Int J CARS (2012) 7:27–34
DOI 10.1007/s11548-011-0602-4

REVIEW ARTICLE

Microsurgical robotic system for vitreoretinal surgery

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Received: 9 January 2011 / Accepted: 29 April 2011 / Published online: 15 May 2011

Abstract
Purpose Robotics may improve vitreoretinal surgery by steadying hand motion, thereby reducing negative outcomes. This study aimed to develop a microsurgical robot for vitreoretinal surgery and to perform clinical procedures using robot-assisted interventions.
Methods A microsurgical system for vitreoretinal surgery was designed to meet specific requirements for the degree of freedom, accuracy, and workspace. The system was intended to provide micrometer accurate manipulation within the eye. The slave manipulator has a tool change mechanism for switching surgical instruments. The slave manipulator is controlled by the surgeon using a master manipulator consisting of multiple joints.
Results The robotic system was used to carry out microcannulation experiments on a pig's eye. A surgeon was able to successfully perform microcannulation.
Conclusions This microsurgical robotic vitreoretinal surgical system showed superior operability compared with a traditional manual procedure, and it demonstrated sufficient potential to warrant further testing in animal trials to assess its clinical feasibility.

Keywords Surgical robot · Microsurgical system · Vitreoretinal surgery · Master–slave system

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Introduction

Microsurgery is challenging because surgeons have to manipulate small instruments with high accuracy and precision in a limited workspace. Microsurgeries are now increasingly being performed thanks to the recent development of advanced diagnostic and interventional technologies available for microsurgery. Vitreoretinal surgery is an ophthalmological treatment where surgeons work on very small and delicate tissues such as the macula or retinal veins. Achieving high accuracy and precision in this surgery is very difficult because of the poor maneuverability of surgical instruments, surgeons' hand tremors, and limited visual information; well-trained surgeons are therefore required in order to obtain better clinical outcomes.

In conventional vitreoretinal surgery, surgeons create two insertion ports in the eye to insert trocars, as shown in Fig. 1a. Surgical instruments are inserted through the trocars to reach the target area on the eyeground. Then, the vitreum is replaced with a substitutable liquid using a vitreum cutter. Next, a light guide is inserted through the trocar, and an interventional tool (e.g., forceps or needles) is inserted through the other trocar. Thereafter, the affected area of the retinal membrane is peeled off, or a drug is released into a retinal vein. In this surgery, surgeons face three problems: difficulty in force and position control of the instruments, limited information from microscopic vision, and hand tremors.

The surgeon has to position the inserted surgical instruments very carefully so as not to apply force at the insertion points where the trocars are fixed; otherwise, soft tissues around the insertion points may be traumatized. This problem is equivalent to the remote center of motion (RCM) problem often mentioned in robotic surgery. The second problem is that the surgeon may have difficulty judging distance between the tool tips and targeted tissue with microscopic

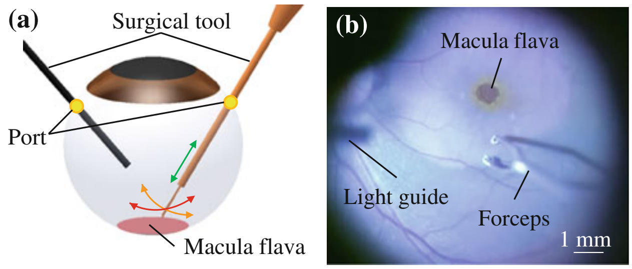

Fig. 1 Vitreoretinal surgery: **a** vitreoretinal surgical setup, **b** microscopic view

vision (Fig. 1b). They usually manipulate the instruments using the shadow of the instruments for estimating distance, but it is still difficult, especially for novice surgeons. The third problem is that the required positioning accuracy in vitreoretinal surgery is approximately 10 µm [1], which is smaller than the average amplitude of hand tremors (approximately 100 µm [2]). Consequently, only skilled surgeons can manipulate the tools accurately and perform the surgery with good clinical outcomes.

