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Detachable-Fingered Hands for Manipulation of Large Internal Organs in Laparoscopic Surgery

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Abstract— **In laparoscopic surgery, surgeons can use only rod-shaped instruments that can be inserted through a trocar and therefore high technique is required. To overcome this problem, much work has been done to develop multi-degree-of-freedom forceps. However they are still inadequate to grasp, manipulate or push aside large internal organs, like a spleen, pancreas, and liver. This paper proposes mechanical hands with detachable fingers that can be assembled in the abdominal cavity, each of whose parts can be inserted through a trocar. Two types of such three-fingered hands are developed. The three fingers of one are dependently driven and those of the other are independently driven. For each hand, we show fixing and power transmission mechanisms. Power of each hand is transmitted from operator's hand to its fingers by connecting wires with a ball and socket. Experimental results verify that both hands can grasp large and oily objects like internal organs. One goal of this study is to develop simple hands that can be used as a retractor. The other goal is to develop skillful hands that can replace surgeons' hands in hand assisted laparoscopic surgery which is still invasive by making a 7-8cm incision to insert a human hand into the abdominal cavity.**

I. INTRODUCTION

In laparoscopic surgery several trocars are stuck into the abdominal wall and the abdominal cavity is inflated by gas. Surgeons perform surgery in the abdominal cavity by using instruments inserted through the small holes of trocars. This kind of surgery does not make a large incision, and therefore patients can make quick recovery. However, surgeons are not able to manipulate internal organs directly with their hands, and therefore high technique is required. There are a number of studies to develop multi-degree- of-freedom forceps to improve the manipulability of forceps for laparoscopic surgery [1]-[6]. Zeus [3] and da Vinci [4] are commercialized. Such forceps must be small enough to pass through a trocar and they are still not suited for grasping, manipulating, or pushing aside large internal organs. Surgeons often wish to push aside large internal organs around the diseased part to make space for surgery.

We have proposed separable instruments for laparoscopic surgery whose parts can pass through a trocar and can be assembled inside the abdominal cavity to become large instruments. A traditional pursestring suture instrument (PSI) is a useful tool for suturing the cut end of a pipe-shaped internal organ, but it cannot pass through a trocar because it is a T-shaped instrument. Therefore we have developed a separable PSI for laparoscopic surgery[7]. By generalizing this idea, instruments of various shapes can be assembled in the abdominal cavity. This paper proposes a novel detachable-fingered hand, that is, its fingers are detachable from its main body and all of them can be inserted through a trocar. The hand is suited for grasping, manipulating, or pushing aside large internal organs. The separable PSI does not need to transmit power to the part connected to its main body, whereas the hand needs to transmit power to its fingers to bend their joints. This paper presents mechanisms to transmit power to the fingers.

This study has two different goals. One is to develop simple detachable-fingered hands with a small number of degrees of freedom for a single or few functions, e.g. a retractor. Such a hand could be more useful than existing retractors such as ”fan-retractor” and ”snake-retractor” [8]. The former has folded fans that can be expanded to push aside internal organs, but it often catches an internal organ or tissue between its expanded fans and therefore they cannot be expanded widely. The latter has many joints like a snake and can form a spiral shape to gain a large contact area suitable for pushing aside internal organs. However it cannot always form a desired shape. We consider that detachable-fingered hands with a small number of degrees of freedom should be handy. Thus it should be actuated manually without using electric motors or other actuators.

The other goal is to develop skillful detachable-fingered hands with a large number of degrees of freedom, e.g. six or more, to realize high performance aiming at replacement of surgeons' hands in Hand Assisted Laparoscopic Surgery (HALS). HALS is a variety of laparoscopic surgery that uses surgeon's hand. An incision of 7-8 cm is made to insert surgeon's hand into the abdominal cavity (Fig. 1). When it is difficult to perform surgery by using only instruments for laparoscopic surgery, HALS is often applied, which is more invasive than pure laparoscopic surgery. Detachable-fingered hands require only small incisions.

