Soft-material Robot for Ophthalmologic Surgery

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In this paper, a single-degree-of-freedom robot for assisting ophthalmologic surgery is proposed. A soft linear actuator drives the robot, and a needle attached to the tip punctures the cornea. The soft actuator has low friction and generates less stick slip, and there is no backlash since it does not require reduction gears. It can be controlled more precisely than conventional robots using electric motors or pneumatic cylinders. We conducted a cornea penetration experiment and measured the changes in intraocular pressure during intraocular injection using the proposed device.

1. Introduction

Ophthalmologic surgery is one of the most difficult surgical procedures. It requires the precise positioning of forceps within about 100 μm, which is smaller than the vibration of a normal human hand. Only a limited number of surgeons are available, and patients must wait for a long time to undergo such a surgery.

Robotic surgery is a possible solution to problems encountered in ophthalmologic surgery. Robots generally have high precision up to 10 μm order. Surgical robots have filters to remove hand vibration. Da Vinci (Intuitive Surgical Inc.)[1] and Senhance (TransEnterix Inc.)[2] are the representative commercial robots for laparoscopic surgery.

Laparoscopic surgical robots have sufficient precision to conduct eye surgery. Culjat *et al.* carried out intraocular surgery using da Vinci.[3] The robots designed specifically for ophthalmic surgery have also been developed.[4–8] They are more compact than the robots for laparoscopy, and no interference between manipulators occurs in the narrow space around the eye.

Tadano *et al.* developed a laparoscopic surgical robot driven by pneumatic actuators,[9] as opposed to conventional surgical robots that are driven by electric motors. The robot is compact

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and lightweight, since pneumatic actuators output high forces without reduction gears. It is also possible to estimate external forces from the environment, such as those from suture threads and organs, utilizing the back drivability of pneumatic cylinders.

Actuator selection in designing a robot affects the positioning performance and the weight of the system. Positioning by electric motors is easy using high-ratio gears, although it tends to increase the cost for reducing the backlashes of gears. On the other hand, pneumatic cylinders have advantages in weight and cost. Pneumatic actuators, however, cause stick slip between the piston and the cylinder wall, making precise positioning difficult. Stick slip is reduced by using air-bearing cylinders, which increases the cost and decreases the energy efficiency.

A soft-material actuator is a possible alternative to conventional pneumatic actuators. It realizes both high precision and low cost while keeping the advantage of not requiring gears, which is a major advantage of pneumatic actuators. Conventional soft robots[10–14] have been utilized for human robot interactions and the handling of complex-shape objects, which require safe or robust interactions but not precision. On the other hand, elastic actuators are utilized in the field of precision engineering. Kawashima *et al.* developed a precision stage using bellows actuators,[15] realizing a 20 nm positioning error.

In this paper, we present a novel ophthalmologic surgery robot using a soft actuator. It is a single-degree-of-freedom injection device with a needle on its tip. The coil-reinforced-type linear soft actuator[16] drives the needle. We conducted an experiment of inserting the needle into a porcine cornea and measured the transition of the intraocular pressure during insertion.

The rest of the paper is organized as follows. In Sect. 2, we describe the mechanical structure and control system of the proposed surgical robot. Experimental results and discussion are shown in Sect. 3. In Sect. 4, we conclude the paper.