Many computer-assisted systems have been developed to help with microsurgical procedures. Mitchell et al. have developed a steady-hand system [3–5]. This system is a handheld device where the surgeons and system share control of the instrument with force sensors. The force information at the tip of the instrument is used to provide smooth, tremor-free, and precise positional control and force scaling. Additionally, microcannulation of an 80-µm blood vessel was successfully demonstrated using chicken embryos. Iordachita et al. have developed a microforce sensor to detect small contact forces between instruments and tissues [6]. They integrated steady-hand systems and a microforce sensor to perform highly accurate and safe maneuvering of surgical instruments using sensor feedback [7,8]. Riviere et al. have developed the Micron system [9,10]. This handheld system is capable of detecting the movement of a surgeon's hand to distinguish between desired and undesired motions, and the system cancels the undesired motions using a piezo-actuator. They successfully reduced the amplitude of hand tremors from 91 to 60 µm peak–peak, and thus, highly accurate and stable positioning of the tool and reduced hand tremors have been achieved, although the skill of the surgeon influenced the positioning accuracy. Das et al. developed a master–slave system for telerobotic microsurgery [11–14] to improve dexterity of the manual operation. As a demonstration, particles of diameter 0.38 µm were removed from an eyeball phantom. This system used a wire-driven mechanism; this requires additional maintenance costs, and this may be a burden for clinical applications. Because the slave manipulator was not designed to have a RCM, it is not adequate for eye-surgical applications. The authors also developed a master–slave robotic system for vitreoretinal surgery using a parallel mechanism to obtain higher stability and accuracy of instrument positioning [15]. Using this system, the positioning accuracy was increased from 75 to 20 µm. The disadvantage of this system was that the workspace was narrow for various uses in ophthalmological surgery.

The goal of our study is to develop a new microsurgical system that enables surgeons to perform vitreoretinal surgery with high accuracy and precision. To achieve this goal, we have developed a microsurgical master–slave robotic system. This master–slave robotic system has been developed for versatile use in microsurgery, including ophthalmological, neurosurgical, and reconstructive surgical applications. Each slave unit of the robotic system has five degrees of freedom (DOFs) and can be equipped with an interchangeable manipulator. One of the several surgical-tool units, which are mounted with a commercial surgical instrument, is attached to the slave manipulator for the target operation. The DOFs of the interchangeable manipulator may vary from one to three, depending on the surgical instrument to be mounted, and thus, the total DOFs of the slave manipulator may vary from six to eight. In this paper, the detailed design of the developed robotic system and ex vivo experiments conducted to evaluate the performance of the system are described.

Material and methods

Robotic scheme for microsurgery

Surgical robots such as da Vinci (Intuitive Surgical Inc., Sunnyvale, USA) and Robodoc (Integrated Surgical System Inc., Fremont, USA) have already been commercialized to assist conventional minimally invasive surgeries. However, these robotic systems are not adequate for use in microsurgeries such as eye surgery, neurosurgery, and reconstructive surgery, and development of microsurgical robots is desired by surgeons. In microsurgery, the advantages of robots, including high accuracy and precision, can directly contribute to better clinical outcomes.

Possible robotic solutions for microsurgical applications would include handheld devices, cooperative control systems, and master–slave robotic systems. Handheld systems usually have smaller dimensions and are easy to use in clinical cases. Cooperative control systems may also have small dimensions and provide high precision using scaling down of the surgeon's hand motions. However, control based on the force information may become unstable and will require calibration to account for individual differences. On the other hand, the master–slave robotic configuration has many advantages in microsurgery. The master–slave configuration enables scaling down of the surgeon's hand motion. This capability, called motion scaling, is helpful in achieving high accuracy and precision, even when the operator is

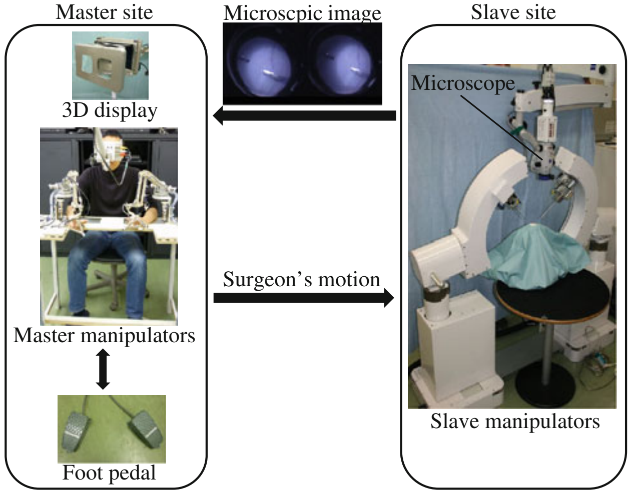

Fig. 2 System overview

a novice surgeon. The amplitude of hand tremors can also be scaled down, thanks to motion scaling, and thus, individual differences in physical capability have less impact on surgical outcomes. Additionally, the master–slave configuration solves the problem of hand–eye coordination in surgery using trocars, which is one of the difficulties in laparoscopic or vitreoretinal surgery. Therefore, we decided to employ a master–slave configuration and have been developing a master–slave robotic system for versatile use in microsurgery (Fig. 2). In our master–slave robotic system, a surgeon controls the slave units by operating the master manipulators while being provided with a 3D microscopic view from a high-definition display.

