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Assemblable Three-Fingered Nine-Degree of Freedom Hand for Laparoscopic Surgery

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***Abstract*— This paper proposes an assemblable hand that can be inserted through trocars for robotic hand assisted laparoscopic surgery (HALS). When it is difficult to perform surgery using only slender laparoscopic surgery instruments, surgeons often apply HALS, which makes an incision about 7-8 cm through which their hand is inserted. This is invasive compared with complete laparoscopic surgery. We proposed robotic HALS to replace a human hand with a robotic hand. We previously developed a three-fingered five-degree of freedom assemblable hand. It is challenging to an assemblable hand with more degrees of freedom (DOF) that can be assembled with a simple assembly procedure. This paper presents an assemblable hand with three fingers and nine degrees of freedom-the 3f9d-hand. Its power transmission mechanisms and assembly procedure are completely different from those of our previous 3f5d-hand. The new hand consists of center, right, and left finger units. The center finger unit connects the operational part at its end and the right and left finger units connect to the operational part outside the abdominal cavity. This facilitates assembly and improves safety, which is a significant improvement compared with the previous hand. Although the hand has no wrist joint, its three finger joints play the role of a wrist joint. A preliminary experiment with a plastic model verified that the proposed assembly procedure was feasible and the hand was easily asembled and disassembled.**

I. Introduction

Laparoscopic surgery uses only small incisions in the abdominal wall and surgeons perform surgery with slender instruments inserted through small diameter trocars. Although this surgery can reduce the physical and mental pain of patients, surgeons with special skills and patience are required. A number of studies have focued on improving the dexterity of forceps for laparoscopic surgery [1]–[11]. The surgical robots in [2]–[7] are remotely operated master and slave systems that use forceps with multiple degrees of freedom. That in [10] is an integrated master and slave system that can the required set up time and space. However, its dexterous forceps are too small to manipulate large internal organs

Typically, grasping forceps with relatively large grippers and retractors, such as a fan or liver retractor, are available for laparoscopic surgery [12]. However, these are still also small for large internal organs and can cause damage to the organs when grasping them with the end of the instrument.

When it is difficult to perform surgery using these instruments, surgeons often turn to hand assisted laparoscopic surgery (HALS), making a 7-8 cm incision, and inserting their hand through the incision (Fig. 1 (a)). Clearly this is more invasive than compared with complete laparoscopic surgery.

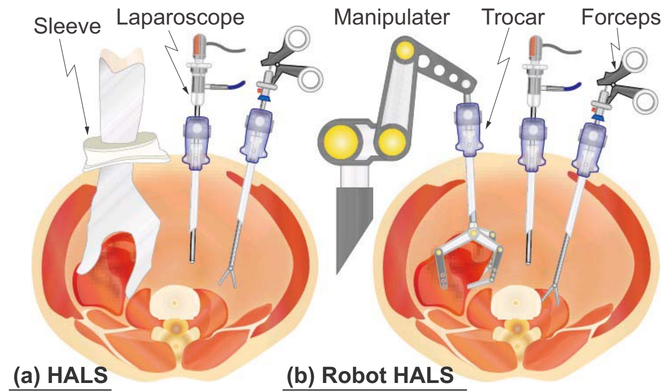

Fig. 1. Proposal of Robot HALS

This study aims at developing a mechanical hand for robotic HALS that can replace the human hand, as shown in Fig. 1 (b). We developed assemblable hands, the parts of which are inserted through trocars and can be assembled inside the abdominal cavity [13]-[15]. There are two directions in this study. First is to develop a simple hand, specialized for a specific task, e.g., retracting or grasping with small number of degrees of freedom, using single trocar assembly [15]. The other is to develop a hand with multiple functions that has a large number of degrees of freedom. Toward this goal, we developed a three-fingered five-degree of freedom assemblable hand (3f5d-hand) that works like a human hand [14]. Its ability to grasp and retract internal organs was verified in *in nivo* experiments.

However, the 3f5d-hand needs improvement. It does not have a wrist joint. The assembly and disassembly procedures are complex and require time and skills. The hand is too large for the abdominal cavity. It is a challenging to develop an assemblable hand with as many degrees of freedom as possible that can be assembled and disassembled with as simple a procedure as possible. This motivated us to develop a new assemblable hand with a different assembly and disassemby procedure. This paper presents a three-fingered nine-degree of freedom assemblable hand (3f9d-hand).

