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Microsurgical robotic system for the deep surgical field: development of a prototype and feasibility studies in animal and cadaveric models

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Object. To enhance the surgeon's dexterity and maneuverability in the deep surgical field, the authors developed a master–slave microsurgical robotic system. This concept and the results of preliminary experiments are reported in this paper.

Methods. The system has a master control unit, which conveys motion commands in six degrees of freedom (X, Y, and Z directions; rotation; tip flexion; and grasping) to two arms. The slave manipulator has a hanging base with an additional six degrees of freedom; it holds a motorized operating unit with two manipulators (5 mm in diameter, 18 cm in length). The accuracy of the prototype in both shallow and deep surgical fields was compared with routine freehand microsurgery. Closure of a partial arteriotomy and complete end-to-end anastomosis of the carotid artery (CA) in the deep operative field were performed in 20 Wistar rats. Three routine surgical procedures were also performed in cadavers.

The accuracy of pointing with the nondominant hand in the deep surgical field was significantly improved through the use of robotics. The authors successfully closed the partial arteriotomy and completely anastomosed the rat CAs in the deep surgical field. The time needed for stitching was significantly shortened over the course of the first 10 rat experiments. The robotic instruments also moved satisfactorily in cadavers, but the manipulators still need to be smaller to fit into the narrow intracranial space.

Conclusions. Computer-controlled surgical manipulation will be an important tool for neurosurgery, and preliminary experiments involving this robotic system demonstrate its promising maneuverability.

Key Words • **robotics** • **microsurgery** • **neurosurgery** • **anastomosis** • **dexterity** • **rat**

Robotic manipulator systems have been introduced in various surgical fields[4,10] not only to enhance the surgeon's dexterity in less invasive surgical procedures, but also to increase the safety and accuracy of surgery. Using mechanical devices that can only be furnished by robotic systems, these systems also make possible tasks that previously were impossible.[6,10] An additional benefit lies in the fact that the robotic system can be telecontrolled.[18] The amount of surgical education and skill development provided to clinicians may soon become limited due to lowered surgical case volumes, especially in the face of the development of nonsurgical methods, the increasing numbers of neurosurgeons, and increasing social demands for high-quality care. In the future, difficult tasks that cannot be managed without surgery will be treated by less experienced surgeons. To overcome the difficulties inherent in this circumstance, we must develop tools capable of managing complicated tasks in less experienced hands.

Abbreviations used in this paper: AChA = anterior choroidal artery; CA = carotid artery; MM-1 = Micromanipulator Type 1; 3D = three-dimensional.

Although various stereotactic and endoscopic robotic manipulator systems have been introduced in neurosurgery,[1,5,9,15] no practical robotic micromanipulator has been developed that can be used in routine microsurgical procedures.[11,14,17] Microneurosurgery in the deep surgical field should be the ideal indication for the use of robotic systems, which have the advantage of enhanced dexterity and accuracy. We developed a prototype of a microsurgical robotic system, MM-1, that can be used in routine neurosurgical procedures. In this paper we describe the prototype and report the results of feasibility experiments we performed in rats and cadavers.

Materials and Methods

Robotic System

We used three criteria to develop our robotic system: 1) the system should be applicable in either the superficial or deep (> 9 cm in depth) general neurosurgical field; 2) the system should be able to pass through a narrow corridor and should have wide freedom of motion (> a 3 × 3–cm² field) for delicate procedures in the deep sur-

