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Assemblable Pursestring Suture Instrument for Laparoscopic Surgery

Toshio Takayama, Toru Omata, Kazuyuki Kojima, and Naofumi Tanaka.

***Abstract*— We have proposed a novel concept of assemblable instruments for laparoscopic surgery, that is, their parts can be disassembled to pass through trocars and can be reassembled inside the abdominal cavity to become large instruments. By applying this concept, this paper proposes an assemblable pursestring suture instrument (PSI). In gastrectomy, a purse string suture on the esophagus is made preparatory to the anastomosis of the esophagus and the small intestine with a circular stapler. A traditional PSI cannot pass through a trocar because of its T-shaped jaws and a PSI that can be used in laparoscopic surgery is highly desired, which motivates us to develop the assemblable PSI. We have developed two prototypes of the assemblable PSI. The experiment with the first prototype verifies that it can be assembled in the abdominal cavity. However it cannot generate a grip force enough to hold the esophagus. We propose a two-DOF unfolding linkage mechanism for the gripper of the second prototype. The in vivo experiment with the second prototype verifies that it can make a satisfactory purse string suture.**

I. INTRODUCTION

In laparoscopic surgery, only small incisions are made on the abdominal wall and trocars are inserted through them. Surgeons perform surgery in the abdominal cavity inflated by pressured gas by using slender instruments inserted through trocars. While patients can make quick recovery, surgeons need high techniques to perform surgery with slender instruments with poor dexterity.

There are a number of studies to develop multi-degree-of-freedom forceps to improve the dexterity of forceps for laparoscopic surgery [1]-[6]. Among them, Zeus [3] and Da Vinci [4] are commercialized surgical robots that have master-slave dexterous forceps. Such forceps are still small in diameter because they must be able to pass through a trocar. Therefore only small tools can be installed at their front ends.

If large and complicated shaped instruments were available in laparoscopic surgery, they could make laparoscopic surgery easier. We have proposed a novel concept of assemblable instruments for laparoscopic surgery and developed an assemblable three-fingered hand [7]. Its units can be disassembled to pass through trocars and can be assembled in the abdominal cavity to become a three-fingered hand. Assembling enables us to design more complicated shaped instruments with higher stiffness than unfolding and flexion because all units can be as large as the inside diameter of a trocar.

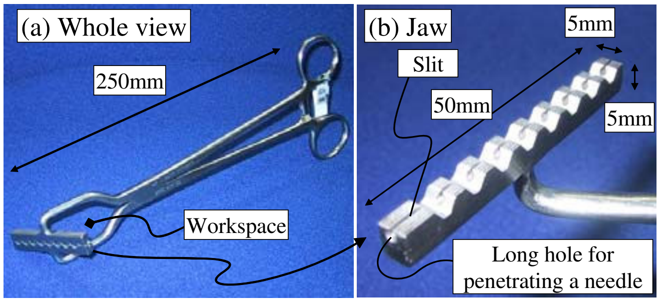

Fig. 1. Traditional puresestring suture instrument

This paper proposes an assemblable pursestring suture instrument (PSI). Figure 1(a) shows a traditional pursestring suture instrument for abdominal surgery, which is useful tool to make a purse string suture (see Figure 2(b)). It is a suture like a drawstring purse. In gastrectomy, this suture is made preparatory to the anastomosis of the esophagus and the small intestine with a circular stapler. A circular stapler is an instrument that staples organs or tissues circularly and cuts off the inside of the circle.

The traditional PSI cannot pass through a trocar because of its T-shaped jaws. Currently surgeons perform surgery with instruments smaller than 12mm in diameter until they need to use the T-shaped PSI, and make an incision of about 50mm to insert it. Clearly this is invasive and this also makes the view of the abdominal cavity worse because the abdominal cavity cannot maintain inflated due to such an incision. Therefore a PSI that can be inserted through a 12mm trocar is highly desired, which motivates us to develop an assemblable PSI. A PSI must be able to grip an organ firmly with a large grip force. We propose a two degree of freedom unfolding linkage mechanism that can generate a large grip force for the assemblable PSI. The design technology for robot hands can contribute to developing such an mechanism. We consider that this is one of important directions of robotics to make a contribution in the real world.

