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A Study on Wire-Wire Driven Abdominal Cavity Mobile Micro Robot

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Abstract—**NOTES (Natural Orifice Translumenal Endoscopic Surgery), a recently developed form of minimally invasive surgery, has attracted attention as a new laparoscopic operation. However, manipulation of forceps throughout the surgery continues to be a burden to surgeons. Our previous research focused on designing a model that could carry forceps and a camera through the abdominal cavity. The first prototype, a wire-tube driven micro robot, relied on the action of two suction cups for movement along the peritoneum (abdominal wall). However, the actions required to carry out the turning motions of the first prototype were strongly influenced by the rigidity of the tube. In order to solve this problem, in this study, we proposed a wire-wire driving mechanism for the robot, then developed a simulation model for investigating design and control issues. Based on the investigation, a new prototype was designed to determine the feasibility of the robot. Our results showed the robot's potential as a NOTES support device.**

I. INTRODUCTION

NOTES (Natural Orifice Translumenal Endoscopic Surgery), a latest minimally invasive surgery, has attracted attention as a new laparoscope operation. NOTES is a procedure in which forceps are inserted through a natural orifice (mouth, anus, and vagina, etc.), and a hole is cut at the site to reach intra-abdominal cavity. Because this surgery is able to minimize incision size and in turn, the amount of pain, it is believed to increase the patient's QOL (Quality Of Life) [1]. This approach may hold tremendous potential, however, several issues must be addressed before it is introduced into the clinical care. One main issue is that the pathway from the surgeon's fingertip to the targeted site is generally longer than that of usual endoscopic operations, causing the manipulation of forceps to become a complex task. Compared with the multi-link manipulator for usual endoscopic surgery [2], [3], the devices developed for moving and operating inside the body could be expected to be used as surgical support to tackle the issue.

A robotic system that uses two suction cups and a tube- wire driving mechanism for in-vivo movement has been reported [4]. This robotic system performs injection to the myocardium, moving along the epicardial surface by controlling the attach and release of two suction cups. However, the differences in character between the epicardium and abdominal wall make it impossible for the robot to function effectively during a NOTES surgery. In [5], a robotic system for NOTES support (for the gallbladder removing, as reported) has been reported. The robot attaches to the peritoneum relying on a strong magnetic field (0.66T-1.5T), and moves along the abdominal cavity using an external magnet stage. However, the strong magnetic field makes it impossible to use tools and surgical supplies containing magnetic metals. Moreover, the effects of long-term exposure to strong magnetic fields are not yet clear.

In our previous research, we focused on developing a micro mobile robot that could transport forceps and/or a camera to targeted surgical sites, while at the same time enhancing the visibility of the intraperitoneal environment [6]. In order to achieve stable movements, it was proposed that the peritoneum (abdominal wall) be used as the surface for movement in the abdominal cavity. Two suction cups were used to attach the robot to the peritoneum. The movement of the cups was then controlled using a wire-tube driving mechanism, in which 3 pairs of wire-tube were used for 3 D.O.F. (Degree Of Freedom) movements, i.e., moving forward/backward, turning left/right, and moving up/down. For each wire-tube pair, the tube was fixed to the rear housing containing the rear suction cup, and the wire was fixed to the front housing containing the front suction cup. In an experiment using porcine peritoneum, an adsorption force of 150g was measured, which is enough for the supposed task.

However, since the wires passed through and were therefore constrained by the corresponding tubes, the turning motions of and operation for the motions of the first prototype were strongly influenced by the rigidity of the tube.

In this study we attempted to solve this problem by utilizing a wire-wire driving mechanism. In other words, the 3 tubes fixed to the rear housing were simply replaced by 3 wires.

Using this driving mechanism, it was expected that the constraint on the front wires from the rear tubes could be relaxed. However, it became clear that, due to the operation force and their own weight, deflection may occur on the relaxed wires, which would affect the effectiveness of the operation. Therefore, it is necessary to ensure that the wires are properly restrained.