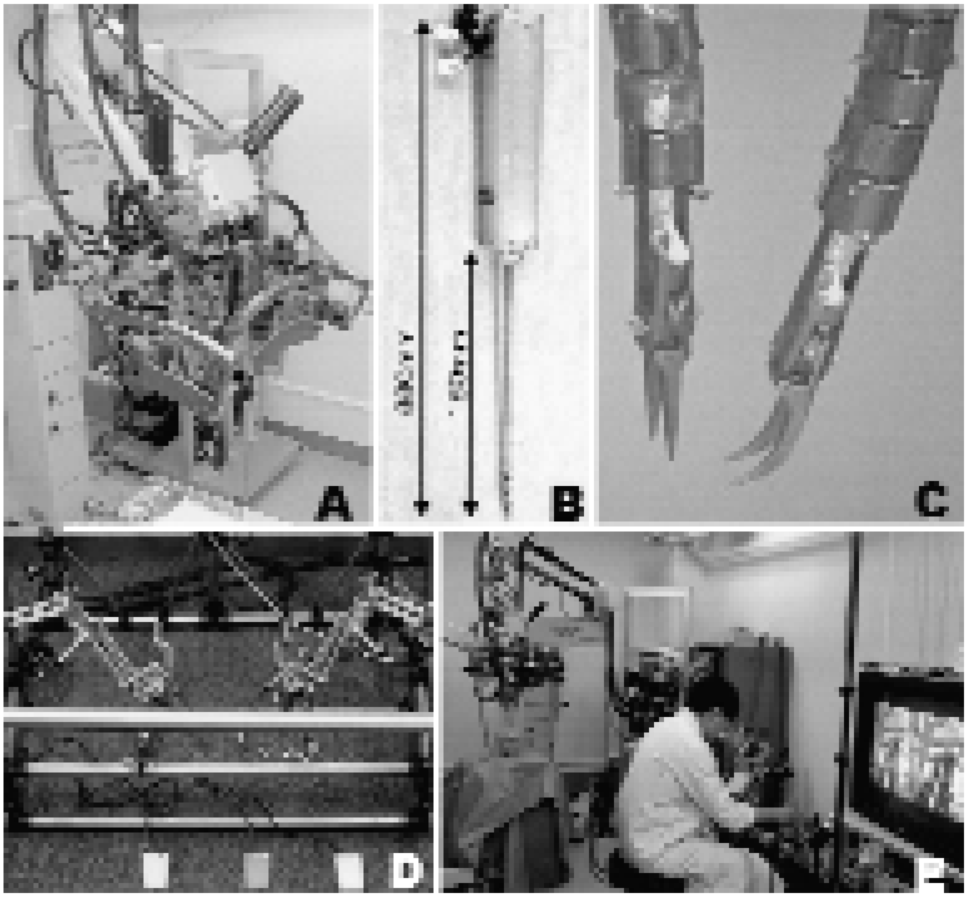

FIG. 1. Photographs depicting the MM-1 system. A: Radius guide system for moving the micromanipulators. B: Micromanipulators with fine forceps and the motorized tip-flexion mechanism. C: Tips of the micromanipulators. D: The master control system with two hand pieces and three foot switches. E: Overview of the system.

gical field; and 3) the system should be able to perform various surgical tasks, including stitching with a needle and knotting sutures.

The robotic system we developed is a master–slave telerobotic system controlled by computer signals connected with local area network signals. Details of the mechanics of this system have been reported elsewhere.[2] We used VX Works–run computer systems (Wind River, Alameda, CA) to control the master signals and slave motions. The slave system comprises two manipulators capable of motorized motion in six degrees of freedom. These two manipulators are attached to the base of the unit, which has an additional six degrees of freedom and an electromagnetic locking system. The six-degrees-of-freedom motions in each manipulator include motion in the X, Y, and Z directions; rotation around the z axis; flexion of the tip up to 90° on either side of the plane of the manipulator, and gripping and releasing of the forceps. The tip of the manipulator can be flexed 2 cm in any direction and was designed to allow a relatively wide range of motion in the depths of a narrow surgical field. The shaft of each manipulator is 18 cm long and 5 mm thick.

The X-Y-Z motion takes place around a fixed point, which varies from 2 to 11 cm from the tip (Fig. 1A–C). The manipulator can be moved on the radius guide 10° in each direction. The stepping motor is used for X-Y-Z motion, with a radius guide of 0.00087°/driving motor pulse and a z axis of 0.00056 mm/driving motor pulse. A DC servo motor (Maxon Motor AG, Sachseln, Germany) is used for motion of the micromanipulator tip. At the present time, each manipulator is equipped with fine-tipped, curved, and straight forceps. The tip of the manipulator can move at a speed ranging from 0.00087 to 50 mm/second. The master–system is a bimanual device that can control movement in seven degrees of freedom. This system includes three foot switches, which work as a crutch for motion, to control the speed of the manipulator, and to control the combinations of manipulator motions (Fig. 1D). An overview of the entire system is depicted in Fig. 1E. Experiments were performed at a master-slave scale-down ratio varying between 20:1 and 40:1. The maximum torque of this system was measured as 20 N for the manipulator motion and the forceps grip. The mechanical construction of the system is summarized in Table 1. A new manipulator with a sterilizable tip and an intermediate compartment, as well as other types of interchangeable instruments, such as laser fiber holders, microscissors, electric bipolar coagulators, and microcup forceps, are currently under development.

