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Master Manipulator with Higher Operability Designed for Micro Neuro Surgical System

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***Abstract*— The master and slave surgical assistant systems have been studied actively. However, regarding the master system, the manipulator should be designed for each surgical field because the target workspace and precision are different. Furthermore, operability is important for safety reasons. Therefore, the authors analyzed the motion of surgeon first and then developed a master manipulator suitable for the operation of micro neuro surgery. Some experiments were conducted to evaluate the control method and show the effectiveness of the proposed manipulator control method.**

I. INTRODUCTION

Recently, engineering knowledge has been actively utilized in the medical field. For example, technology such as CT and MRI allows us to observe the patient's body with minimal invasiveness. In addition, simulation techniques to help with preoperative planning and navigation techniques to assist the surgeon during the operation have been developed.

In the field of neurosurgery, it is possible to perform microsurgery under the microscope. However, the doctor's hands perform the operation observing the magnified view; it is impossible to exceed the accuracy of the doctor's hands, because it is the forceps that operate the micro angiorrhaphy and tumorectomy. Consequently, development of a micro neuro surgery system allowing manipulation in the deep surgical field is necessary.

The neuroArm[1] and NeuRobot[2] are assisting micro-neurosurgical robot systems. These robots target micro processing (the micro angiorrhaphy and tumorectomy) in the deep surgical field. It is possible to operate precisely by moving the slave system by moving the master system slowly (Fig.1). Meanwhile, although the slave system has been studied actively, the master system has not. For the adoption of operative assistance, and for safe and precise operation, efficient robot systems are required. Therefore, the authors analyzed the hand-movement of the operator and considered the motion-response suitable to the microsurgery. From this knowledge, a master-slave system was implemented and the mechanism and operability were evaluated.

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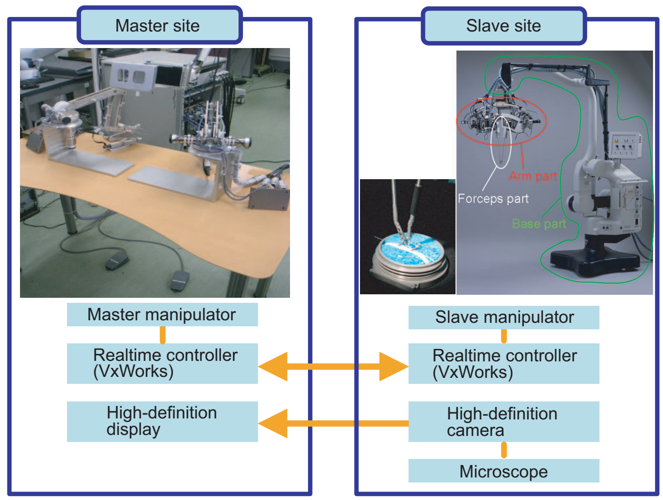

Fig. 1. System overview

II. MASTER MANIPULATOR DESIGNED FOR MICRO NEURO SURGERY

A. Working area of the micro processing

Micro processing allows operation using only the fingertip while fixing the elbow, the front arm, and the wrist. Additionally, in doing so, the fixing position is much more convenient than the floating position. From the point of motion economy, motion of the hand is divided into the motion of the finger, the wrist, the front arm, the upper arm, and the shoulder. The operator is most tired in the first case. From the adoption of the operation assistance system, it is possible to change the motion scale; even so, the doctor's operation is as small as the operation on the table. With that, we considered the motion of the operator on the table.

B. Design of workspace and mechanism

Required degree of freedom (DOF) and workspace were analyzed in the case of hand motion on the table. First, posture control was investigated. Concerning the freedom to determine posture, the human hand has bend and rotation freedom as shown in Fig.2. To realize these degrees of freedom, three rotational axes are implemented. Arbitrary posture can be obtained with the gimbal mechanism. However, the mechanism has a singular point called the gimbal lock that must be taken into account.

