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Medical Engineering and Microneurosurgery: Application and Future

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Abstract

Robotics and medical engineering can convert traditional surgery into digital and scientific procedures. Here, we describe our work to develop microsurgical robotic systems and apply engineering technology to assess microsurgical skills. With the collaboration of neurosurgeons and an engineering team, we have developed two types of microsurgical robotic systems. The first, the deep surgical systems, enable delicate surgical procedures such as vessel suturing in a deep and narrow space. The second type allows for super-fine surgical procedures such as anastomosing artificial vessels of 0.3 mm in diameter. Both systems are constructed with master and slave manipulator robots connected to local area networks. Robotic systems allowed for secure and accurate procedures in a deep surgical field. In cadaveric models, these systems showed a good potential of being useful in actual human surgeries, but mechanical refinements in thickness and durability are necessary for them to be established as clinical systems. The super-fine robotic system made the very intricate surgery possible and will be applied in clinical trials. Another trial included the digitization of surgical technique and scientific analysis of surgical skills. Robotic and human hand motions were analyzed in numerical fashion as we tried to define surgical skillfulness in a digital format. Engineered skill assessment is also feasible and should be useful for microsurgical training. Robotics and medical engineering should bring science into the surgical field and training of surgeons. Active collaboration between medical and engineering teams and academic and industry groups is mandatory to establish such medical systems to improve patient care.

Key words: microsurgery, robotics, training, engineering, skill

Introduction

In the area of surgical technique, there are significant gaps between neurosurgery and science. The disease pathologies that can be treated through surgery have been clarified by scientific research, and surgeons can be systematically trained to address them. But it is actually quite difficult to learn surgical techniques in a scientific manner. Surgeons learn technique through personal effort and by watching expert surgeons, and there are only a few systematic methods to learn technique, especially for microneurosurgery.[1,2] Because of the difficulty in developing high-level surgical skill through systematic methods, highly skilled and popular surgeons have often been called "God's hands" or "Buddha's hands."

At the same time, it is difficult to define the technical standards of surgical skill and this creates drawbacks in conducting randomized controlled trials in the field of surgery. How can we make surgical training and evaluation scientific? And how can we carry out systematic education in surgical skill for each trainee to obtain these skills? These are the perennial questions in the field of microsurgery.[3,4]

We are now in the era of emerging techniques for alternative, non-open surgical methods to manage routine surgical pathologies such as solitary tumors (radiosurgery), simple aneurysms (endovascular coils) and carotid or vertebral stenosis (stent placement).

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As a result, young neurosurgeons will be facing very complicated cases requiring extremely high-level surgical skills without enough surgical experience.

Medical engineering and microsurgical robotic systems show good possibilities in filling these gaps. Robotic surgical systems provide more secure and accurate surgical preciseness than human hands and allow the surgeon to perform tasks safely, which cannot always be done by human hands.[5] Surgical learning curves are also much less steep with robotics than with open surgery.[6] In addition, by using robotics and medical engineering technology, we can record the numerical and spatial data of surgical techniques and analyze this data in a scientific manner. Nevertheless, despite several experimental, preclinical or clinical studies,[7,8] a robotic neurosurgical microsurgery system has not been established as commercially available equipment, nor has a systematic surgical-skill evaluation system been developed.

In this article, we describe our work in developing a microsurgical robotic manipulator system[9,10] and a skill assessment method through the use of medical engineering technology.[11] Future perspectives are also discussed.

I. Developing a robotic microsurgery system

When developing robotic systems, we often face the following questions:[12,13]

1. Do we need robotics in real neurosurgery?
2. If yes, where do we need robotic technology during surgery?

These are difficult but basic questions to be answered. Among commercially available surgical systems, the Da Vinci system is used during laparoscopic surgery, especially in the narrow pelvic cavity, a somewhat difficult zone to operate in with free hands even with laparoscopy.[14] The Cyber knife and Gamma knife systems both apply radiation with machine-driven heavy equipment that cannot be easily handled by human hands. The Renishaw robotic system enables very accurate stereotactic approaches.[15] The NeuRobot system, developed in Japan, allows transendoscopic surgical procedures for, for example, intraventricular tumors and hydrocephalus.[16] The NeuroArm is the only microsurgical system currently used in a clinical setting, and was originally developed to be used in surgeries inside an open-MRI bore.[17] Common features in which all these systems are used are tasks difficult to be done by human hands and procedures requiring good accuracy.

Our goals in developing a microsurgical system are as follows:

1. Create a robotic system that enables very delicate and complicated procedures in a deep surgical field, such as under the endoscope.

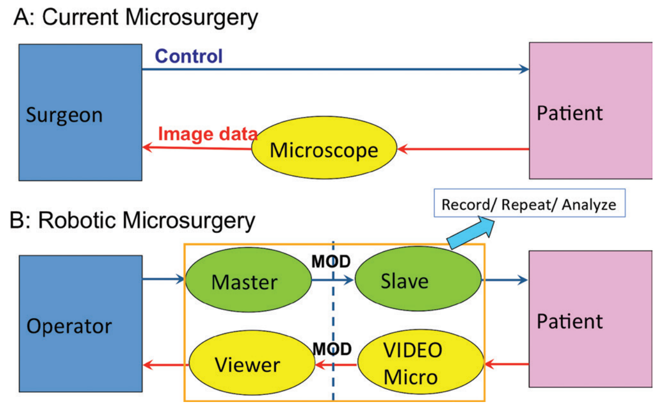

Fig. 1 The concept of robotic microsurgery. A: During routine microsurgery, we observe the surgical view through the microscope directly and operate using our own hands. B: For robotic microsurgery, we watch the surgical field through a video microscope away from the surgical site. The view can be modified to suit the operator and additional information, such as the temperature of the surface, traction strength, etc., can be added. The operator also uses a robotic manipulator. There are computers between the surgical site and the operator, and all procedures can be modified, such as reducing the scale of motion, diminishing tremors, or changing the mode of motion. At the same time, we can record all information in a motion log and repeat and analyze the motions.