Detachable-fingered hands with a large number of degrees of freedom are too complicated to operate manually. Thus it should be actuated by electric motors or other actuators and controlled in a master-slave manner. This type of robot hand robotizes surgeons' hands. It will be a surgical robot completely different from those such as ”da Vinci” which robotizes forceps.

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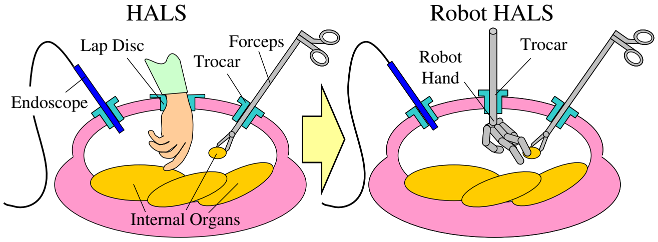

Fig. 1. Proposal of Robot HALS

We have developed two experimental models of three-detachable-fingered hands to verify the feasibility of the proposed concept. The three fingers of one of them are dependently driven and those of the other are independently driven, which are discussed in Sections 2 and 3, respectively. For each hand, its fixing and power transmission mechanisms are described.

II. DETACHABLE-FINGERED HAND WITH THREE DEPENDENTLY DRIVEN FINGERS

A. *Overview*

Detachable-fingered hands require followings: (1)All separated parts can pass through a trocar. (2)They can be assembled easily without using an excessive force in the abdominal cavity. (3)After assembling, they are rigidly connected with one another. (4)Power can be transmitted from outside the abdominal cavity to the fingers of the hand. (5)The hand can be disassembled and its parts can be taken out from the abdominal cavity through a trocar.

To verify the feasibility of such assembling and power transmission, we have developed the detachable-fingered hand with three dependently driven fingers shown in Fig. 2. This hand consists of a cylindrical main rod and three cylindrical one-dof fingers arranged every 120 deg. The main rod is 16 mm in diameter and 300 mm in length, and the fingers are 12 mm in diameter and 50 mm in length.

B. *Fixing and Power Transmission Mechanisms*

Figure 3 shows the mechanism of the hand. (a) is the bottom view (view from the palm) and (b) is the cross section cut along the dotted line in (a). Inside the main rod, sliders 1, 2, and 3 are arranged every 120 deg to fix the three fingers, respectively. The end of each slider is a wedge which fits wedge 9 of the finger. Sliders 1, 2, and 3 are extended to the operator side (upper of Fig. 3(b)). The operator pulls up/pushes down these sliders to fix/release the fingers, respectively. In the center of the main rod, there is ball pull 4 which drives the fingers, encircled by the three sliders. Ball pull 4 is connected to rod 5, which is also extended to the operator side. The operator pulls up or pushes down handle 7 attached to rod 5 to drive the fingers.

Figure 4 shows the fixing mechanism for one finger. (a) Coil spring 13 is holding slider 1. (b) By pushing wedge 9 of the finger into the hole of the main rod, slider 1 is pulled down and the hole of slider 1 faces that of the main rod. (c) When wedge 9 is completely pushed into the hole, the wedge of slider 1 fits wedge 9 and they are held by spring 14 temporarily. (d) After inserting other fingers into the holes of the main rods, slider 1 is pulled up strongly by tightening fixing screw 8, and the fingers are fixed on the main rod. In Fig. 4, fixing screw 8 is drawn as a small screw, but actually it is a large screw whose thread is cut around the main rod as shown in Figs. 2 and 3. Screw 8 can pull three sliders 1, 2 and 3 together to fix the three fingers.

