Hand-held Multi-DOF Robotic Forceps for Neurosurgery Designed for Dexterous Manipulation in Deep and Narrow Space

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Abstract— **Neurosurgical procedures require precise and dexterous manipulation of a surgical suture in narrow and deep spaces in the brain. This is necessary for surgical tasks such as the anastomosis of microscopic blood vessels and dura mater suturing. A hand-held multi–degree of freedom (DOF) robotic forceps was developed to aid the performance of such difficult tasks. The diameter of the developed robotic forceps is 3.5 mm, and its tip has three DOFs, namely, bending, rotation, and grip. Experimental results showed that the robotic forceps had an average needle insertion force of 1.7 N. Therefore, an increase in the needle insertion force is necessary for practical application of the developed device.**

I. Introduction

The anastomosis of blood vessels located deep inside the brain is one of the most difficult procedures in microsurgery. Dura mater suturing in transnasal neurosurgery also requires exceptional skill. It is expected that the dexterous and precise manipulation of surgical tools in such surgical procedures in deep and narrow spaces in the brain would be enhanced by robotic assistance. Robots used for neurosurgery include NeuroArm [1] developed by McBeth et al., Neurobot [2] developed by Hongo et al., and MM-2 [3] and a master-slave microsurgical robot [4] developed by the group of the present authors. Although these robots have been shown to enhance the precision of instrument manipulation during microsurgery, further improvement of the dexterity in performing complicated surgical tasks in a deep and narrow space is necessary.

The available workspaces for the relevant surgical procedures are illustrated in Fig. 1. The workspace can be modeled by a cylinder of diameter 20 mm and length 100 mm. An endoscope and two surgical instruments are inserted into such small workspaces. The dexterous and precise manipulation of a surgical suture at the bottom of this workspace using thin and long surgical instruments was the target task of this study. The straightforward approach for such procedures involves the use of joints at the tip of the surgical instrument, and precise control of the motion of the tip using actuators. This paper proposes multi–degree of freedom (DOF) robotic forceps for performing this type of complicated surgical task in a small space.

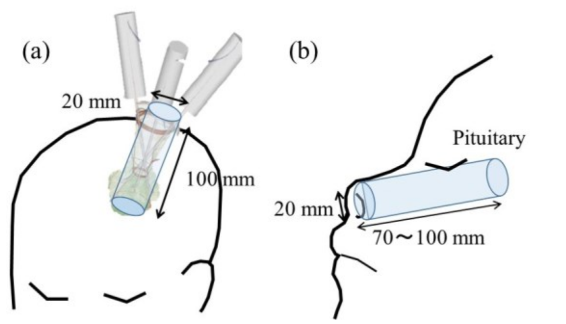

Figure 1 Available workspaces for surgical instruments: (a) for anastomoses in a deep and narrow space and (b) in transnasal neurosurgery.

II. Multi-DOF forceps

A. Design

Figure 2 shows the conceptual design of the neurosurgical robot with multi-DOF robotic forceps for dexterous manipulation in a deep and narrow space in the brain. It is conceived that the multi-DOF robotic forceps, which is actuated by a driving unit, would be mounted on an endoscope holder (e.g., Point Setter Endoscope Holder, Mitaka Kohki. Co., Ltd., Japan) or a robotic holder, and manually positioned in the surgical space. Previously developed neurosurgical robots are large because they are designed to approach the surgical site by themselves. Our proposed manual positioning of the robot enables it to focus on the surgical tasks and also reduces its size and weight. The miniaturized robot would occupy less space in the operating theater and come at a reduced cost. This paper presents the design and development of the multi-DOF robotic forceps. A hand-held version was designed and developed for the present evaluation of its fundamental performance.

The design of the dimensions and DOFs of the multi-DOF forceps with Denavit–Hartenberg parameters is shown in Fig. 3. The forceps shaft should be sufficiently thin so that it does not obstruct the endoscopic view and allows for sufficient maneuvering space inside the workspace. Hence, by also taking into consideration the diameters of available neurosurgical instruments, the diameter of the robotic forceps was set at 3.5 mm. The tip motions have three DOFs, namely, bending, rotation, and grip.

