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Development of Selective Driving Joint Forceps Using Shape Memory Polymer

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***Abstract*— In this study, we developed a selective driving joint forceps (SDJF) for laparoscopic surgery. The SDJF has a mechanism that the driving joints can be selected arbitrarily, therefore each joint doesn't require an individual actuator for operating. The developed SDJF has six joints that can be operated using only four actuators. Each joint has 2-degrees-of-freedom (DOF) of flexion. Therefore, the SDJF has the same working area as the forceps having six driving joints (each joints can bend ±30° around the X and Y axes). The mechanism of the SDJF is realized by fixing each joint with a collar made of shape memory polymer. The proposed mechanism not only reduces the number of actuators required for joint operation, but also has the rigidity of the forceps, which is important in surgery. In addition, a driving section of the forceps is driven by pneumatic cylinders, therefore, the forceps joint has high-back-drivability, lightweight and high-output. We measured the heating and cooling time required to change the driving joint, dynamic response and rigidity of the prototype SDJF.**

I. Introduction

In recent years, there has been an increasing demand for minimally invasive surgery to reduce patients' burden. Laparoscopic surgery, which is representative of minimally invasive surgery, requires only several 5-10 mm holes to be made in the abdominal cavity, so it can minimize damage to normal tissue that does not need to be damaged and has excellent esthetics [1] [2]. However, minimally invasive surgery has a problem that the movement of the instruments in the abdominal cavity is limited and the lesion site can be treated from a limited attitude. This problem reduces the work efficiency of the doctor. To solve this problem, many researchers and company engineers have been actively researching multi-degrees-of-freedom (DOF) forceps.

Kim et al. developed a multi-DOF forceps manipulator with wire antagonistic mechanism [3]. This forceps has 4-DOF and a wide range of motion in the abdominal cavity. However, it is difficult to reduce the forceps diameter because many wires are connected to joints and go through in the shaft.

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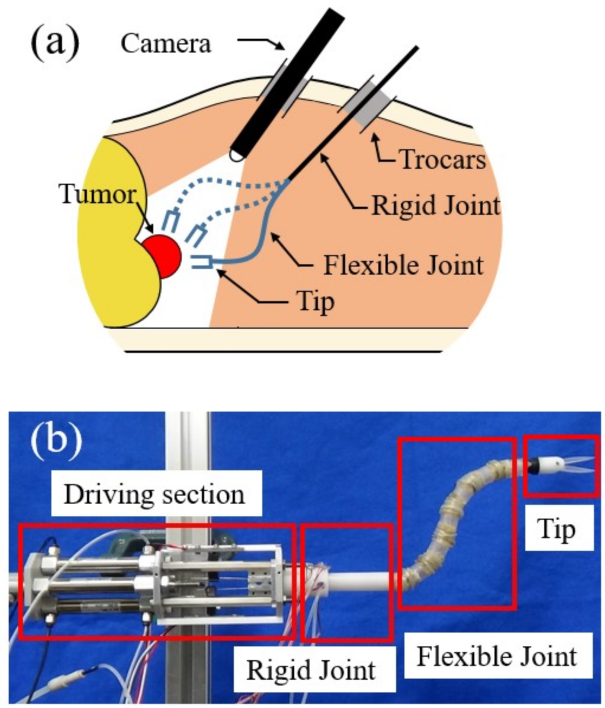

Fig. 1: Design requirement and mechanical concept of the developed forceps. (a) The forceps tip is desired that it can approach the tumor from a wide range angle like open surgery. (b) The driving actuators of forceps are kept outside of the patient's body.

Degani et al. developed the robot HARP which consists of two structures of exoskeleton and endoskeleton [4] [5]. In this mechanism, the number of actuators can also be minimized. However, because of the structure consisting of two skeletons, the driving part of the robot outside the body is very large. This limits the insertion of other forceps and instruments.

