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Force-detecting gripper and force feedback system for neurosurgery applications

Takeshi Yoneyama, Tetsuyou Watanabe, Hiroyuki Kagawa

School of Mechanical Engineering, Kanazawa University
Kakuma-machi, Kanazawa 920-1192, Japan
81-76-234-4683
yoneyama@t.kanazawa-u.ac.jp

Junichiro Hamada, Yutaka Hayashi, Mitsutoshi Nakada

Department of Neurosurgery Graduate School of Medical Science, Kanazawa University
Takara-machi, Kanazawa 920-8641, Japan

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Abstract

Purpose For the application of less invasive robotic neurosurgery to the resection of deep-seated tumors, a prototype system of a force-detecting gripper with a flexible micromanipulator and force feedback to the operating unit will be developed.

Methods Gripping force applied on the gripper is detected by strain gauges attached to the gripper clip. The signal is transmitted to the amplifier by wires running through the inner tube of the manipulator. Proportional force is applied on the finger lever of the operating unit by the surgeon using a bilateral control program. A pulling force experienced by the gripper is also detected at the gripper clip. The signal for the pulling force is transmitted in a manner identical to that mentioned previously, and the proportional torque is applied on the touching roller of the finger lever of the operating unit. The surgeon can feel the gripping force as the resistance of the operating force of the finger and can feel the pulling force as the friction at the finger surface.

Results A basic operation test showed that both the gripping force and pulling force were clearly detected in the gripping of soft material and that the operator could feel the gripping force and pulling force at the finger lever of the operating unit.

Conclusions A prototype of the force feedback in the microgripping manipulator system has been developed. The system will be useful for removing deep-seated brain tumors in future master–slave-type robotic neurosurgery.

Keywords

Neurosurgery, robotic surgery, brain tumor, manipulator, force feedback

Introduction

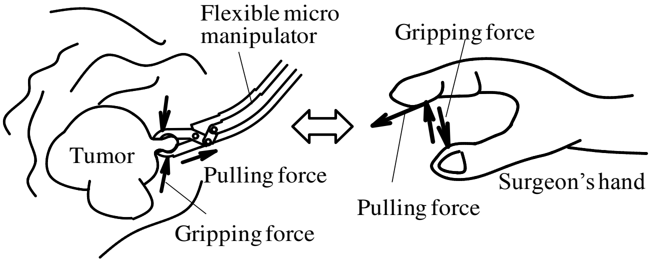
For less invasive surgery, operations using manipulators with endoscopes have become popular, and surgical robotics has been also widely used in the field of abdominal and urological surgeries [1-3]. However, higher performance is necessary in a robotic system for neurosurgery because brain tumors can be seated deep within the brain and surrounded by healthy tissue, with only a narrow space for approaching tools [4]. Concerning robotic surgery for the resection of deep-seated tumors, Hongo, Goto et al. developed a micromanipulator system named "NeuRobot" for removing brain tumors [5-8]. It was an excellent system and achieved good surgical results from 2002 to 2003. However, the application is now limited to non-clinical use owing to changes in laws of the Japanese Government in 2004 [9]. Kan, Nishizawa et al. have developed a micromanipulator system named "HUMAN" [10,11]. Morita et al. have developed another manipulator system that can operate in deep surgical fields [12]. Okayasu et al. developed a hydraulically driven flexible manipulator for neurosurgery [13]. Arata et al. have been developing volume control suction tools with flexible manipulators to remove brain tumors [14,15].

In order to approach deep-seated tumors and remove them through the narrow space, further miniaturization of the manipulator with flexible operation is necessary. Furthermore, in order to increase the precision in gripping the tumor and increase the surgeon's feeling of the grip, a force feedback system would be useful.

Robotic surgery systems with force feedback have been studied by many researchers. Tavakoli et al. listed the requirements of surgical haptic interfaces in the master-slave system [16]. Takahashi et al. developed augmented force feedback capability by detecting the drawing forces of the shafts in the manipulator [17]. Thielmann et al. have detected gripping and manipulation forces greater than 10 N using a 7 degree-of-freedom (DoF) force/torque sensor in versatile instruments for robotic surgery [18]. Tholey et al. developed disposable forceps capable of measuring force with strain gauges [19]. Hashiguchi et al. developed a force estimation method by monitoring the pressure of pneumatic actuators in a pneumatically driven forceps manipulator [20].

Although many attempts have been made to develop force feedback in surgery systems, as of yet, there is no force-detecting gripper and no force feedback in the neurosurgery master-slave operating system. The general operation for removing the deep-seated brain tumor is a piece-by-piece removal using manually handled forceps. Force sensation at the gripping finger is important for the surgeon to feel the force when touching the tumor and to sense the pulling force when removing the tumor. During the operation to remove deep-seated tumors by the micromanipulator using the master-slave system, force feedback to the surgeon is one of the most important functions to feel the gripping force and pulling force during removal of the tumor. The force detection at the manipulator and force feedback at the surgeon's finger is illustrated in Fig. 1.

Because feeling the forces that occur during tumor removal are vital to the surgeon, the authors have been developing a force-detecting gripper with the flexible micromanipulator for neurosurgery [21]. The force-detecting gripper can detect both gripping force and pulling force during the gripping and removal of soft material. These detected signals are transmitted to the operating system. Force sensors are also installed at the finger lever and finger holder. During the operation, the micromanipulator moves according to the operated motion and the surgeon can feel the gripping force as the force resistance for closing the finger and can feel the pulling force as the friction at the finger surface by the control software in the operating system.