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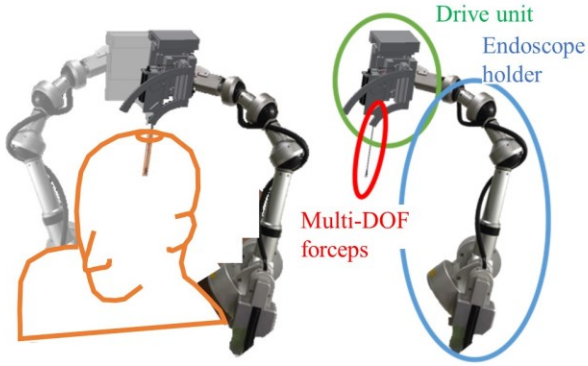

Figure 2 Conceptual design of the neurosurgical robot with multi-DOF robotic forceps.

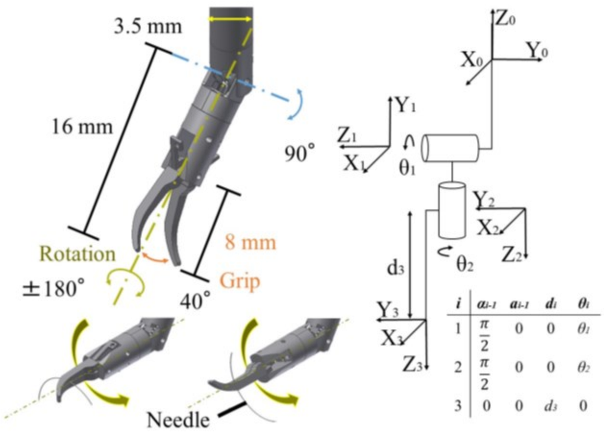

Figure 3 Design of the tip of the multi-DOF robotic forceps.

The maximum bending angle was designed to be 90° to facilitate positioning of the gripper on the target located at the bottom of the workspace. Rotation about the tip of the axis was designed to have a range of ±180° to enable placement of the needle at the bottom of the workspace without changing the position and posture of the shaft. The rotational axis was designed to intersect with the bending axis to afford intuitive manipulation of the bending and gripping motion and simplify control of the motion by actuators. The maximum opening angle of the gripper was set at 40° based on the opening angles of available microsurgical instruments. The length of the tip (i.e., the length from the bending axis to the tip of the gripper) was made as short as possible for easier manipulation in the small workspace, and the length of the gripper was designed to be 8 mm, which is relatively long. The long and curved gripper was designed to facilitate its endoscopic observation by the surgeon.

Figure 4 shows the design of the double-pin-gear mechanism that realizes the DOFs of bending and rotation. The design of the mechanism is based on the hand-held multi-DOF needle driver used for pediatric surgery, which was developed by the group of the present authors; the details of the mechanisms are shown in [5, 6]. The gripper is opened by a torsion coil spring and closed by pulling the wire running through the center of the bending joint.

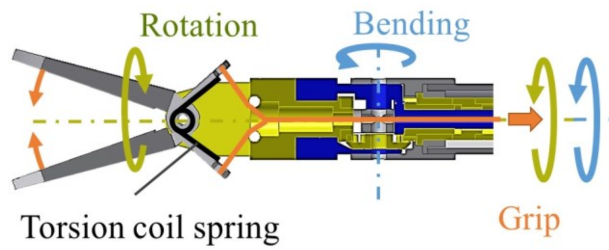

Figure 4 Sectional view of the gripper and double-pin-gear mechanism.