Regarding the layout of rotational mechanism, the following conditions are met.

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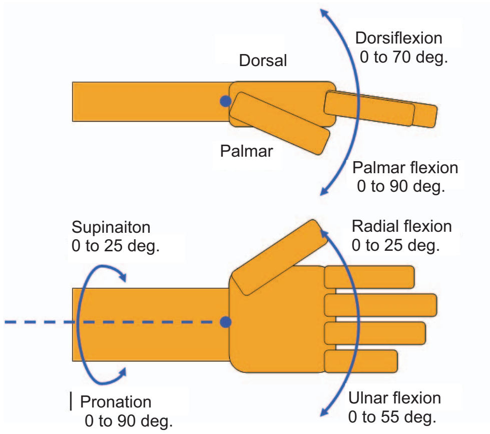


Fig. 2. Hand posture

1) Position of gripper follows hand, regardless of translational motion.
2) Enough workspace is provided.

The mechanism and workspace of the manipulator are determined satisfying the conditions above. About (1): the motion range of the wrist is different for each person and axis, and the posture of the hand is changed to the space, even when the posture of the wrist is fixed to the forearm (Fig.3).

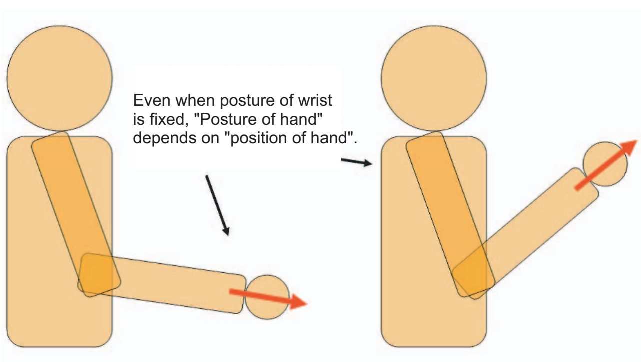


Fig. 3. Change of hand posture by arm motion

It is difficult to avoid the singular point, and, depending on the location of the hand, there is a condition that the operability is low. Therefore, a translational mechanism to follow only the change of the wrist without any shift of posture and a posture control mechanism to follow only the change of the wrist attitude were investigated. (Fig.4). About (2), the workspace similar to the hand motion is designed for the translation part.

Position of hand and posture of device were analyzed according to the arm motion. Position of hand is defined as the start point, and posture of device is set as a vector (Fig.5). It is assumed that the arm motion on the table is composed of the upper and forearm motion on the orthogonal plane and the rotational motion of the plane. The vector space was investigated using the link mechanism.

In order to operate with hands on a table, a linkage to approach the intended area from above was proposed (Fig.6). Working area of linkage can correspond to the working area of a surgeon's arm by appropriate parameters; the posture of the gripper cannot correspond to the posture of the surgeon's hand because the posture of the linkage is the inversion of the posture of the surgeon's joint. The posture of L2 does not correspond to the posture of the forearm and the wrist of the surgeon, and the posture of L1 is similar to the posture of the forearm and the wrist. Therefore, the posture of the forearm and the wrist should correspond to the posture of L1. A linkage is suggested to make L1 correspond to the posture of the gripper by adding parallel linkage in the previous linkage (Fig.7). The working area and posture of the gripper with this linkage make a vector field similar to Fig.5 by setting appropriate parameters. Therefore, a master manipulator with this linkage and parameters were suggested.