Visual System

The 3D visual system includes a high-definition video-camera 3D-projection system developed by NHK Engineering Services, Inc. (Tokyo, Japan). The prototype of this visual system has been described elsewhere.[20] The system consists of one high-definition video camera with a 2010 × 1086–pixel resolution; right- and left-lens images are captured through a beam splitter. This system provides a signal four times higher in each visual field than the regular National Television Systems Committee camera. The image is then projected on a 6-in, high-definition, liquid crystal display. Pixels on this display measure 138 μm (one fourth the size of regular liquid-crystal pixels) and 500,000 pixels are projected on the screen. The resolution is five times higher than that of ordinary monitors. Through a prism lens viewer, the surgeon has a clear 3D view of the operative field. In our cadaver study, for approaches involving a narrow surgical field in which the 3D system could not provide a good view, we used a hybrid endoscope-holder system (Olympus Endo-Arm system; Olympus Corp., Tokyo, Japan).

TABLE 1
*Mechanical characteristic of the prototype MM-1**

Component	Technical Description	Size, Weight, and/ or Critical Nos.
hanging base	6 DFs, electromagnetic locking system	can hold up to 21 kg
radius-guide slave system	stepping motor in X, Y, & Z directions, & rotation	30 cm × 40 cm, weight 10 kg, radius-guide angle: 10°
manipulator	2 DC servo motors, mobilizing tip flexion & forceps (instrument) grip & release	flexion 2 cm of the tip, 90° to each side of the plane, grip torque 20 N & manipulator torque 20 N
master manipulator	control system w/ 7 DFs, hand controls, & 3 ft switches	50 cm × 70 cm
controlling computer	VX Works, 1000 MHz, signal transmission through an LAN (100 MHz)	not applicable
visual system	HD video-camera system attached to a 300-mm microscope lens & a 3D video display system	HD camera w/ 2,000,000 pixels & 6-in LCD w/ 500,000 pixels

* DF = degree of freedom; HD = high definition; LAN = local area network; LCD = liquid crystal display.

Pointing Accuracy

Five right-handed surgeons, each of whom had been practicing neurosurgery for longer than 10 years, pointed to eight points in the 2 × 2–mm² shallow surgical field by using their right hands and in the deep surgical field (9 cm in depth) by using their left hands. Each surgeon was asked to repeat the pointing in five squares in a randomly assigned sequence for a total of 40 pointings. Initially, each surgeon was allowed to practice robotic control in the X, Y, and Z directions for 20 minutes. The tasks were first performed using the robotic system and then repeated freehand, as in routine microsurgery. Pointing errors were measured through digital magnification by using a commercially available software program (Photoshop version 7.0; Adobe Systems Inc., San Jose, CA). Errors and time requirements were compared between the right (shallow) and left (deep) hands, and between freehand microsurgery and robotic manipulation.

Animal Model

To evaluate the dexterity, maneuverability, and feasibility of this system in performing complex neurosurgical procedures, we carried out two types of tasks by using 20 Wistar SPF rats (220–440 g each, Charles River Japan, Yokohama, Japan). All animal-related procedures were conducted in accordance with guidelines for the care and use of laboratory animals set by our university review board. Anesthesia was induced in the rats by using halothane gas and their body temperatures were maintained at 36°C. After the experiment, the animals were killed by an overdose of deep anesthesia.

The first task we performed was closing a half-wall arteriotomy in the CA (average diameter 1 mm) in 10 Wistar rats by using 10-0 nylon stitches. The CA was exposed and isolated through routine microsurgical techniques, and half of the wall was transversely sectioned after the proximal and distal portions of the artery had been clipped. Next, a glass tube 12 cm long and 5 cm wide was placed over the arteriotomy and the two robotic manipulators were passed through the glass tube. Using a few 10-0 nylon stitches, the robotic manipulator closed the arteriotomy within this space. Interrupted sutures were used to increase the frequency of the manipulations of the robotic hands. Time requirements and immediate patency rates were assessed.