The gripping force was calculated using the model shown in Fig. 5. Based on the wire pulling force F_w and the parameters shown in Fig. 5, the gripping force F_g is given by

$$F_g = \frac{a_1 F_w \sin(\theta_b + \theta_c)}{2a_2 \cos\theta_a} - \tau_1 \tag{1}$$

Using values of $\theta_a = 23.5°$, $\theta_b = 56.9°$, $\theta_c = 35.8°$, $a_1 = 2.5$ mm, $a_2 = 5.0$ mm, and $\tau_1 = 0.10$ N, the gripping force F_g is obtained as

$$F_g = 0.3F_w - 0.10 \tag{2}$$

Ignoring friction, the gripping force would be 4.1 N for a wire pulling force of 15 N.

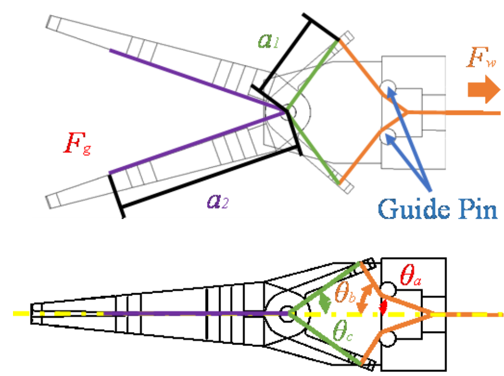

Figure 5 Model of the gripping mechanism.

B. Development

Figure 6 shows the fabricated multi-DOF forceps. The multi-DOF forceps and an endoscope were inserted in a transnasal neurosurgical model fabricated by rapid prototyping. Good endoscopic view of the forceps tip was confirmed, as shown in Fig. 6(c).

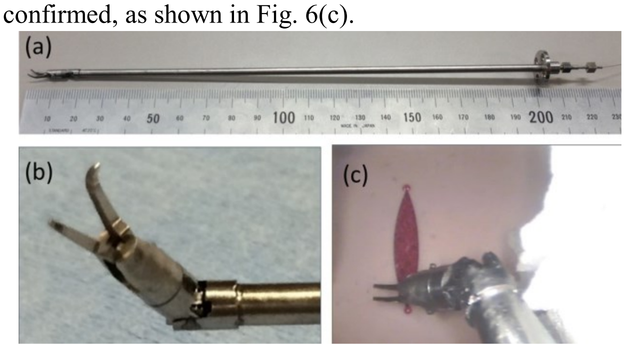

Figure 6 Multi-DOF forceps: (a) the shaft, (b) an enlarged view of the forceps tip, and (c) the endoscopic view.

The double-pin-gear mechanism with intersecting axes enables forceps of such small diameters to have two DOFs. However, the pin gears interact with each other, and their simultaneous control is necessary. Additionally, the high friction necessitates a strong wire pulling force. A driving unit with actuators and a hand-held control unit were therefore designed and developed for simultaneous manipulation of the 3-DOF motion by one hand, as shown in Fig. 7.

The drive unit incorporates three 10-mm-diameter brushed DC motors (DCX10L EB KL 6 V, Maxon Motor AG, Switzerland), each of which was integrated with a planetary gearbox (GPX 10 64:1) and an encoder (ENX 10 EASY 128IMP). The gripping force, rather than the gripping angle, is controlled once the gripper is closed. The motion limit of each DOF is controlled to avoid possible mechanical failures.

Three miniature encoders are mounted on the hand-held unit to measure the finger motions. The middle finger is used to control the gripping angle, and the thumb is used to control the bending angle. The index finger is used to control the rotation angle at the tip. The rotational axis of the part rotated by the index finger lies on the middle plane of the hand-held unit and is aligned parallel to the shaft of the multi-DOF forceps. This design enables intuitive and simultaneous control of the 3-DOF motions by one hand. The hand-held multi-DOF forceps can be easily disassembled, as shown in Fig. 7(b), to facilitate replacement of each unit. The multi-DOF forceps does not have actuators or sensors and can thus be sterilized. This modular design was intended to facilitate future modification of the robotic forceps.