2. Materials and Methods

2.1 Mechanical structure of ophthalmologic surgery robot

Figure 1 shows the overall structure of the proposed ophthalmologic surgery robot. A needle for ophthalmologic injection is attached to the tip of the linear soft actuator. The soft actuator
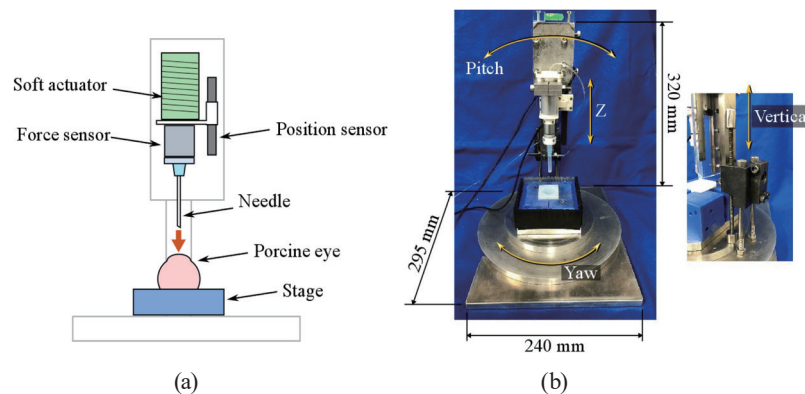

Fig. 1.   (Color online) Ophthalmologic injection robot. (a) Schematic drawing. (b) Prototype.

shown in Fig. 2 inside an aluminum pipe generates linear motion. It has a coil-reinforced structure, with the main body made of cylindrical silicone rubber (Smooth-sil 960, Smooth-on Inc.) and the stainless-steel coil (L066, Accurate Inc.) covering the rubber. The coil constrains the radial expansion of the rubber. The inner and outer diameters of the silicone cylinder are 16 and 18 mm, respectively, and the length of the cylinder is 35 mm. The wire diameter of the coil is 1 mm. The soft actuator weighs 22 g, while a pneumatic cylinder with the same inner diameter weighs 50 g. The characteristics of the silicone material are shown in Table 1.

The maximum output force of the actuator is 60 N when the supply pressure is 0.3 MPa, which is much larger than the required force of about 1 N. A smaller actuator is desirable for achieving a compact robot, although the current prototyping process using 3D-printed molds limits the minimum actuator size.

The soft actuator bends when external force or moment is applied radially. A linear guide (SSEB13, MISUMI) constrains the actuator motion to prevent the bending. The friction of the linear guide is ignorable compared with that of conventional pneumatic cylinders.

The intraocular pressure can be adjusted using a water tank and a precision regulator shown in Fig. 3. The linear-motion unit is mounted on the 4-degrees-of-freedom (DOF) base unit: yaw, vertical, pitch, and Z-axes. The base unit adjusts the location and orientation of the needle. These joints are passive and rotated manually.

2.2 Measurement and control system

Figure 4 shows a block diagram of the control system. The control system is a cascaded proportional-integral-differential (PID) control, in which an inner pressure control loop is included in an outer position control loop. The variables qz and qz_{ref}, and P and P_{ref} are the actuator displacements along the Z-axis in Fig. 1(b) and the air pressures in the actuator, respectively, where the subscript ref denotes the reference value. Control gains are defined in Table 2.

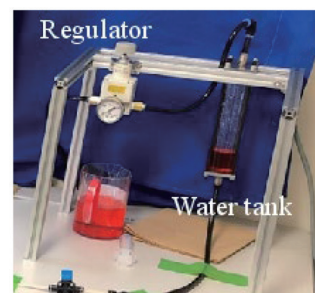Fig. 2.   (Color online) Soft actuator.

Fig. 3.   (Color online) Intraocular pressure adjusting unit.

Table 1
Characteristics of silicone rubber.[17]

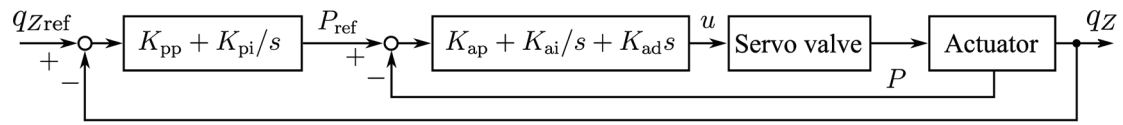|	
Shore hardness (A)	60
Specific gravity (g/cc)	1.25
Elongation at break (%)	270
Tensile strength (psi)	650

Fig. 4.　　Block diagram of position control.

Table 2
Control gains.

