outer shafts, at its center. The inner shaft has a hex key to turn the screw on its end. The urethane tube attached at the end of the outer shaft holds the screw with its head inserted into the tube. The inner shaft can rotate and translate with respect to the stationary outer shaft and therefore it can tighten the screw. As shown in (b), the gripper has claws at its upper and lower jaws. They fit the key holes on the finger unit. This enables the gripper to grasp the finger unit tightly in the abdominal cavity. The finger unit has a penetrating hole of 3.1 mm in diameter which is a little larger than the screw so that the screw can stick out the hole without being tightened. Figure 8 shows the connection of the body and finger units. The finger unit also has a pin on its side which fits a hole on the body unit for easier adjustment of their positions and orientations. The finger unit is fixed to the body unit by tightening the screw.

B. Drive mechanism

Figure 9 (a) shows the structural diagram of the mechanisms, (b) the arrangement of cables inside of the body unit, (c) the cross section of the body shaft and (d) the side view of the bowl-shaped pulley. The five cables (cable i∼v) and the inner and outer shafts transmit power from the operation part to the finger joints. The inner and the outer shafts are eccentrically located so that the five cables can be arranged in the body shaft as shown in (c). The dimensions of the cables are 0.45 mm in diameter and 0.03 mm in strand diameter. Their strength is 153 N.

Next, we describe the power transmission mechanisms of the 3f5d-hand.

Middle finger: As shown in (b), three cables i, ii, and iii drive joints 3a and 4. This cable mechanism is the same as that of Stanford/JPL hand [9]. Cables ii and iii drives pulley M_1 via pulleys M_3 and M_4 which are free about joint 4. Pulley M_1 in turn rotates joint 3a. Cable i drives pulley M_2 which in turn rotates joint 4.

Forefinger: The power transmission mechanism from the body shaft to the forefinger in the finger unit uses a pair of gears, gears a and A, which are engaged when assembled. Cables iv and v drive gear a which in turn rotates gear A. In the finger unit gear A rotates pulley F_1 which in turn rotates joint 2a with cable vi.

Thumb: The power transmission mechanism from the body shaft to the thumb also uses pairs of gears, gears b and B, and gears c and C. Gears b and c are fixed at the ends of