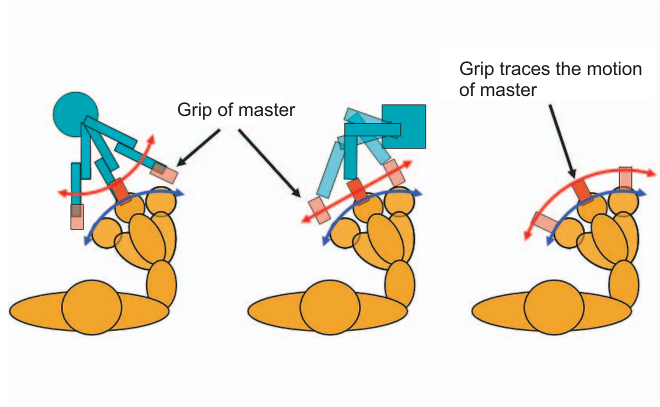


Fig. 4. Mechanism of translation

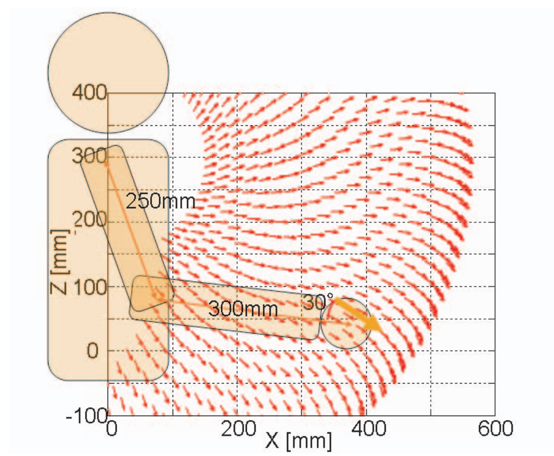
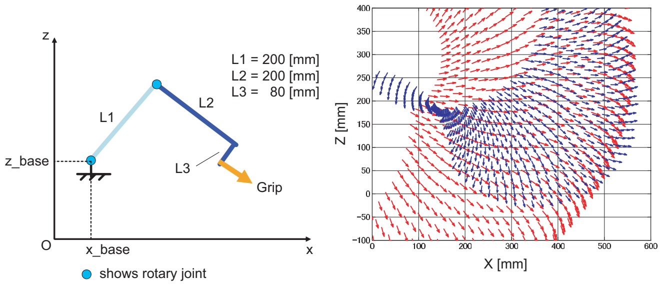


Fig. 5. Working area of arm

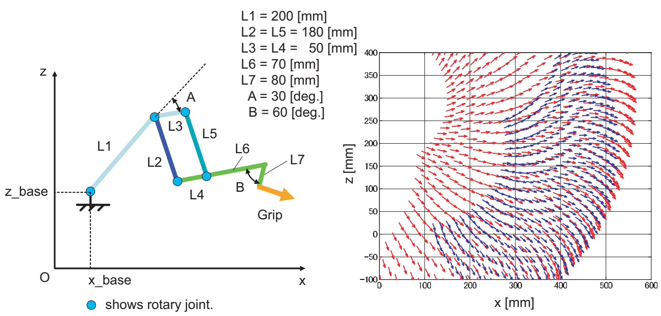
C. Implementation of master manipulator

Figure 8 shows the overview of developed master manipulator. PEEK (polyetherketone), A2017, and SUS304 are used and are lightweight. Each joint has a rotary encoder to measure the position and posture of the hand. DC motors are mounted at the translation part and gripper to feed back the



(a) Linkage mechanism (b) Working area

Fig. 6. Example of simple link



(a) Link mechanism (b) Working area

Fig. 7. Suggested link mechanism and working area

force information and to compensate for gravity.