This paper is organized as follows. Section 2 introduces purse string suture and the traditional PSI for abdominal surgery. Section 3 presents the first prototype of an assemblable PSI and Section 4 discusses the problems with the first prototype found in an in vivo experiment. Section 5 presents the second prototype and Section 6 shows its effectiveness in another in vivo experiment.

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T. Takayama and T. Omata are with the Tokyo Institute of Technology, 4259, Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa, 226-8502 Japan (corresponding author to provide phone: (+81)45-924-5468; fax: (+81)45-924-5468; e-mail:`takayama@pms.titech.ac.jp`).

K. Kojima and N. Tanaka are with the Tokyo Medical and Dental University, 1-5-45, Yushima, Bunkyo-ku, Tokyo, 113-8519 Japan

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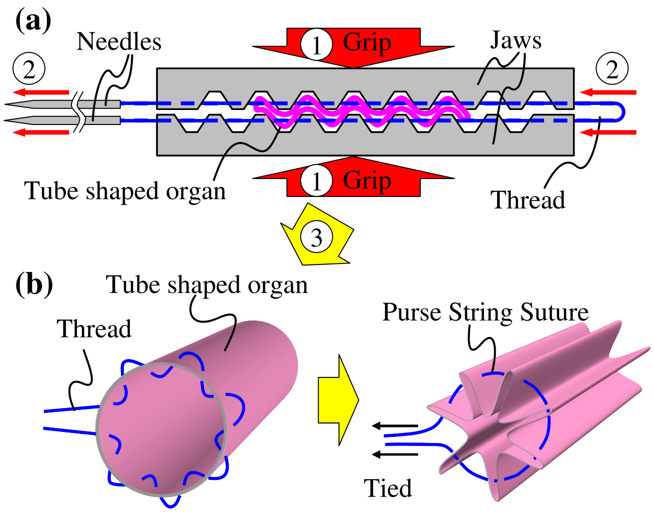


Fig. 2. The purse string suture

II. TRADITIONAL PURSESTRING SUTURE INSTRUMENT

As shown in Fig. 1, the PSI has the T-shaped upper and lower serrated jaws. Figure 2 shows the procedure to make a purse string suture with the PSI. It is as follows: (1) Grip a tubular organ between the jaws. The organ is caught and deformed between the teeth. (2) Stick two needles and a single thread connecting them into the holes of the upper and lower jaws from one side to the other. (3) Amputate the esophagus and open the jaws. The thread can be removed from the PSI through the slits on the jaws (see Fig. 1 (b) for slits).

Note that the esophagus must be amputated while closing the jaws and keeping hold of the thread. This enables a fine amputation of the esophagus. Otherwise if it is amputated before the purse string suture, the amputated esophagus easily sinks into the diaphragm. To amputate the esophagus, the PSI needs a sufficient workspace between its arms (see Fig. 1 (a)).

In gastrectomy, the esophagus and the small intestine are anastomosed as shown in Fig. 3. The procedure is as follows. (1) Make a purse string suture at the opening end of the esophagus but do not tie the opening with the thread yet. (2) Insert an anvil from the opening of the esophagus and tie the opening and the rod of the anvil together. (3) Insert a circular stapler from the opening of the small intestine and stick its center rod through the wall of the small intestine. (4) Connect the center rod of the stapler to the rod of the anvil, and fire the stapler to anastomose the esophagus and the small intestine. (5) Finally close the opening of the small intestine with a linier stapler. In this procedure, a poor purse string suture could result in an incomplete anastomosis, which makes hospitalization of patients longer.