Many mechanisms have been proposed for multiple degree of freedom surgical tools for laparoscopic surgery using cables [2]-[7], gears [8], and linkages [9]-[11]. We developed power transmission mechanisms for the 3f9d-hand that

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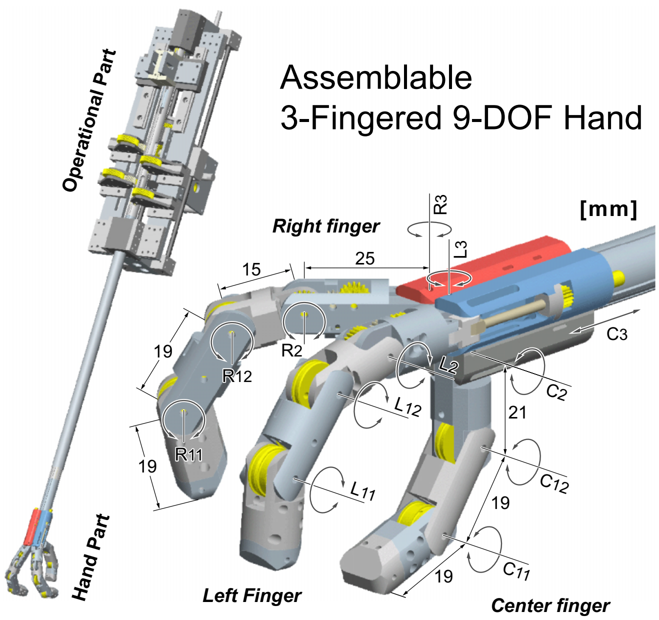

Fig. 2. Assemblable three-fingered nine-degree of freedom hand

combine these mechanical elements.

This paper is organized as follows: Section II presents the design of the new assemblable hand, Section III shows the proposed assembly procedure and a preliminary *in vivo* experiment for assembling it, using a plastic model, Section IV describes the mechanisms of the 3f9d-hand, and Section V shows the developed hand.

II. Design Concept

A. Three-fingered nine-degree of freedom hand

Figure 2 shows the computer model of the 3f9d-hand. This hand has nine active joints (C_{11}, C_2, C_3, R_{11}, R_2, R_3, L_{11}, L_2, and L_3) and three passive joints (C_{12}, R_{12}, and L_{12}). The joint set of C_{11} and C_{12} is interlocking and the two joints rotate equally. The same is true for the joint sets R_{11} and R_{12}, and L_{11} and L_{12}. The entire center finger translates forward 5 cm and backward 3 cm along the body shaft, which is denoted by joint C_3. R_3 and L_3 rotate $\pm 90°$ from the configuration where the right and left fingers are fully extended. Joints C_2, R_3, and L_3 also rotate 90°. The assembled hand is slightly smaller than the 3f5d-hand. Its dimensions are shown in Fig. 2.

Figure 3 shows examples of configurations that the 3f9d-hand can perform. Although it has no wrist joint, the 3f9d-hand can grasp from the side and top, as shown in Figs. 3 (a) and (b). The three finger joints, R_2, C_2, and L_2, play the role of a wrist joint. A wrist joint is highly desirable but makes the design of a multiple degree of freedom assemblable hand significantly difficult because all power transmission lines for finger joints must pass through it. Wrist equivalence, using the three finger joints, is an alternative solution. Figures 3 (c) and (d) show the action of pushing object objects aside to make space and Fig. 3 (e) illustrates pinching by closing the fingers. The reverse of pinching is opening the fingers to