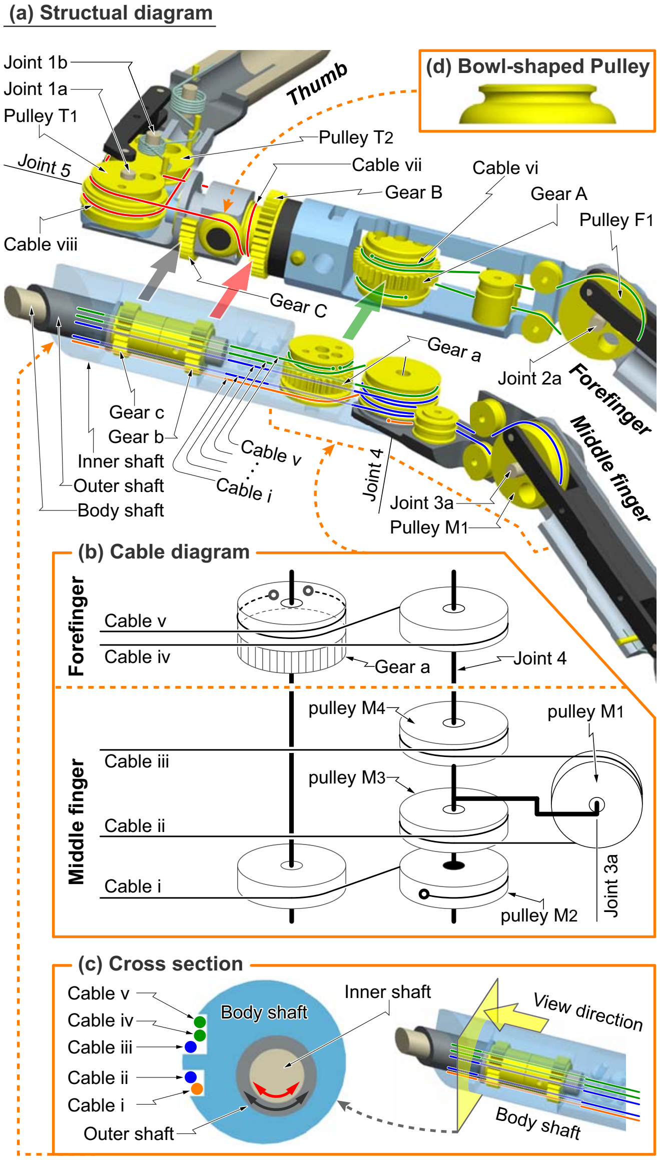

Fig. 9. Schematic diagram of the power transmission

the inner and outer shafts, respectively, and the rotations of them drive gears b and c. Gear b rotates gear B which in turn rotates joint 1a via pulley T_1 and cable vii. Pulley T_1 rotates pulley T_2 which in turn rotates joint 1b with cable viii after 90 degrees rotation of joint 1a from the configuration in which the thumb is in full extension. Gear c rotates gear C which in turn rotates joint 5. The rotation axes of gear B and pulley T_1 are orthogonal. The bowl-shaped pulley shown in (c) can effectively twist cable vii 90 degrees in a small space.

The shape-fitting mechanism shown in Fig. 10 is used for the two joints of each finger, that is, joints 1b and 1c, joints 2a and 2b, and joints 3a and 3b.

IV. EXPERIMENTS

A. Measurement of fignertip forces

We measured the fingertip forces of the thumb, forefinger, and middle fingers when joints 1a, 2a, and 3a are driven in the opening and closing directions, respectively. For joints 4 and 5, we do not measure the fingertip forces because the power transmission mechanism for joint 4 is almost the same as that for joint 3a, and that for joint 5 is the same as that for joint 2a.

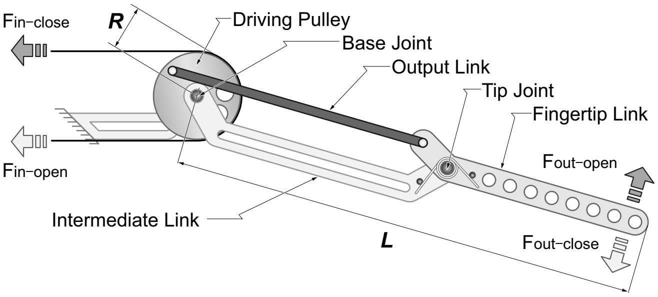

Fig. 10. Shape fitting mechanism of the fingers

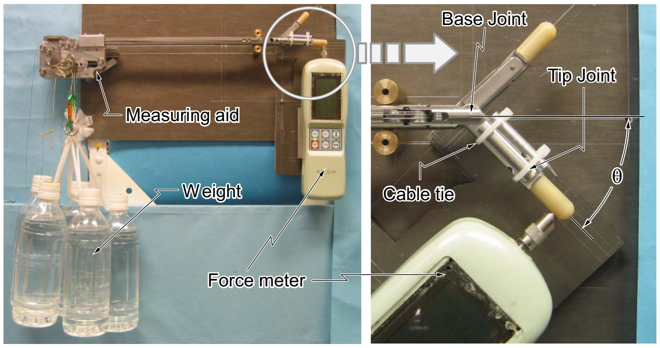

Fig. 11. Experimental setup

Figure 11 shows the experimental setup. For each joint, a weight (500 ml bottled water) was hung on its drive cable at the end in the operating part. The measuring aid uses some pulleys to change the direction of the gravity. As shown in Fig. 10, let $F_{in-close}$ and $F_{in-open}$ be the input forces, that is, the tensions of the cable, in the closing and opening directions, respectively. Let also $F_{out-close}$ and $F_{out-open}$ be the fingertip forces in the closing and opening directions.

The maximum fingertip force the finger can exert is the smallest when the figner is stretched out. To evaluate the fingertip force in the worst case, we maintain the finger stretched out by stopping the distal joint with a cable tie.