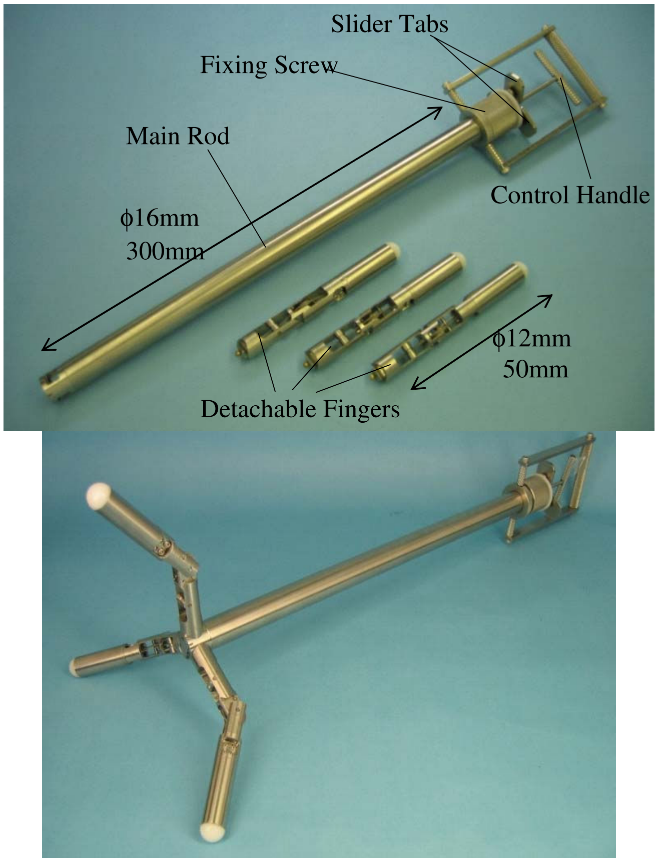

Fig. 2. Detachable-fingered hand with three dependently driven fingers

By loosening screw 8, the sliders are pulled down so that the fingers can be detached. If this fails, the operator can move the sliders directly by pushing tab 6 attached to the three sliders (Until now this failure has not occurred).

Figure 5 shows the bending motion of the fingers. Pulley 10 and stainless wire 11 are used to bend the fingers. Wedge 9 has a small hole in its center through which stainless wire 11 passes, and ball terminal 12 is connected to the end of stainless wire 11. When the finger is inserted to the main rod, ball terminal 12 is inserted into the hole in ball pull 4, which has three holes for the three fingers. By pulling up rod 5 connected to ball pull 4, the three ball terminals are pulled up and the three fingers are bent simultaneously.

The restore torque of coil spring 14 opens the finger when the wire tension is released as shown in Fig. 6. Let r be the radius of the pulley, F_{in} be the tension of the wire, L be the length of the finger, and K be the restore force by the coil