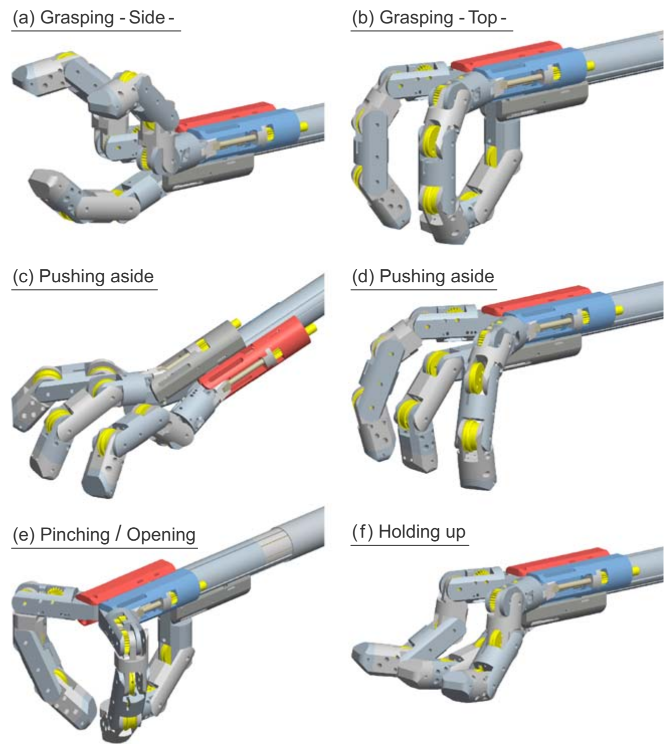

Fig. 3. Manipulations performed by the 3f9d-hand

make space. In Figure Fig. 3 (f) the hand is holding up an object, such as an internal organ, with the three fingers.

The 3f9d-hand is assembled from three units-the center, right and left units, as shown in Fig. 4 (a). Each unit consists of a finger and a shaft. The center unit also has an outer pipe and an operating part at its back to operate the nine degrees of freedom. The right and left units are symmetric. The cross section of each shaft is fan, shaped with a center angle of 120° and radius of 6mm as shown in Fig. 4 (b). The three units are bundled to form a hand as described in the next

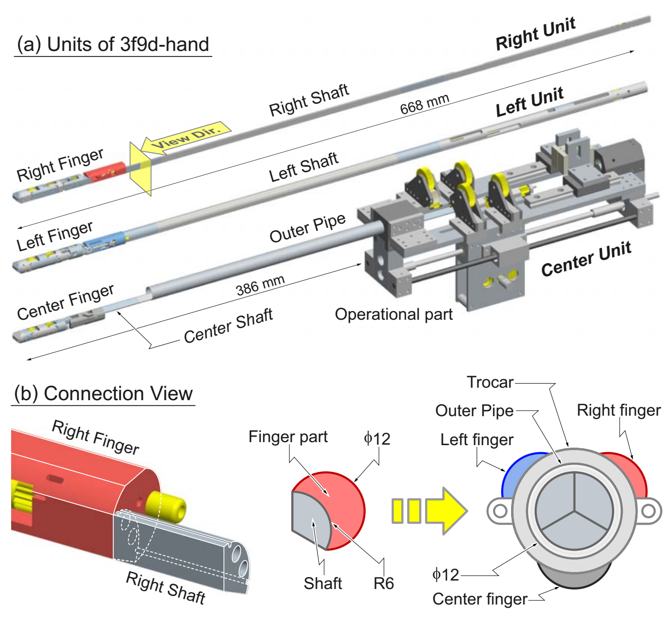

Fig. 4. (a) Units and (b) their cross sections

section.

The outer pipe has outer and inner diameters of 12.7 and 12.1 mm, respectively, so that it can be inserted through a trocar. Currently, the operational part is being developed without actuators. In future we will achieve control over the 3f9d-hand in a master-slave manner.

III. Assembly Procedure

In laparoscopic surgery, three to five trocar ports are placed in the abdominal wall. Typically, there is a pair opposite to each other. For assembly and disassembly, the 3f9d-hand uses such a pair. Figure 5 illustrates the proposed assembly procedure in the following steps:

Step 1: Insert the center unit and outer pipe through trocar 1. Stop inserting the outer pipe at the end of the trocar.
Step 2: Insert only the center finger alone into the abdominal cavity so that the right and left shafts can be inserted into the outer pipe from the abdominal cavity. Insert the right unit through trocar 2 and then into the outer pipe. Connect the end of the right shaft to the operational part.
Step 3: Repeat step 2 for the left unit.
Step 4: Connecting the end of the left shaft to the operational part completes the assembly of the 3f9d-hand. After assembly, only trocar 1 is used.