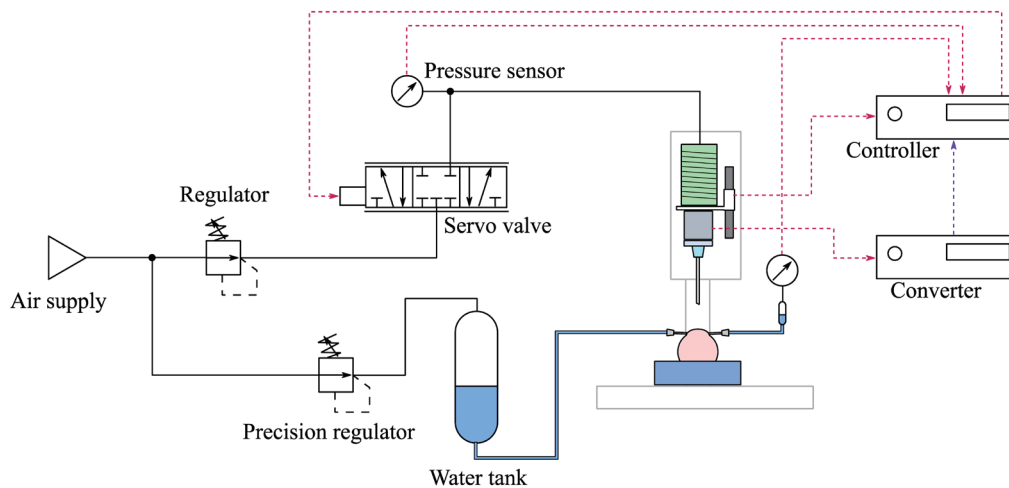| Proportional gain for position (kPa/mm)	K_{pp}	0.1
Integral gain for position (kPa·s/mm)	K_{pi}	100
Proportional gain for pressure (V/kPa)	K_{ap}	0.04
Integral gain for pressure (V/kPa·s)	K_{ai}	1.0
Differential gain for pressure (V·s/kPa)	K_{ad}	0.025

Fig. 5.　　(Color online) Control system setup.

Figure 5 shows the electric and pneumatic circuits. The pressure is controlled using a signal measured by a pressure sensor (PSE540, SMC Corp.) acquired via a 16-bit AD converter (AI-1616L, Contec Co., Ltd.). The position is controlled using a magnetic linear encoder (AS5311, ams AG) with a resolution of 2 μm, which is attached in combination with a magnetic scale (LMS-I1-L1000-W10-A10-K, Bogen Electric GmbH). The magnetic pole pitch of the scale is 1 mm. It is a noncontact encoder based on a hall sensor technology. The gap between the sensor chip and the scale is kept constant by the mechanism using the linear guide.

We also introduced a sensor to measure the intraocular pressure for monitoring. It is a precision pressure sensor (ZSE30AF-01-C-MG-X580, SMC Corp.) with the measurement range from −10 to +10 kPa. A force torque sensor (BL NANO, BL-Autotec Co., Ltd.) between the actuator and the needle measures the contact force. The actuator automatically reduces the velocity when the contact between the needle and the cornea is detected by the force torque sensor. The sampling time of the control loop is 1 ms. The control gains are shown in Table 2.

2.3 Experimental protocol

In this study, we measured the transition of the intraocular pressure during the insertion of a needle into a porcine cornea. A porcine eye is placed on the stage centered on the base unit as shown in Fig. 6. A transparent ring and anchor screws fix the eye. We inserted two cannulas: one for reflux and intraocular pressure adjustment, and the other for intraocular pressure measurement.

In the experiment, the motion of the robot is given as follows:

Step 1: Approach at V_1 mm/s until the needle touches the cornea.

Step 2: Change the needle velocity to V_2 ($<V_1$) and moves for L mm to penetrate the cornea.

Step 3: Stop for T s in the anterior chamber.

Step 4: Return to the initial position at V_3 mm/s.