Master manipulators

The master manipulators of the master–slave robotic system have been reported in detail in our recent publication [16]. The master manipulators have high operability, and each of them has seven DOFs: three DOFs for translation, three DOFs for orientation, and one DOF for grasping. Because gimbals are used for the DOFs for orientation, the operator can control the master manipulator in translational directions without changing the posture of the hand. During an operation, the hand motion of the surgeon is measured by the master manipulators and scaled down and then transmitted to the slave manipulators to perform the operation in real-time. Data transmission is intermitted while the foot pedal is being depressed by the surgeon. The motion-scaling factor may vary according to the surgical procedure; in vitreoretinal surgery, a magnification ratio of 40× was chosen so that the scaled down amplitude of hand tremors is smaller than the required precision in vitreoretinal surgery. In summary, the master manipulator has many advantages and is suitable for microsurgery.

Slave manipulators

Functional requirements and environmental constraints

The microsurgical robotic system for vitreoretinal surgery needs to satisfy certain requirements with respect to DOFs, accuracy, workspace, RCM, sterilization, and compatibility with the surgical environment. The details are described in the following.

(1) Workspace: the required workspace for the robot to align the incision point with the tip of a surgical instrument is a cube measuring 100 mm on each side. The human eye is approximately 24 mm in diameter, and in vitreoretinal surgery, the distance between the incision points and the axis of the eye penetrating the pupil is approximately 9 mm. Thus, a rotational angle of 40° around the insertion point can provide a sufficient workspace (Fig. 3). The required angular range of the rotational DOF about the axis of the surgical tool is from −90° to 90°.
(2) Robotic DOFs: three translational DOFs are necessary to align the incision point with the tip of the instrument (Fig. 4a). Additionally, one DOF of translation is needed to insert the instrument into the eye through a trocar. During the operation, two rotational DOFs and one translational DOF are needed (Fig. 4b). Another DOF is necessary if the design of the surgical

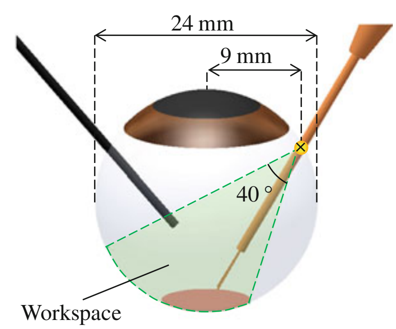

Fig. 3 Workspace

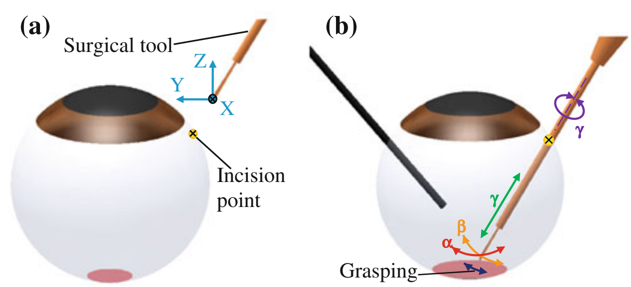

Fig. 4 Required DOFs: **a** positioning to the incision point, **b** positioning in the eye

instrument is not symmetric about the axis; for instance, a rotational DOF is required for forceps, but not for a light guide. Another DOF is also required for grasping the forceps.

(3) Accuracy: in vitreoretinal surgery, target tissues are retinal membranes or neovascular vessels in the retina. The diameter of the targeted retinal vessels is approximately 50–150 µm, and the thickness of the retinal membrane is several micrometers. Thus, the required positioning accuracy of an instrument tip in vitreoretinal surgery is approximately 10 µm [1], and to meet the required positioning accuracy, the required resolution of the tip positioning of the instrument is 5 µm.