As with the previous experiment, a simulation model of the

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robot was developed, this time using the new wire-wire driving mechanism. After carrying out an investigation into possible design and control issues, a prototype was created to confirm the robot's capabilities.

II. OUTLINE OF THE NEW STYLE ROBOT'S

A. *Specification of the new robot*

As described in the introduction, the front and rear housings are operated by 6 wires to realized 3 D.O.F. (Degree OF Freedom) movements up to 150gf adsorption force is achieved using vacuum pressure (maximal 0.69MPa). Fig.1 shows the design of the new robot. Aside from the driving mechanism, all other design conditions remain the same as the first prototype (see [6]).

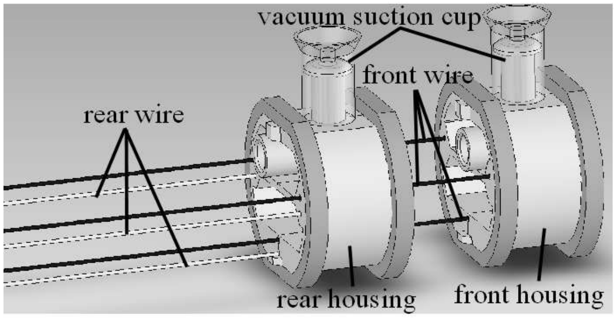


Fig.1 An illustration of the new robot

B. *Phase transition for various movements*

1) *moving forward/backward*

The phase transition of forward motion is depicted in Fig. 2. The arrow labeled "F" expresses force of operation. In one forward movement, the front suction cup is released and pushed forward a certain distance by the attached wires, where it then reattaches to the peritoneum. Next, the rear suction cup is released and pushed in the direction of the front cup, where it too reattaches.

By reversing the direction of force we can attain backwards movement.

2) *turning left/right*

Turning motion is confirmed by making difference between the stretching-out length of left and right wires. The phase transition diagram of turning right is shown in Fig. 3. Only the right front wire is pulled after Phase1, which is the same as the moving forward motion, thus, the left wire will bend towards right, and the front housing will turn right. Turning left could be achieved by making stretching-out length of right wire longer.

3) *moving up/down*

Vertical movement is also possible by making difference between the stretching-out length of upper wires (those two wires close to suction cups) and lower wire (one single wire) (Fig.4).