For each joint, $F_{out-close}$ and $F_{out-open}$ were measured 5 times and their averages were calculated with $F_{in-close}$ and $F_{in-open}$ increased. Figures 12, 13 and 14 show the experimental results of the fingertip forces of the middle, forefinger and thumb fingers at the joint angle θ=45 degrees. Equation (1) gives the theoretical value of the fingertip force, which assumes that there is no loss of power in the mechanism where R is the radius of the pulley and L is the distance between the base joint and the point of measurement for each finger. The values of these variables are shown in Table I.

$$\begin{cases} F_{out-close} = \dfrac{R}{L} F_{in-close} \\ F_{out-open} = \dfrac{R}{L} F_{in-open} \end{cases} \tag{1}$$

TABLE I

RADIUS AND LENGTH OF EACH FINGER

Components	Radius[mm]	Length[mm]
Second finger	5.675	61
Forefinger	5.675	62
Thumb	5.025	67

The ratio of a measured fingertip force to theoretical one defines the transmission ratio of the finger. As shown in Fig. 12 the measured fingertip forces of the middle finger are smaller than the theoretical ones. The transmission ratios in the closing and opening directions are 40∼50 % and 50∼60 %, respectively. As described in section III, the power transmission mechanism of the middle finger is complicated, which increases the friction between its moving parts and decreases its power transmission ratios. However the adequate fingertip force of 2 N is obtained when the input force is 40 N which is much smaller than the maximum strength of 153 N of the cable.

For the forefinger, as shown in Fig. 13, both the fingertip forces in the opening and closing motion reach almost 3 N when the input force is 40 N, and the high transmission ratios of 70∼80 % are obtained, respectively.

For the thumb, as shown in Fig. 14, the power transmission ratios in the closing and opening directions are about 35% and 40 %, respectively. The principal factor is also the friction between the moving parts. However the fingertip force still reaches almost 2 N with the input force of 80 N. It is our future work to reduce the frictions.

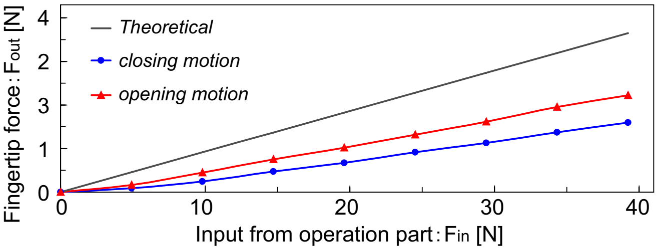

Fig. 12. Experimental results of the fingertip forces (middle finger)

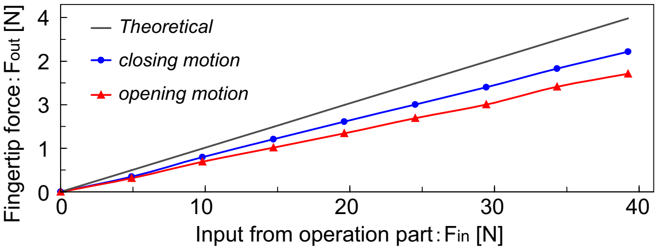

Fig. 13. Experimental results of the fingertip forces (forefinger)

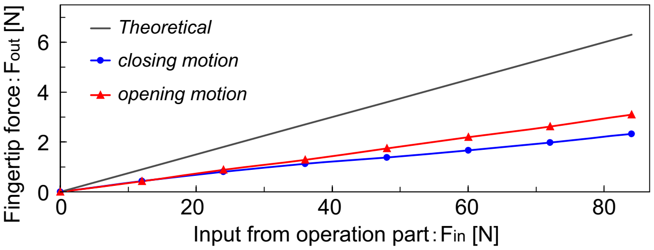

Fig. 14. Experimental result of the fingertip forces (thumb)

B. Assembling, disassembling, and manipulation

We assembled and disassembled the 3f5d-hand in a closed space (hemispherical space of 30 cm in diameter) by watching laparoscopic images. Figure 15 shows the photos of assembling, which correspond to the assembling steps in Fig. 6. In the assembling, it was difficult to position the hex socket head screw and the location pin to the body unit since the perception of a depth perspective in a laparoscopic view was difficult. However repeating practice enables us to assemble and disassemble the hand in 73 and 74 seconds, respectively.

Figure 16 shows the photos of manipulation experiments with the assembled hand. The 3f5d-hand can grasp a rubber sack filled with water (185 g), a bottle cap (2.6 g), a softball (188 g) and a pen (27 g). It can push aside a book efficiently by expanding the fingers in a plane. The 3f5d-Hand can also open the section of a sponge by driving its fingers in the opening direction.