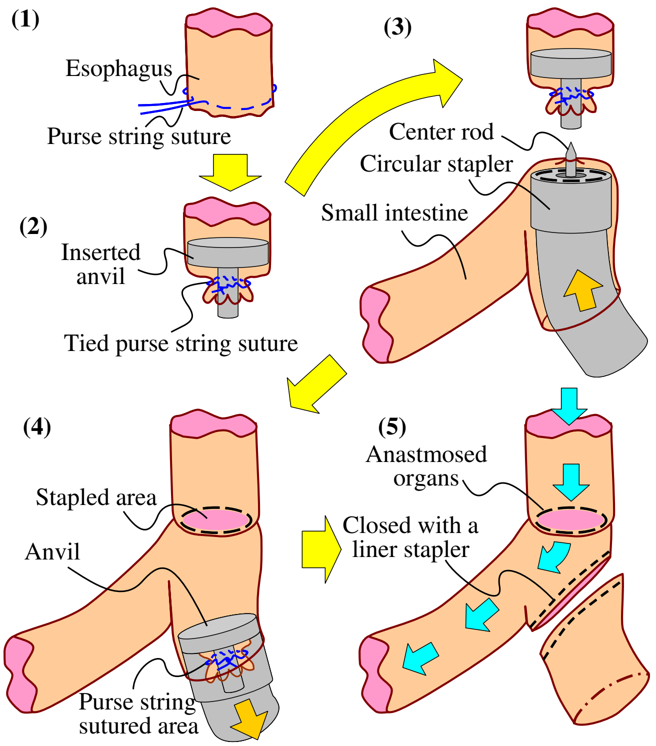
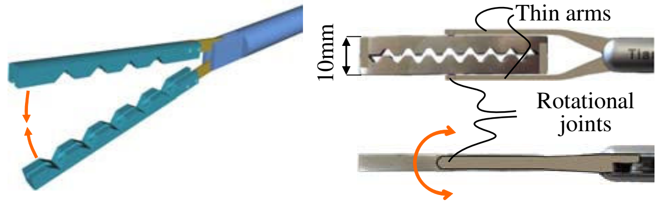


Fig. 3. Anastomose of the esophagus and the small intestine with a circular stapler



(a) Linier Arrangement (b) Rotational mechanism

Fig. 4. Other possibilities

To develop a PSI that can be inserted through a trocar, one may think of some methods other than assembling. One way is to arrange jaws in line with the rod as shown in Fig. 4 (a). Commercial products of this configuration were once available. The problem with this configuration is that needles stuck through the PSI point to the diaphragm and often injure it.

Another way is to introduce revolving joints at the bases of the upper and lower jaws as shown in Fig.4 (b). As mentioned, a PSI needs to grip a tubular organ with a large grip force. The arms of the gripper in Fig. 4 (b) must be thick enough to sustain a large grip force. However this is difficult because the total size must be smaller than 12mm in diameter, whereas the pair of jaws is 10mm in height. In addition, a stopper is necessary to stop the revolving joints. This also makes the arms of the gripper thicker and even for trocars larger than 12mm in diameter, say 15mm, it is difficult to develop a PSI based on this design.

Therefore we propose the assemblable PSI of which jaws and gripper can be inserted into the abdominal cavity through different trocars and can be assembled to become a T-shaped PSI. The advantages of this method are that once it is assembled, it can be used as a traditional PSI and that needles do not point to the diaphragm.