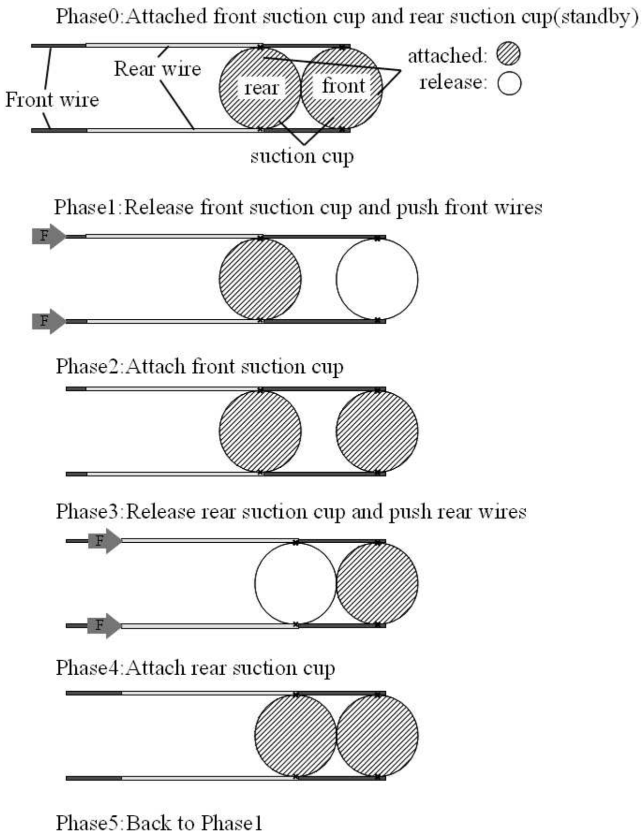


Fig.2 Phase transition diagram for moving forward

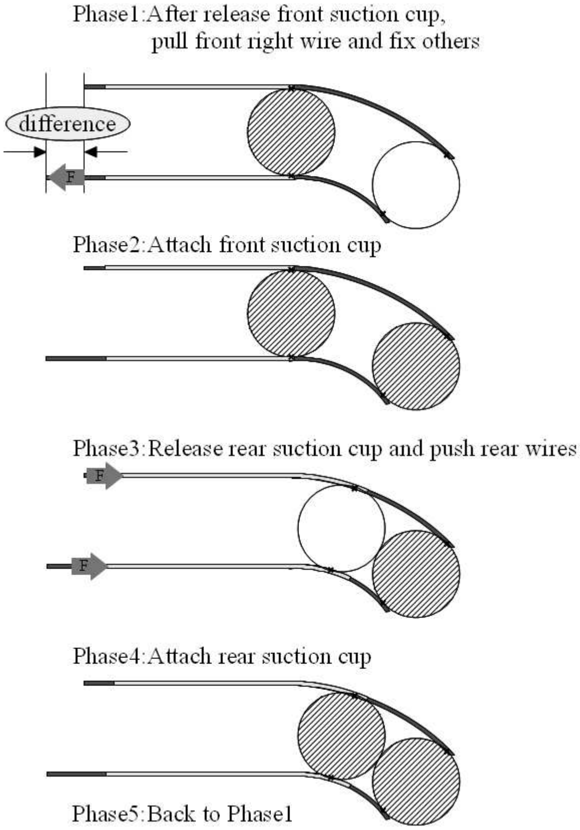


Fig.3 Phase transition diagram for turning right

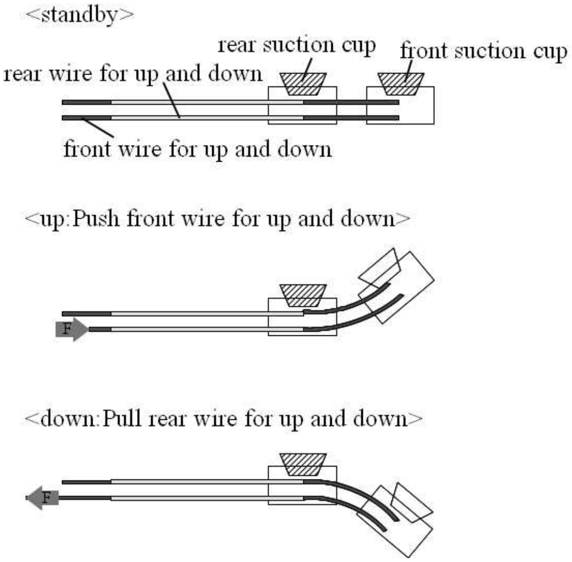


Fig.4 Phase transition diagram for moving up/down

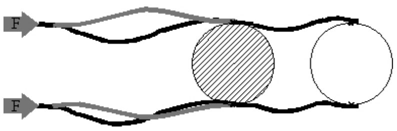
C. The deflection issue of the wires

As previously mentioned, the deflection of the wires would affect the effectiveness of the operation, thus should be investigated.

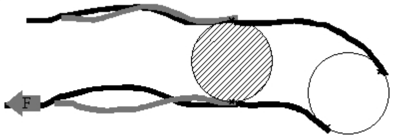
Due to the deflection, 1) the full operation force cannot be transmitted (Fig.5); 2) the adsorption force would also be influenced (Fig.5), in addition the suction is weak to shear force and bending moment. Thus, our next step was to identify to what extent deflection affected movement, then determine the best way to minimize the effects.