(a) Detecting the gripping force and pulling force to remove the tumor

(b) Feeling of the gripping force and pulling force at the surgeon

Fig. 1 Illustration showing the force detection at the manipulator and force feedback at the surgeon's finger during resection of a brain tumor

In this paper, the design and fabrication of a force-detecting gripper with flexible manipulator and the force feedback system to the operating unit are described. The force feedback capability is also investigated by a basic operation test. The design specification of the detection of the gripping force is 1 N for both the gripping and pulling forces. The force feedback on the surgeon's finger is estimated to be 3 N for the gripping force resistance and 1 N for the friction indicating the feeling of the pulling force resistance. Force reflecting servo control is adopted as a control system for precise positioning and force feedback. The diameter of the manipulator shaft to be passed through the hole in the endoscope is 3 mm, and its length is approximately 200 mm. The flexion angle at the end of the manipulator is expected to be more than 20°.

Force-detecting gripper

The gripper and the flexible manipulator were designed to be inserted through the 3-mm-diameter hole in a conventional rigid endoscope. Because the main task to remove a brain tumor is to grasp the tumor and pull it by forceps, cup-type forceps were chosen as the main gripper to remove the brain tumor. The mechanism and structure of the force-detecting gripper is shown in Fig. 2. The forceps consist of a fixed clip and movable clip. The movable clip is operated by the link connected with the inner shaft. The gripper closes when the inner tube is pulled backward. The force-detecting structure has been fabricated in the fixed clip. The detailed structure of the fixed clip with strain gauges is shown in Fig. 3. For the detection of the gripping force, a square hole is cut laterally on the detecting part of the clip in order to leave horizontal parallel plates. Strain gauges are attached to the upper and lower plate surfaces. The gripping force deforms the plates with elongation and contraction of the surface. The strain gauges detect these strains as a change in electric resistance. To detect the pulling force by the gripper, a vertical square hole is machined at a different position and a vertical thin plate structure remains. Tensile stress occurs on this surface when the pulling force is applied. Strain gauges are also attached to this surface to detect the strain from the tensile stress. From the basic test on the gripping of soft material that has similar hardness to that of a brain tumor, the maximum force is expected to be approximately 1 N for both gripping and pulling. The thickness of each thin plate was decided through finite element analysis to obtain adequate strain by each stress. All the parts were made of stainless steel.

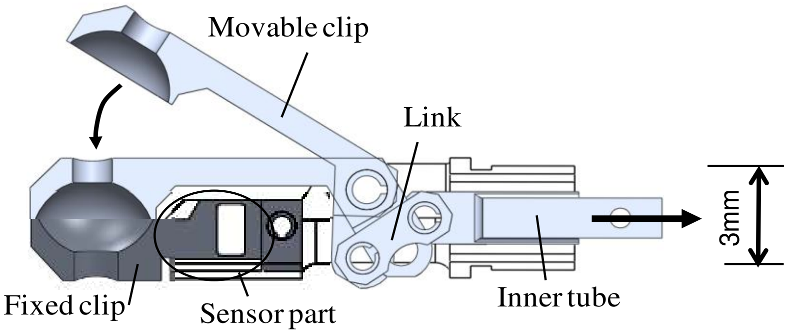


Fig. 2 Composition of the microgripper with the inserted force-detection clip

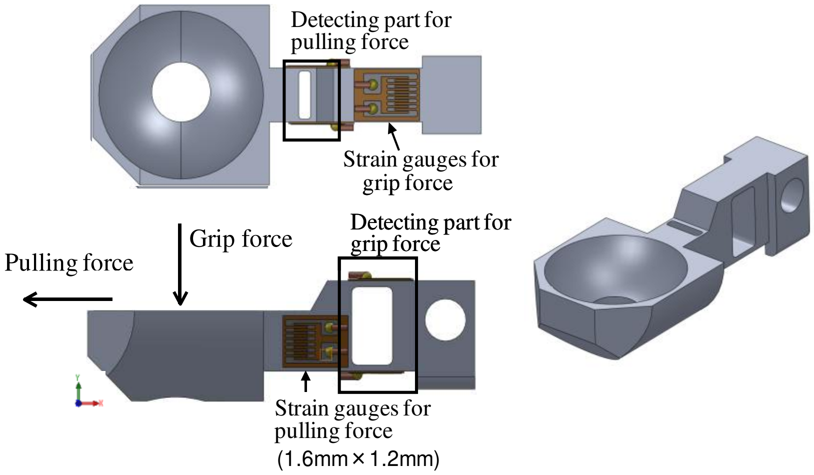


Fig. 3 Force detection structure and application of strain gauges in the force-detection clip

The base size of the strain gauges (KFR-02N-120-C1-16; Kyowa Strain Gages) is 1.6 mm × 1.2 mm, which is the minimum size of the commercial strain gauges. Because the size of the detection block is smaller than the base of the strain gauge, the base film of the strain gauge is cut around the periphery and attached at the detecting position. The lead wires from the strain gauge were passed around the link and led through the central hole in the inner tube.

After assembling the force-detecting clip, the output performance was examined. For the calibration of the gripping force, a wire was connected on the cup and was drawn in the direction of the gripping force. The drawing force was detected using a load cell. For the calibration of the pulling force, a wire tied to the cup was drawn in the pulling direction and the pulling force was measured using a load cell. Detected strain for a 1-N gripping force was 500×10^{-6} and interference from the pulling force was negligible. On the other hand, output strain for the 1-N pulling force was approximately 50×10^{-6}; smaller than expected, and interference from the gripping force was nearly the same as the main output. To obtain the actual gripping force and pulling force in the situation of a combined force, a calibration matrix was applied to the detected outputs. The force resolution is 0.01 N for the gripping force and 0.1 N for the pulling force. The resolution of the pulling force should be improved by increasing the resistance of the strain gauge or other detection structure. To reduce the noise in the output signals of the sensors, a Butterworth filter with a cut-off frequency of 10 Hz was used.