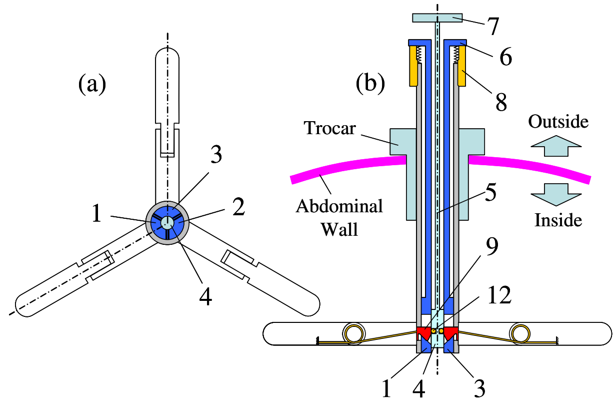

Fig. 3. Structure of the hand

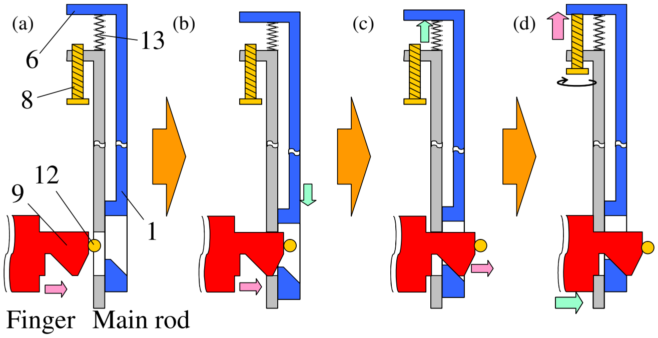

Fig. 4. Fixing mechanism

spring. The finger tip force F_{out} is given by

$$F_{out} = \frac{r}{L} F_{in} - K \quad (1)$$

C. Experiments

We did an experiment to verify the proposed power transmission from the handle to the fingers. The hand and a force meter are fixed on the experimental apparatus shown in Fig. 7 so that the fingertip can make contact with the force meter at a right angle and at a desired joint angle. The weight hung on the handle generates the wire tension F_{in}. It was increased from 0 kg to 10 kg by 1 kg. The limitation of the wire tension is decided by the available tension of the ball terminal shown in the catalogue. The fingertip force F_{out} was measured 10 times and their average was calculated at the joint angles 0, 45, 90, and 120 deg.

Figure 8 shows the results of this experiment. For each joint angle, the experimental data is close to theoretical one when the input force is smaller than 30 N. But when it is larger than 30 N, the transmission ratio decreases about 75-85 percent. This is because the wire bends almost squarely at wedge 9 and its friction increases.

In real use, surgeons would push aside internal organs or sort tissues by increasing and decreasing fingertip forces frequently. Thus we did an experiment of increasing the weight from 0 kg to 10 kg by 2 kg and decreasing it by 2 kg and F_{out} was measured. The results are shown in Fig. 9. Hysteresis appears as shown in Fig. 9. This is also because of the friction of the wire.

These experimental results verify that the power transmission by using wire and ball terminals is valid though it shows some influence of friction. Next we did the following experiments of assembling, grasping, and disassembling inside a box for the abdominal cavity. (1) The main rod was inserted from one hole and one finger was inserted from another hole as shown in Fig. 10. (2) After assembling the first finger temporarily, the main rod was rotated and the second and third fingers are assembled similarly. (3) When all fingers are assembled, they are fixed by tightening up screw 8.