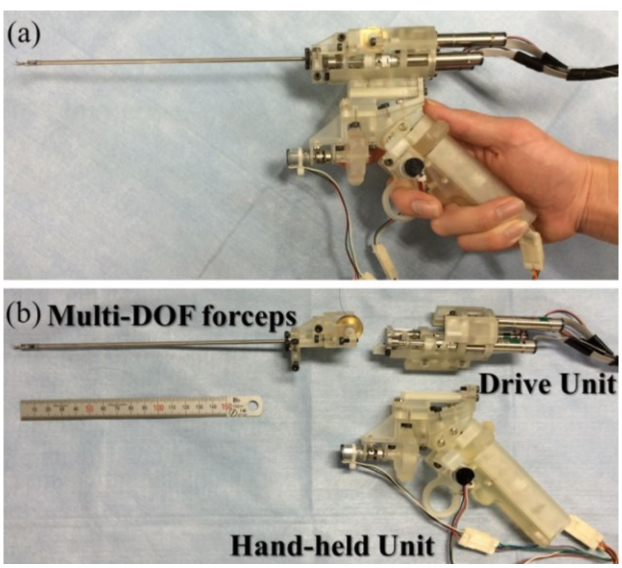

Figure 7 Hand-held multi-DOF robotic forceps: (a) manipulation by one hand and (b) disassembly.

III. Experiments

Experiments were performed to evaluate the fundamental performance of the hand-held multi-DOF robotic forceps, including the controllability of the bending and rotation motions and the needle insertion force.

A. Bending and Rotation

The bending and rotation motions were evaluated by actuating the angles over their maximum range. The bending and rotation angles were measured from images recorded during the experiment. Each axis was actuated in steps of 1/8 of the motion range (i.e., 11.25° for bending and 22.5° for rotation) up to the motion limit, and the motion hysteresis was observed. Regarding the bending angle, the measurement was taken when the gripper was opened and closed. This was because the tension of the gripping actuation wire running through the bending joint affects the bending motion.

Figure 8 shows the measured bending angle. One more motion step was required to reach the limit of 90°. The hysteresis was mainly due to the backlashes of the pin gears and transmission gears inside the actuation unit. Smaller hysteresis was observed when the gripper was closed because the tension of the gripping actuation wire applied forces between the gears and eventually reduced the effect of the backlashes. The gripping actuation wire ran through the bending mechanism, and the tension of the wire impeded the bending motion at large bending angles.

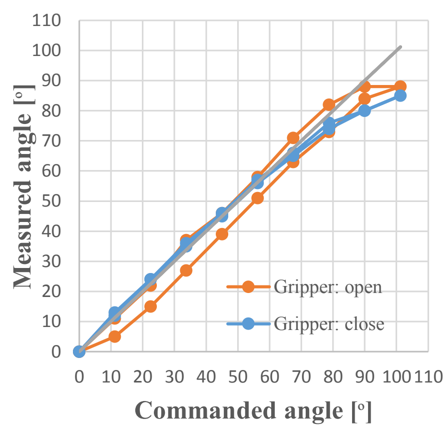

Figure 8 Bending angle.

Figure 9 shows the results of the rotation angle measurement. One more motion step was required to reach the limit of 180°. Motion hysteresis was once again observed due to the backlashes of the pin gears and transmission gears inside the actuation unit.

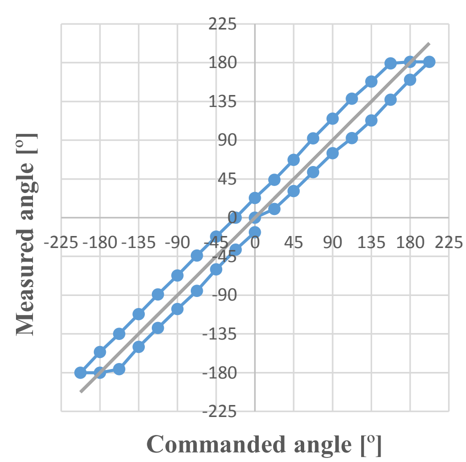

Figure 9 Rotation angle.