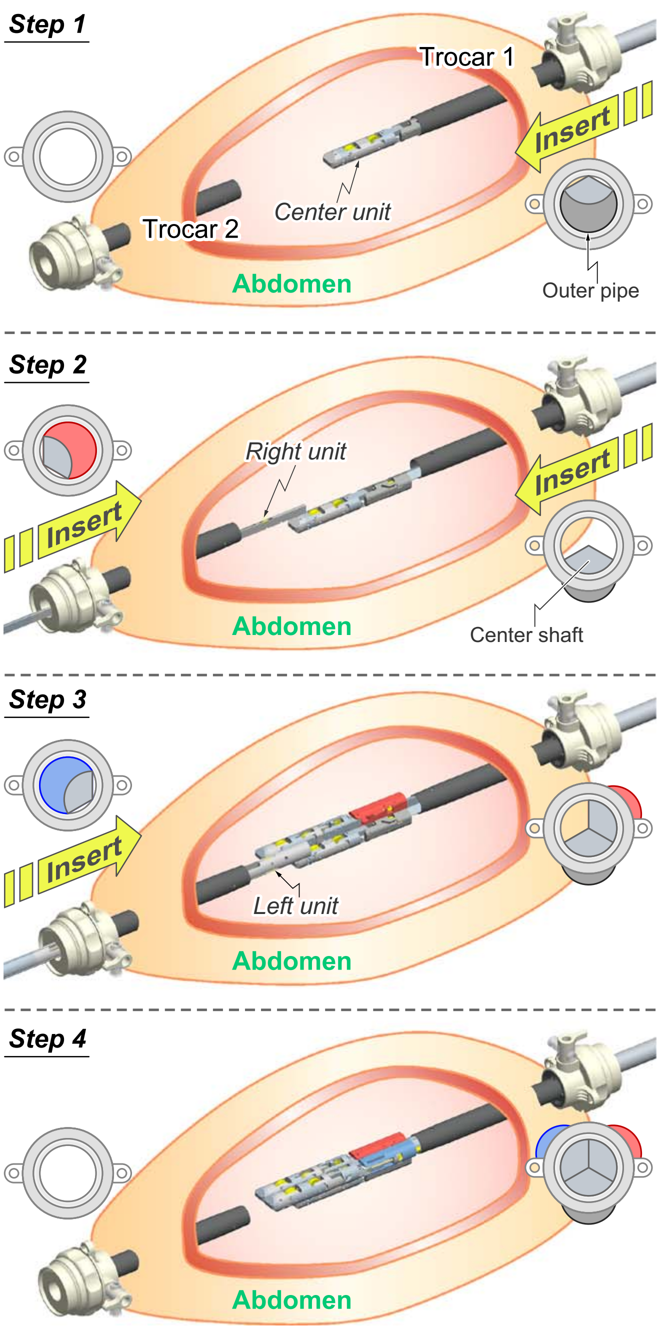

Fig. 5. The proposed assembly procedure for the 3f9d-hand

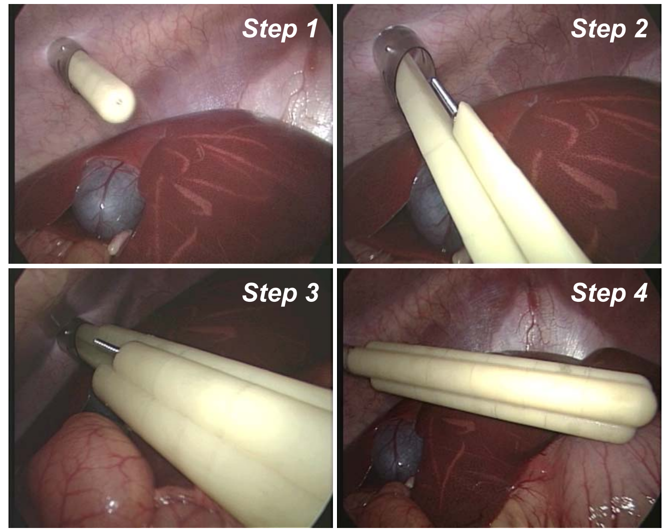

Fig. 6. *In vivo* experiment

The disassembly procedure is the reverse of the assembly procedure. The previous 3f5d-hand used a screw for assembly in the abdominal cavity and it was difficult to position the screw in the screw hole. The new 3f9d-hand does not require such complicated operations. Power transmission is connected outside the abdominal cavity. This facilitates the assembly and improves safety by avoiding dropping of parts inside the abdominal cavity, this is a significant feature of the 3f9d-hand.