2. Create a microsurgical system that provides accurate surgical preciseness beyond that of human hands, such as suturing vessels with a diameter of 0.3 mm.

Before developing a surgical robotic system, we needed to translate our surgical procedures into a mathematical and engineering setting. With a robotic system, we must be able to modify vision and motions according to the procedure and task (Fig. 1). This process of development included a few basic steps:

1. Define surgical procedures in mechanical terms and dimensions: Because robots can move only in pre-determined ranges and directions, unlike the human body and hands, we need to specify the essential range and instrument motion in mathematical terms.
2. Set the location of operators and the visual system and understand time lag: To control a robotic system, we need a master. If we could create a compact master system, surgeons would be able to control the robot as they do their own hands over the operating table. But the current set-up has a separate master (controller) and slave (manipulator), so the operator needs to sit away from the patient. This set-up is advanced as a telesurgery system,[18]

but a slight time lag can occur between the actual master control and slave manipulator. Thus, a televisual system that can show the current surgical field conditions is also necessary.

3. Include haptic sensation and transmission: Currently, haptic sensation is rarely included in surgical robotic systems because of their immaturity of development. While the NeuroArm system includes a haptic device,[19] the feeling it provides is not as good as real surgical sensation. Haptic information, of course, helps surgical dexterity and security; thus, a good haptic system needs to be developed.

4. Develop methods to translate the intentions of the operator to mechanical manipulators: We need to create a master robotic controller to sense the motion of human hands and translate that motion into a signal to move the robotic system. The translation of motion can be one-to-one exactly the same or can be modified into magnified or scaled-down motion, or completely different motions, such as the ones a computer game controller makes. Also, instead of confining the system to surgical methods traditionally done by human hands, we can create new robot-oriented surgical methods. For example, rather than suturing vessels one by one with stitches, we could develop a vessel-sewing machine.

Project 1. Developing a microsurgical robotic system for deep and narrow surgical fields[9]

Our system consists of a microsurgical robotic controller (master robot), a robotic manipulator (slave robot), and a 3-dimensional (3D) video-microscope (Fig. 2). The surgeon controls the robotic manipulator using a master controller away from the surgical field.

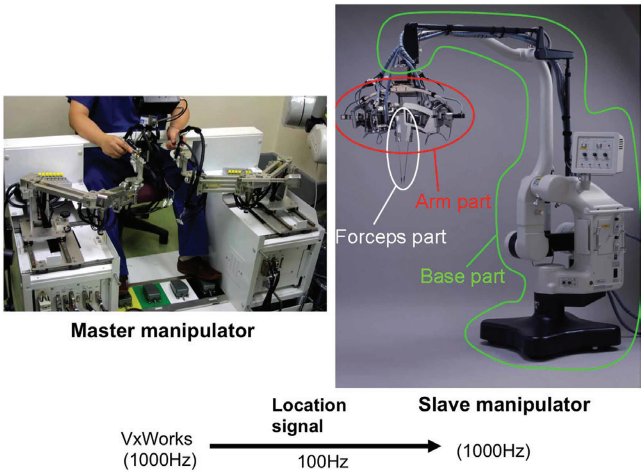

Fig. 2 Robotic system: A slave manipulator is hung over the microscope base and controlled by the master manipulator. Control signals are transmitted through 100-Hz location signals.

The master-and-slave signal communication is transmitted through a local area network with a 100-Hz signal frequency. The video microscope is crafted from a regular microscope and a high-vision video camera to capture right and left eye signals on one camera system. This image is shown to the operator through a 6-inch high-vision display separating the right and left views. Viewing systems are often a 2D projection for laparoscopic robotic systems, but in our initial trial using a 2D monitor, we realized that it is extremely difficult to control a robotic system with 2D in the microscopic field. Therefore, we incorporated a 3D viewer into our system.

The master systems are equipped with control arms, which can capture the operator's hand motion in 6 degrees of freedom. Then, the hand motion is scaled down to 1/10 with a one-to-one motion scale, and modified signals are conveyed to the slave manipulators. Initially, we were using the master system common in laparoscopic surgery. But as we use wrist and hand motion during microsurgery, rather than arm motion as in laparoscopic surgery, we created a new master system specifically for microsurgery according to hand-motion analysis during microsurgery as described later.

The slave manipulators are equipped with a flexion mechanism at the tip of the manipulator to facilitate wider surgical manipulation in a deep field. One arm of the robotic manipulator has 6 degrees of freedom and is 18 cm in length and 5 mm in diameter.[10] As the definition of motion range, right and left manipulators move in the range of 4-cm squares, and 2-cm overlapping zones are created between manipulators for interactive procedures (Fig. 3A).

Although the robotic system is not built only for anastomoses, the task here was mainly the anastomosis of vessels because the technical standard of anastomosing vessels is very high and success in this procedure would prove that the robotic system can be used in complicated surgical procedures.

We have tested and modified our system as follows:

1. Accuracy tests (Fig. 3B): First we carried out an accuracy test in which we aimed crossing points of 1 mm graphic note in sequential fashion. We asked five right-handed operators to do the tasks using their right hand in a shallow surgical field and their left hand in a deep field. These tasks were done first freehand and then with the robotic manipulator under the microscope. Errors in both procedures were measured and compared between left deep and right shallow surgical fields. Deep field accuracy with the left hand using robotics was similar to that of right-hand shallower surgical procedures