(4) RCM: for robotic vitreoretinal surgery, the incision points should precisely coincide with the robotic RCMs so as not to damage the tissues nearby. It is possible to fix the RCM by software, but this can reduce accuracy and safety because of extra actuators being activated to maintain RCM, resulting calculation errors. On the other hand, a mechanical RCM can be achieved with a minimum number of actuators and thus be less influenced by calculation errors. Thus, a robot with mechanical RCM can be safer and more accurate than one with RCM defined by software.

(5) Sterilization: surgical instruments to be inserted in the eye must be sterilized. Therefore, a commercial surgical tool (i.e., forceps, a light guide, or a vitreous cutter) needs to be easily disassembled from the unsterilized robotic part of the surgical-tool unit. Additionally, a sterilizable piece needs to be placed between the commercial surgical tool and the unsterilized robotic part.

(6) Compatibility with surgical environment: the surgical robotic system must not interfere with the surgical environment. In eye surgery, a microscope is positioned and fixed above the eye, and the robotic parameters need to be controlled considering this obstacle in the workspace. Additionally, in robotic surgery, time to interchange surgical tools must be short, ideally within 1–2 min. Since the operation time in vitreoretinal surgery is about 30 min and the surgical instruments need to be interchanged three to four times, a robotic design to enable easy tool change is needed.

Design and development

The slave units are shown in Fig. 5a. Each slave unit measures $390 \times 408 \times 1{,}058.5$ mm and has five DOFs. The motion range of each axis is summarized in Table 1. In the proposed surgery, the tip of the interchangeable manipulator, whose details are described below, is positioned at an insertion point using the three DOF translations (X, Y and Z axes in the figure). These DOFs are not activated once the position is fixed.

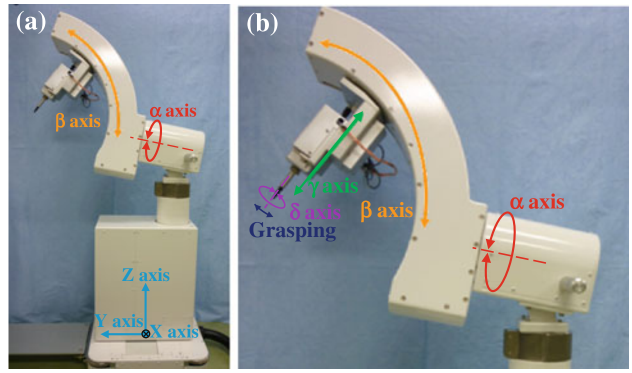

Fig. 5 Slave manipulator: **a** DOFs of the slave unit, **b** DOFs activated during the manipulation in the eye

Table 1 Specification of the surgical unit

Axis	X, Y, and Z axis	α axis	β axis
Motion range	−75 to 75 mm	−90 to 90 deg	0–80 deg
Unit of motion	0.1 µm	0.00045 deg	0.0009 deg
Max. motion speed	353 mm/s	162 deg/s	12.9 deg/s

The two rotational DOFs (α and β axes in the figure) are being activated during the operation to control the posture of the surgical tool while keeping the RCM at the intersection of these two axes (Fig. 5b). The interchangeable manipulator can be easily assembled to the slave unit, as shown in Fig. 6a. The interchangeable unit is composed of a translational stage (Fig. 6b) and a surgical-tool unit (Fig. 6c). The designs of the interchangeable manipulator, translational stage, and surgical-tool units are shown in Fig. 6d.

A translational stage was developed (Fig. 7), and it has one translational DOF (γ axis). To satisfy the required workspace, the translational stage was designed to travel 65 mm, and the maximum translational displacement in the eye was designed to be 35 mm, considering that the diameter of the human eye is approximately 24 mm. The unit of translational motion is 2.2 µm, and this motion was achieved using a DC motor (RE16+MENC13+GP16A, Maxon Motor Co., Ltd., Tokyo, Japan) and a ball screw (MTF0601-3.7+110LT, THK Co., Ltd, Tokyo, Japan) transmitted by a belt drive. The translational stage can be easily assembled with one of the surgical-tool units using two screws, allowing easy and quick changing of the surgical-tool unit during operations. The specifications of the translational stage are summarized in Table 2. Three surgical-tool units were designed as shown in Fig. 8a, and one of the units is mounted on the translational stage, based on the required operational task.