In Step 1, the system detects the contact when the measurement of the force detected by the sensor exceeds a threshold of 0.1 N. The entire procedure is shown in Fig. 7, and the control parameters are shown in Table 3.

3. Results and Discussion

Figure 8 shows the experimental results. The upper, middle, and lower plots present the actuator displacement, the force measured by the force sensor, and the intraocular pressure, respectively. From this figure, the overall position tracking performance is good, even when it is driven by a soft actuator.
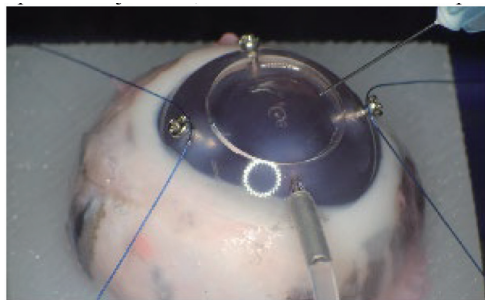
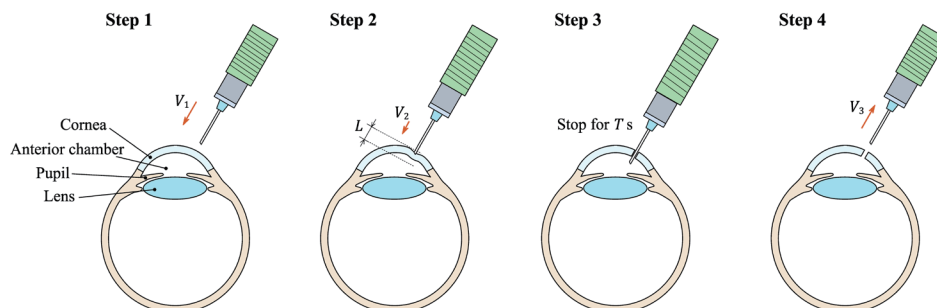Fig. 6.   (Color online) Experimental setup.

Fig. 7.   (Color online) Needle insertion procedure.

Table 3
Needle insertion parameters.

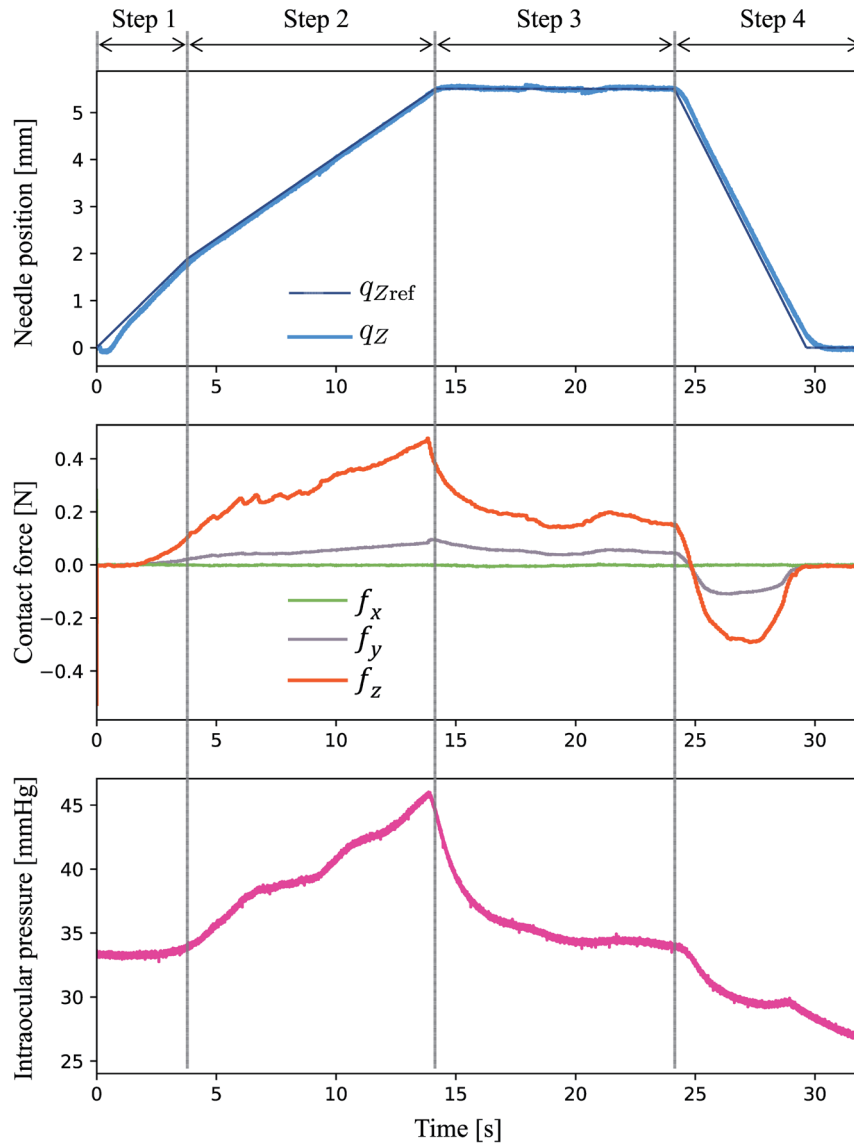|	
V_1 (mm/s)	2.0
V_2 (mm/s)	0.5
V_3 (mm/s)	1.0
L (mm)	3.0
T (s)	10.0