As described above, various multi-DOF forceps have been developed. However, there are problems that the number of actuators increases in accordance with the number of driving joints, and the driving section and forceps diameter become large. Such a complex mechanism makes the manufacturing will become difficult, and the development cost will become high. In addition, another problem in multi-DOF forceps is reduced stiffness. The rigidity of the forceps is a critical factor in the suturing and excision operations. Interestingly, some researchers use special materials such as silicon and shape memory alloys for forceps instead of rigid link mechanisms [6] [7]. Since most of the approaches using special materials do not require actuators, the driving part can be miniaturized. However, it is difficult to reduce the diameter of forceps to obtain the required output and rigidity. In addition, many special materials use deformation of the material itself, so the dynamic characteristics are not good.

In this study, we propose a forceps that can select the driving joint arbitrarily in order to realize a wide range of motion and high joint stiffness in the abdominal cavity. We named the proposed mechanism as a selective driving joint forceps (SDJF). Its design requirement and mechanical concept are shown in Fig. 1. This is a novel method combining a rigid mechanical structure and flexible material, shape memory polymer (SMP). SMP is a special material whose rigidity varies with temperature and is also applied to medical equipment [8]. Recently, it has also been studied as an actuator and is expected to be used in engineering applications [9] [10]. In this study, the joint motion is suppressed by securing each joint with a collar made of SMP. The developed mechanism in Fig. 1 (b) has six joints that can be individually operated using common actuators. The required number of actuators does not depend on the joint number since only the driving joints are operated by the actuator and the other joints are fixed by extremely high rigidity. The change of the driving joint is only made by the control of SMP and is independent of the output and control of the actuator.

By adopting this mechanism, the operation range of the proposed forceps is the same as multi-DOF forceps, while maintaining the rigidity of the 2-DOF forceps manipulator, which is used in surgery at present.

The rest of this paper is composed as follows. In Section 2, we introduce the concept and the details of the mechanism of the SDJF. In Section 3, we conducted three basic experiments using the SDJF and examined the practicability of the SDJF. First, we confirmed experimentally the heating and cooling times required to change the driving joint. Second, we verified the step response and frequency response of the developed forceps. Finally, we measured the stiffness of the forceps by a static loading experiment. In Section 4, we discuss the considerations of the studied problems. Section 5 describes the conclusions of this study and future issues.

II. Selective Driving Joint Forceps

The overall view of the developed forceps is shown in Fig. 2. The SDJF has six bending joints covered by SMP collar. This SMP collars realize the joint selection method. The ball joint is expected to reduce the joint diameter and improve the stiffness [11]. Each joint length is 24 mm. Each ball joints can bend ±30° around the X and Y axes. The tip of the forceps can rotate around the Z axis independently. The SDJF is 12 mm in diameter and can be inserted into the trocar of laparoscopic surgery. Next, the SDFJ theoretical workspace is shown in Fig. 3. The SDJF has 12-DOFs in the flexion joint and 1-DOF in the rotation mechanism. Only driving joints can be manipulated at a time, and only 3-DOF are available during manipulation (2-DOF in the flexion and 1-DOF in the rotation). However, since the driving joint can be freely changed by the control of SMP, the working range is equivalent to that of the multi-DOF forceps having six driving joints (2-DOF for each joint flexion, ±30° range about the X and Y axes). The workspace size is 100 × 100 × 80 mm. To realize a multi-DOF forceps having six driving joints in a