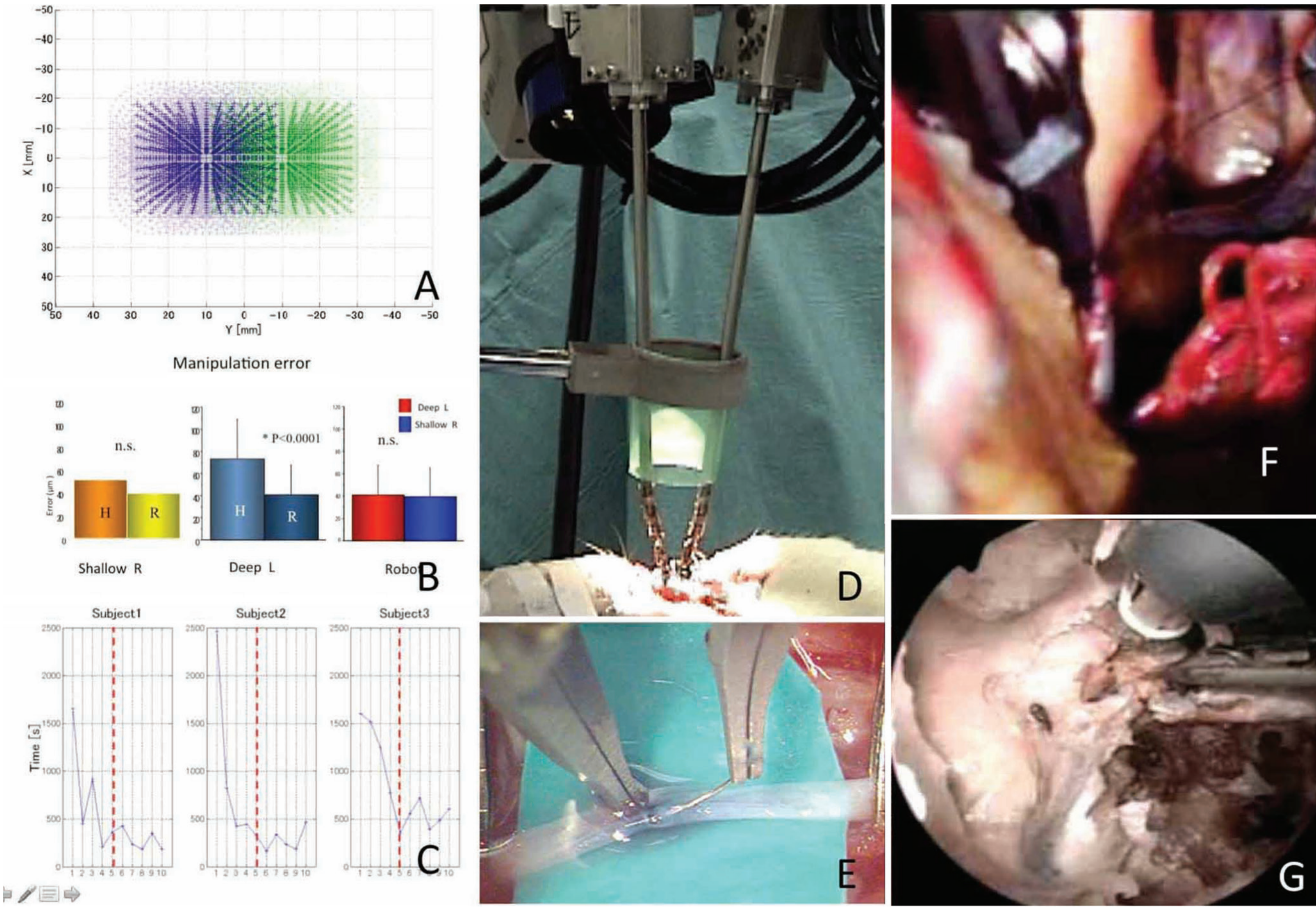

Fig. 3 Dimensions and tests of the deep surgical system. A: The surgical range of slave manipulators. Right (*green*) and left (*blue*) manipulators move in the range of 4-cm squares, and 2-cm overlapping zones are created between manipulators for interactive procedures. B: Pointing accuracy tests. The pointing accuracy with the dominant (usually *right*) hand in a shallow surgical field and the non-dominant (*left*) hand in a deep surgical field was compared between manual and robotic techniques. No difference was noted on the right side, but during deep left-hand procedures, robotic accuracy was significantly better. When robotic procedures were compared, the right and left accuracy was identical. Thus, with robotics, we can use the left hand as accurately as the right. C: Learning curve. Three operators who never performed microsurgery practiced suturing vessels under the microscope. After 60 minutes of practice, all participants were able to perform a vessel anastomosis within 10 minutes. D, E: The carotid artery of a rat was anastomosed at a depth of 9 cm and a width of 4 cm. With manual procedures, 60% of the specimens showed patency while patency was confirmed at 100% with robotic manipulation. F: Cadaveric experiments. The sylvian fissure was opened and an artificially torn anterior choroidal artery was sutured. G: Transnasal endoscopic pituitary surgery was mimicked with a cadaver. Even under a 70-degree scope, the procedure could be done easily because of the readjusted hand-eye coordination.

using robotics or done manually. Robotic accuracy was much better than manual accuracy in the left deep surgical field.

2. Learning process (Fig. 3C): We recruited three engineering students who had never performed microsurgical procedures or robotic manipulation. With the robotic system, all of them were able to place needles and suture artificial vessels under the microscope and the duration of their task stabilized within 60 min. These results indicate that a robotic surgical procedure can be learned relatively quickly within a limited time.

3. Deep vessel anastomosis (Fig. 3D, E): For this test, the carotid artery (ϕ1.0 mm) of a Wister rat was cut and anastomosed in a surgical field 9 cm deep and 4 cm wide. Manual and robotic procedures were performed in 10 animals in each scenario. Manual anastomosis had a patency rate of 60%, while patency with the robotic system was 100%. While robotic anastomosis required twice the time compared to