After a few mechanical adjustments, we performed the second task—complete anastomosis—in 10 Wistar rats. With the aid of an operative microscope, the CA was prepared and a surgical field 9 cm high and 4 cm in diameter was produced over the artery by using a height-adjustable ring. The CA was completely divided after the distal and proximal segments had been clipped. After one side of the arteriotomy had been sutured, the clip was turned and the back side of the artery was sutured. Time requirements and vessel patency were assessed. After each suture had been placed, it was cut by an assistant using the regular microsurgical method. All animal procedures were performed by a single surgeon (S.S.).

Cadaver Model

The cadaver experiment was undertaken to evaluate the clinical applicability of this system and to identify any technical and conceptual problems associated with the prototype. A formalin-fixed cadaver head was prepared using the perfusion–fixation method. After sectioning of the head, the major arteries and veins were cannulated and irrigated for 24 hours. Following this procedure, colored latex was infused to define the arterial and venous systems.

We used the robotic system to perform a routine frontotemporal craniotomy, the suboccipital craniotomy approach to the cerebellopontine and cerebellomedullary cisterns, and transnasal pituitary

TABLE 2
*Errors and time required in pointing experiments**

Experiment	Errors Per Pointing (μm)†	Time Required for 8 Pointing Procedures w/in 2 × 2 mm² (sec)
shallow surgical field		
freehand maneuvers by rt hand	57.5 ± 35.2	22.0 ± 6.4
robotic maneuvers controlled by rt hand	50.74 ± 35.0‡	84.1 ± 18.7
deep surgical field		
freehand maneuvers by lt hand	92.3 ± 51.8	33.9 ± 9.9
robotic maneuvers controlled by lt hand	67.7 ± 39.4§	91.4 ± 27.2

* Values are expressed as means ± standard deviation
† Measured using Photoshop.
‡ Not significantly different compared to freehand in shallow surgical field ($p = 0.054$).
§ Significantly less error ($p < 0.0001$, unpaired Student t-test).

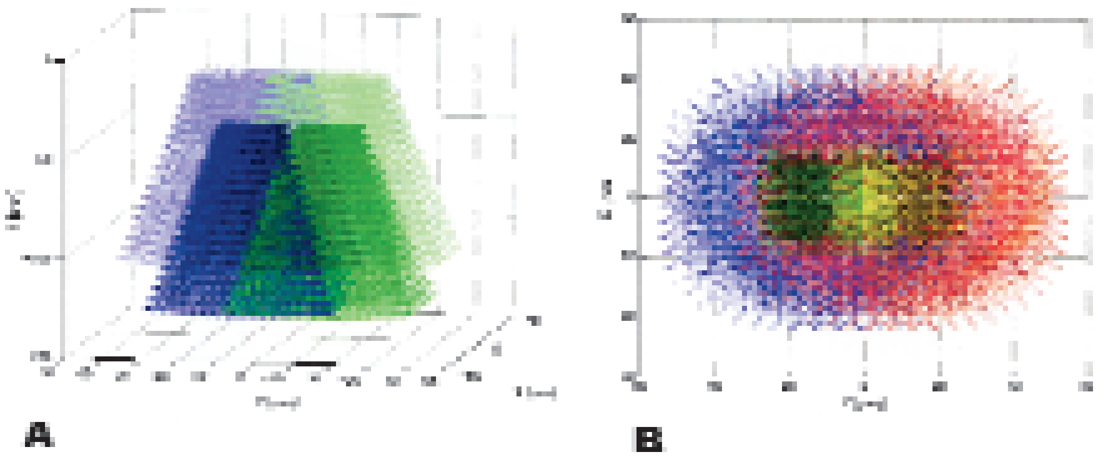

FIG. 2. A: Three-dimensional graph demonstrating the range of motion of the tips of the two manipulators (one blue and the other green) both short and long distances from the immobilized point of the manipulator (darkest blue and green). Lighter blue and green areas show where the tip of the manipulator is flexed to the maximum degree. Note the areas of overlap between the manipulators, where complex procedures such as replacing needles and holding arteries during stitch placement are done. B: Graph showing the maximum range of motion of the tips of the instruments in a two-dimensional projection. The yellow and green areas represent regions where the manipulator is not flexed; the red and blue areas, regions where the manipulator is flexed.

procedures. All procedures were videotaped. The technical feasibility of each procedure, any problems or potential disadvantages that we encountered, and complications due to the use of the robotic system were assessed.

Statistical Analysis

The statistical analysis was performed with the unpaired Student t-test. A probability value less than 0.05 was considered significant.