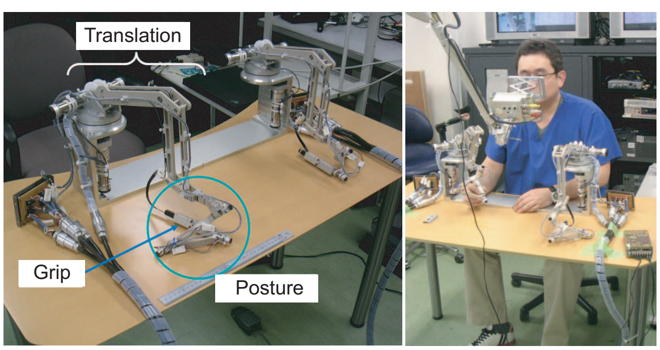


Fig. 8. Overview of master manipulator

This master manipulator has a structure of rotary joints and links (Fig.9). The space coordinates must be calculated from each joint angle. Base coordinates $\sum_0$ are defined in the manipulator, and the coordinates at the center of translational tip posture are computed. Each joint is defined as Joint1, ... , Joint4 from the base; transformation matrix for the joint is set to bfT_1, ... , bfT_4. The transformation matrix is expressed as follows.

$$\vec{T}_n = \begin{bmatrix} \vec{E}_n & \vec{p}_n \\ 0 & 1 \end{bmatrix} \tag{1}$$

Using the equation above, the frame vector T_t is given by the posture and position of the translational tip in base coordinates $\sum_0$ with the following equations.

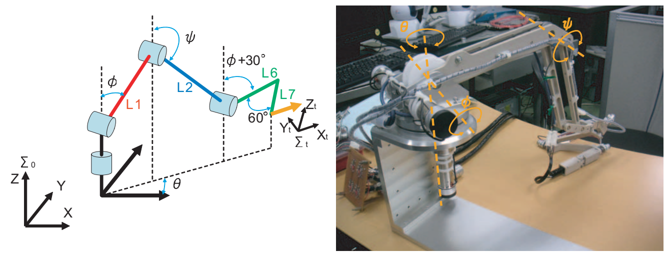


Fig. 9. Translation control mechanism

$$\vec{T}_t = \vec{T}_1\vec{T}_2\vec{T}_3\vec{T}_4 = \begin{bmatrix} \vec{E}_t & \vec{p}_t \\ 0 & 1 \end{bmatrix} \tag{2}$$

$$\vec{E}_t = \begin{bmatrix} S(\phi+\frac{\pi}{3})S\theta & -S\theta & S(\phi-\frac{\pi}{6})S\theta \\ S(\phi+\frac{\pi}{3})C\theta & C\theta & S(\phi-\frac{\pi}{6})C\theta \\ C(\phi+\frac{\pi}{3}) & 0 & C(\phi-\frac{\pi}{6}) \end{bmatrix} \tag{3}$$

$$\vec{p}_t = \begin{bmatrix} (L_1S\phi + L_2S\psi + L_6S(\phi+\frac{\pi}{6}) + L_7S(\phi+\frac{5\pi}{6}))C\theta \\ (L_1S\phi + L_2S\psi + L_6S(\phi+\frac{\pi}{6}) + L_7S(\phi+\frac{5\pi}{6}))S\theta \\ L_1C\phi + L_2C\psi + L_6C(\phi+\frac{\pi}{6}) + L_7C(\phi+\frac{5\pi}{6}) \end{bmatrix} \tag{4}$$

Figure 10 shows the configuration of the posture part. A coordinate $\sum_t$ is prepared at the tip of the translation part, and the coordinates of the posture part $\sum_r$ are calculated from $\sum_t$. Each joint is named Joint α, ..., Joint γ, and the transform matrix is defined as $\mathbf{T}_\alpha$, ...$\mathbf{T}_\gamma$, respectively.

The coordinates $\sum_t$ correspond to the center of the posture part. The position and posture of the posture part in the coordinates $\sum_t$ are given by the frame vector ${}^tT_r$ obtained in the following equations.