A. Preliminary assembly experiment

We used a plastic model of the 3f9d-hand to conduct a preliminary *in vivo* experiment to verify whether the proposed assembly procedure is feasible. The model has the same dimensions as the actual 3f9d-hand but no joints or driving mechanisms. Figure 6 shows the photographs of the *in vivo* experiment. We can confirm that the proposed assembly procedure is feasible. Assembly and disassembly took 96 sec and 46 sec, respectively.

IV. Mechanism Design

A. Power transmission

To drive the three fingers, the 3f9d-hand uses cables, gears, shafts, and control cables. The cables are 0.45 mm in diameter and 0.03 mm in strand diameter. Their strength is 156 N. We used a Polytetrafluoroethylene (PTFE) tube (outer diameter: 1.5 mm, inner diameter: 0.5 mm) as the outer control cable. Next, we describe the power transmission mechanisms for the 3f9d-hand.

Left finger: Figure 7 (a) shows a structural diagram of the mechanisms and Fig. 7 (b) shows a schematic diagram of the left finger. There are three power transmission lines corresponding to the three active joints:

(1) Cable L_1 inside the control cable drives pulley L_{11}, which rotates joint L_{11}. The joint set L_{11} and L_{12} have an interlocking joint mechanism that rotates the two joints equally in the same direction. Cable L_{12} is crossed between pulleys L_{11} and L_{12}, which provides the interlocking drive.

(2) The rotation of shaft L_2 drives the worm screw via a stainless wire, with a diameter 1.2 mm and a strand diameter, 0.08 mm, connected to shaft L_2. The stainless wire can transmit torsion torque even when the proximal joint L_3 rotates. We used the stainless wire for the wrist of another assemblable hand and experimentally verified that it can transmit torsion torque. The worm wheel drives the gear train L_{21}, L_{22}, and L_{23}, which in turn rotates joint L_2.

(3) The rotation of shaft L_3 drives the gear train L_{31}, L_{32}, and L_{33}. Ggear L_{33} has an inner female screw that drives the feed screw, which in turn drives the linkage mechanism. It converts the translational motion of the feed screw into the rotation of joint L_3.

The maximum fingertip force exerted by joint L_{11} and L_2 is limited by the allowable bending stress of gears L_{21} and L_{22}. It is computed as 4.11 N in this configuration when the left finger is in full extension. The maximum fingertip force exerted by joint L_3 is limited by the allowable stress of the feed screw. It is computed as 4.13 N in the same configuration.

Right finger: The power transmission mechanism is the same as that of the left finger due to the symmetric architecture.

Center finger: Figure 8 (a) and (b) show the structural and schematic diagrams of the center finger mechanism, respectively. There are two power transmission lines corresponding to its two active joints:

(1) Cable C_1 inside the control cable drives pulley C_1, which in turn rotates joint C_{11}. The joint set C_{11} and C_{12} has an interlocking joint mechanism like that of the left finger.

(2) The rotation of the shaft C_2 drives the gear train C_{21}, C_{22}, and C_{23}. The gear C_{23} has an inner female screw that drives the feed screw, which in turn drives the linkage mechanism. It is the same as in the left finger.