Each surgical-tool unit is equipped with a commercial surgical instrument (i.e., forceps, a light guide, and a vitreum cutter). A rotational DOF (δ axis) was implemented for tools whose design is asymmetric about their long axis,

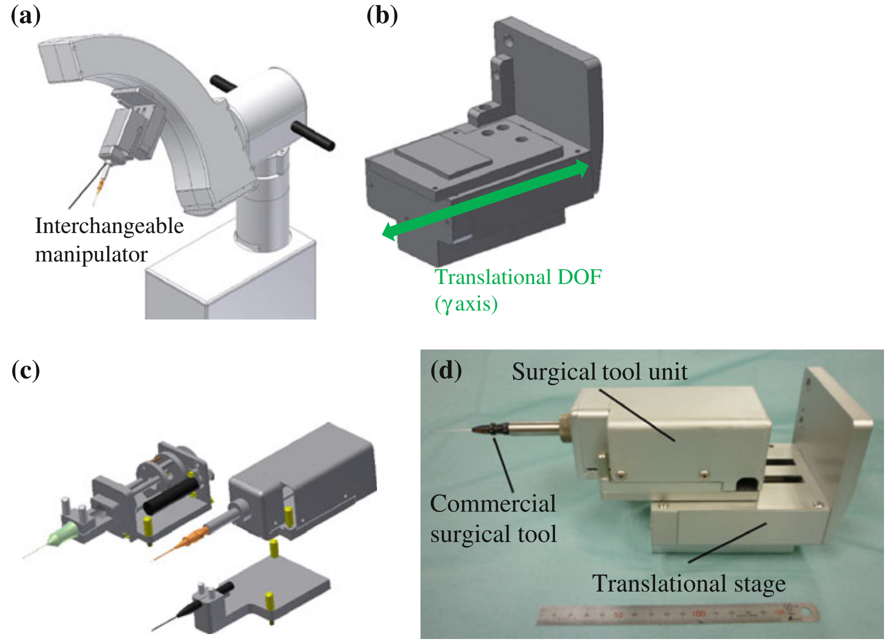

Fig. 6 Interchangeable manipulator: **a** assembly of the interchangeable manipulator to the slave unit, **b** translational stage, **c** surgical-tool units, **d** photo of the interchangeable manipulator

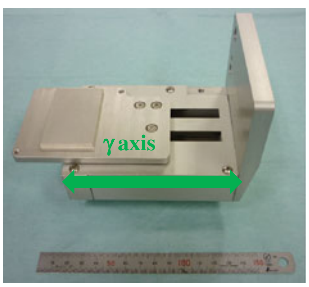

Fig. 7 Translational stage

Table 3 Specification of the surgical-tool unit for a light guide

Specification	Unit	Value
Height	mm	34
Width	mm	69
Length	mm	119
Length with the light guide	mm	186

Table 2 Specification of the translational stage

Specification	Unit	Value
Height	mm	112.5
Width	mm	97
Length	mm	124
Stroke	mm	0–65
Unit of motion	μm	2.2
Max. translation speed	mm/s	28

and an additional DOF for grasping was implemented for the forceps. Additionally, each of the surgical-tool units was designed to have a sterilizable piece between the surgical instrument and the unsterilized surgical-tool unit.

The surgical-tool unit for a light guide (8065751165, ALCON JAPAN Ltd., Tokyo, Japan) is shown in Fig. 8b. The specifications are summarized in Table 3. The surgical-tool unit for a vitreous cutter (8065751122, ALCON JAPAN Ltd., Tokyo, Japan) has one DOF for rotation around the axis of the instrument, achieved by a DC motor (RE13+MENC13+GP13A, Maxon Motor Co., Ltd., Tokyo, Japan) transmitted by a belt drive (Fig. 8c). The unit of rotation is 0.026°, and the motion range is from −180° to 180°. The vitreum cutter is used to cut and remove the vitreum. The specifications are summarized in Table 4. The surgical-tool unit for grasping forceps (a forceps attachment; 704.44, ALCON JAPAN Ltd., Tokyo, Japan) has two DOFs for rotation about the instrument axis (δ axis) and grasping (Fig. 8d). The rotation mechanism is the same with the surgical-tool unit for the vitreum cutter. The closing angle of the forceps' tip can be controlled by gradually pushing part of the forceps attachment by a thin shaft of diameter 2 mm mounted on a ball screw (MSSRK601-41-F4-R4-T4-Q4-S8-E3, MISUMI Co., Ltd, Tokyo, Japan) driven with a DC motor (RE10+MENC10+GP10A, Maxon Motor Co., Ltd., Tokyo, Japan). The grasping forceps are used to remove an affected area of the retinal membrane. The specifications of this unit are summarized in Table 5. A micro-injector (IM-9B, NARISHIGE Co., Ltd., Tokyo, Japan) was mounted on the surgical unit for the vitreous cutter using a specially designed adapter. A micropipette can be attached to the micro-injector to release a drug into a retinal vessel to resolve a clot.