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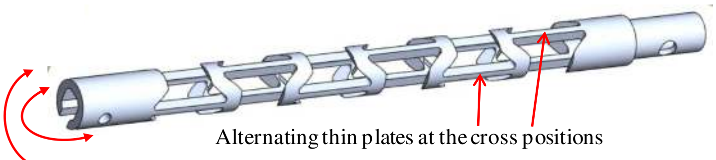
Flexible micromanipulator

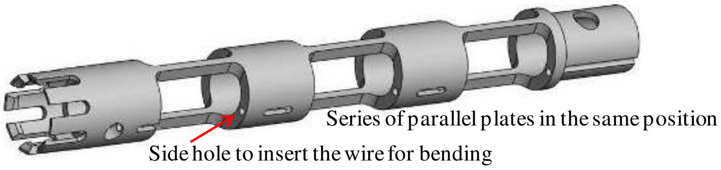
The flexible micromanipulator consists of an outer flexible tube with wires and an inner flexible tube, as shown in Fig. 4. The flexible part in the outer tube is made of thin plates connected with rings. Using electro-discharge machining, this structure was made from a single bar. The tube material is a super elastic metal called “Gum Metal” [22], which is a beta-type titanium alloy developed by Toyota Central R&D Laboratory. The elastic strain limit is 2.5% and Young’s Modulus is 45 GPa. This material has good medical adaptability for use in implants and medical tools. Two stainless-steel wires were inserted into the small holes, which were machined in the connecting parts between the thin plates. The terminals of the wires were fixed at the end of the flexible tube. If the wire on one side is pulled, the flexible tube bends toward the side of the pulled wire.

The inner tube must be flexible in two directions because it is rotated within the flexed outer tube. Therefore, the thin plate parts for one direction and the others for the perpendicular direction are arranged one after the other on the inner tube. The flexible part of the inner tube is also made of “Gum Metal”.

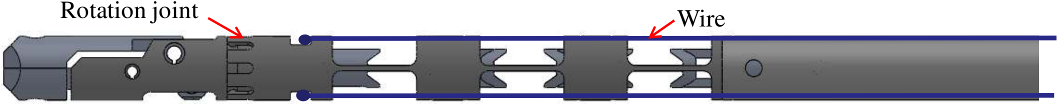
As the flexion mechanism is elastic deformation of the thin plates, there is a limit of the flexion angle owing to the elastic criteria of the material. The limit of the flexion angle is 30° by a force of 8 N on the pulling wire. The end of the gripper can achieve a circular area with a radius of 14 mm at a distance 23 mm from the end of rigid endoscope.



(a) Inner tube with two-dimensional flexibility



(b) Outer tube with unidirectional flexibility



(c) Assembled flexible manipulator

Fig. 4 Composition of the micromanipulator with unidirectional bending flexibility and rotatable gripper at the end

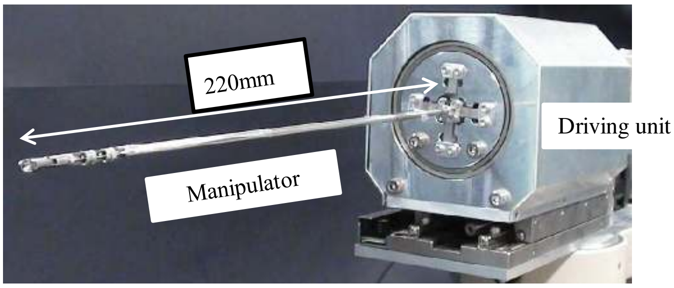
Manipulator driving unit

The driving unit of the manipulator is shown in Fig. 5. The device has five stepping motors for pulling the inner tube to close the gripper, for rotating the inner shaft to rotate the gripper, for pulling the wire of the outer tube to bend the manipulator, for rotating the entire manipulator both with the outer tube and inner shaft and for straight motion when approaching the manipulator to the tumor. A stepping motor has an advantage of precise positioning because it rotates according to the number of the pulses given by the controller.

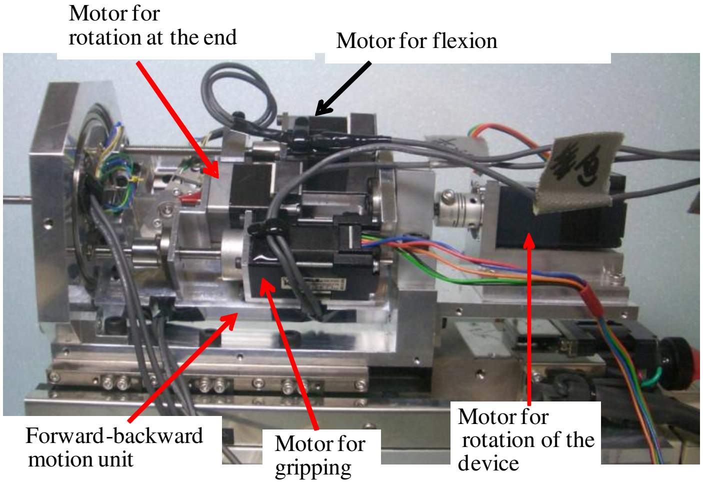
An example of the driving motion for closing the gripper is shown in Fig. 6. The stage of the inner shaft moves straight to close the gripper by the ball screw rotated by the driving motor. The ball screw is connected directly with the motor shaft. The combination of a ball screw and straight guide is widely used in machine tools for precise motion and positioning. Another motor to rotate the inner shaft is set on the stage.

The straight motion of the sliding stage by the motor for flexion is transmitted to the wire drawing lever.

There are two force sensors for detecting the force applied on the outer tube and for detecting the pulling force on the wire. When the driving force is applied on the wire for flexion, the force is transmitted to the outer tube. Furthermore, when the gripper grasps a target and pulling motion is actuated by the translation motor, pulling force will influence the driving force of the inner shaft. For these reasons, the sensor installed in the gripper clip has the advantage of detecting the gripping force and pulling force directly. On the other hand, during the clinical operation, additional force may be applied on the gripper externally by touching the tissues around the tumor being removed. The external touching force may influence the detection of the gripping force and pulling force. The detection of the forces of the outer tube and the flexion wire at the driving unit will be useful to distinguish such additional forces in future investigations.