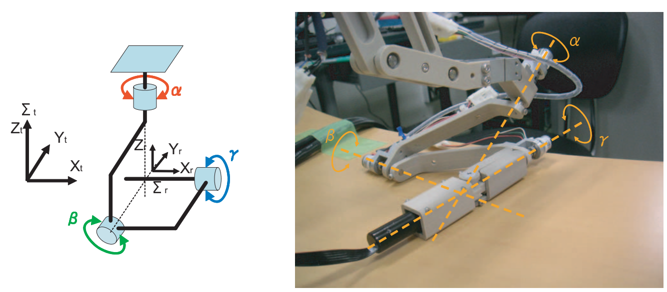


Fig. 10. Posture control mechanism

$${}^t\vec{T}_r = \vec{T}_\alpha\vec{T}_\beta\vec{T}_\gamma = \begin{bmatrix} {}^t\vec{E}_r & {}^t\vec{p}_r \\ 0 & 1 \end{bmatrix} \tag{5}$$

$${}^t\vec{E}_r = \begin{bmatrix} C\alpha C\beta C\gamma + S\alpha S\gamma & C\alpha S\beta & C\alpha C\beta S\gamma - S\alpha C\gamma \\ S\alpha C\beta C\gamma - C\alpha S\gamma & S\alpha S\beta & S\alpha C\beta S\gamma + C\alpha C\gamma \\ S\beta C\gamma & -C\beta & S\beta S\gamma \end{bmatrix} \tag{6}$$

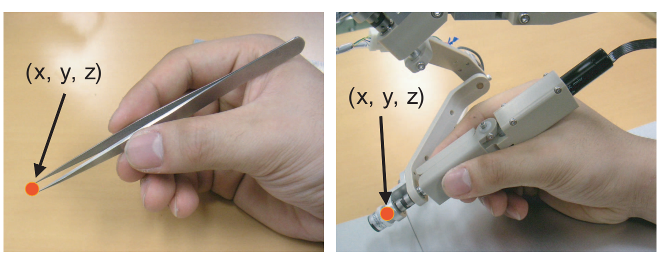
$$
{}^{t}\vec{p}_t = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{7}
$$

III. CO-OPERATION METHOD OF MASTER AND SLAVE MANIPULATOR

The developed master manipulator and slave manipulator can be operated by arbitrary correspondence of motion. The master manipulator has 6-degrees-of-freedom (translation: 3 DOF, posture: 3 DOF) except the holding motion; meanwhile, the slave manipulator has 5-degrees-of-freedom (translation: 3 DOF, bend: 1 DOF, rotation: 1 DOF). In short, master and slave manipulators have different amounts of freedom. Therefore, it is necessary to consider appropriate correspondence of motion.

A. Correspondence of translation

When surgeons operate with forceps or other instruments, the position of the end of the instrument is important. Wide motions are made by shoulders and arms; meanwhile, when surgeons operate microsurgically, such as during the suture of fine blood vessels, they move their wrists and fingers with their hands fixed on the patient's brainpan. The scale-down function of the master manipulator makes the surgeon's motion on the slave manipulator larger; however, the surgeon's movement is still minimal. We suggest correspondence of the end of the forceps of slave manipulator with not the position of the hand, but with the end of the gripper of the master manipulator (Fig.11). The correspondence of motion permits simple operation of the slave manipulator using the wrist and fingers.

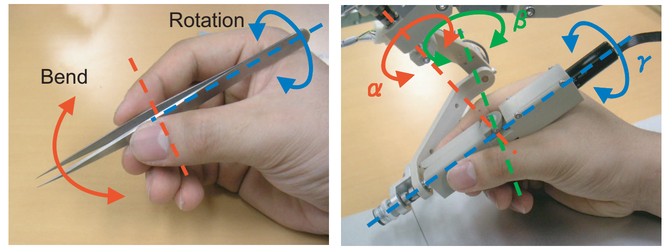


(a) Pincette (b) Master manipulator

Fig. 11. Correspondence of linear motion

B. Correspondence of bend/rotation

Master and slave manipulators have different amounts of freedom, so we can not coordinate the posture of the gripper in the master manipulator to the posture of the end of the forceps in the slave manipulator. It is necessary to study the appropriate correspondence of motion. Thus, we propose to correspond the motion of the forceps in the slave manipulator to the motion of the forceps. Concretely, we correspond the motion of the manual bend to the motion of the α axis in the slave; the motion of the manual rotation we correspond to the motion of the γ axis in the slave (Fig.12).