Fig. 8.   (Color online) Experimental results.

When the needle advanced about 2 mm, the force measurement along the Z-axis (f_Z) exceeded the threshold, and the needle slowed down. During Step 2, the intraocular pressure continued to increase from 33 to 46 mmHg, since the eyeball was being compressed by the

pushing force from the needle. In Step 3, both the force and the intraocular pressure decreased, although the needle was in a stationary state. This was because the shape of the eyeball gradually recovered after the needle completely penetrated the cornea.

The change in intraocular pressure was large, even though the pressure was adjusted by the regulator. This is due to the mechanical deadband of the regulator. The range within which pressure can be adjusted by the regulator ranged from 0 to 0.2 MPa (1500 mmHg), while the pressure change in this experiment was less than 1% of the range of the regulator. To reduce the pressure and damage to the eye components, it is desired to introduce a pressure controller using a precision pressure sensor.

The positioning performance is important for precise surgery. The steady-state positioning error shown in Step 3 in Fig. 8 is 0.05 mm. It is similar to that of the conventional robot driven by pneumatic cylinders.[18] The desired precision is 0.1 mm, considering the future application of the robot to retinal vessel cannulation surgery, where the diameter of the target blood vessel is about 0.1 mm.[19]

It seems enough for the proposed robot to conduct cannulation, although a more precise robot is desirable considering a safety factor. The control performance should be improved to make full use of the frictionless feature of the soft actuator. Besides the dynamic modeling of the robot and the feedforward control, a better sensor system, such as a laser encoder and low-noise electric circuits to increase the feedback gains, will be necessary to improve the positioning performance. It is also necessary to evaluate the precision when the robot is extended to multiple DOFs.

4. Conclusions

We proposed an ophthalmologic injection device. A linear soft actuator drives the injection needle. The soft actuator has a high positioning ability since it has no friction or backlash. We confirmed the good position control performance of the device achieved by introducing a cascaded pneumatic control system. An intraocular pressure adjustment device with a water reservoir and a precision air regulator is also developed.

Using the proposed system, we acquired the initial data on the dynamic transition of intraocular pressure. The intraocular pressure increased by about 20 mmHg, and we found the necessity to use the feedback control system to regulate the intraocular pressure to reduce damage to the eye components during an eye surgery.

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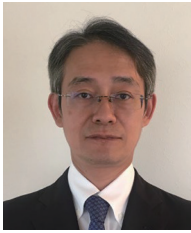
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