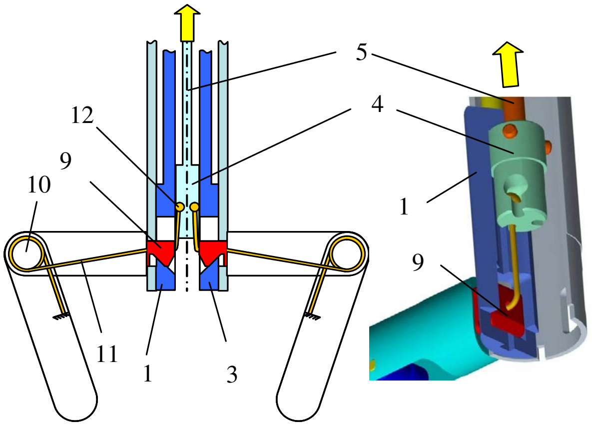

Fig. 5. Power transmission mechanism

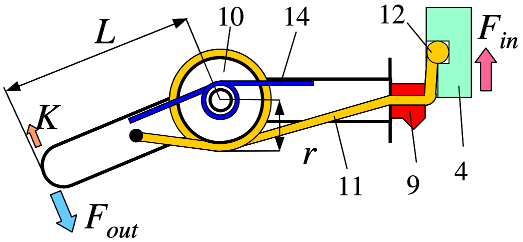

Fig. 6. Wire driven finger

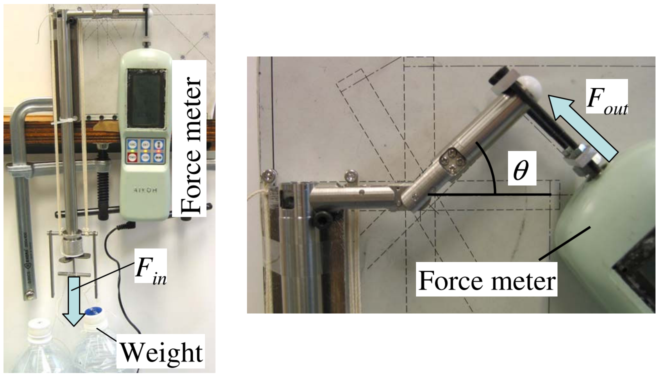

Fig. 7. Experimental setup

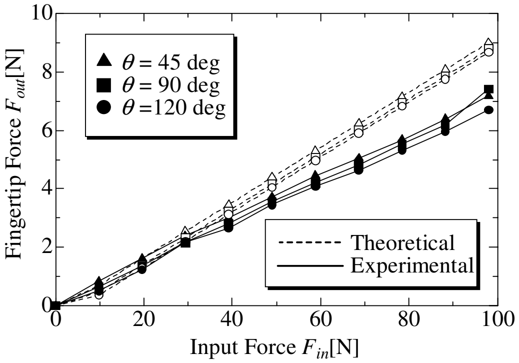

Fig. 8. Experimental results of power transmission

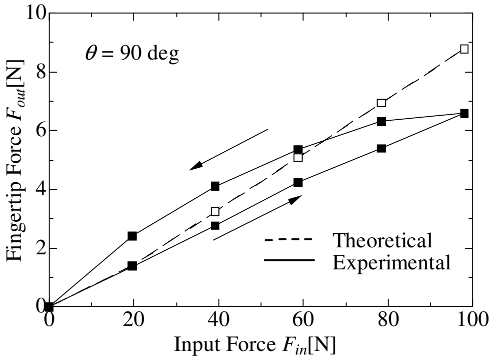

Fig. 9. Experimental results of increasing and decreasing the input force

The reverse of this operation can make the fingers detached. Actually the fingers cannot pass through a trocar from inside to outside because a trocar has a valve that stops backflow of the gas in the abdominal cavity. Thus an auxiliary gripper that can be inserted from a trocar is necessary to take out the fingers in real use.

In the experiment it took about 45 sec to assemble the hand with the direct view from the side. We also assembled the hand in a dome of 30 cm in diameter that imitates an abdominal cave with a laparoscope. The laparoscopic view provides a poor perspective and confuses our perception of directions. Nevertheless it still took only about 60 sec.

The assembled hand can grasp oily and non-rigid objects such as a piece of oily chicken and a rubber sack filled with water (185 g) as shown in Fig. 10 (4) and (5).

D. Problem and Improvement

It is most likely that the hand will be used with its fingers being down. Sliders 1, 2 and 3 are pulled up to fix the fingers. Because of their own weights, they tend to move down, which could drop the fingers while they are held by spring 13 temporally before tightening up screw 8(Fig. 11).

This problem can be solved by reversing the direction of holding, that is, sliders 1, 2, and 3 should hold the fingers when they are pushed down. The second experimental model discussed in the next section adopts this improvement.