(a) Pincette (b) Master manipulator

Fig. 12. Correspondence of bend/rotation

IV. EXPERIMENTAL RESULTS

A. Evaluation of master manipulator mechanism

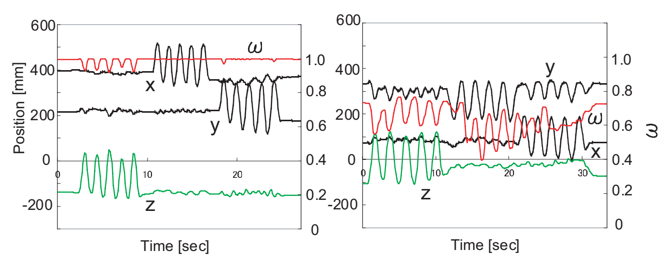
The master manipulator is designed to homologize the degree of freedom of posture control to the movement of wrists and to expand the workspace by controlling the translation part according to the workspace of the human hand. The mechanism of the master manipulator is evaluated in this section.

Examinees operate the translation part without changing the posture of their wrists. In the experiment, the manipulability of the operation was evaluated. Manipulability is a barometer to express usability of the manipulator. It is described with Jacobean of posture control as shown in the following equation.

$$
\omega = |detJ| = \sqrt{detJJ^T} = |\cos\beta| \tag{8}
$$

An experiment was conducted with an examinee. Fig.13 shows the position in the translational motion and the calculated manipulability at the position.

Although the value of manipulability changes slightly in up/down motion, it can be kept high with the proposed method. This shows that it is easy to change the posture of the hand at any tip position of the master manipulator and that the proposed manipulator mechanism has high operability in the translation and also in the posture control. The system is designed to match the hand motion to the manipulator control and gives the surgeon smooth posture control of wrists without translational operation.



(a) Proposed (b) Conventional

Fig. 13. Manipulatability

B. Evaluation of correspondence of motion between master and slave systems

Operability of the proposed translation control was evaluated. In the evaluation, the paired comparison method is used. Compared methods are as follows (Fig.14).

(a) Correspondence of the center of the grip with the end of the forceps
(b) Correspondence of the end of the grip with the end of the forceps

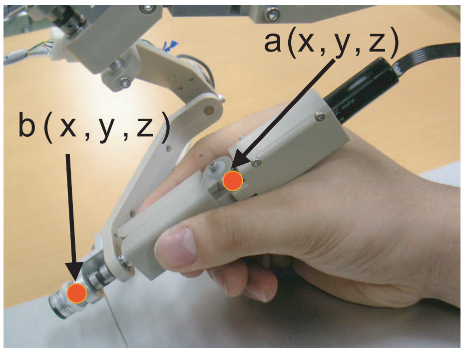


Fig. 14. Translation (a),(b)

The task in the experiment is pointing of the grid on 1 mm graph paper. The needle is fixed at the tip of the robot forceps, and the operator indicates the grid with the tip (Fig.15). Time to indicate some points is measured and evaluated.

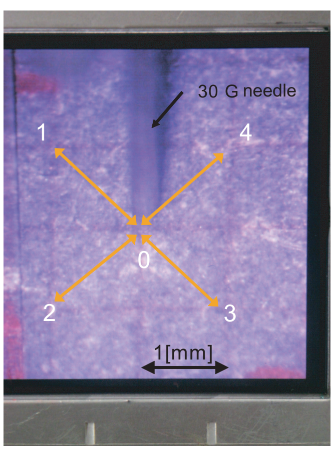


Fig. 15. Graph paper for pointing experiment

Three examinees conducted the tasks five times in order (b)-(a)-(b). Time to complete the task and the precision of indication were measured. Fig.16 and Fig.17 show the result of averaged error and time, respectively.