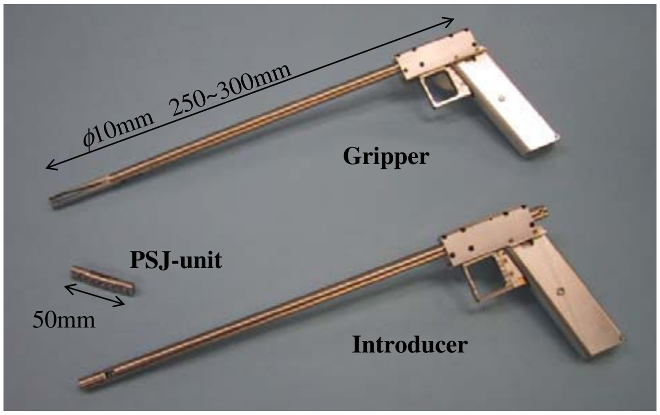


Fig. 5. All units of the first prototype of an assemblable PSI

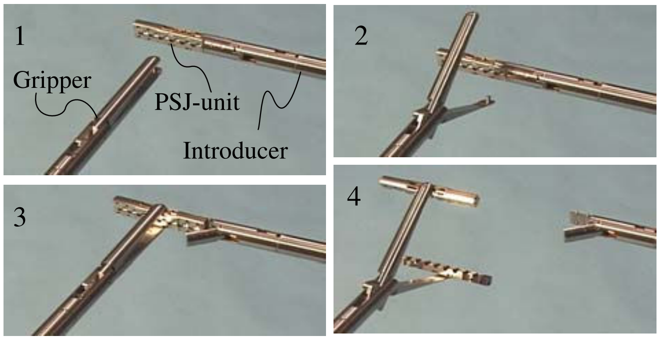


Fig. 6. The assembling procedure

III. FIRST PROTOTYPE OF AN ASSEMBLABLE PSI

We developed the first prototype of an assemblable PSI shown in Fig. 5. It consists of three units: the pursestring suture jaw unit (PSJ-unit), the gripper, and the introducer. All units are smaller than 10mm in diameter so that they can pass through usual trocars.

This assemblable PSI uses two trocars for assembling. Figures 6 (1) through (4) show the assembling procedure. (1) The introducer with the PSJ-unit is inserted through a trocar and the gripper is inserted through another trocar (In the photos, trocars are not shown). (2) The gripper holds the PSJ-unit. (3) The gripper and the PSJ-unit are connected and the introducer releases the PSJ-unit. (4) After assembling, the introducer is unnecessary and removed from the abdominal cavity. It does not occupy the trocar. The disassembling procedure is just the reverse of this assembling procedure.

The positions of the trocars are generally fixed in surgery and the orientation of the PSJ-unit is dependently determined. In the beginning of this study, we considered that the connection angle of the PSJ-unit should be selectable as shown in Fig. 7 and we employ a connection by fitting polygonal pins into polygonal holes as shown in Fig. 8. The connection angle can be either 30[deg], 90[deg], or 150[deg]. This causes a problem as we will discuss next. As for the gripper, we design its gripping mechanism by following a usual forceps mechanism. This also causes a problem.

We install a connection mechanism in the PSJ-unit, not in the gripper, as shown in Fig. 8. This is because the gripper is too complicated to be provided with a connection mechanism. The connection mechanism in the PSJ-unit is actuated by the introducer.

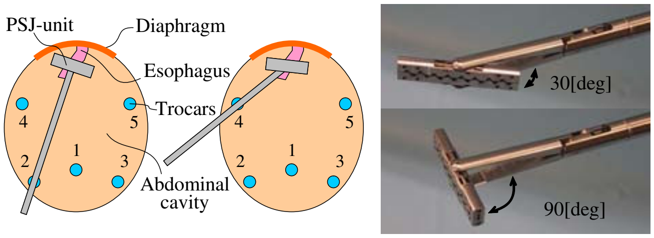


Fig. 7. Connection angle of the jaws and the gripper

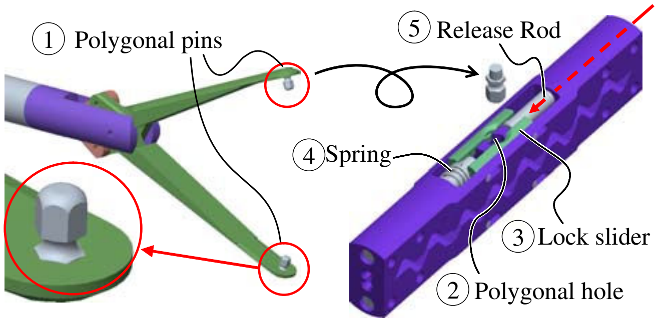


Fig. 8. Connection mechanism

Figure 9 shows the process of the connection. Inside the PSJ-unit, each jaw has lock slider 3 that sandwiches polygonal hole 2. Lock slider 3 has a hook and a dent. (1) By default, spring 4 pushes the hook of lock slider 3 and it overlaps polygonal hole 2. (2) To open polygonal hole 2, push release rod 5 with rod 6 of the introducer (rod 6 is shown in Fig. 10). Then the hook of lock slider 3 does not overlap polygonal hole 2. (3) In this state, polygonal pin 1 can be inserted into polygonal hole 2. (4) Pull rod 6 and spring 4 returns the hook of lock slider 3. It catches the neck of polygonal pin 1. This completes the connection of the gripper and the PSJ-unit.