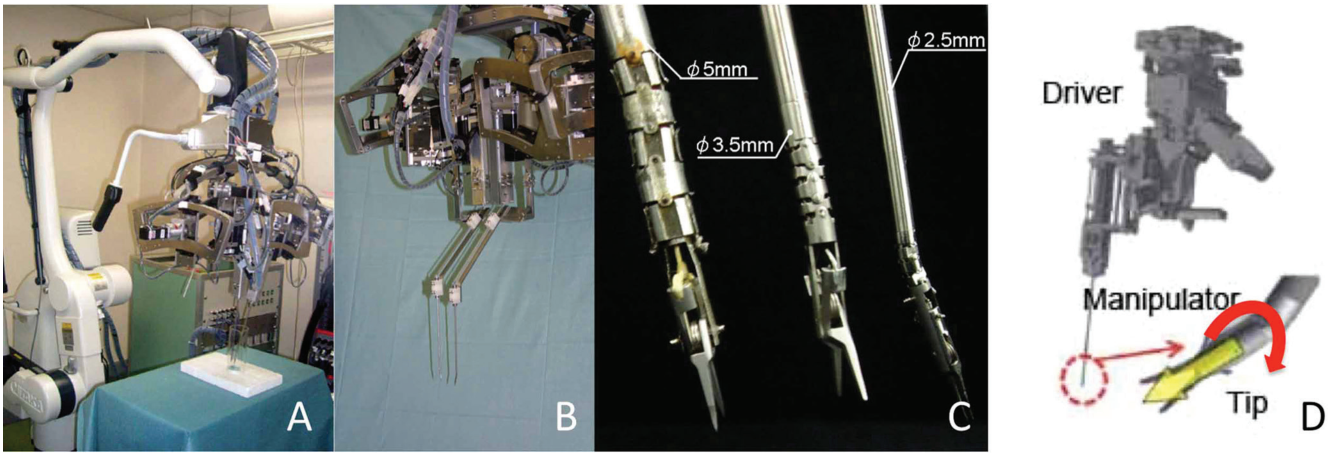

Fig. 4 Modification of deep surgical system manipulators. A: Micromanipulator MM-1. Two 5-mm manipulators with tip flexion mechanisms were fixed to the arm portion that hangs over the base. B: Micromanipulator MM-2. The manipulator shaft is shaped as a bayonet so as not to obscure the line of sight of the microscope. C: Shafts were thinned gradually, but mechanical fragility became a problem. D: A multi degree of freedom (DOF) manipulator is being developed.

the manual procedure, the accuracy in placing the needle was superior with the robot.

4. Cadaveric simulation of intracranial surgery (Fig. 3F, G): To mimic real surgical procedures, cadaveric experiments were done with the robotic system. After the craniotomy was carried out through a routine manual procedure, the robotic system was used to dissect the sylvian fissure and suture a torn anterior choroidal artery. The posterior fossa approach was also simulated and microvascular decompression of the facial nerve was mimicked. All procedures could be done with steady movements of the robotic manipulators. But our robotic manipulator was too thick in diameter and we sought a thinner manipulator for the posterior fossa surgeries. After thinning the manipulator shaft to 3.5 mm, we repeated the simulations. We could perform endoscopic endonasal pituitary surgery using two robotic arms through both nostrils. With the 70-degree scope, hand-eye coordination is good with robotic control because we can reset the viewing angle and hand motion in the same direction.

5. Scaling down the manipulator and adding a crank system (bayonet) (Fig. 4): Our system was scaled down first to a 3.5 mm diameter, then to 2.5 mm (MM-2). While the manipulator became thinner, mechanical fragility became a problem. To address this problem, we created a crank (bayonet) type robotic manipulator and found this design prevented conflict between the robotic mechanics and the visual equipment, and flexion and forceps mechanisms could be applied to the tip of the manipulator. This redesigned system, however, was too fragile to perform anastomosis and animal experiments. We also needed rotation at the tip of the bayonet manipulator to perform delicate procedures at a depth. This manipulator body could not be rotated, like the previous single-shaft manipulators, to change the angle of the forceps.

We are now working on another deep surgical system with 7 degrees of freedom, including rotation and flexion at the tip, and which can be used in endoscopic procedures such as endonasal cranial base surgeries.[20]

Project 2. Developing a robotic manipulator system for super-fine procedures[10]

Simultaneous with the development of a deep surgical field robotic system, we are working on a robotic manipulator that is suited for super-fine surgical procedures, such as anastomosing vessels 0.3 mm in diameter, which can be done in a shallow surgical field. We created a two-arm robotic manipulator system with a degree of freedom of 6 (MM-3, Fig. 5). Mechanical vibrations were diminished by adjusting the encoder software. Tremors of the operators using the master controller can be neutralized, and the scale-of-motion magnification can be changed according to the surgeon's preference. This system can be used for anastomose artificial vessels 0.3 mm in diameter, and we are now conducting animal studies. We are also analyzing the effects of scaling motion reduction and regulation according to the defined surgical field, motion control with imaging tracking of manipulators, and automated surgical procedures.

Our tests show that super-fine procedures can be done with this robotic system. Software support for