C. Evaluation of correspondence of motion master and slave systems 1

Operability of correspondence of bending is evaluated in this section. When the correspondence is evaluated, a pair comparison method is used. The methods are as follows (Fig.18).

(a) Correspondence of hand motion with forceps motion. Rotation corresponds to bending of forceps.
(b) Correspondence of motion of the end of the grip with forceps motion. Rotation of α-axis corresponds to bending of forceps.

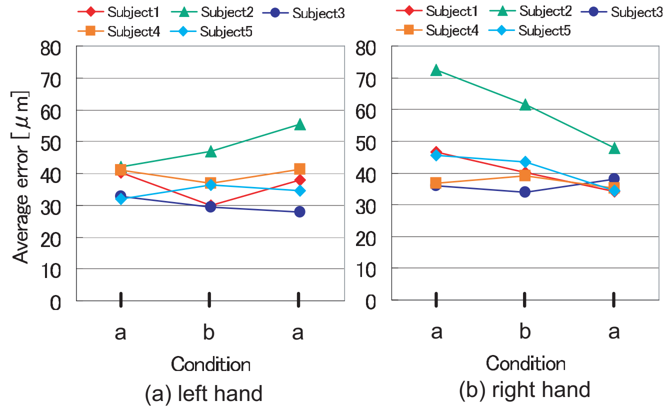


Fig. 16. Averaged error

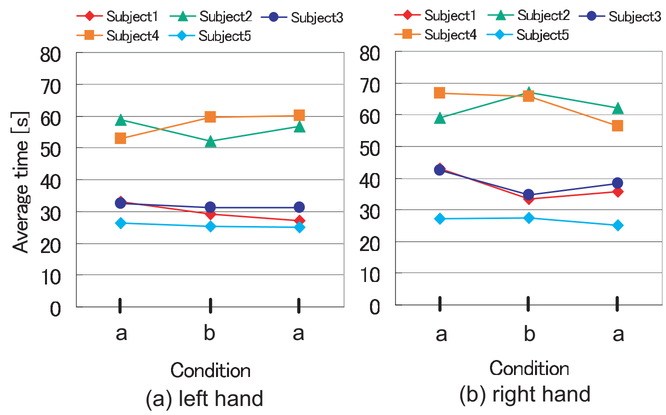


Fig. 17. Time error

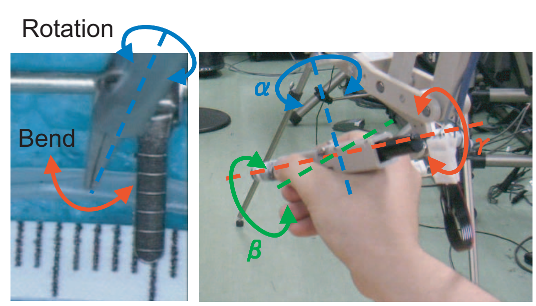
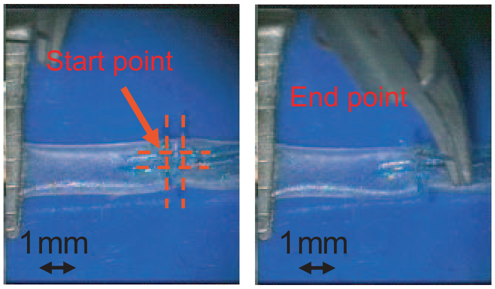


Fig. 18. Correspondence

The task is insertion of a needle into 1mm across tube. An examinee inserted the needle into the intended area using translation and bend (Fig.19).