IV. EXPERIMENTAL RESULTS WITH THE FIRST PROTOTYPE

We did an experiment on a pig whose abdominal cavity is of the same size as that of humans. Five trocars were placed as shown in Fig. 7. Trocar 1 was placed beside the naval. We used trocar 1 for an endoscope, trocar 2 for the introducer, and trocar 3 for the gripper. A surgeon handled the gripper, and another handled the introducer. We obtain the following satisfactory results.

1. The PSI can be assembled in the abdominal cavity without difficulty.
2. The connection mechanism does not separate the gripper and the PSJ-unit unintentionally. It can separate them when it is released.
3. The connection angle between the gripper and the PSJ-unit is not necessarily selectable because the esophagus is enough soft.

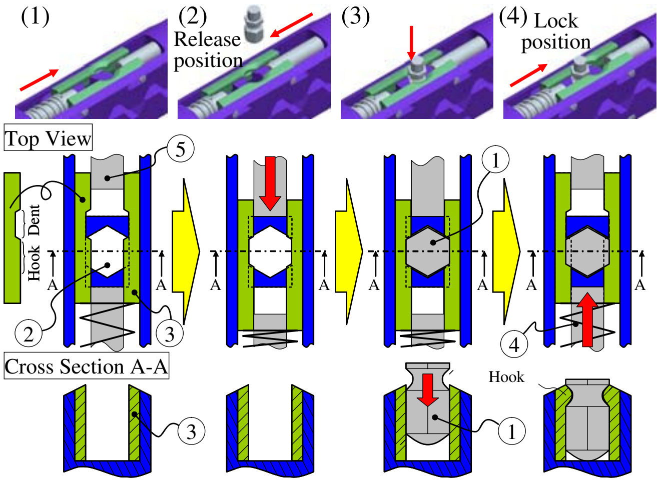


Fig. 9. Process of the connection

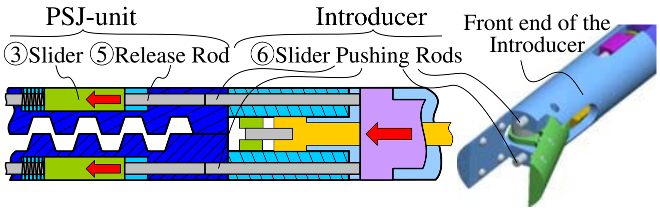


Fig. 10. The connection mechanism of the PSJ-unit and introducer

However, we have the following problematic results.

1. The connection with the polygonal pins and holes has large rotational looseness.

2. The gripper cannot generate a grip force enough to grip the esophagus.

The large looseness of the connection is caused by the round of the edges of the polygonal pins that is gradually enlarged by a twisting force during repeated use.

Our conclusions are as follows:

1. We need to develop a new gripper that can pass through a trocar, that can generate a large grip force, and that can possess a sufficient workspace in its arms.

2. A new PSJ-unit is also necessary for the new gripper. It can employ the same connection mechanism expect for the polygonal pins which should be replaced with suitable pins.

3. The introducer of the first prototype can be re-used.

Problem with the gripper: The remainder of this section discusses the problem with the gripper developed by following a traditional forceps mechanism. Figures 11(a) and 12(a) show its linkage mechanism when it is opened and closed, respectively. Figures 11(b) and 12(b) show the motions of the output, connecting, and input links. The input rod that moves to the right and left rotates the output link about the fixed pin via the connecting link. Let f be the internal force exerted in the connecting link, and joint shafts 1 and 2. The strength of these elements limits the maximum force of f, denoted by f_{max}, and also limits the maximum grasping torque. It is given by $T_{max} = f_{max} \times L$ where L is the length between the fixed pin and the connecting link. The length L becomes small when gripping (Fig. 12), and large when opening (Fig. 11). This is not suitable for generating a large grip force. Moreover the input rod drives both the upper and lower arms, which requires a double force.