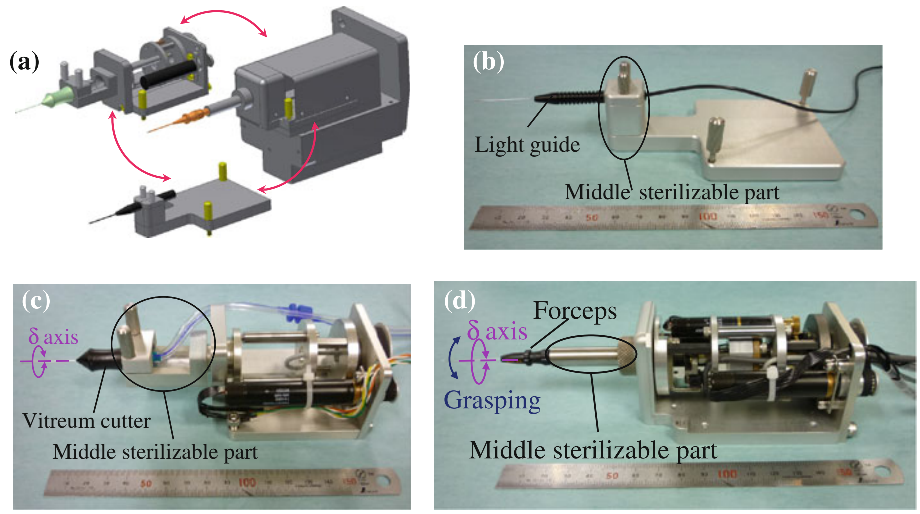

Fig. 8 Interchangeable manipulator: **a** assembly of a surgical-tool unit to the translational stage, **b** surgical-tool unit for a light guide, **c** surgical-tool unit for a vitreum cutter, **d** surgical-tool unit for forceps

Table 4 Specification of the surgical-tool unit for a vitreum cutter

Specification	Unit	Value
Height	mm	48
Width	mm	69
Length	mm	138
Length with vitreum cutter	mm	199
Angle	deg	−180 to 180
Unit of motion	deg	0.026
Max. rotation speed	deg/s	2280

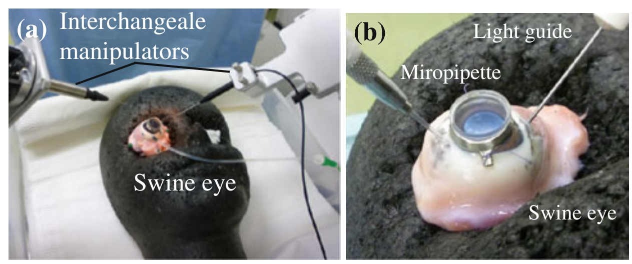

Fig. 9 Ex vivo experiment: **a** experimental setup, **b** insertion of surgical tools into the eye

Table 5 Specification of the surgical-tool unit for forceps

Specification	Unit	Value
Height	mm	48
Width	mm	59
Length	mm	171.5
Length with forceps	mm	221
Rotational angle	deg	−180 to 180
Unit of rotation	deg	0.026
Max. rotation speed	deg/s	2280
Range of grasping angle	deg	0–20
Unit of grasping angle	deg	2

Results

An ex vivo experiment was carried out to evaluate the feasibility of our system using a swine eye (Fig. 9). The size of the swine eye is similar to that of the human eye and is approximately 24 mm in diameter. The eyeball was removed 12 h prior to the experiment and kept at 4°C. In the experiment, microcannulation was performed, and the master manipulators were operated by a surgeon with 10 years of clinical experience.

Retinal vessel microcannulation is one of the most difficult procedures in vitreoretinal surgery and is hoped to become a new treatment method for central retinal vein occlusions [17,18]. The difficulty in this procedure is that the surgeon has to insert a micropipette tip of diameter 20–50 µm into a vessel of diameter 50–150 µm and then maintain the position for 1–2 min until the drug release is completed. Some complications associated with the procedure have been reported [19], and this is probably because high skill is required to perform such a difficult task [20]. We hope that our robotic system will be helpful in enhancing the accuracy and precision of tool maneuvering, leading to better clinical outcomes.