The backlash problem is typical of gear transmission systems. Despite the problem, a gear transmission mechanism is preferable when multi-DOF motions are required in such small instruments. This is because it enables high-precision multi-DOF motion using a large actuation force and a wide motion range compared to a wire or pneumatic actuation mechanism. Additionally, the hysteresis caused by the backlashes creates fewer problems when the forceps is controlled by a hand-held unit or by a master-slave system because the operator can easily adjust the position through the microscopic view.

B. Needle Insertion Force

The needle insertion force is the most important parameter in the design of microsurgical forceps. The needle insertion force generated by the proposed multi-DOF mechanism was therefore measured to assess the feasibility of the mechanism. The needle insertion force is affected by the gripping force and the friction between the gripping surfaces.

The experimental setup is shown in Fig. 10. The thread of the surgical suture (5-0, Ethicon) was fixed to the force sensor (MAD-3, Wacoh-tech Inc.), and the needle was gripped at a point 5 mm from the gripper axis. The needle was pulled upward by the multi-DOF forceps, and the force was measured when the needle slipped from the gripper. The procedure was repeated five times for each of the bending angles of 0°, 45°, and 90°. A pulling force of 15 N was applied to the gripping actuation wire. This measurement procedure was designed to enable evaluation of the effects of the gripping force, friction, and bending angle.

The measurement results are presented in Table 1. The average needle insertion force was approximately 1.7 N. The robotic forceps could hold the needle; however, the needle easily slipped or rotated when it was pushed against a skin model made of synthetic rubber. The gripping surfaces were knurled to increase the friction between the needle and the surfaces; however, the needle insertion force was not sufficient to firmly hold the needle.

This problem can be attributed to the high friction in the gear transmission mechanisms. Although the rotating guide pins were used, as shown in Fig. 5, to reduce the friction between the gripping actuation wire and the mechanism, the wire was stiffened by its deflection by a small bending radius. This necessitated the use of a larger force to close the gripper. The slight deformations of the gripper also generated high friction. Therefore, an increase in the needle insertion force is necessary to enable insertion into relatively stiff membranes such as dura mater. The design of the gripper will be accordingly modified to achieve deflection of the gripping actuation wire by a larger bending radius. The material of the parts will also be changed to one having higher hardness to avoid deformation.

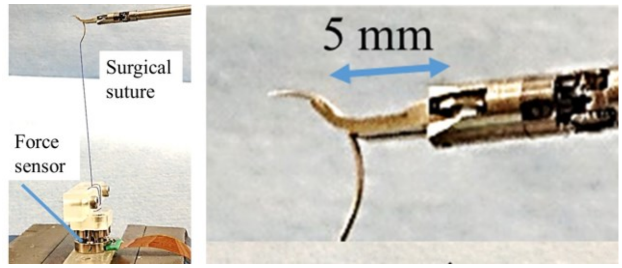

Figure 10 Experimental setup for needle insertion force measurement.

TABLE I. NEEDLE INSERTION FORCE

	Needle Insertion Force [N]			
Bending Angle [°]	Min.	Max.	Ave.	SD
0	1.2	1.8	1.4	0.24
45	1.4	2.2	1.8	0.34
90	1.6	2.3	1.8	0.26
Ave.	1.2	2.3	1.7	0.33

IV. CONCLUSION

A hand-held multi-DOF robotic forceps was developed for precise and dexterous manipulation of a surgical suture in a deep and narrow space such as in the brain. The diameter of the forceps is 3.5 mm, and the motion of its tip has three DOFs. The DOFs of the bending and rotation motions are achieved by a double-pin-gear mechanism with intersecting axes. The gripper is actuated by a wire that passes through the bending joint. A drive unit that could be intuitively controlled by one hand was developed to implement a hand-held version of the robotic forceps for evaluation of its fundamental performance. The experimental results showed that the robotic forceps produced an average needle insertion force of 1.7 N. To increase the needle insertion force, design modifications are necessary that would reduce the backlashes of the gear transmission mechanisms at the instrument tip and in the hand-held unit, as well as the friction of the wire actuation.

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