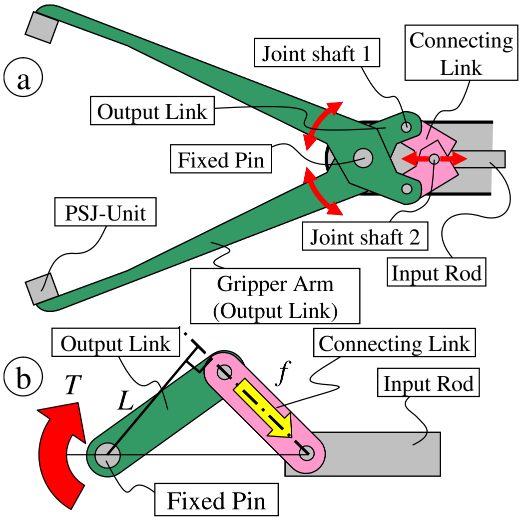


Fig. 11. Gripper with a traditional linkage mechanism (Opening)

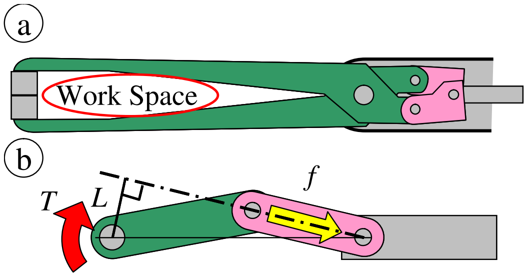


Fig. 12. Gripper with a traditional linkage mechanism (Gripping)

One way to generate a large grip force is to make the arms of the gripper short and thick. However, this makes the workspace between the arms small.

V. SECOND PROTOTYPE OF AN ASSEMBLABLE PSI

We developed the second prototype of an assemblable PSI shown in Fig. 13. The new gripper has the two degree-of-freedom folding linkage mechanism shown in Fig. 14. It has two sliders, the grasping and folding sliders, to drive

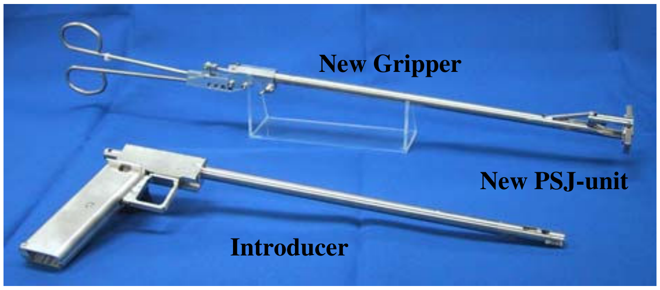


Fig. 13. Improved prototype of an assemblable PSI

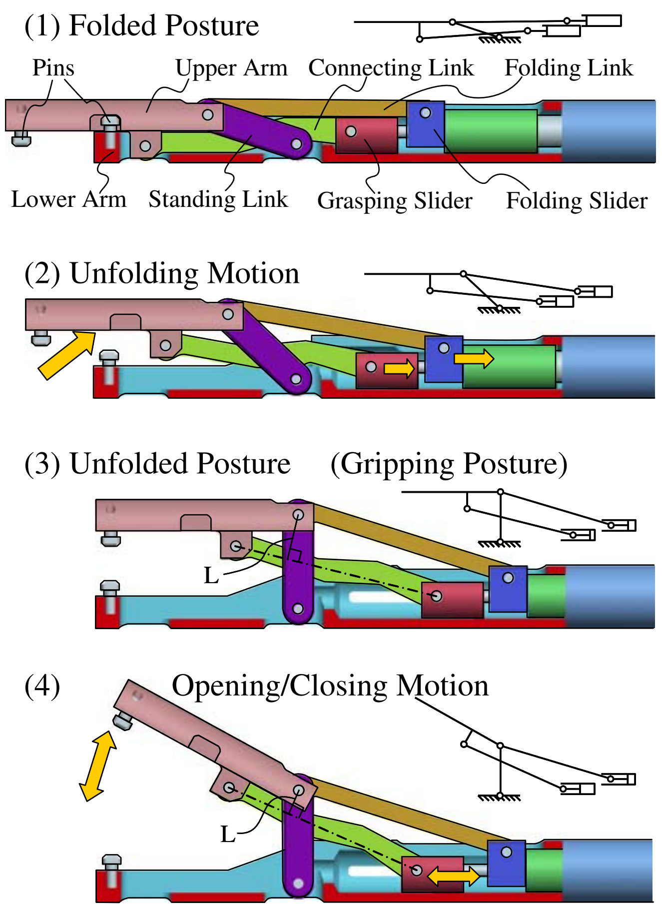


Fig. 14. Folding mechanism of the improved gripper

the mechanism. When the gripper passes through the trocar, it is folded as shown in Fig. 14(1). To unfold the gripper the grasping and folding sliders are driven to the right together (Fig. 14(2)). Then the standing link rises and the gripper unfolds (Fig. 14(3)). By driving the input slider to the left/right, the upper arm opens/closes with the connection link (Fig. 14(4)), respectively. Fig. 14(3) is the posture of the gripper when it grips the PSJ-unit.