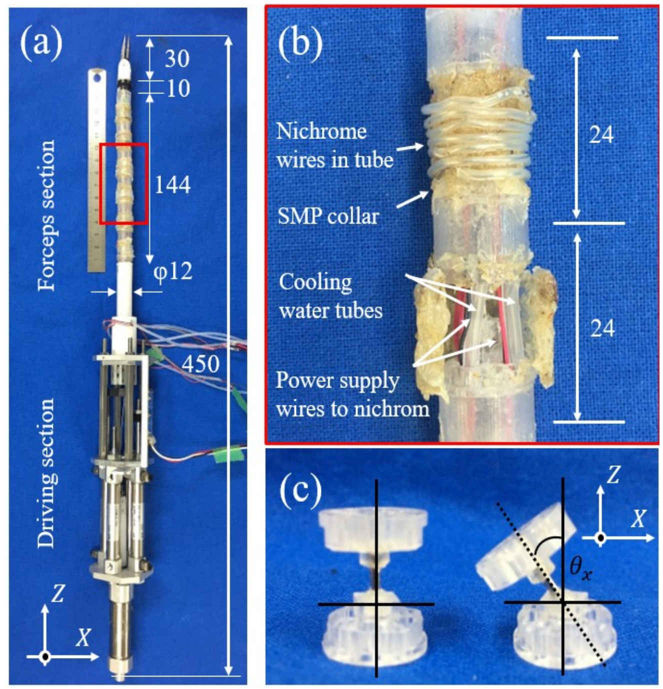

Fig. 2: Overall view of the SDJF. (a) The driving section consists of five pneumatic cylinders, and the forceps section consists of six bending joints and a gripper. (b) An enlarged view of the joint and its components. (c) The ball joint can bend between ±30° around the X and Y axes.

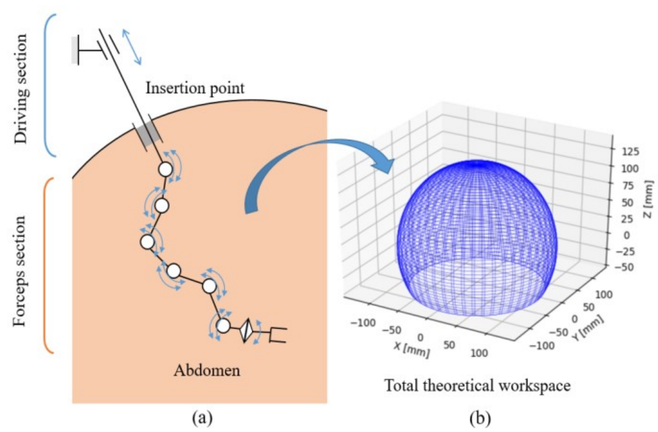

Fig. 3: Total theoretical workspace. (a) DOF: holder = 1, bending joints = 12 (2×6 joints), rotation joint = 1, and gripper open/close = 1. (b) The SDJF has the same working range of the multi-DOF forceps having six driving joints.

conventional structure, twenty-four actuators and wires are needed to tendon drive each joints with two actuators, and the mechanism will become complicated. On the other hand, the SDJF is easy to realize because it requires only four actuators for bending and one actuator for rotation. The joint selection method and the SDJF details are described in the following sections.

A. Joint Selection Method

In this study, we developed the SMP collar that fix or release the joint motion, and also proposed its joint selection method. The SMP is hard in room temperature but gets flexible when heated. Fig. 4 shows the joint drive patterns of the SDJF. The SMP collars are placed at each joint to limit the joint motion. When all SMP collars are hard, all joints are constrained and the wires cannot change the posture of the SDJF. At this time, the manipulator has no-DOF. When the SMP collars becomes soft by heating, the corresponding joints are unlocked and able to be operated by the wires. When the SMP is cooled and solidified, the joint becomes hard again, the joint is fixed at the current angle. Therefore, it is possible to use the forceps both as a usual single-DOF one by heating only one collar and as a long flexible one by heating multiple collars simultaneously. It is possible to conduct surgical operations in narrow space, by repeatedly heating and cooling the joints to make a complex shape, and then activate the distal joint like conventional surgical robots.

There are two main advantages to using this mechanism with forceps. First, we can decrease the number of actuators and downsize the driving section. As described in Section I, the driving section of conventional multi-DOF forceps tends to become large. It was difficult to increase the number of actuators and driving joints. On the other hand, the selective driving joint mechanism can operate many joints with only four actuators. Therefore, the number of 2-DOF flexional joints can be increased without increasing the number of actuators and driving section size. The proposed mechanism has the working area equivalent to that of multi-DOF forceps with the same number of joints. The second advantage is a high stiffness. In the case of conventional forceps, increasing the number of joints significantly reduces rigidity. On the other hand, the proposed mechanism covers each joint by the SMP collar. Therefore, when a load is applied to the tip of the forceps, there is no need to control the actuator to bend the forceps in the opposite direction to the load. This makes it possible to achieve rigidity independent of the actuator output.