(a) Micromanipulator attached to the driving unit



(b) Arrangement of motors in the driving unit

Fig. 5 Micromanipulator attached to the driving unit and arrangement of the motors

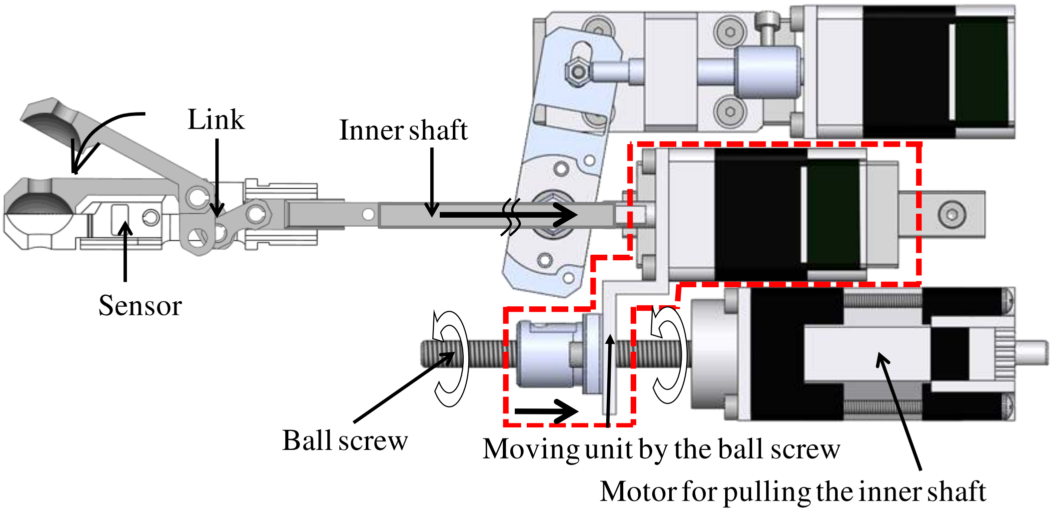
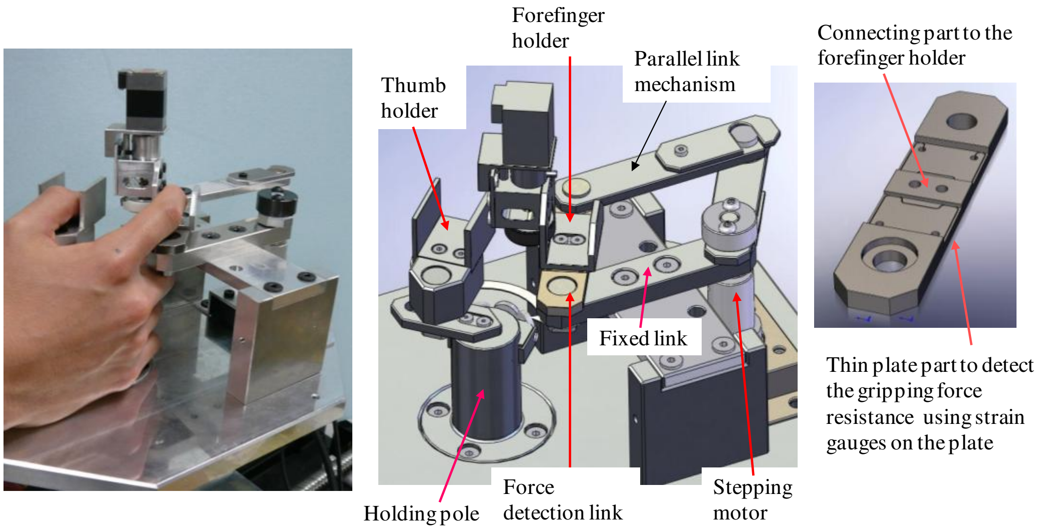


Fig. 6 Closing the gripper by pulling the inner shaft using a ball screw

Operating unit

The surgeon's grip operation device is shown in Fig. 7. The finger link is made of a 4-link mechanism. A force sensor is installed in the finger holder lever, which detects the gripping force at the operating system. Finger link motion is transmitted to the motor link. A change in the finger link angle is detected as a change in the rotation angle of the stepping motor. The closing angle of the manipulator gripper is assigned from the rotation angle of the motor. Gripping force feedback is applied by the motor rotation so that the force detected using the force sensor coincides with the desired value in relation to the gripping force on the manipulator.



(a) Picture of the grip part in the operating unit

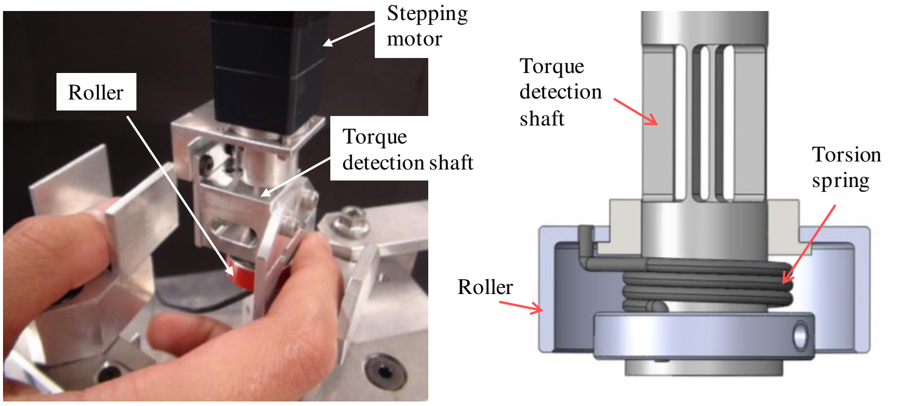
(b) Composition of the grip part from a view point similar to that in the left picture

(c) Force detection link

Fig. 7 Setup for detection of the grip force resistance and actuating stepping motor in the operating unit

In order to transmit the pulling force at the gripper as the friction force on the finger surface, a friction roller is equipped at the side surface of the finger lever as shown in Fig. 8. A torsion spring is installed in the roller to apply friction force according to the twisting angle of the spring. The torque generated by the friction at the roller surface is detected by a torque sensor connected between the roller and the stepping motor. By the control system, the control algorithm calculates the desired friction force according to the pulling force on the slave gripper, and then, the roller rotates to generate this force.