In this unfolding mechanism, the length between the rotation axis of the upper arm and connecting link *L* becomes large at the gripping posture in Fig. 14(3), and it becomes small at the opening posture in Fig. 14(4). Therefore this mechanism can generate a large grip force and can open the jaws quickly.

In the unfolding mechanism the upper arm is lifted up by the standing link, which makes a sufficient workspace between the upper and lower arms. The upper and lower pins do not overlap at the folded posture so that the arms can be thick and strong. We measured the grasping force of the traditional PSI and it is about 100N. We designed the new gripper so that it can generate 100N of grasping force based on an FEM analysis.

To prevent the looseness in the connection mechanism, each arm of the new gripper has two pins as shown in Fig. 15. Therefore the connection angle is only 90deg. To avoid interference between the lower pins and the upper arm, there are small cavities at the sides of the upper arm.

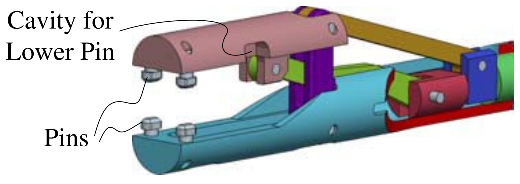


Fig. 15. Front end of the improved gripper

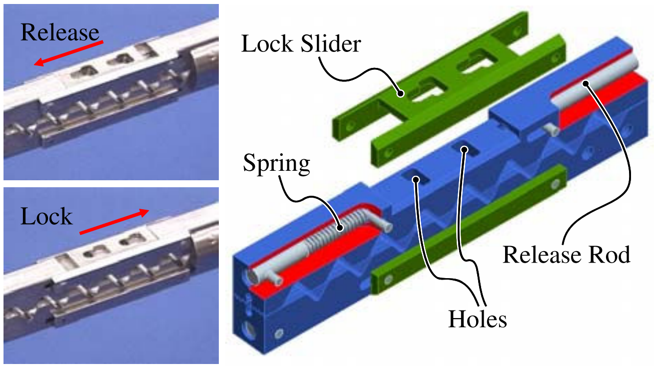


Fig. 16. Improved pursestring suture jaw unit

As mentioned in section 3, the first prototype is designed so that all its units can pass through a 10mm trocar. Afterward we learned that trocars in usual use are 12mm in diameter. Therefore we designed the connection mechanism of the second prototype with a large lock slider that covers the PSJ-unit as shown in Fig. 16, which improves the mechanical strength and eases the fabrication. Figure 17 shows the assembling of the second prototype.

VI. EXPERIMENTAL RESULTS WITH THE SECOND PROTOTYPE

We did an in vivo experiment for the second prototype. The second prototype could be successfully assembled. It could grasp the esophagus with a grip force large enough in Fig. 18 and successfully made a purse string suture.