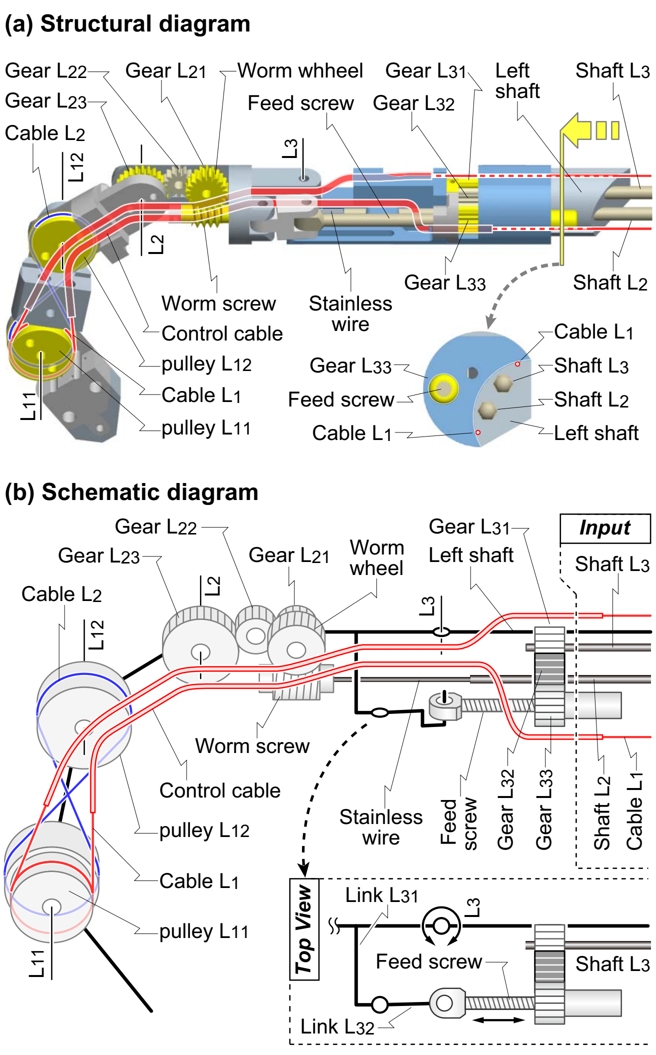

Fig. 7. Diagrams of power transmission in the left finger

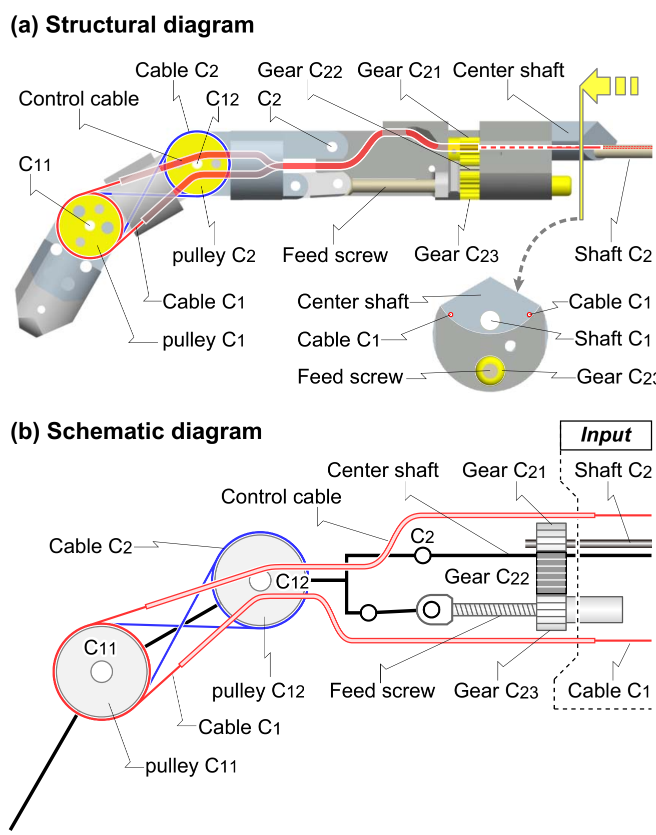

Fig. 8. Diagrams of power transmission in the center finger

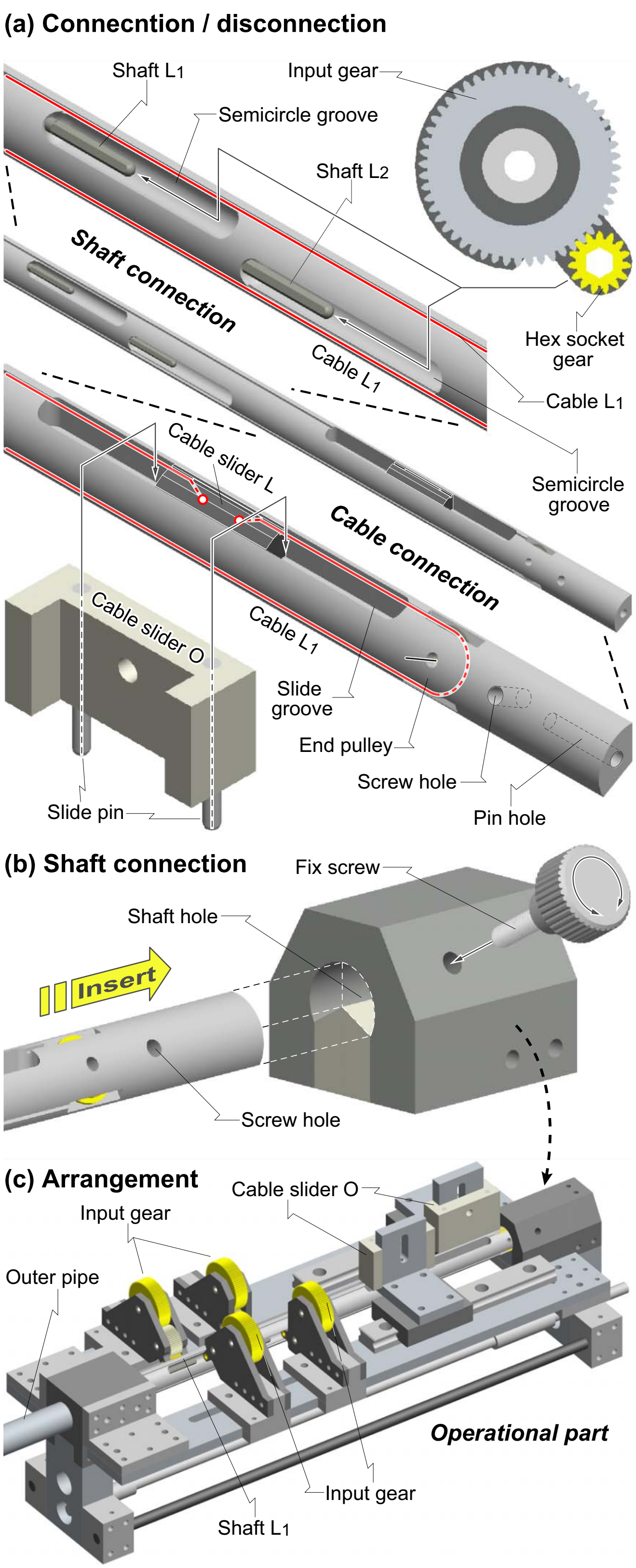

Fig. 9. Schematic diagrams of the left unit end and operational part

The maximum fingertip force exerted by joints C_{11} and C_2 is limited by the allowable bending stress of the feed screw. It is computed as 7.31 N in the configuration when the left finger is in fully extended.

B. Connection/disconnection

In the 3f9d-hand, the left and right units are connected to the operational part and power transmission is established. The center unit is connected to the operational part and connection or disconnection is not required. Figure 9 (a) shows the schematic diagram of the end of the left unit. Shafts L_1 and L_2, and cable L_1 are those that appeared in Fig. 7.

A gear with a hexagonal socket is set in the operational part. The end of each shaft is hexagonal and is inserted into the socket. This establishes rotational power transmission from the operational part to the shaft. The two ends of cable L_1 are fixed to cable slider L of the left finger, which slides along the slide groove. The cable slider O set in the operational part has two pins using which it can be inserted in the cable slider L. This establishes translational power transmission from the operational part to cable L_1.

Figure 9 (b) shows a schematic diagram of the connection mechanism for the left unit. The end of the left unit is inserted into the shaft hole and the position of the screw hole and that of the operational part is adjusted. Then the fixing screw is tightened to connect the left finger unit to the operational part. The same procedure is repeated for the right finger.

V. Developed Hand

Figures 10 (a) and (b) show the 3f9d-hand when assembled and disassembled, respectively. Fig. 10 (c) shows the cross sections of the right and left shaft. It has holes, 2.0 mm in diameter, in which shaft L_2 and shaft L_3 can rotate and cable grooves into which cable L_1 is arranged. It is the longest part (250 mm) hand parts.

We assembled and disassembled the 3f9d-hand in a closed space; a hemispherical space of diameter 30 cm. Figure 11 shows the photographs of assembly, corresponding to the assembly steps in Fig. 5. Figure 12 shows examples of configurations that the 3f9d-hand can take.