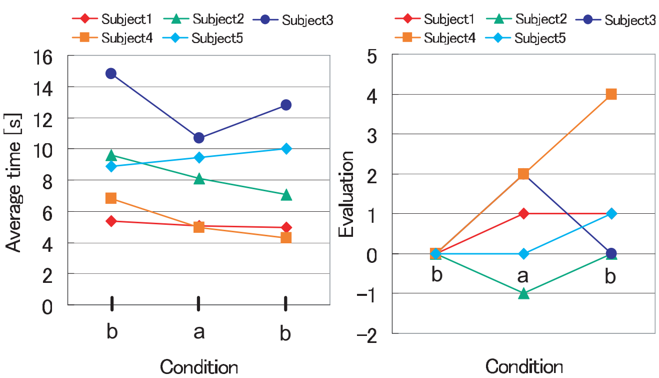


(a) Start point (b) End point

Fig. 19. Start and end points

Five examinees conducted the tasks 10 times in order (b)-(a)-(b), and the time of performing tasks was measured. Results are shown in Fig.20. The difference between correspondence of motion (a) and (b) is not so decisive that we can judge which has better operability. In subjective appraisal, one examinee says (a) has better operability, another says (b) has, and the rest of the examinees find no clear difference between (a) and (b).

That is why the tasks are too simple to differentiate between (a) and (b).



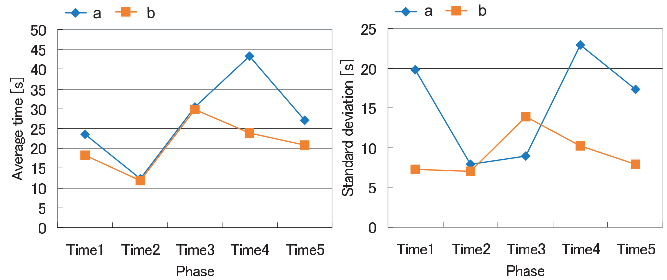
(a) Average time (b) Evaluation

Fig. 20. Average time and evaluation

D. Evaluation of correspondence of motion between master and slave systems 2

Operability of correspondence of bend and rotation was evaluated in this section. 1mm was cut across the tube, a needle with suture was gripped, the needle was inserted, and the suture was tied. This operation was repeated in order (b)-(a)-(b) by 10 stitches. The examinee is a cranial nerve surgeon. The results are shown in Fig.21. The time to divide tying task into the following phases was measured.

- Time1: from gripping a needle or suture to gripping it by the right forceps in appropriate position for insertion
- Time2: from end of Time1 to moving the needle to insertion position
- Time3: from inserting the needle to extracting the needle by the left forceps
- Time4: from extracting suture of appropriate length to finishing first tie
- Time5: from end of Time 4 to finishing second tie



(a) Average time (b) Standard deviation

Fig. 21. Average time and standart deviation

Results show that correspondence of motion (b) takes less time to finish tasks as a whole. It takes longer to finish Time1, Time4, and Time5 in the case of correspondence of motion (a). Time1 means how long it takes to grip the needle by the right forceps in the appropriate position for insertion. During Time1, we arranged the needle position by the right and left forceps, and bending and rotation motion of forend might be used. We adjusted the length of the suture and tied it at the first time during Time4, and at the second time during Time5. When we made a loop of suture for tie or when we pushed forceps through the loop, a bending and rotation motion was also used. Therefore, we can consider that finishing those tasks in a shorter time means the bending and rotation motion was operated smoothly. Referring to Fig.21, standard deviation of Time1, Time4, Time5 in case of corresponding of motion (a) is 2 times as much as in the case of corresponding of motion (b). Judging from that, we consider corresponding of motion (b) makes the operation stable.

V. CONCLUSIONS

In order to improve the operability of the master-slave system for neurosurgery in the deep surgical field, the authors analyzed the motion of surgeon and then developed a master manipulator suitable for the operation of micro-neurosurgery. Some experiments were conducted to evaluate the control method. The manipulator control to correspond the end of the grip to forceps motion shortens the time of the suturing task.

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