B. *The SDJF Details*

The details of the flexible joint are shown in Fig. 5. One bending direction of the forceps joint is driven by two wires, centered on the ball joint. Each joint is wound with a collar made of the SMP. In this research, we used the SMP 55 of the Filament Studio, which can be output by a 3D printer. The molding temperature of the SMP is 200 ℃ and the reaction temperature is 55 ℃. In this prototype, the diameter of the SMP collar is 11.0 mm and the thickness is 0.5-0.75 mm. To heat the SMP collar, a nichrome wire coated with a silicon tube winds around each collar. Nichrome wire is an alloy with high electrical resistance used in electric stoves. In this prototype, the SMP is heated with the nichrome wire. In addition, a silicon tubes for water cooling is arranged inside the joint to improve the SMP's deformation responsiveness. In this research, we used saline as a coolant to decrease risk of leakage in vivo.

The details of the driving section are shown in Fig. 6. Four pneumatic cylinders pull four wires independently to achieve 2-DOF. The pneumatic cylinder's stroke is 30 mm. The driving section has only four pneumatic cylinders for bending, but six joints (12-DOFs) can be actuated by using the method described in Fig. 4. A potentiometer is attached to each pneumatic cylinder to measure the displacement of the wire. The advantages of pneumatic actuator compared to the electric motor are as follows. First, the pneumatic actuator has a high power-to-weight ratio. This makes the driving unit lightweight

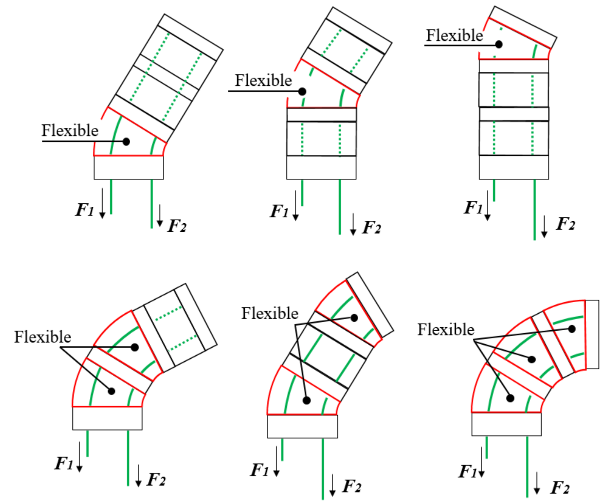

Fig. 4: Concept of the selective driving joint mechanism. There are various patterns of the driving joint choice and this provides a sufficient workspace. In some cases, only one joint is selected, and in other cases, multiple joints can be selected. The wire is given pre-tension to prevent loosening. F_1 and F_2 are pulling force of the wires.

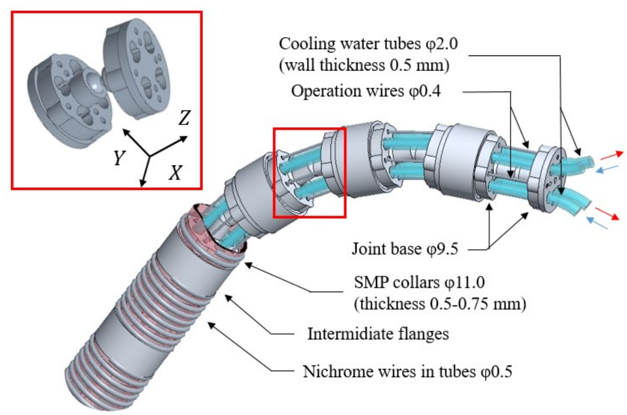

Fig. 5: Flexible joint details. The flexible joint consists of ball joints, operation wires, SMP collars, intermediate flanges, nichrome wires, power supply to nichrome wires, and cooling water tubes.