A computer simulator was developed to investigate design and control issues for the new robot. Specifically, forces exerted on the suction cups and wires were inspected. Moreover, the result from the tests on the stimulator helped decide the most appropriate restraints for wire-pairs and wire-bending.

Based on the investigation by the robot simulator, a prototype robot with the new driving mechanism was made. Further comparisons were made between the wire-tube and wire-wire driving mechanism.



(a) Deflection at the time of forward movement



(b) Deflection at the time of turn movement

Fig.5 Deflection assumed to produce at the time of operation

III. CONSTRUCTION OF THE NEW ROBOT

A. Simulation model

The robot model and the physical system were constructed in Working Model 2D version 7.0 (MSC Software, USA), and the control system was based on MATLAB version 7.0 (The Math Works, USA). Since the working model is 2D, the simulator was built so that the surface for moving was in the plane of the working model, giving a top view of the robot. For that reason, the wire for up and down was omitted (Fig.6). The dimensions of the new robot's are shown in TABLE Ⅰ, which were determined based on the first prototype robot.

TABLE I
SIZE OF THE NEW STYLE ROBOT'S SIMULATION MODEL

	Front housing	Rear housing	Wire
Length[mm]	14.5	14.5	400
Width[mm]	27	27	0.8
Mass [g]	5	5	0.88

Since the Working 2D software depicts only rigid body simulation, flexible wire movements could not be expressed directly. Instead, wires were indirectly represented by small rigid links connected to a rotating spring. Various materials could be expressed by changing the constant of the rotational spring.

Considering the trade-off between the computational cost and simulation accuracy, two separate models were created, a 10-link and a 40-link model. The 10-link model with the lower computational cost, was used to verify the manipulation of the new robot, and derive the control policy. Then, the 40-link model was used to explore the manipulation details, and investigate influences of the deflection and wire-binding.

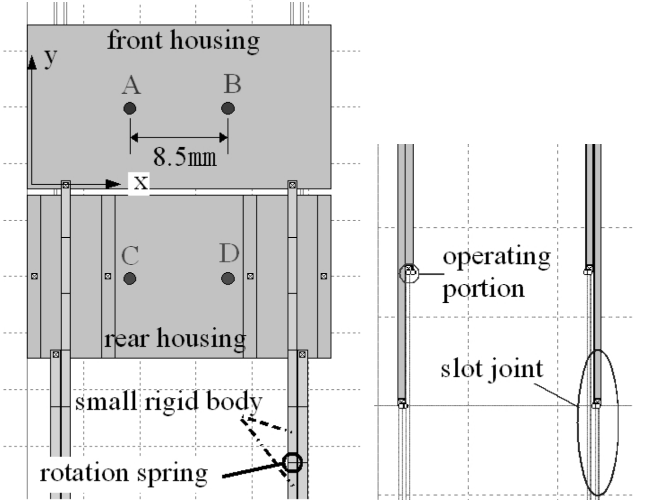
Because the suction cups are soft, and because there are 2 states for each cup (“attached” and ”freed”), the following simulation strategy was chosen to avoid complex modeling.

When in “attached” state, a force proportionate to the distance between the initial positions of A-D (4 fixed points on the two housings, the distance between A and B, C and D is equal to the suction cups’ diameter: Fig.6) and their current positions, would be exerted to pull back the suction cup. This force is called adsorption friction. The reaction force of the adsorption friction is treated as the load on the suction cup in the horizontal plane (parallel to the plane shown in Fig.6). When in “freed” state, there is no force acting on the suction cup, allowing it to move freely.

Moreover, suction is weak to rotation along suction cup’s vertical axis. Therefore during that manipulation, the adsorption force of the suction cups is lower than that of the static state. The force working on A-D was used to calculate the rotation moment.