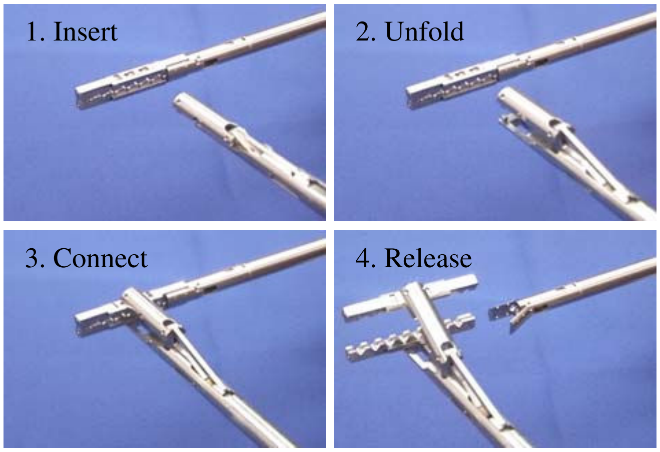


Fig. 17. Assembling with the second prototype

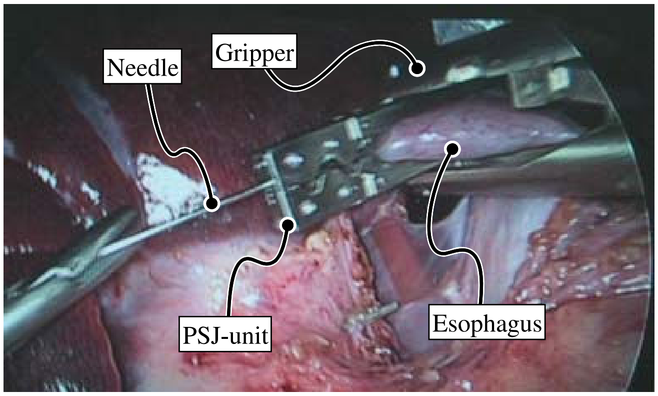


Fig. 18. In vivo experiment

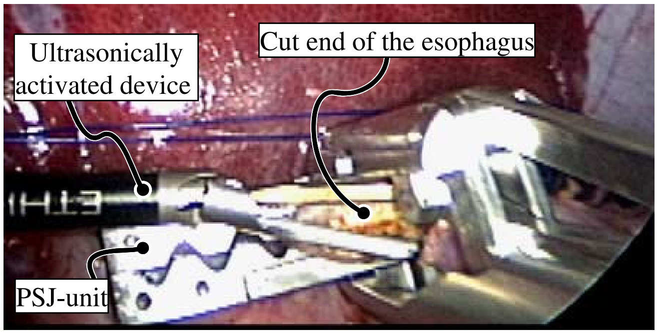


Fig. 19. Amputation of the esophagus

Figure 19 shows that the gripper has a sufficient workspace between its upper and lower arms for amputation with an ultrasonically activated device. It took 45 seconds to assemble and 55 seconds to disassemble the assemblable PSI. The total time of using the assemblable PSI to make the purse string suture (step (1) in Fig. 3) was 17 minutes and 45 seconds. Next an anvil was inserted into abdominal cavity. Figure 20 shows the tied anvil with the purse string suture (step (2) in Fig. 3). After anastmosing with a circular stapler (step (4) in Fig. 3), we amputated the anastmosed portion and confirmed that a satisfactory anastmosis was obtained as shown in Fig. 21.

We had another opportunity to conduct an experiment of assembling during the intervals of other experiments, and confirmed that the assembling could be performed without significant trouble. We dropped the PSJ-unit in the abdominal cavity once. Because of the poor perspective of the laparoscope, the surgeon misunderstood that the connection of the PSJ-unit and the gripper was completed and removed the introducer. Although we could pick it up without difficulty with a usual 5mm forceps, this is not desirable. Making marks on the PSJ-unit and the gripper could simplify the positioning and alignment and could reduce the possibility of dropping the PSJ-unit.

VII. CONCLUSION

This paper proposed an assemblable pursestring suture instrument applying our novel concept of assmblable instruments for laparoscopic surgery. We proposed a two degree of freedom unfolding linkage mechanism for its gripper. An in vivo experiment verified that the assemblable pursestring suture instrument made a satisfactory purse string suture. We are improving the ergonomics of the assemblable PSI aiming at a clinical test. Our future work is to make a purse string suture on other tubular organs such as the duodenum, the small and large intestines, etc. To reduce the production cost is also our future work.

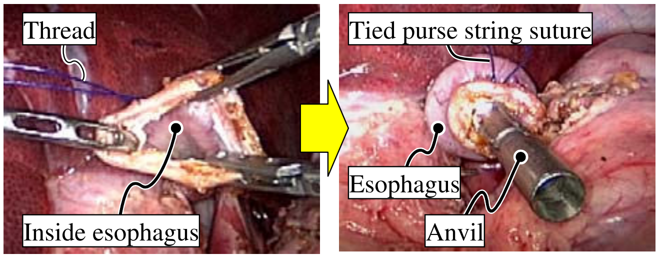


Fig. 20. Tied anvil with the purse string suture

Fig. 21. Anastomosed organs

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