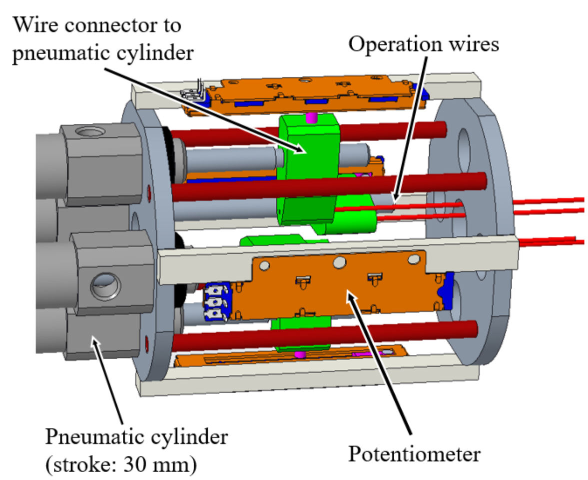

Fig. 6: Driving section details. The driving section consists of four pneumatic cylinders for bending the joints in two directions and one pneumatic cylinder for gripper opening and closing. Note that this paper focuses to realize the bending motion as our first prototype, and the rotation motion of the forceps tip will be realized in our future work.

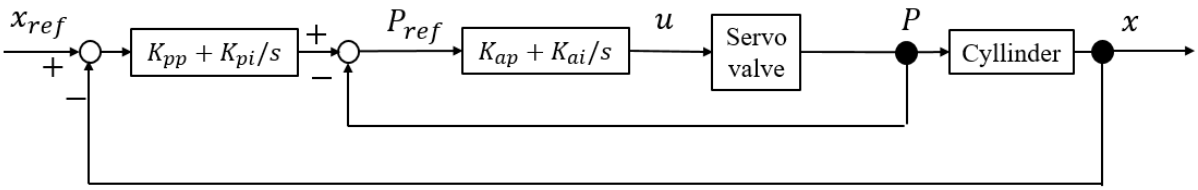

Fig. 8: Block diagram of the pneumatic cylinder position control system, including pressure control system in the inner loop

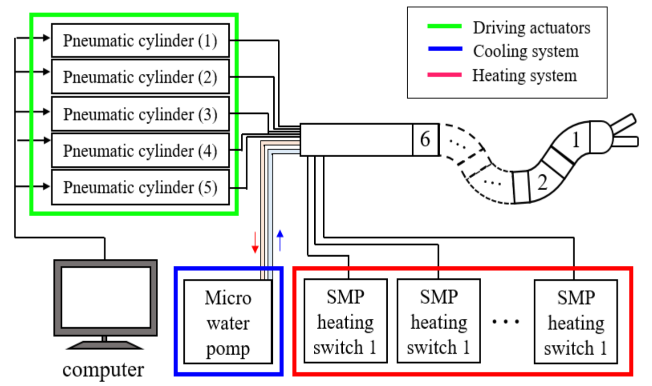

Fig. 7: Experimental apparatus of the developed SDJF. The SDFJ consists of five pneumatic cylinders, a cooling system, a heating system for supplying current to nichrome wire, and a control PC for pneumatic cylinders.

and compact and reduces the risk of contact with the surgeon. Second, it is high-back-drivability. Thanks to this advantage, the external force on the forceps tip can be estimated without attaching a force sensor by using the pressure information in the pneumatic cylinders.

The experimental apparatus of the developed the SDJF is shown in Fig. 7. A current in nichrome wire at each joint is controlled by a separate switch, and 0.8 A (voltage is 2.4 V) is applied by pushing the switch to make the SMP deformable. In addition, the flexible joint is always cooled by the saline pumped up by the micro-water-pomp, and its circulation time is 0.12 ml/sec.

III. Experiment

We carried out three experiments to measure the basic performance of the SDJF. First, we measured the heating and cooling time required to change the driving joint. Second, we measured the step response and frequency response of the SDJF and verified its dynamic characteristics. Finally, we measured the stiffness of the SDJF by a static loading experiment. Detailed descriptions of these experiments are as follows.

A. Heating and Cooling Time Evaluation

The SDJF has a sufficient workspace that can be achieved with a small number of actuators, however, it is necessary to change the driving joint. In this experiment, we measured the required time to change the driving joint. Concretely, a sine wave target position is given to control the pneumatic cylinder and the SMP collar in the joint 6 shown in Fig. 7 is heated and cooled during the bending motion. By measuring the forceps tip angle, the required time of state change between soft and hard states of the SMP collar can be obtained.