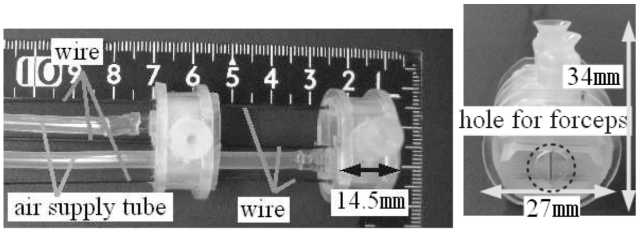
B. The real robot

The real robot, controlled using the wire-wire mechanism was designed and manufactured, as shown in Fig.7. The mass of the robot's main body (not including the wires) is 9g. In order to compare it to the first prototype, the only factor that differed was the driving mechanism.



(a) Housing and wire model (b) Operating portion

Fig.6 Details of the simulation model



(a) Robot upper part (b) Robot front part

Fig.7 The size of the new prototype

IV. RESULTS

Since the deflection is the necessity of the new driving mechanism and main subject of investigation, in this paper, the experiment results relating to deflection were primarily described.

A. *Wire-binding simulation*

The left-turn simulation was carried out on the 40-link model. Formula (1) denotes the force required to manipulate the wire, where *t* denotes time, *pull* is a gain coefficient, and *ply* is the distance between the front wire and the rear wire.

$$F_{lpull} = 40t \cdot pull(\, ply - 30\,) \qquad (1)$$

Adsorption friction at points C and D are calculated using formula (2), where *n* and *m* are gain coefficients, *fx* and *fy* are the distances between the current positions and initial positions points *Px* and *Py*.

$$\begin{aligned} F_x &= -n \cdot sign(\, fx - Px\,)(\, fx - Px\,)^2 \\ F_y &= -m \cdot sign(\, fy - Py\,)(\, fy - Py\,)^2 \end{aligned} \qquad (2)$$

These formulas were empirically deduced through experiments using the 10-link model.

Deflection can be controlled by wire-binding, i.e., by constraining the relative movement of the paired wires. Physically, this can be done using a short ring. In the simulation model, this constrain was implemented as a small rigid body with a slit, as shown in Fig.8. The width of the slit was set to 2mm, 3mm, 5mm, and 7mm respectively. In this version of simulation, in order to save computation power, the rigid body was fixed to ground, that is, it does not move with wire. The position of wire-binding was set to most deflected position, decided by simulation without wire-binding.

Fig.9 shows the changes in the deflection during the manipulation. TABLE Ⅱ and Ⅲ show the maximal load of Y direction, and maximal turning angle of the front housing, respectively. Narrowing the slit reduced deflection and adsorption force (i.e., load to suction cups), although it also decreased turning angle. However, since the width of the slit is too big, the "7mm constraint" case could not reduce the deflection as same as the "no constraint" case.

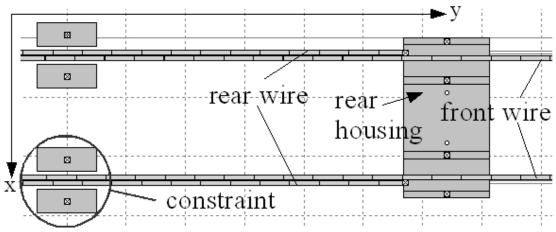


Fig.8 The constraint method of the wire in the simulation

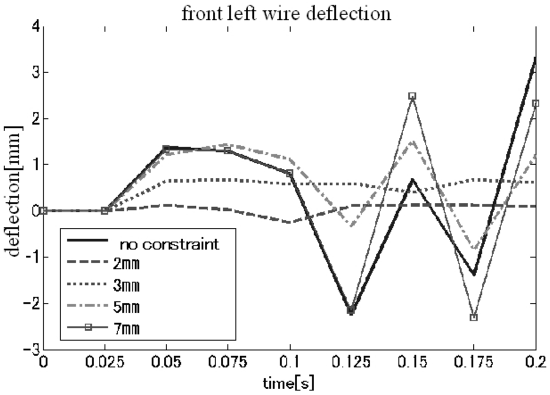


Fig.9 Front left wire deflection in each constraint width

TABLE Ⅱ

THE Y DIRECTION MAXIMUM ADSORPTION FRICTION OF C AND D POINT

$[N*10^{-6}]$	no constraint	2mm	3mm	5mm	7mm
C	3.64	1.43	2.04	4.67	5.28
D	3.63	0.59	0.95	2.59	4.13
difference	0.016	0.835	1.09	2.08	1.15