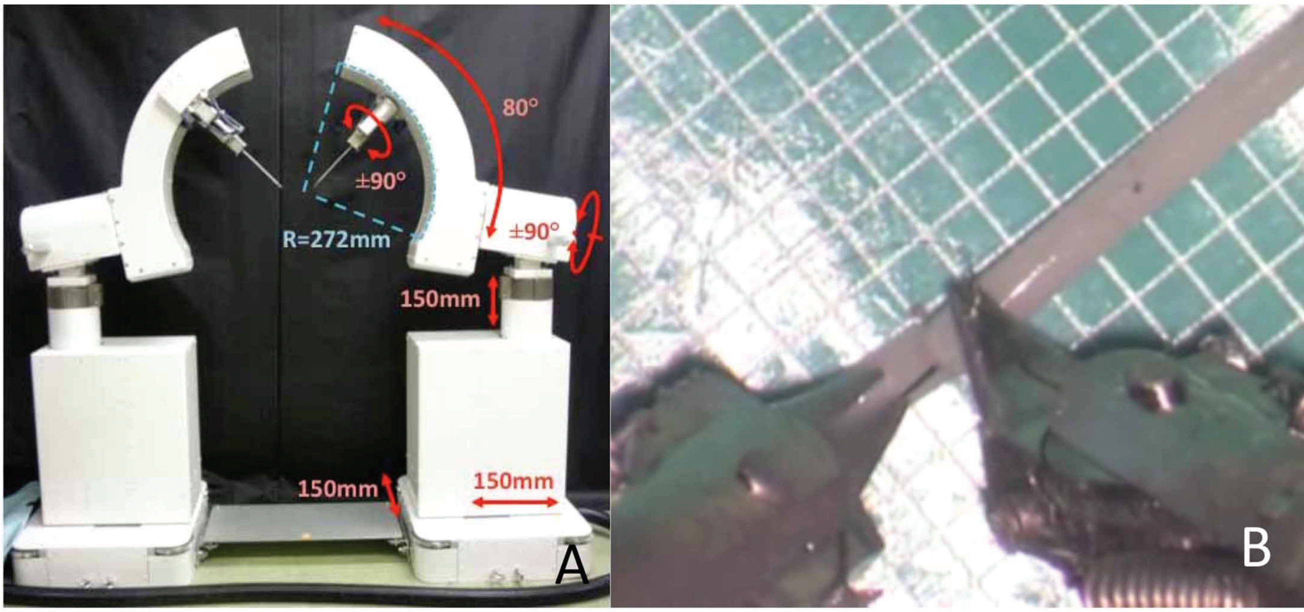

Fig. 5 Ultrafine microsurgical system. A: Micromanipulator system MM-3 consisted of a fixed bilateral arm box. The dimensions of the systems are as indicated. B: The tips of the manipulators were modified to accommodate microvessel suturing.

Fig. 6 Modification of the master manipulator. A: The first master was diverted from a laparoscope robotic system. With this system, we needed to move our arms to control microprocedures. B: The second master was created to control the robotic system mainly with hands and fingers. C: The third master was created by modifying a commercially available phantom system. This system is equipped with active-motion feedback, and we can evaluate the value of haptic feedback and other haptic experiments.

surgical safety and mechanical automation are being tested. As a result of these two robotic projects, we have developed master manipulators fit for microprocedures (Fig. 6).

II. Digital surgery projects

The digital surgery projects were conducted based on three concepts:

1. By using robotics and/or medical engineering technology, we can record all surgical procedures, including motion speed, range, acceleration, strength, and tremor and other accidental motion, and analyze skills and define surgical skillfulness.
2. With these techniques, we can record and archive procedures done by master surgeons and highlight the features that constitute mastery to allow trainees to experience the master surgeons' procedures in simulated surgical fields.
3. With such techniques, surgeons can be trained efficiently with digital data supports.

Project 1. Robotic data analysis (Fig. 7)

Data from robotic procedures are stored in 100-Hz signals in a log. Because the robot controls 7 motions at the same time in the right and left manipulators (distance of X, Y, X axis, α β γ angles and grip on/off)

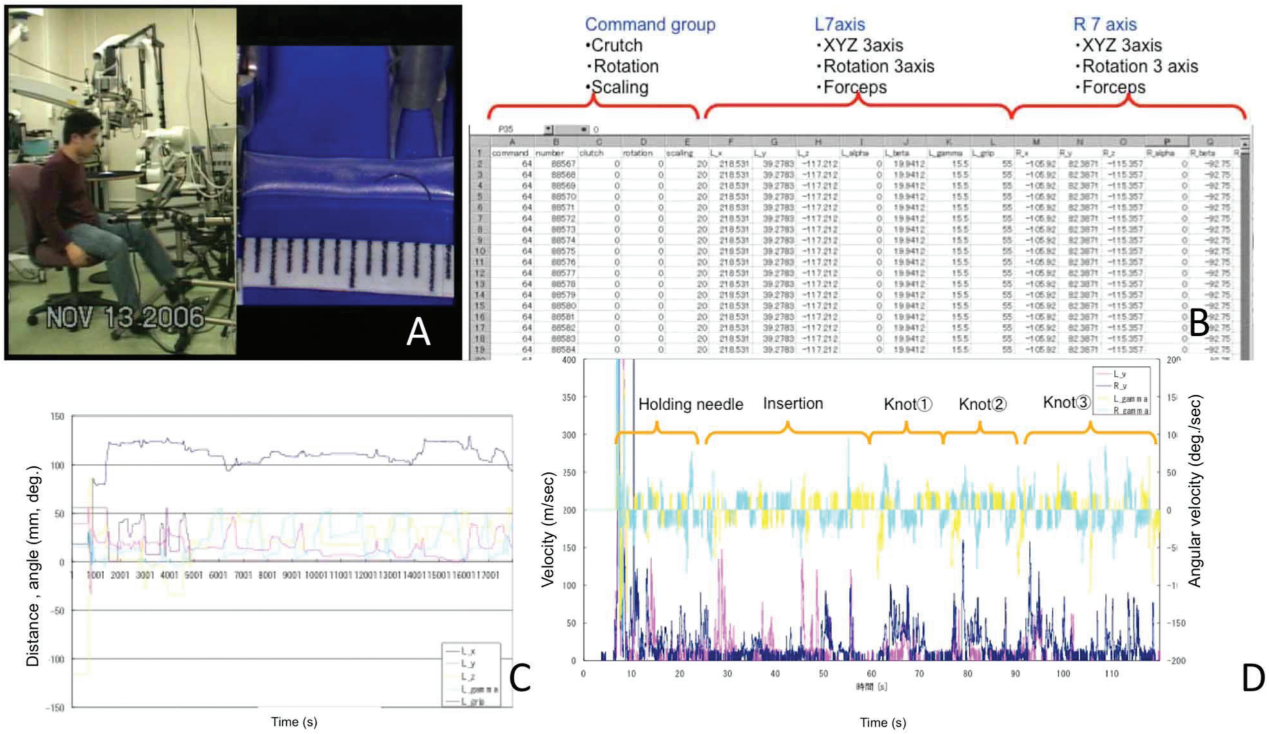

Fig. 7 Digitalization of robotic motions. A: With the type 2 master/slave and MM-2 manipulator, vessel anastomosis was performed and motion logs were stored. B: There are 17 items of data per hertz from the right and left manipulators, as well as three command prompts. 1700 signals were stored per second and more than 10,000 signals were stored per minute. C: Examples of the data from the left manipulator (distance, angle and grip) according to the phases of the procedures. D: Velocity and angular velocity according to the phases of the procedures. We could evaluate which procedures were done carefully (slowly) and analyze left and right coordination and efficacy.

and crutch, rotation, and scaling signals (total 17 signals per hertz), the motion log stored more than 100,000 signals per min. We could then analyze this log according to the phases of procedures (Fig. 7C). Rather than watching a motion on the video, we can see the digital data of motion and compare the right and left motion ranges, and analyze the trends in motion according to the phase of a procedure. Our next step is to compare motion logs between the expert robotic surgeons and novice robotic surgeons. By comparing trends, novice surgeons can see where they need to modify and improve by using quantitative and qualitative data.