Fig. 8 shows the block diagram of position control. In this study, we use a position control system that includes pressure control as the inner loop. P_{ref} [kPa] is the target pressure. u [V] is the control voltage of the servo valve. The pressure control system has a proportional gain K_{ap} is 0.11 V/kPa and an integral gain K_{ai} is 11.0 V/(kPa-s). x_{ref} [mm] is the target position. The position control system has a proportional gain K_{pp} is -5.0 V/mm and an integral gain K_{pi} is -50.0 V/ (mm-s). These values were determined experimentally.

Fig. 9 shows the experimental results. The left vertical axis is the angle of the forceps. The right vertical axis is the current input to the nichrome wire. The horizontal axis represents time. The pink step input is the supplied current value by the switch, the red dashed line is the target value of the forceps (sine wave amplitude=30°, frequency =1.3 rad/s), the blue solid line is the actual position of the forceps tip measured from the forceps image, and the green solid line is the angle amplitude of the forceps tip in one cycle. From the experimental result, we confirmed that it took 10 s for the joint to become operable and 40 s for the joint to become inoperable. These are very long time to use in real surgery, however, we consider that the time can be shortened by improving the heating and cooling system.

B. Response Evaluation

The SDJF uses the SMP collar to fix the joint, and it might inhibit joint bending and makes delay even in the soft state. The delay causes discomfort to the forceps operator. To evaluate this risk and responsiveness, we measured the step response and frequency response of the SDJF during the SMP collar softening and verified its dynamic characteristics.

First, we measured the step response of the SDJF during the SMP collar was preheated to 55 ℃ by nichrome wire, and the room temperature was 23 ℃. The control system and gain values are the same as those in Section III-A.

Fig. 10 shows the experimental results. From these results, we confirmed the delay when the step target angle was input

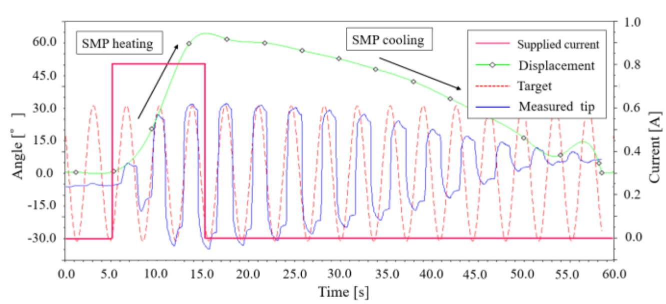

Fig. 9: Heating and cooling time about the joint 6. The experimental result shows the time, required to select the joint 6 as the driving joint. The water cooling is always done.

in each joint. The vertical axis is the angle and the horizontal axis is the time. The dotted red line represents the step target angle, and the solid lines represent the joint angles calculated from the measured position of the pneumatic cylinder. The angles in Fig. 10 are filtered data used a moving average filter whose data length of 34 to remove the potentiometer noise. The experimental result in Fig. 10 seems like a response of first-order lag system, and we evaluated the response with the assumption of that system. The experimental results showed a delay of 0.1-0.3 s in each joint. The delay of 0.3 s is large in the surgery support robot. Operators can tolerate up to 0.4 s delay during surgery but are very stressed during the operation [12]. The delay time is preferable to be 0.2 s or less [13]. This SDJF delay may be due to the fact that the SMP physical model is not included in the control system. Therefore, we will consider implementing the SMP model into the control system in our future work. Also, the delay will be improved by reducing the thickness of the SMP collar, but it will cause to decrease in rigidity.

Second, in order to evaluate the dynamic characteristics, we inputted a sine wave target angle and examined the response. Fig. 11 shows the response when a target angle is given at a frequency of 1 rad/s. The dotted red line represents the target angle, and the blue line represents the joint angle. The results show that the delay is small in continuous operation during SMP softening.