TABLE Ⅲ

THE AMOUNT OF THE MAXIMUM TURN OF THE FRONT HOUSING

[rad]	no constraint	2mm	3mm	5mm	7mm
maximum turn	0.352	0.318	0.345	0.457	0.566

B. *Left-turn results on the robot*

Similar experiments were carried out in the real robot. As shown in Fig.10, the front and rear wires were constrained by using pieces of straw, with the inner diameter of 2 mm, 3.79 mm, 5 mm, and 6.14 mm. Using the same conditions as the simulation experiment, the wire-binding was put at the position 100 mm behind the rear housing.

The robot moved across a piece of transparent film on a flat, level surface of an endoscopic surgery training kit. The pictures shown below depict the bottom view of the robot.

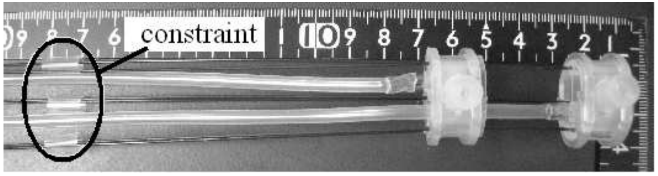


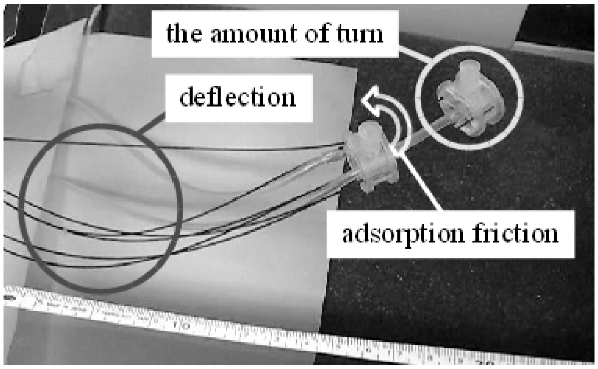
Fig.10 Wires constrained in the real robot

Results are shown in Fig. 11-12. In order to compare the simulation results, only pictures relating to the left-turn motion of the front housing are shown.

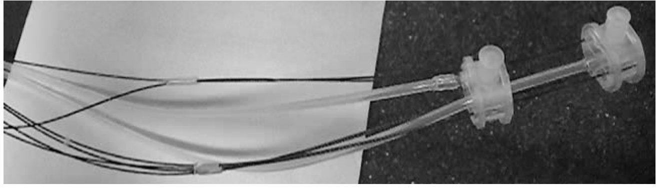
A tendency observed, in the simulation experiment, is that a tighter constraint could result in a smaller deflection, but as a side effect, a smaller turning angle (Fig.11).

Fig.12 shows the changes in voltage at the front and rear suction cups. A jump to 6v indicates that the suction cup has been released, while a voltage of 0 shows that the cup is attached to the surface. A tact switch was used to enable the “attached” state. When a suction cup was moved to a right position with a good posture (ready for attach), the tact switch is pushed.

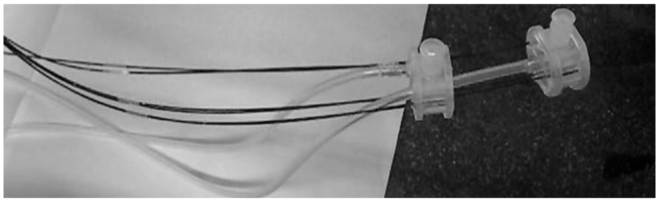
The time interval between when the tact switch is pushed and when the voltage falls to zero can be considered as the time it takes for the suction cup to attach to the surface. Comparing the hatching portion of “no constraint” case (Fig.12(a)) and “5mm constraint” case (Fig.12(b)), it is clear that 5mm constraint could result in easier manipulation.