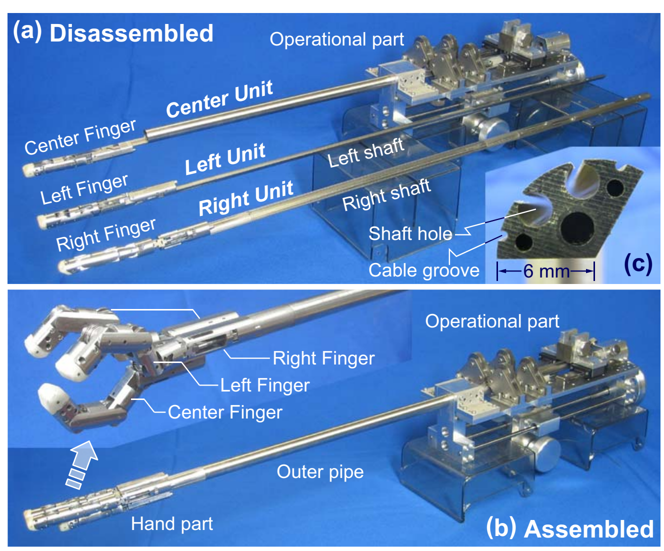

Fig. 10. Developed assemblable three-fingered nine-DOF hand

VI. CONCLUSION

This paper proposes a three-fingered nine-degree of freedom assemblable hand and describes its assembly and disassembly procedure and mechanical design. Its feathers include its nine active joints; for more than the previous 3f5d-hand. Its three finger joints play the role of a wrist joint, which enables the hand to grasp a target from the side and top. The connection/disconnection of its finger units is performed outside the abdominal cavity, which facilitates assembly and disassembly and improves safety.

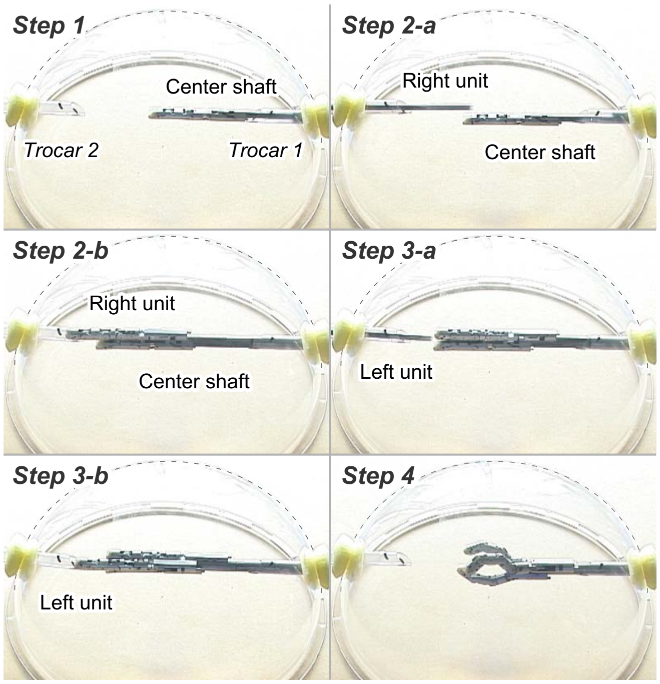

Fig. 11. Assembly experiment of the developed 3f9d-hand

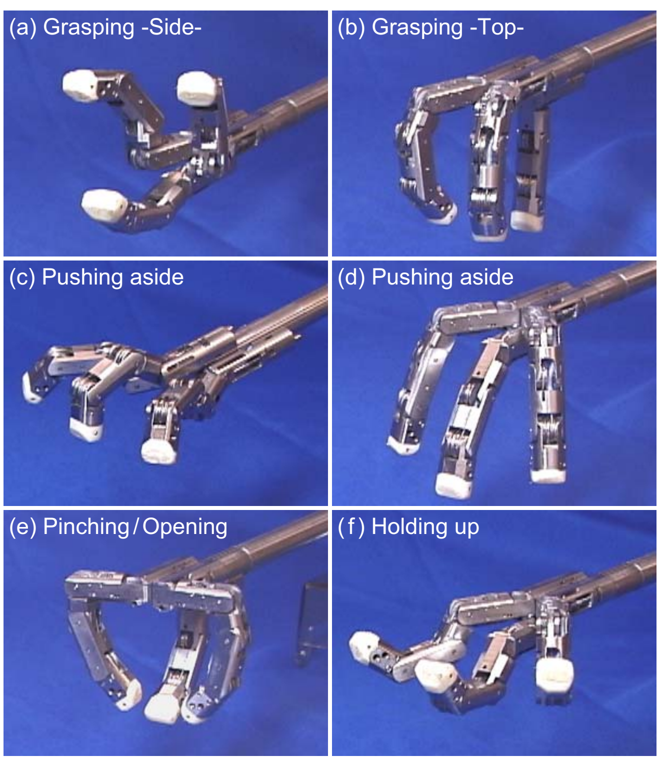

Fig. 12. Configurations of the developed 3f9d-hand

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