Project 2: Strength measurement during free-hand microsurgical procedures (Fig. 8)

We recruited 7 neurosurgeons (3 experienced and 4 trainees) to anastomose artificial vessels (ϕ1 mm) under the microscope and measured the force they applied to the right and left tweezer tips. We analyzed trends in the strength of both hands and found that trainees use very strong force with the left hand and almost no rhythmical on-and-off force changes with this hand. Based on this data, we instructed the trainees to avoid forcing their left hand and use relaxed, rhythmical motion on the left. After practicing for 1 hour, most of the trainees showed a decrease in the force used in the left hand, while minimal changes were noted in experienced surgeons.

Project 3: Developing a skill assessment system (Fig. 9)[11)]

In addition to the strength-measuring method, we incorporated a 3D Polaris localizer and motion detector to the skill-analysis system. We asked 23 neurosurgeons to carry out anastomosis of artificial vessels (0.7 mm in diameter). Each surgeon's years of experience and surgical volume were registered. We recorded each surgeon's procedure on video and collected data, including time requirement, range of motion, motion path length, degree of tremor, and forces at the tip of the forceps. All video footage was reviewed blindly by three expert surgeons, and a clinical visual score of surgical skills was assigned according to the four main components of

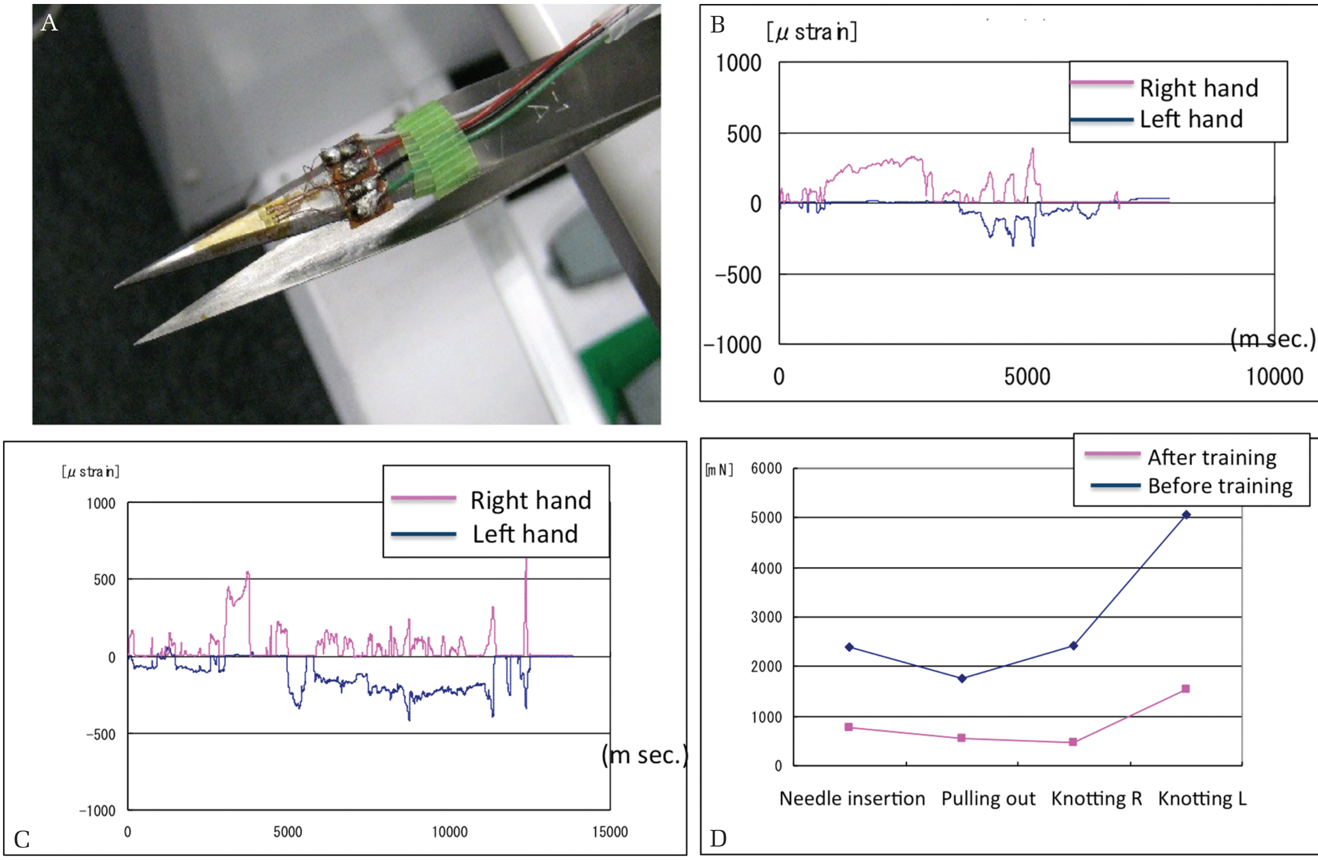

Fig. 8 Strength measurement and training. A: Strain gauges were attached to the forceps, and strength at the tip of the forceps was measured during manual vessel anastomosis. B: Experienced surgeons can move both hands rhythmically and with equal strength to tie knots. C: Young surgeons lacked rhythmic movement and forced the left hand continuously during procedures. D: After being notified of problems during the procedure according to digital data, with 1 hour of training, young surgeons reduced the left hand strength significantly. Rapid improvement was noted within a short period.

performance: the handling of needles, the handling of sutures, the methods used to tie knots, and the appearance of the sutured vessel. These scores were used to classify surgeons as skilled or unskilled. Then, the anastomosis procedure was divided into 5 steps (3 needle-placement steps including insertion, pushing, and extraction of the needle, suture handling, and knot tying) and data were allocated to each step. The difference between skilled and unskilled surgeons was associated with recent surgical volume rather than years of experience. Engineered scores, including performance time, range of motion, path length, degree of tremor, and force during each procedure, were compared between skilled and unskilled surgeons. Performance time, trajectory length, range of motion, and strength when pulling the needle from the vessel were significantly less among skilled surgeons.