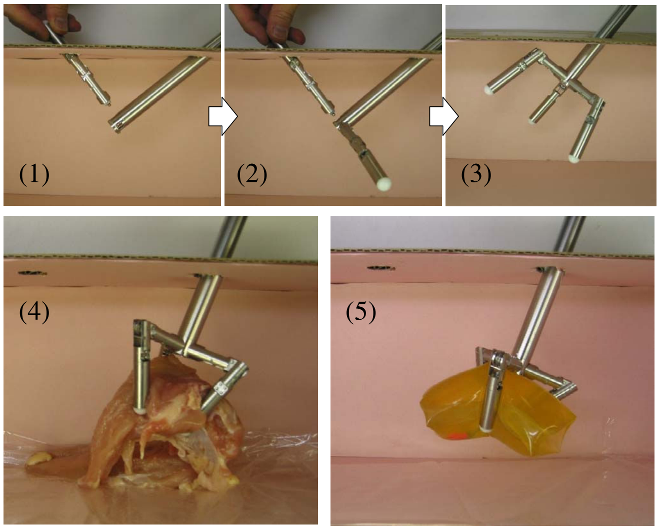

Fig. 10. Assembling and grasping in the closed space

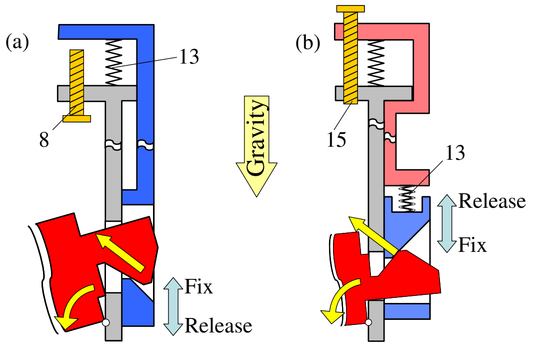

Fig. 11. (a) Problem with the slider mechanism and (b) its improvement

III. DETACHABLE-FINGERED HAND WITH THREE INDEPENDENTLY DRIVEN FINGERS

A. Overview

The first experimental model of a detachable-finger hand in Section 2 can bend its fingers only dependently, thus it can perform only simple grasping. If all fingers can be driven independently, they can perform not only grasping but also more dexterous manipulation, e.g. exploring the contour of an organ. In addition the diameter of the main rod of the hand in Section 2 is 16 mm so that it cannot pass through trocars with diameter 12 mm that are normally used. Therefore we have also developed a detachable-fingered hand with independently driven fingers whose main rod is 12 mm in diameter shown in Fig. 12.

B. Fixing Mechanism

This hand uses three ball terminals and ball pulls to independently drive its fingers as shown in Fig. 13. Three ball pulls 1, 2, and 3 are attached to rods 4, 5, and 6, respectively, which are operated with a human hand to drive the fingers. Ball pull 1 is arranged between forked wedge 11 of the finger to make its main rod thinner as shown in the right close-up of

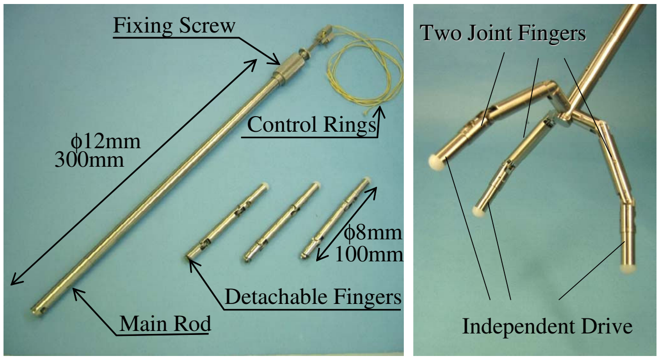

Fig. 12. Detachable-fingered hand with three independently driven fingers

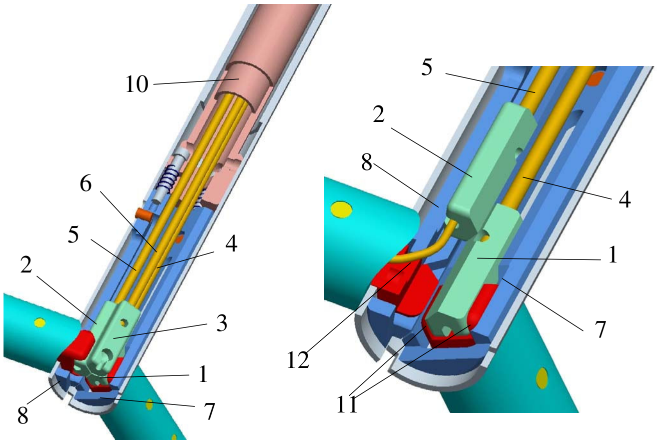

Fig. 13. Independent power transmission mechanism

Fig. 13. Slope 12 relaxes the sharp bend of the wire and can reduce its friction. Three sliders 7, 8, and 9 fix the fingers. In Fig. 13, slider 8 is shown in section and slider 9 is not shown to make a view of the inside of the main rod.