A commercial micropipette made of glass (GD-1, NARISHIGE Co., Ltd., Tokyo, Japan) was modified using a puller (PC-10, NARISHIGE Co., Ltd., Tokyo, Japan) and a microgrinder (EG-400, NARISHIGE Co., Ltd., Tokyo, Japan) to bend the tip because ideally the tip should be inserted horizontally to the vessel. The outer diameter of the micropipette was approximately 30 µm, and the inner diameter was approximately 20 µm. The tip of the micropipette was bent by 30° at a distance of 1 mm from the tip. The micropipette was then attached to the micro-injector mounted on the surgical-tool unit. The pig's eye was fixed to a table with pins, and a trocar was not used for the micropipette.

After the tips of the interchangeable manipulators were positioned at the insertion points using the three DOFs of the slave unit, two surgical tools (the light guide and the

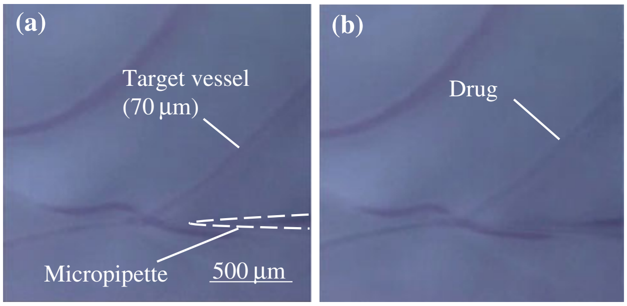

Fig. 10 Result of microcannulation: **a** insertion of the tip, **b** drug being injected and replacing the blood

micropipette) mounted on the surgical-tool unit were inserted using the one DOF of the translational stage. This positioning was conducted by an engineer receiving instructions from the surgeon who was observing the relative positions of the tip to the eye.

Next, the surgeon operated the master manipulators to move the two rotational DOFs of the slave unit and one DOF of the translational unit in order to perform microcannulation to vessels located at the eyeground. The surgeon successfully performed microcannulation three times (Fig. 10). The outer diameters of the blood vessels were 70, 90 and 110 µm. In manual microcannulation, maintaining the position of a micropipette during drug delivery is difficult because of hand tremors, but this was not a problem during robotic surgery. In the experiment, the surgeon deactivated all DOFs of the robot by depressing the foot pedal as soon as the tip of the micropipette was successfully inserted into the blood vessel. In this way, even hand tremors that were sufficiently small for performing tool positioning thanks to the scale-down function were completely filtered during the drug-release procedure. Each microcannulation took about 5 min, and the drug release took about 1 min.

Discussion and conclusion

Setup time is one of the most important problems in robotic surgery as a shorter operational time is always preferable from the clinical viewpoint. In the experiment, it took 8–10 min for the initial positioning of the tips of the surgical tools at the insertion points of the swine eye. Considering that the average operational time is 1 h, it is preferable for the initial positioning time to be decreased to 1–2 min. As this procedure is not yet automated, we plan to place a camera to obtain a bird's-eye view so that the instruments are automatically positioned, possibly using visual servoing. During the micropipette positioning in the eye, small vibrations of the tip were observed. Although the vibrations were not big enough to affect the procedure, the causes should be investigated. Possible causes include errors in the control loop, inadequate filtering of the surgeon's hand motions, and inadequate motor-control parameters. By eliminating the unwanted vibrations, the accuracy of the tool positioning will be further enhanced. In the ex vivo experiment, an extracted eyeball was used, and thus, the eyeball had no blood flowing in its blood vessels. Therefore, in vivo experiments are necessary before applying the surgical robotic system in clinical cases. In conclusion, a microsurgery robotic system was developed for vitreoretinal surgery, and several robotic units were developed to equip eye-surgical instruments on the system. Microcannulation was performed in an ex vivo experiment, and a micropipette of diameter 30 µm was successfully inserted into retinal vessels of diameter 70, 90 and 110 µm, demonstrating good performance of the system.

Acknowledgments This work was partially supported by Grant-in-Aid for Scientific Research (S) 18106005, Japan Society for the Promotion of Science (JSPS). The authors thank Mr. Young Min Baek, Mr. Yasuhide Kozuka, Mr. Shinichi Tanaka, and Dr. Kanako Harada for fruitful discussions.

Conflict of interest None.

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