We also conducted an experiment to evaluate the maximum weight that the 3f5d-Hand can grasp. Figure 17 shows the experimental setup. The hand grasps the aluminum block (30×30×47 mm, 112 g) on which the plastic bottle is hung. By putting water into the bottle continuously, we measured the weight of water when the block fell from the hand. During the experiment, the fingertip force of each finger were set 2∼4 N. The hand can grasp the block with up to 1.2 l of water. Note that the maximum weight is affected by the shape, surface friction and hardness of a grasped object.

In this experiment, backrush and skipping cogs did not occur. The assembling method by using a screw is effective

Fig. 15. Assembling experiment in a closed space

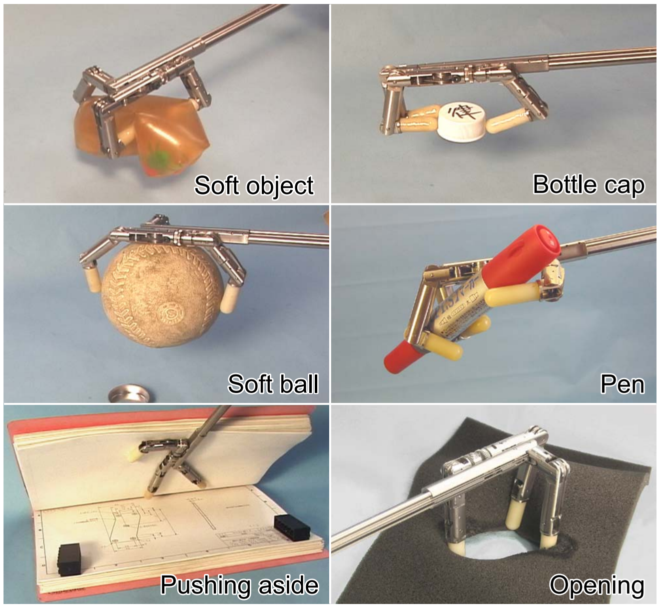

Fig. 16. Manipulation with the hand

Fig. 17. Weight exp.

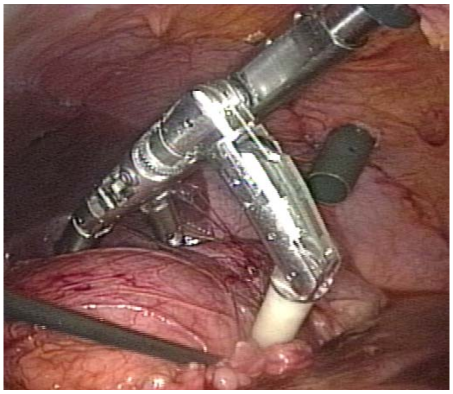

Fig. 18. In Vivo experiment

in fixing the finger and body units rigidly and in transmitting power between them.

We had a short time opportunity to conduct an In Vivo experiment. Figure 18 shows the photos of the In Vivo experiment. We can confirm that the assembling in the abdominal cavity is possible. However it took about six minutes since the space in the abdominal cavity was smaller than expected and the laparoscopic view was poor. Note that this is the result of only one test since it was performed in the remaining time of other experiments. Better laparoscopic views taken from an appropriate direction could make the assembling time shorter.

V. DISCUSSION

Based on the experiments, we consider that we should make the following improvements for our future work.

1) The 3f5d-Hand has five degrees of freedom and it is hard to operate them manually.
   Solution: As mentioned, this hand should be controlled in master-slave manner. Therefore holding manipulators should be introduced.
2) Training is necessary to assemble and disassemble the 3f5d-hand
   Solution: A possible way to simplify the assembling is to create keyways on the top and bottom faces of the body unit in which the upper and lower jaws of the installation tool can fit. This simplifies the alignment of the screw and the screw hole. Instead of using a screw, using a band that snaps around the body unit could simply the assembling. In addition, if a holding manipulator is introduced, robotizing the assembling and disassembling procedures is a solution. Robots surpass humans in precise positioning.
3) The gears used in the power transmission mechanisms could touch internal organs or tissues and could injure them.
   Solution: Make the gears smaller than the fingers in diameter and install a cover case outside the gears.
4) The shape-fitting mechanism of the fingers can fit to hard objects but cannot to soft objects.
   Solution: Adopt other drive mechanisms, such as an interlocking joint mechanism in which two joints equally or proportionally rotate.

As mentioned, the other direction of this study is to develop simple hands with small degrees of freedom specialized for a single task such as grasping or pushing aside. We are also developing an easy-assemblable simple hand in that direction.

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