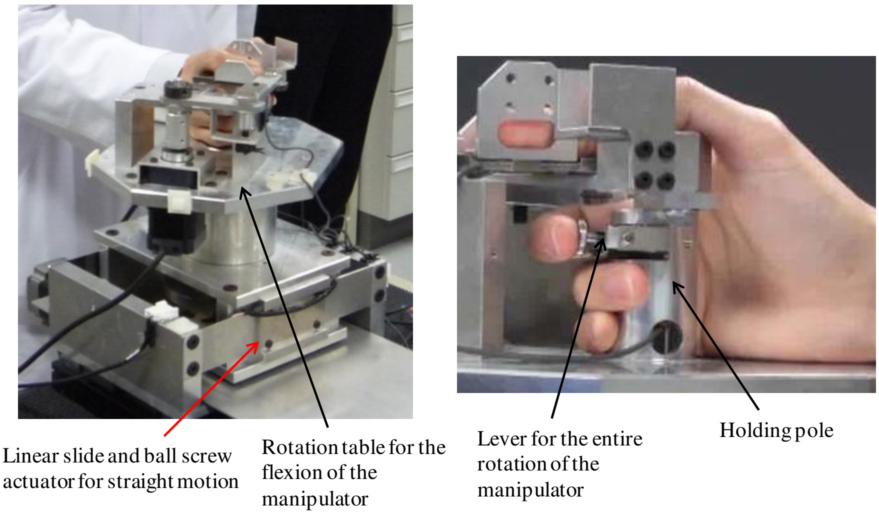
The entire master operating unit is shown in Fig. 9. We intended to design the operating unit according to the flow of the surgical procedure to remove a tumor, including approaching the target tumor, bending and rotating the manipulator, closing the gripper and retraction of the device. All the operating motions are assisted by stepping motors. The surgeon holds the vertical pole by the middle finger, the third finger, and the little finger. By rotating the holding pole with the table, the end of the slave manipulator flexes in the rotated direction. There is a switching lever on the rear side of the pole to rotate the gripper at the end. By pushing or pulling the lever with the middle finger, the gripper rotates according to the selected direction. The operating table is equipped on the sliding stage with a ball screw actuator. By moving the pole forward, the slave manipulator moves forward according to the moving distance of the operating table. A load cell is also installed between the operating table and the sliding stage to detect the surgeon's driving force. It is used to relay the driving resistance to the surgeon according to the pushing force detected at the driving unit of the slave manipulator. The switch to rotate the entire slave manipulator is on the other side to be operated by left hand, but is now being improved to be included in the operating unit of the right hand.



(a) Fitting of the forefinger surface with the friction roller

(b) Torsion spring between the roller and the torque detection shaft

Fig. 8 Friction roller to apply the pulling force on the surface of the finger



(a) Straight sliding unit and rotation table in the operating unit

(b) Lever for the entire rotation of the manipulator on the rear side of the holding pole

Fig. 9 Master operating unit

Control system

The developed controller is a bilateral controller [23] constructed by a force reflecting servo controller for the master part and a virtual impedance model-based controller for the slave part. The force reflecting servo controller is used in order to feedback the forces exerted on the slave manipulator directly to the operator. Another merit of this construction is high operation performance at the master/operation device (e.g., if no force is exerted, the master part is power-assisted). The impedance controller is inserted in order to prevent operator forces/commands that are directly transmitted to the slave manipulator, and to reduce the effects of unexpected disturbances such as impacts and impulses. The details of the control law are as follows.

i) Without contact

$$\begin{cases} f_m + K_f f_m = C_d \dot{x}_m \\ f = C_d s_p \dot{x}_s \end{cases} \qquad (1)$$

ii) With contact

$$\begin{cases} f_m + K_f (f_m - s_f f_s) = C_d \dot{x}_m + K_d \Delta x_m \\ f - s_f f_s = C_d s_p \dot{x}_s + K_d s_p \Delta x_s \end{cases} \qquad (2)$$

Where,

$$f = C_c(\dot{x}_m - s_p\dot{x}_s) + K_c(x_m - s_p x_s) \tag{3}$$

Here, f_m, f_s, and f are the master operation force, the slave contact force, and the driving force respectively. The positions of the master and the slave manipulators are denoted as x_m and x_s, respectively. The differences between the present positions and the positions at the time of contact are denoted as Δx_m and Δx_s for the master and the slave manipulators, respectively. C_d, C_c, K_d, and K_c are the virtual impedances and s_f and s_p are scale factors. K_f is a force gain. The inertia terms are omitted to improve the response of the system. The values for the gains and parameters are determined by try and error as C_d= 0.01, C_c= 0.01, K_d= 0.01, K_c= 2.0, s_f= 1.0 and s_p = 0.1.

The controller for the master part is described first. In (2), $K_f(f_m - s_f f_s)$ is regarded as the force reflecting servo input, in order to reduce the difference between the operation force and exerted forces on the slave manipulator. The other part of (2) represents the control model for the master device part (see Fig. 10). If the slave manipulator is free, the exerted force becomes zero, the reference point (the point of contact) vanishes, and then (2) becomes (1). In this case, $K_f f_m$ represents power assist, and operation performance increases.

Next, the controller for the slave part is described. In (2), f is the control input derived from the impedance model (3). The model has the role of dampening the control input from the master part. As can be seen from (3), the differences of positions and velocities between the master and slave parts results in the driving force f, and its magnitude depends on not only the differences but also the impedance gains. The other part of (2) represents the control model for the slave manipulator. (1) represents the case when the slave manipulator is free.