The fingers of the first experimental model are fixed by pulling up its sliders, whereas those of this hand are fixed by pushing down its sliders. The three sliders of this hand are thin in the thin and long rod (12 mm in diameter). Thus they could be buckled easily by a compressive stress. To avoid this, the three sliders are united to pipe-shaped slider 10 as shown in Fig. 14. (It is a cross section as Fig. 3 (b)) A pipe is strong against compression. Thus united pipe-shaped slider 10 can be made thin, and rods 4, 5, and 6 for driving the fingers can be arranged in the pipe. Spring 13 pushes branch slider 7 when the finger is held temporarily. After inserting all fingers, by tightening up screw 15, united slider 10 pushes down the three branch sliders, which fixes the fingers. In Fig. 14, screw 15 is drawn as a small screw, but actually it is a large screw just like fixing screw 8 of Fig. 3.

However, because of spring 13, united slider 10 cannot pull up the branch slider if its wedge and the wedge of the finger are jammed. This fails to release the finger (Until now this failure has not occurred). For safety we introduced pin 14 as shown in Fig. 15 so that united slider 10 can pull up the three branch slider securely.

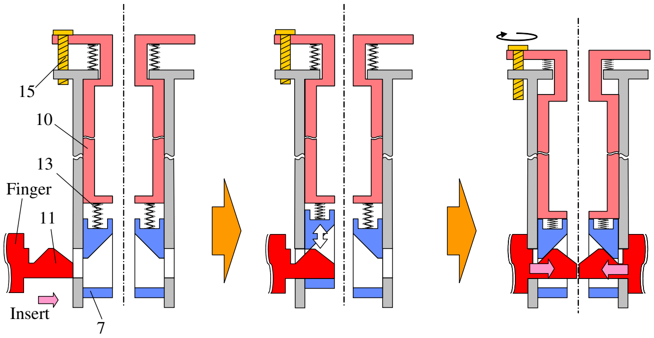

Fig. 14. Branch sliders (two of them are shown) and united slider

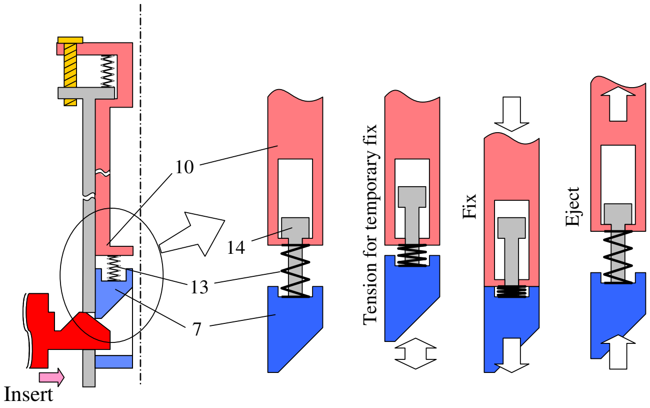

Fig. 15. Pin 14 to securely release the fingers

C. Experiments

We developed two-joint shape fitting fingers for this hand to hold objects more flexibly. But experiments show that the maximum fingertip force is about 2 N, and about 50 percent of the transmitted force is lost in the fingers. This is because the fingers are made thin, 8 mm in diameter, and their pulleys are too small to rotate smoothly. It is our future work to redesign fingers for this hand.