This project showed that the engineered measurement of surgical procedures correlated well with traditionally evaluated the surgical skill and can be used to mathematically define the surgical skills. While we have not evaluated skill improvement after training by using such a data resource, we believe a surgical rehearsal and training system can be developed and should enhance technical training in the near future.

III. Future perspectives

Our goal of these robotic projects is to create and establish robotic microsurgery that enables surgeons to perform very delicate or difficult tasks more safely and securely. Although we are currently developing robots to play the surgeon's role, they can be reassigned as assistant robots or carry out other roles, such as a scrub nurse helping with surgical equipment. With robotic surgery, all tasks and information can be stored, replayed, and easily analyzed and related to outcomes. Robotics should advance surgical science.

Our next goal with the robotic system was to automate simple or routine tasks. We tested the feasibility of

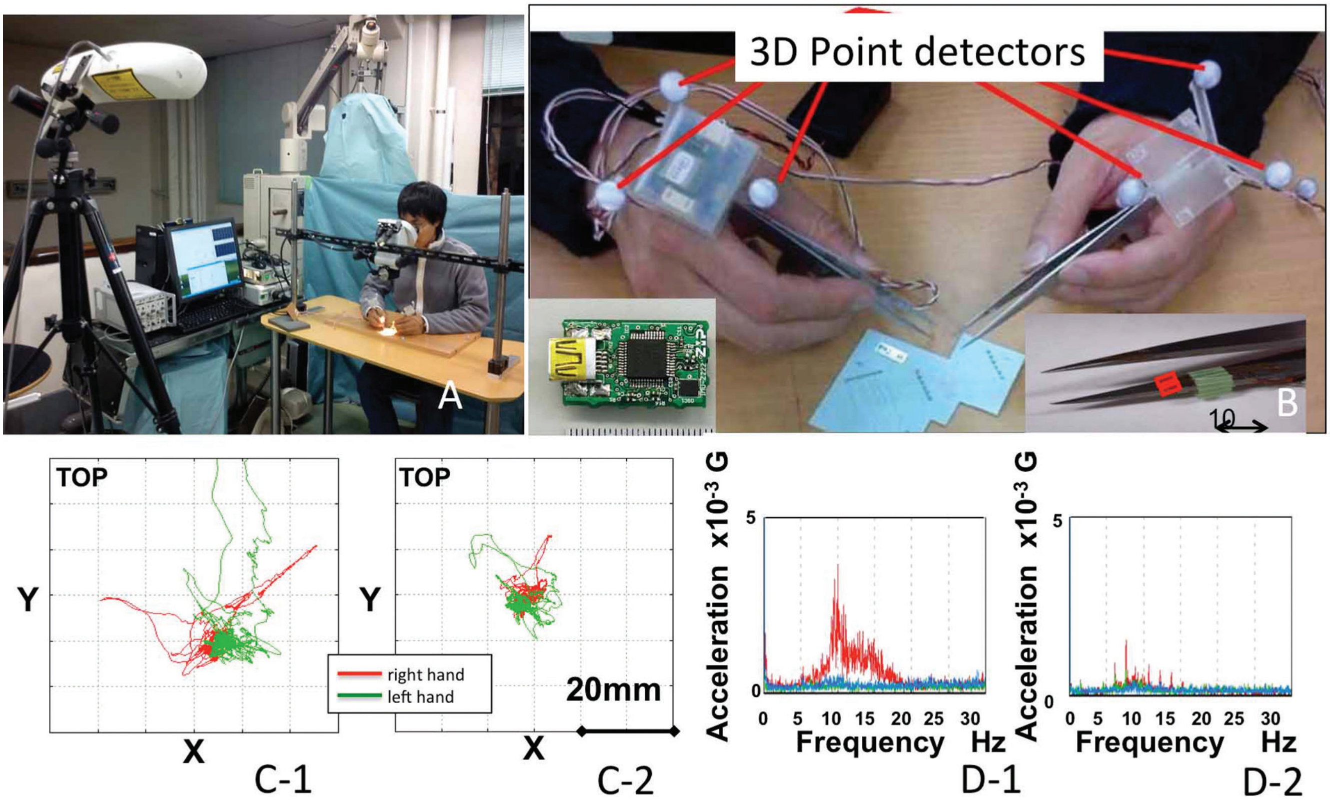

Fig. 9 Skill assessment system. A: The system included a Polaris 3D infrared location detector. B: In addition to the 3D point detectors for Polaris, motion detectors (right lower inset) and strain gauge (left lower inset) were attached to the bilateral tweezers. C: Trajectory of the forceps during 1 stich of anastomosis viewed from the top. *Red line*: Right hand trajectory, *Green line* : Left hand trajectory. Compared to unskilled surgeons (C-1), the movements of skilled surgeons (C-2) were confined within a narrower space. The tract length was also shorter. D: shows the amplitude spectrum of the right-hand acceleration calculated by a fast Fourier transform (FFT). In unskilled surgeons (D-1), tremors were higher than in experienced surgeons (D-2).

automation with our MM-3 system. The automation begins with teaching the robot how to move, either according to a signal order on the computer or by averaging our own trials. We can repeat the robotic motion a specific number of times, after which the robot's computer can divide the procedure into several sequences, average them, and pick the best route to move the system. Furthermore, the robotic system can move automatically over the calculated best route. This can be done smoothly and the procedure time can be shortened according to the maximum speed of the robotic system. Such automated motion can be overridden by human hands to deviate from the calculated track to the desired one according to the real surgical situation. We have not tried to move the manipulator automatically under the guidance of a navigation-system or sensor guidance, but this should be feasible. We now see the possibility of incorporating automation into some part of a robotic surgical procedure, which can be done safely with maintained human control.