From (2), we have

$$f_m = \frac{1}{1+K_f}\left(C_d\dot{x}_m + K_d\Delta x_m\right) + \frac{K_f}{1+K_f}s_f f_s$$

If K_f is large, $f_m = s_f f_s$. This means the master operation force matches the slave contact force. In that case, considering the difference between (2) and (3), we have

$$(C_c + C_d)(\dot{x}_m - s_p\dot{x}_s) + (K_c + K_d)(x_m - s_p x_s - \frac{K_d}{K_c + K_d}(x_{mc} - s_p x_{sc})) = 0$$

where $\Delta x_m = (x_m - x_{mc})$ and $\Delta x_s = (x_s - x_{sc})$, in which x_{mc} and x_{sc} are x_m and x_s at the time of contact, respectively.

Letting $x_c = \dfrac{K_d}{K_c + K_d}(x_{mc} - s_p x_{sc})$ and $e = (x_m - s_p x_s - x_c)$, we have

$$(C_c + C_d)\dot{e} + (K_c + K_d)e = 0$$

Then, $x_m = s_p x_s + x_c$ and $\dot{x}_m = s_p\dot{x}_s$

When $K_c >> K_d$, $x_m = s_p x_s$.

We note that there will be a similar relationship when using (1) in place of (2).

Note that in this controller, force feedback is realized by decreasing the speed of the master manipulator. The schema for the controller is shown in Fig. 11.

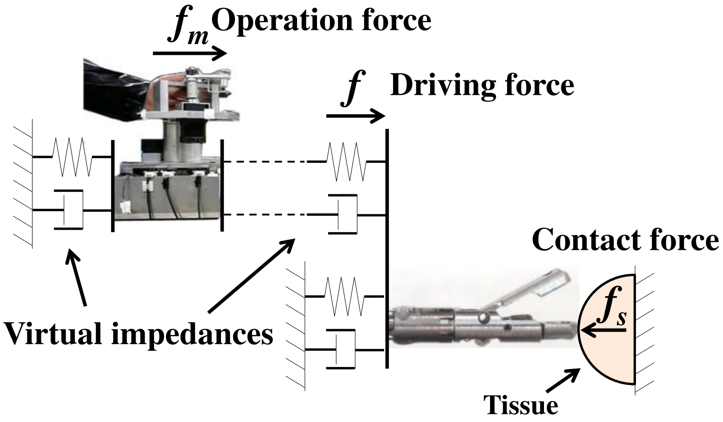


Fig. 10 Control model for the total system between the micromanipulator and the operation unit

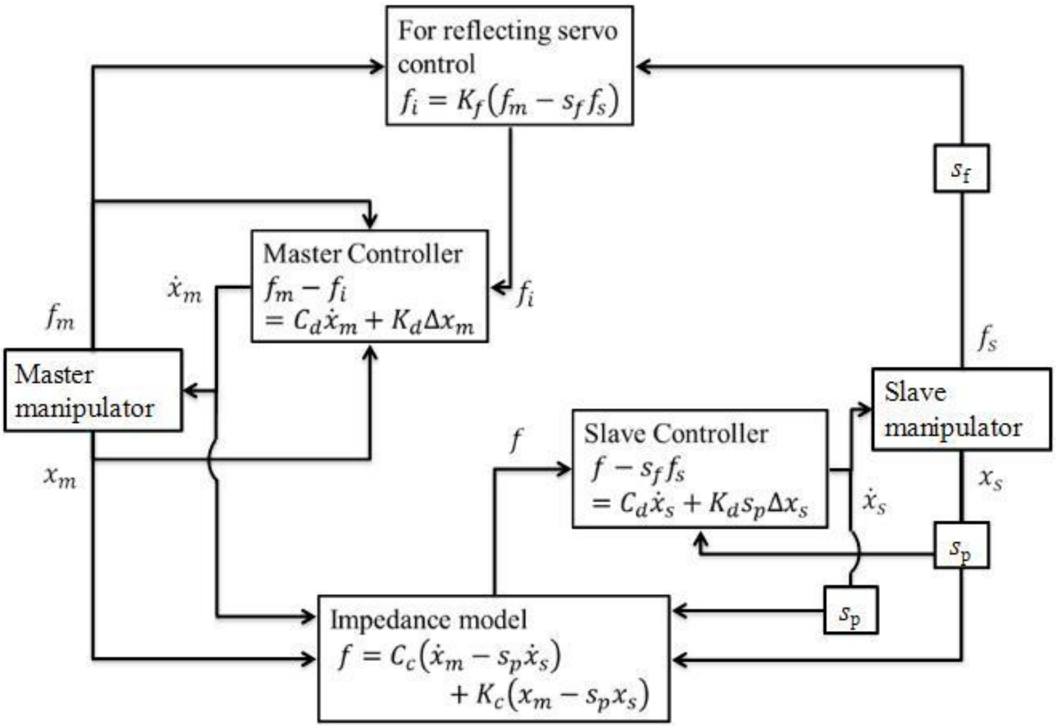


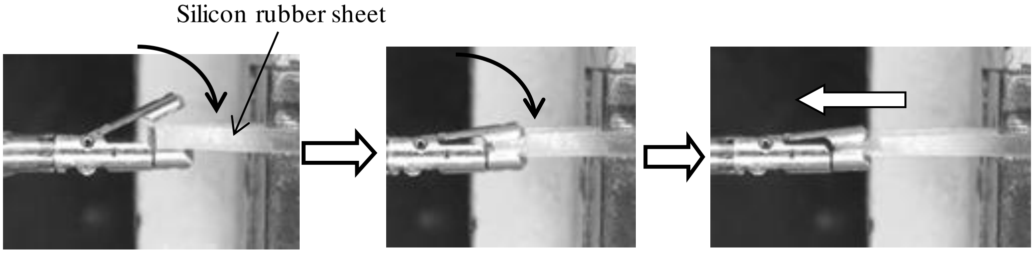
Fig. 11 Force reflecting and impedance control schema