Results

Range of Motion of the Manipulators

Combining the two manipulators with and without tip flexion created the surgical field depicted in Fig. 2. This combination created an overlapping surgical area in which both manipulators could function so they could cooperate in handling needles or performing other sophisticated bimanual procedures.

Pointing Experiment

Table 2 shows the mean errors of each point, the mean times required for pointing to the eight points of the square, and the standard deviations for each set of experiments for all surgeons. In the deep surgical field in which pointing was performed by the left hand, the pointing error was significantly greater when pointing was freehand with the aid of the microscope than when accomplished using the robotic system ($p < 0.0001$). In the shallow surgical field in which pointing was performed by the right hand, pointing was less improved when using the robotic system ($p = 0.054$). Errors were significantly less when pointing was done in the right side of the shallow surgical field than in the left side of the deep surgical field, regardless of whether the pointing was freehand or performed using the robotic system. The time requirements, however, were three to four times longer in both shallow and deep surgical fields when the robotic system was used.

Animal Experiments

Figure 3 depicts the suturing procedure performed by the MM-1 system. Figure 4A shows the average time required to complete one stitch in the CA in each rat during the first

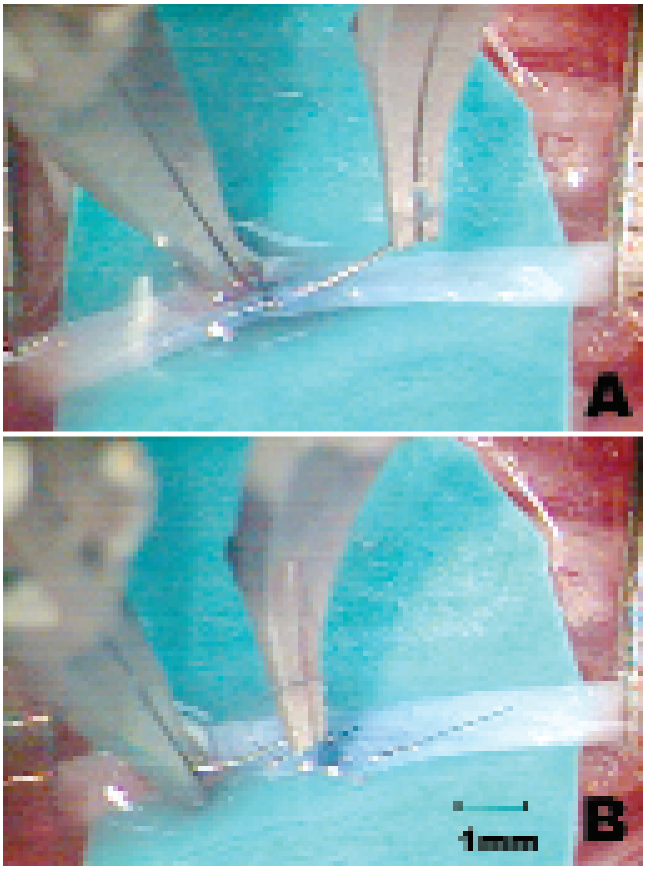

FIG. 3. Photograph showing closure of the arteriotomy by the robotic system. A: Placing a suture. B: Knotting.