The application of similar technologies in other surgical specialties, such as ophthalmology and pediatric surgery, which require very delicate procedures, has been tried and research is ongoing.[21] Plastic and orthopedic surgical teams are collaborating with our projects.

Discussion

With the advancement of noninvasive surgical techniques to treat simple pathologies that were once treated through open surgery, future surgeons face complicated pathologies without enough surgical training. To fill the gap between less surgical experience and pathologies requiring talented surgical skills, robotic surgical systems and engineered training systems should be strong additions. We have developed a deep working microsurgical robotic system to fulfill part of this goal. During this development, we realized the various differences between medicine and engineering. To apply engineering technology to medicine, especially to surgery, we need to define the procedures and tasks in mathematical and mechanical terms. Through this translation, we now understand that combining medicine and engineering enhances the scientific aspect of medicine, which used to be traditionally dependent on experience-based and observation-based practice. Additionally, in developing the future medical field and advancing medicine, such translation of medical terms and tasks into engineering terms and dimensions should be very useful. For example, we should be able to incorporate engineering methods in diagnosis and nonsurgical treatments.[22] Doctors need to sharpen their five senses to analyze a patient's physical status and pathology, and we should now be able to measure the consistency and elasticity of a mass, skin, or other tissues. We should be able to develop automatic tactile sensory machines to determine physical conditions.

In the field of radiology, automatic methods for detecting aneurysms are being tested to highlight aneurysms on magnetic resonance imaging. Aneurysms have various anatomical features and a computer could eventually find such areas automatically.[23] In another example regarding daughter sacs, we actually do not have an exact definition of this term and we should translate it to mathematical terms such as a non-sphericity index or an acute change in the round configuration. For cancer, we should be able to detect extra structures in a specific subject's image by comparing them with average human image data. Similar techniques have been used to calculate the Z-score in the VSRAD method to detect atrophy of the hippocampus.[24] Of course, a computer-based internal search robot in a patient's electronic medical record could detect a non-approved mixture or dose of medicine, early abnormal trends in vital signs or laboratory data and, eventually, an automatic diagnosis and treatment recommendation system can be developed. Hence, engineering can be applied to any field of medicine with the translation of medical conditions to measurable and mathematical terms.

Robotic surgery has several important features, as shown in the basic concepts. These differences can be enhanced into new surgical dimensions. Telesurgery is one example. Trans-Atlantic and transcontinental laparoscopic robotic surgery has been done with the Da Vinci system.[18] Such technology may not be needed in an area where surgeons are readily available. But, for example, on the moon, on the space station, or in specific areas where surgeons are not available, such telesurgical measures can be of good value. Attempts at telesurgery show that a signal-conduction delay can be managed to carry out simple and standard surgical procedures, such as cholecystectomy, as long as the signal delay is within a few milliseconds. However, whether this same concept can be applied to neurosurgical procedures and emergency medicine, which often require prompt and appropriate responses to unexpected events, remains to be seen.

Another important feature is consistency in the quality of the procedure. In the field of surgical science, it is difficult to conduct randomized controlled trials to establish the best medical practice because it is difficult to standardize surgical outcomes and define surgical quality. By incorporating robotic surgery into such studies, technical standards can be established relatively easily. So, evidence-based surgical practice can be applied in some complicated pathologies.[25]

In the field of neurosurgery and skull-base surgery, several robotic systems were tested on the basis of experimental or clinical settings. Some researchers developed new robotic systems including the NeuroArm and NeuRobot, both of which were tried in experiments and human subjects,[19,26] but their use did not spread to other institutions because of economic burdens and the difficulty in applying universal surgical indications. Other teams have tried to apply the widely available Da Vinci system to cranial and cranial-base surgeries.[27] While this system has potential, its clinical use is described in only one case report because the tools are too thick for cranial surgery and the angle of the arm is too wide to use in narrow surgical fields. To overcome such problems, we need to develop appropriately sized robotic systems that can be moved in specified cranial and cranial-base surgical fields with reasonable cost.

This article summarizes our academic projects in developing microsurgical robotic systems, and other projects that apply engineering science to medicine are described. In the collaboration between medicine and engineering, we have noticed imperatives in creating real cooperation: 1) the need to understand each other's language and nuances with frequent face-to-face meetings, site visits, and frank conversation, and 2) the need to avoid a one-sided order to create a new system. In our collaboration, we have met once a month for the past 15 years. Each student and doctor visited each other's sites, such as surgical suites and machinery rooms, to create robotic parts. Knowing how the surgeries are performed is extremely important for engineers and their students to understand why some procedures are difficult to accomplish with human hands and to recognize that the brain is soft. If a medical or engineering team created a robotic system from the perspective of only one side, without seeing the process, the final product would be of no use. Frequent modification is necessary to produce usable systems, and frank discussion is extremely important in understanding each other's concept to create real collaboration.

We have many issues to resolve before using our systems in human trials, but some of them should be easily solved through collaboration with industrial robotic makers. While there are many top-rated robotic manufacturing companies in Japan, we could not obtain any meaningful contributions from these companies. This is partially because of these companies' hesitation to be involved with machines that directly influence human life and daily activities, and partially because of the difficulty in agreeing on contracts, licenses, or patents on inventions between the academic and commercial teams. But such problems are minimal compared to the development of new medical technologies to help even one single patient.

"One man's life is heavier than earth." This motto should be prominent and of the highest value in creating real collaboration between academia and industry.

Conclusion

This article summarizes the current trends and our work in developing a microsurgery robotic system and applying engineering technology to surgical training and skill assessment. While some technical challenges still exist, robotic systems are feasible and can be very accurate in performing difficult tasks. In addition, with engineering technology, surgical skill can be mathematically assessed and scientifically analyzed, facilitating surgical training.

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Disclosure

Authors have no conflict of interest to be disclosed.

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