Basic force feedback test

In order to verify the force feedback system, a basic test of the gripping force feedback and pulling force feedback was implemented. A silicon rubber sheet with an elastic modulus of 170 kPa was prepared as the gripping object so that the gripping force and the pulling force were definitely detected by the developed gripper. The actual elastic modulus of the brain tumor has been reported to be approximately 8 kPa [24]. The task is that the slave gripper holds the rubber sheet by operation of the master finger motion and then only the slave manipulator is drawn to maintain grip of the rubber, as shown in Fig. 12. The operator holds the operation pole and closes the finger to grip the rubber at the slave gripper and keeps closing the finger as the slave manipulator is drawn backward. The purpose of this test is to examine how the gripping motion is transmitted to the slave gripper and how the gripping force and pulling force is transmitted to the operator's finger. During this operation, the gripping force and pulling force at the gripper clip and the operating force at the finger, friction force applied on the finger surface are compared as well as both the gripping and pulling motions. The test was performed ten times, and a typical result is shown in Fig. 13.

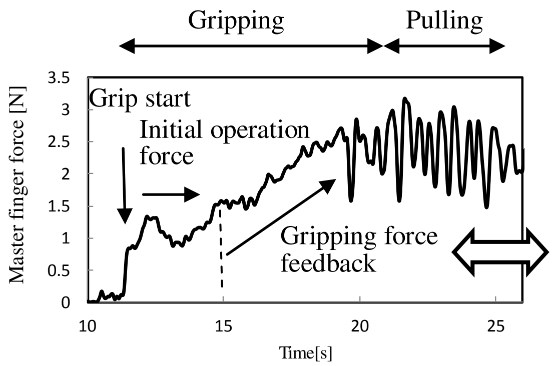
At first, by the initial operating force, the master gripper and the slave gripper start closing in the same way. When the gripping force exceeds some threshold value in the slave gripper, force feedback begins and the master speed decreases. Gripping force feedback at the master finger increases as the gripping force of the slave manipulator gripper increases. The operator increases the closing force according to the gripping force feedback, but the master speed, namely the operating lever speed, decreases. Thus, the operator feels kinesthetic feedback of gripping. During the gripping phase, the friction force and the pulling force feedback are also increased. This is due to the tension on the rubber caused by the difference between the center of the gripper and that of the rubber sheet. Because the gripper consists of a fixed clip and movable clip, the fixed clip does not move from the initial touching surface of the rubber sheet and only the other surface is compressed by the movable clip. The center of the rubber sheet then moves toward the side of the fixed clip, producing tension, as observed in Fig. 12 (b).

After gripping the rubber sheet, the slave manipulator was moved to pull the material. In this experiment, the master finger is kept closed to maintain the grip of the rubber material and to feel the change of the friction at the finger surface. As the increase of pulling force in the slave manipulator gripper, the friction force applied on the finger surface of the operator increases relatively. During the pulling process, the gripping force applied on the master finger and friction on the finger surface had a repeated vibration. Vibration is added for increasing the perception of friction. Konyo et al. proposed a haptic display system for friction by utilizing stick-slip contact phenomena that activated FA II type receptors [25-27]. Although the vibration affects the motion of the operators, it is very effective for the friction sensation. We selected the magnitude of the vibration amplitude by trial and error in order to minimize the effect of the vibration on operator motion. In spite of such slight variation, the friction force applied on the master finger is kept proportional to the pulling force of the slave gripper. The pulling force in this experiment may be slightly larger than that during actual resection of the brain tumor in order to obtain a certain response of the sensor. This will be improved by increasing the resolution of the pulling force sensor. The value of the friction applied on the finger surface was adequate at this level for feeling the friction force. On the other hand, the vibration from the friction causing a change in the pressure on the master finger may be problematic. It should be investigated in future studies.

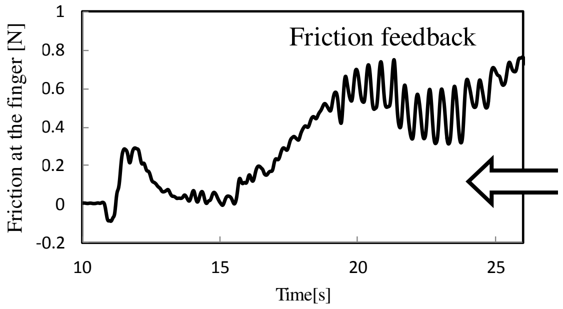


(a) Start of gripping (b) Gripping finished (c) Pulling

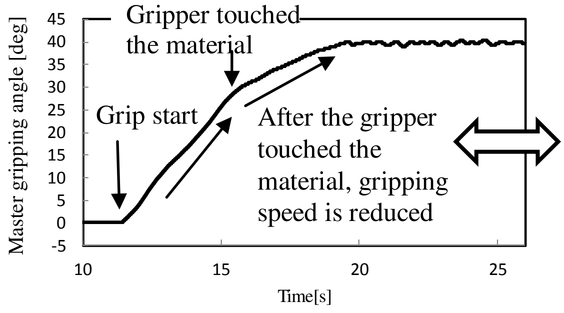
Fig. 12 Motion of the microgripper in the basic force feedback test