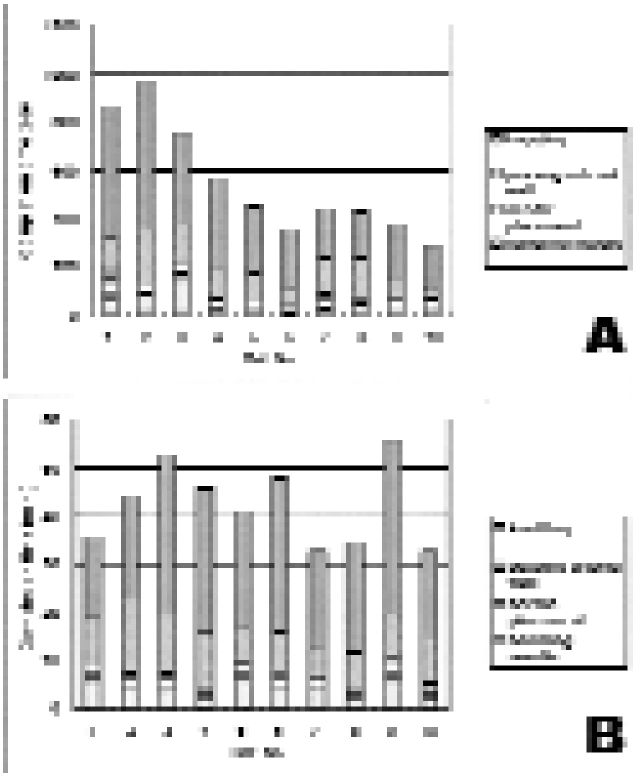

FIG. 4. A: Bar graph showing the time required to complete one stitch in the initial part of the animal experiment (half arteriotomy closure). The time required decreased significantly over the course of the 10 animal procedures. Knotting the suture took the longest and was the most varied time. B: Bar graph demonstrating the time required to complete anastomosis in the second part of the animal experiment. The mean anastomosis time was 42.4 minutes and did not decrease during the course of the last 10 animal procedures. Knotting required the most time.

10 animal experiments. A mean of 552 seconds was required to place and knot one stitch. The time spent doing this task in the first three animals was significantly different from the time spent doing it in the last three animals. Knotting took the longest time and the duration of this movement was the most varied. Eight of 10 CAs were patent after the artery was unclamped. The two failures were caused by bleeding after the clamp was removed.

In the first 10 animal experiments, the motor boxes of the manipulator occasionally collided during suturing and their tips moved in an unwanted direction. We made adjustments by adding a software switch to prevent such a collision and a foot switch to control the movement of the malleable part of the manipulator. After these improvements had been made, we performed a complete anastomosis in 10 Wistar rats. Figure 4B shows the time required for complete anastomosis and the times of the component actions in the second 10 animals. The total time required for anastomosis (10–12 stitches) on average was 42.4 minutes. Each stitch required a mean of 4.1 minutes, and knotting required the longest time. No significant improvement in the time requirement was seen over the course of the second set of experiments. The anastomosis was successful with patency in all animals.

Cadaver Experiment

Frontotemporal Transsylvian Approach. After a medium-sized frontotemporal craniotomy had been performed and the dura mater opened, the sylvian fissure was opened using the robotic system (Fig. 5A1 and A2). The arachnoid was torn with two forceps and gradually opened to the cranial base to expose the internal CA and the AChA. We made an arteriotomy in the AChA, and sutures were placed using the robotic system (Fig. 5A3). This maneuver was successful, and the sylvian fissure was opened and retracted in the usual manner. Tip flexion was useful in opening the fissure and slowly mobilizing the arteries and veins, but rotation and withdrawal of the flexed manipulator tip was dangerous to the surrounding neurovascular tissue.

Suboccipital Retrosigmoid Approach to the Cerebellopontine and Cerebellomedullary Angle Cisterns. A small craniotomy (2.5×4 cm^2) was made in the retrosigmoid area. After the arachnoid had been dissected using routine microsurgical procedures, we placed the two manipulators of the robotic system through the craniotomy (Fig. 5B1). The Olympus EndoArm was used for visual equipment. We mobilized the posterior inferior cerebellar artery near the facial nerve exit zone and placed a muscle piece under the artery beyond the lower cranial nerves (Fig. 5B2). The manipulations were secure and accurate. The malleable manipulator arm proved handy in reaching the object in the angled endoscopic view.

We also were able to use the robotic manipulator to move the vertebrobasilar junction. While moving the two manipulators, we lost two lower cranial nerve fibers due to the width of the manipulator shaft.

Endonasal Transsphenoidal Route in the Cranial Base

After we had exposed and opened the sella turcica and tuberculum sellae by using routine microsurgical equipment including the endoscope, we placed one manipulator through a nostril (Fig. 5C1). The pituitary gland was dissected using this manipulator (Fig. 5C2). After we had removed the tuberculum sellae and some of the planum sphenoidale anterior to the pituitary gland, the manipulator was used to handle the anterior communicating artery in the cistern; this was accomplished with the guidance of a 70° angled scope, which was placed in the sphenoid sinus (Fig. 5C3). Using the 70°C scope, robotic control was easy becaue the surgeon's hand movements could be matched to the visual image through computer control.