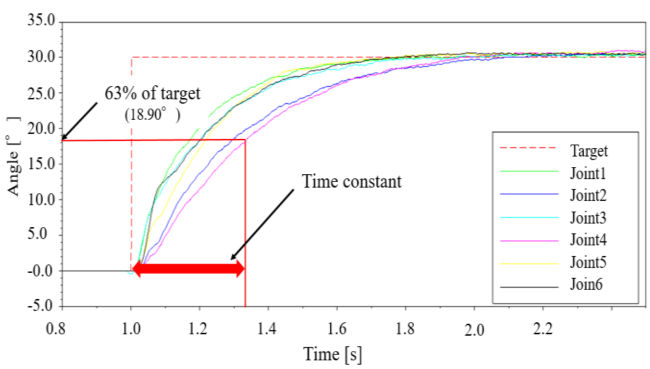

Fig. 10: Step response of the joint bending. The SMP collar of each joint was softened and made operable (after heating for 10 s). The data were filtered by the moving average filter to remove the potentiometer noise.

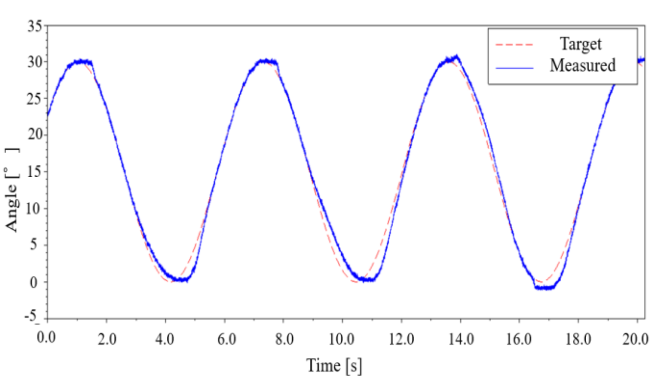

Fig. 11: Frequency response of the joint 1 to sinusoidal input (sine wave amplitude=15 degrees, frequency =1 rad/s). The red dotted line is the target joint angle, and the blue solid line is the joint angle.

C. Rigidity Evaluation

The rigidity of forceps is important for surgical task such as suturing work and lifting organs etc. Therefore, we measured whether the SDJF had sufficient rigidity. As a verification method, we loaded the forceps tip and measured its deflection. Fig. 12 shows a device for measuring the deflection of the SDJF. The deflection is measured with a laser range finder, and the loading mass is between 250-430 g. In this experiment, in order to just clarify the basic performance of the SDJF, the SMP collar is in a hard state during measurement and there is no feedback control by the pneumatic cylinder.

Fig. 13 shows the measurement results. The vertical axis indicates deflection and the horizontal axis indicates weight. The red line shows the amount of deflection as the weight increases, and the blue line shows the amount of deflection as the weight decreases. The results showed that the developed forceps deflected 3.92 mm at a weight of 430 g. This is as rigid as wood of the same shape, indicating sufficient rigidity. In addition, it was confirmed that a weight of 400 g can be gripped in any posture without pneumatic cylinder compensation force, as shown in Fig. 14. In contrast, no additional force is required to deform the SMP after heating.

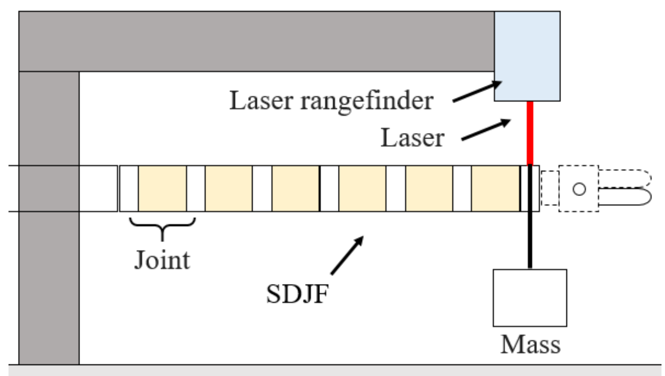

Fig. 12: Flexural rigidity measuring device. This device is composed of a guide structure fixing the driving section of the SDJF, a weight for applying external force to the forceps tip, and a laser range finder for measuring the deflection of the forceps tip.