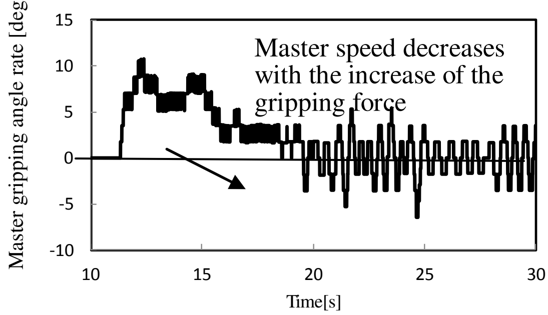
(i) Master finger force



(ii) Friction at the finger

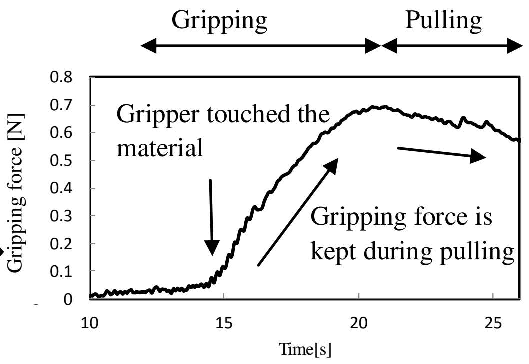


(iii) Master gripper angle

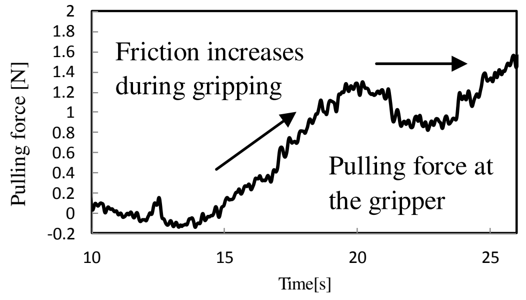


(iv) Master gripping speed

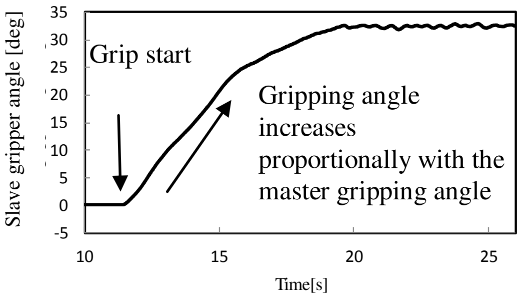
(a) Master side



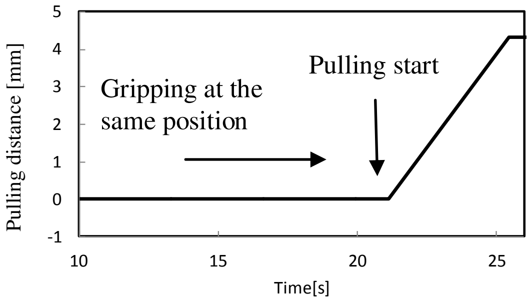
(v) Gripping force at the slave



(vi) Pulling force at the gripper



(vii) Slave gripper angle



(viii) Slave gripper pulling distance

(b) Slave side

Fig. 13 Gripping force and pulling force feedback with both motions in the basic test

Discussion

In this research, a force-detecting gripper has been developed with a flexible micromanipulator and force feedback system in the operating unit using a bilateral control program.

One of the advantages of the developed gripping sensor and the manipulator are their small sizes. To install the sensor in the gripper at a size of 3 mm, the machining of the sensor block and sensor fitting and subsequent wiring were the biggest challenges. No such direct measurement of direct force using a microgripper was performed in previous research on robotic surgery. Direct measurement at the gripping clip allows for accurate force feedback to the gripping finger on the surgeon's operating unit. Another great advantage of the developed microforce-detecting gripper is that not only the gripping force but also the pulling force is directly measured at the gripper. Detection of the gripping force will be useful in estimating the difference between the tumor and normal tissues. Detection of the pulling force will be useful in confirming the resection of the tumor and knowing the resection resistance. The effects from the magnetic field generated by the electric current are negligible because its strength is comparable to that of is in the same level of the Earth's magnetic field. To prevent injury or damage from broken cables or the leak of electric current from the wires, the controller should switch off the electric supply when abnormal output occurs. In such a case, the controller operates a simple position control system.

Flexibility of the gripping end of the micromanipulator expands the approaching area and operation tasks around the end of the rigid endoscope. The operability of the manipulator by the operating unit is quite simple, and that the operator can easily touch a target not situated in a straight line with the manipulator.

From a basic test on the force feedback, gripping force and pulling force are well transmitted to the operator as the gripping force resistance and friction at the finger using the bilateral control program. From the relationship between the gripping angle and the gripping force at the microgripper, the hardness of the tissue at the gripping point will be estimated. The difference in the hardness between the tumor and the normal tissue might be distinguished from the grip angle-force relationship. The force resistance at the operation finger is one of the important feedback parameters from the hardness of the tissue. During the pulling force feedback, vibration was applied to increase the friction feeling, but it caused a vibrational change in the gripping force feedback. A more adequate force feedback system needs to be investigated.

Future Work

Force feedback tests should be carried out in various motions that simulate the removal of tumors from brain tissue. How the surgeon senses the gripping force and the friction at the finger during various motions should be investigated to improve the force feedback program and hardware. Adequate friction force applied on the finger surface should be further investigated through these experiments by many operators.

In the resection of brain tumors, additional forces may be applied on the gripper from the tissues around the tumor. Those additional forces must be distinguished from the actual gripping force. In this developed operating system, the master operating unit has been designed according to the motion of removing the tumor using forceps. Therefore, the force feedback of the gripping force and pulling force to the surgeon`s finger is estimated as the most important feedback. Additional force applied from outside of the gripper should be distinguished using other information detected at the slave driving unit and should be transmitted to the surgeon. This is a subject for future studies.

For sterilization during clinical use, the manipulator must be attached and detached. A different design for the attachment structure on the manipulator tubes and the joint system of the cables will be investigated.

The force feedback system on the gripper of the manipulator will be useful in different surgeries using bilateral master-slave robotic surgery.

Conclusions

A force-detecting microgripper that can detect gripping force and pulling force has been developed for the resection of brain tumors. A flexible micromanipulator that can be flexed and rotated at the end of the manipulator has also been developed. The operator can sense the gripping force resistance on the master handle corresponding to the gripping force at the gripper and can sense the pulling force of the target as a friction force applied on the finger surface. This device will assist the work and sensing capabilities of the operator during resection of brain tumors.

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