We did an experiment to measure the transmission ratio of the wire from the operator side to the fixing mechanism, instead of the fingertip. Figure 16 shows the results. As F_{in} increases, the transmission ratio decreases. The transmission ratio is over 70 percent. Because the wire is thin to suit for the thin finger, the ball terminal becomes small and the limit of tension also becomes small. So we limited the tension F_{in} to 35 N in the experiment. This problem can be improved by making the fingers thicker.

Despite the imperfectness of the fingers, we experimentally verify that the hand can be assembled in the closed box, can drive the fingers independently, and can grasp a piece of oily chicken as shown in Fig. 17. Because each finger of the hand has two joints, they do not stick out compared with those of the dependently driven fingers in Fig. 10. This is desirable to prevent collision with internal organs.

To drive the three fingers independently, the left hand of a human operator grips the main rod, and the index, middle

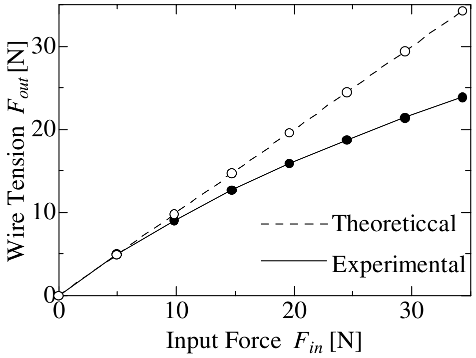

Fig. 16. Experimental results of power transmission

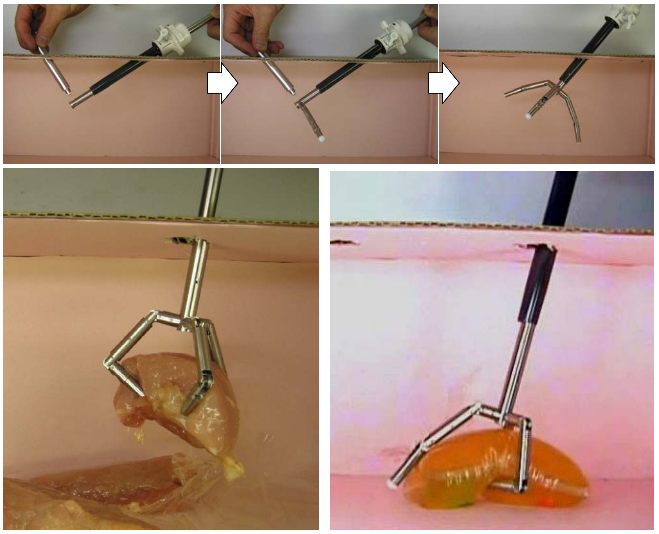

Fig. 17. Assembling and Grasping in the closed space

and ring fingers of his/her right hand pull the control rings (shown in Fig. 12) attached on the end tip of rods 4, 5 and 6. This one-to-one correspondence allows us to control the fingers of the hand intuitively.

In the experiment it took about 45 sec to assemble the hand with the direct view from the side. Then we assembled the hand in a dome by using a laparoscope. This is more difficlut than to assemble the dependently driven fingered hand because the connection mechanisms of this hand are smaller. Nevertheless it took only about 90 sec to assemble this hand.

IV. CONCLUSION

In this paper we proposed novel detachable-fingered hands for laparoscopic surgery. The hand would be able to grasp, manipulate and push aside large internal organs in real use. The developed hands can generate only uni-directional grasping force, because they use wire pulling mechanisms to drive fingers. To improve this drawback, various mechanisms for fixing and power transmission can be designed besides the proposed mechanisms. For example, using gears or water pressure are possible ways to transmit power. It is our future work to study all possibilities of such mechanisms experimentally to develop the simple and skillful detachable-fingered hands proposed in Section 1. It is also our future work to conduct in vivo experiments to improve their functions and ergonomics.

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