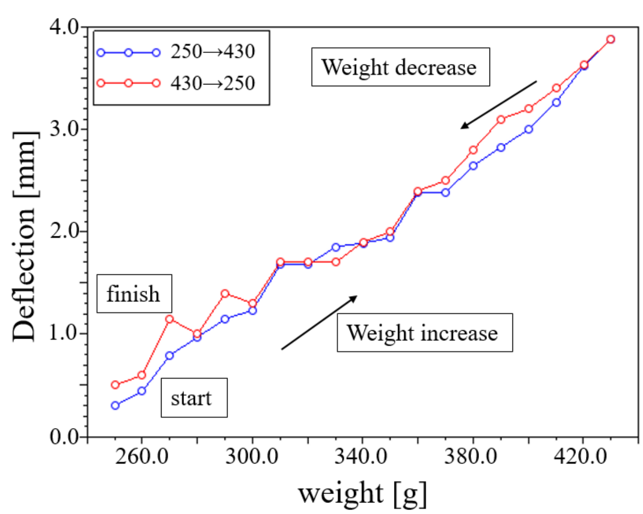

Fig. 13: Experimental results of measuring the flexural rigidity.

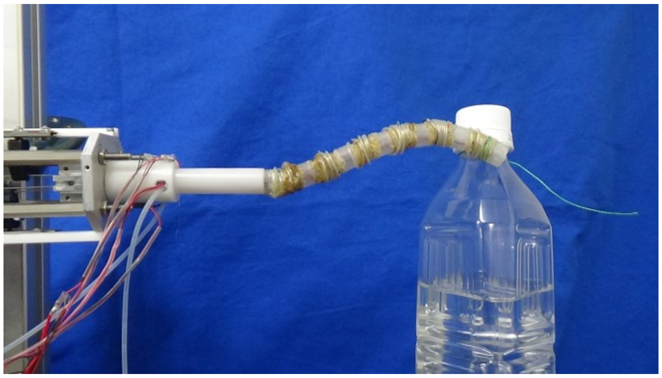

Fig. 14: Forceps lifting a bottle of 400 g without a pneumatic cylinder force.

IV. Discussion

The SDJF solve the problems of the single-articulated forceps (the operating area) and the multi-DOF forceps (the rigidity and number of actuators). In addition, the shaft diameter of the prototype was 12 mm, and further miniaturization is expected in the future, for example, changing the joint type from the ball joint. In this paper, we focused on the forceps manipulator. A future work is to develop a complete tele-operated robot system. The forceps manipulator developed in this study is not the same as any existing one. Conventional surgeon interface can handle only 6-DOFs. Therefore, it is necessary to make a suitable operation system. For example, an interface with the same structure as the manipulator is intuitive [14]. Alternatively, we also consider a route search control system that determines the route to the destination and controls the attitude automatically, will be effective. The forceps manipulator still need to be improve. From the experiment, we confirmed that the response when the SMP softening was faster than that of the hardening. However, it takes about 10 s to soften, and about 20-40 s to harden (these times will also change along with the environment around). Therefore, in the process of selecting joints, it is necessary to go through the steps of heating, operation, and cooling, so it takes a long time. One of the challenges in future research is to improve the heating and cooling system to increase the SMP reaction rate. In addition, the present reaction temperature of 55 ℃ is considered to be too high considering the use in vivo. In the future, it will be necessary to improve forceps so that there will be no problem with a contact in vivo, such as using a material that reacts at a low temperature for SDJF.

V. Conclusion

In this paper, we developed the selective driving joint forceps (SDJF). The driving joint selection mechanism was realized by utilizing shape memory polymer (SMP). The basic performance of the SDJF was measured by confirming the response by step function and by measuring deflection under static load. By checking the response when input the step response, it was confirmed that the SMP did not interfere with the bending motion of the forceps. Static loading experiments have shown that the stiffness of the forceps is independent of the actuator output. These results show the usefulness of the SDJF. In future research, we will improve the SMP response by changing the heating and cooling system, and develop a teleoperation interface system suitable for the SDJF, and perform realistic surgical tasks after constructing a complete surgical robot system.

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