Discussion

The robotic surgical system can be used to enhance a surgeon's ability and dexterity, increase surgical safety, and expand surgical possibilities.[4,6,10] Currently, the most widely used and accepted surgical manipulator systems are daVinci and Zeus, which have been used during laparoscopic or thoracoscopic surgical procedures.[3] Although the benefits achieved using these two manipulators in surgical fields have not been proved in evidence-based strategy,[13] the systems apparently increase the surgeon's dexterity; these user-friendly master–slave systems will expand the field of endoscopic procedures in the future.[21] Nevertheless, these systems are too bulky to be applied in intracranial or spinal

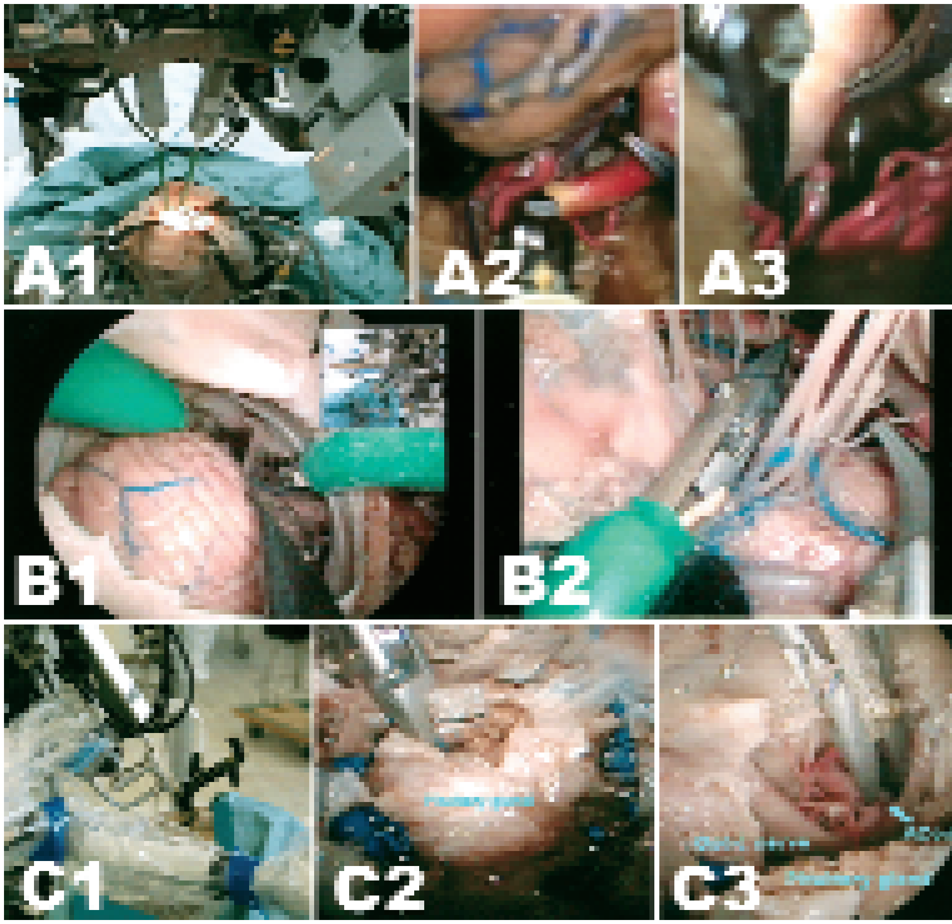

FIG. 5. The cadaver experiments. A: The setup for the frontotemporal approach (1), opening of the sylvian fissure (2), and placement of a stitch in the partially divided AChA (3). B: Introduction of the manipulator into the suboccipital craniotomy (1). The anterior inferior cerebellar artery is manipulated beyond the lower cranial nerves (2). C: Setup for the transnasal approach (1). The pituitary gland is dissected using the manipulator (2). After the tuberculum sellae has been removed, the anterior communicating artery (ACom) and the anterior cerebral artery complex was moved using the robotic manipulator while under the view of the 70˚ scope. Manipulation under this angled view is relatively easy.

neurosurgical procedures. Their arm shafts are 10 mm in width, and they require a wide angle for the two arms to reach the surgical field, prohibiting the entrance of robotic instruments through the narrow surgical corridor. In the field of neurosurgery, several surgical systems have been developed in experimental and clinical settings,[1,5,8,9,15] but a widely applicable robotic system has not been introduced. We believe that deep, complex manipulation through a narrow corridor is the most difficult task and would be the most suitable for use of a neurosurgical robotic system. Although several robotic systems have been used to anastomose very small arteries in a shallow surgical field,[12,16,19] our system is the first to achieve microanastomosis in a deep and confined surgical field. Although anastomosis is not the ultimate goal of our robotic system, the ability to complete such complex procedures should prove the maneuverability of the system.