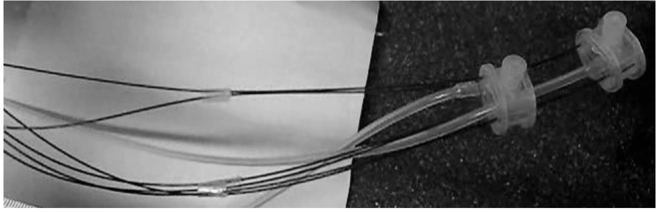
(a) no constraint



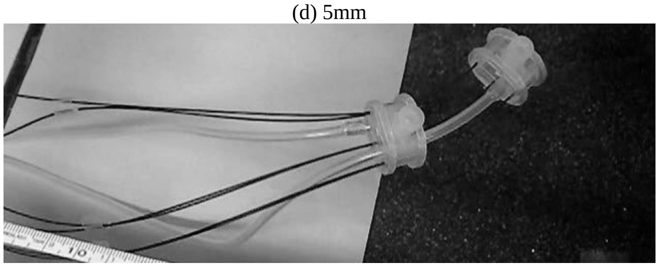
(b) 2mm



(c) 3.79mm

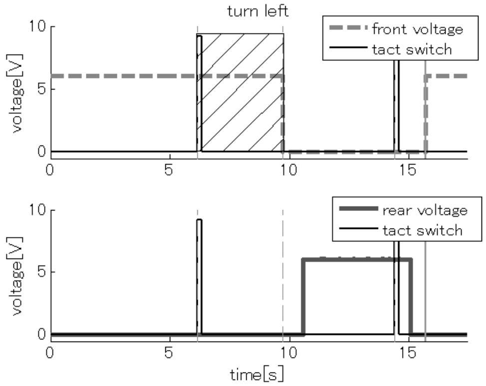


(d) 5mm

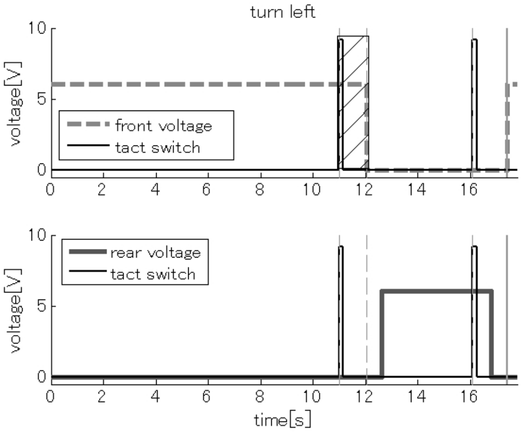


(e) 6.14mm

Fig.11 Turing left of the front housing



(a) no constraint



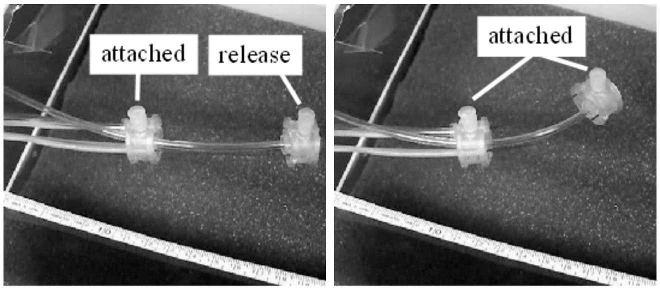
(b) 5mm constraint

Fig.12 Output of pressure sensors and tact switch

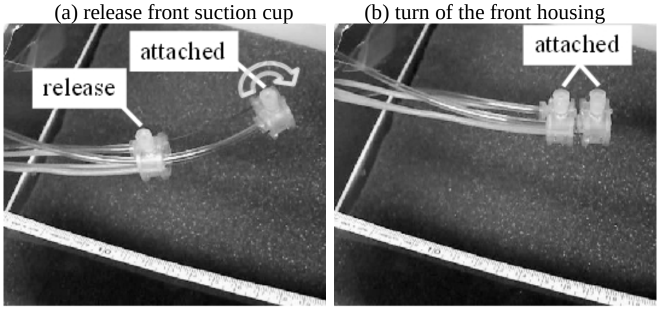
C. First and second robot prototype comparison