In this paper, we describe the development of a prototype of the system and basic experiments. The results of the pointing experiment showed that this system can improve pointing accuracy, especially in a deep setting when performed by the nondominant hand. This system should improve the delicate coordination needed for the deep surgical field and enhance the surgeon's ability.[7] We successfully anastomosed a small artery in a deep and narrow surgical field. Although the same procedures were tried by one surgeon (S.S.) who used routine microsurgical instruments, only six of 10 anastomoses were successful without robotic assistance. The majority of the failures were caused by the inability to place stitches at the precise desired position. This experiment proved that our system surpassed human capabilities in some aspects, and our system can be used for various complex procedures performed with two instruments. The tip flexion mechanism improved the surgeon's ability to perform procedures in the deep surgical field.

Although our system does not have a very wide freedom of motion, the range of motion was sufficient to perform procedures in the deep surgical field. Le Roux and colleagues[14] reported that six degrees of freedom were not enough to place sutures or perform anastomoses in their experiments with the RAMS system. The degrees of freedom allowed by our system, however, focus mainly on the micromovement of instruments in a limited field. Gross movements outside the deep field were maintained by the manual movement of the assisting surgeon. If we equip the system with excessive degrees of freedom, control will become fairly complex. For an easy, user-friendly master control system, the degrees of freedom should be limited to a number the surgeon can easily and safely control using hand movements and a few additional foot switches. Our system reduced the time needed for stitching in 10 experiments, and a small improvement in the time required occurred during the following 10 experiments. This trend indicates that our system has a very steep learning curve and surgeons can adjust their control of the mechanical system relatively easily. Because we could perform fairly difficult tasks with this prototype, we believe the six degrees of freedom and range of motion provided by our system are sufficient.

On the other hand, several difficulties in using the current prototype were delineated in the animal and cadaver experiments. Robotic surgery in our experiments required an unacceptably long operation time to perform tasks, especially for bimanual tasks such as knotting. Although use of our system demonstrated a steep learning curve in the initial animal experiments, no significant improvement was noted after that. Hence, our system requires dramatic mechanical improvements to increase the swiftness of the surgery. Inclusion of a mechanical device that can replace the rather difficult bimanual robotic manipulation needed for an activity such as knotting with a one-touch motion may improve the time requirements. Although automation should not be involved in the initial step of neurosurgical robotics because of safety risks,[17] automated tasks might improve the speed of surgery once delicate safety mechanisms are developed and robotic maneuverings are oriented using the navigation system. The results of the cadaver experiments showed that our manipulators were too thick to be placed in a very delicate and confined surgical field. The manipulator shaft should be less than 4 mm in diameter. Another challenge is the addition of force feedback in all degrees of motion, not only in three dimensions,[17] to perform delicate procedures. Such technology should be developed, making sure not to add any bulk to the fine manipulator.

Surgical procedures in the twenty-first century are required to be safe and accurate. They should also be less invasive so that patients can maintain a high quality of life. Furthermore, standards and high-level surgical skills must be upheld, despite the fact that surgical training and experience may decrease because advancements in nonsurgical methods lead to lower surgical caseloads. Robotic systems can be useful in meeting these requirements. They can facilitate scientific standardization of surgical procedures and allow experienced microsurgical maneuvers that traditionally have been performed by surgical masters to be analyzed with digital signals. With the aid of robotic systems, less experienced surgeons will be able to perform complex surgical tasks more easily. Our prototype MM-1 displays promising results in the initial steps of robotic-assisted neurosurgery, and technical refinements will improve the mechanical efficacy of this system.

Conclusions

We report the development and initial assessment of the feasibility of our prototype robotic system for microsurgery in the deep surgical field. This system was developed to assist human microsurgery, especially in tasks that are deep or difficult to perform freehand. Our design proved suitable and the experimental results are promising. With the addition of mechanical and systematic refinements and miniaturization of the 3D visual system, we believe this system will evolve into a useful microsurgical robotic system that can improve the capabilities and accuracy of the surgeon.

Disclaimer

The MM-1 system is not presently on the market and none of the authors has any financial interest in this robotic system to disclose.

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