Fig. 13 and 14 show the turn motion of the first and second robot prototypes respectively. In Fig. 13, the motion sequence of the first robot was described. After the front housing turns and attaches to the surface, the rear suction cup is released. At that instant, the rotation moment would work on the rear suction cup in the direction denoted by the arrow in Fig.13(c). Fig.13(d) shows that due to the inflexibility of the rigid tube, the rear housing of the first prototype was forced to move in a straight line rather than a curve.

On the other hand, as shown in Fig.14, in the turning motion, the rear housing of the new prototype robot was able to move along the curve. This improvement was a direct result of the increased flexibility of the rear wires.

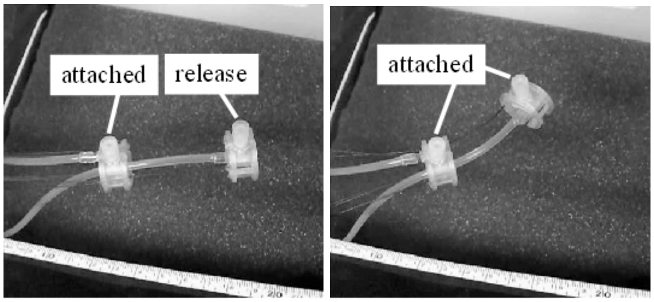


(a) release front suction cup (b) turn of the front housing

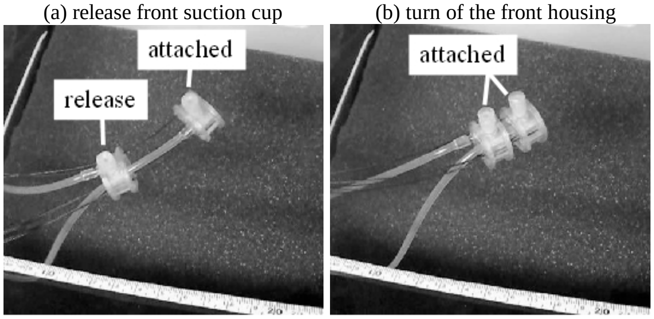


(c) release rear suction cup (d) turn of the front housing

Fig.13 Turn movement of the first prototype



(a) release front suction cup (b) turn of the front housing



(c) release rear suction cup (d) turn of the rear housing

Fig.14 Turn movement of the new prototype

V. CONCLUSION

Despite increased research into NOTES laparoscopic surgeries, the driving mechanism found in micro mobile devices continues to be a hindrance. The purpose of this experiment was to investigate whether a wire-wire driving mechanism would show increased performance over the old wire-tube model. As predicated, the new driving mechanism is a more effective model. However, deflection of the wires creates a new challenge.

A robot simulator with flexible wires and soft suction cups were developed to test the new driving mechanism and investigate the solutions to the problems relating to deflection. Based on the simulator, a robot containing the new driving mechanism was also developed. Six wires were fixed to the front and rear housings to realize 3 D.O.F. of motions. The turning motions of both prototypes were tested and compared.

Results by simulator and real robots presented a consistent tendency, which denotes that the problem caused by the deflection could be solved by appropriately constraining the paired wires by wire-binding.

Therefore, it is reasonable to consider that, by changing to the new wire-wire driving mechanism, the manipulability of the robot improves for NOTES support usage.

Before this device is able to be used in surgeries, however, it will be necessary to miniaturize the robot further, and conduct animal experiments for to ensure it is safe for human use.

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