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CLINICAL INVESTIGATION

Toward robot-assisted vascular microsurgery in the retina

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Abstract • Background: Experimental protocol in our laboratory routinely requires the precise placement of instruments at, or near, the retina. Although manipulators for placing an instrument within the eye presently exist, none of the designs were satisfactory due to limitations on size, accuracy and operability. To overcome these limitations, we have developed a novel six degree of freedom manipulator designed specifically for retinal microsurgery. • Methods: The manipulator is parallel in structure and provides submicrometer positioning of an instrument within the constrained environment of the eye. The position of an instrument attached to the manipulator is commanded by the operator using a hand-held trackball. A computer controller interprets the trackball input and moves the manipulator in an intuitive manner according to mathematically constrained modes of operation. • Results: Over 50 retinal vessels in the live, anesthetized cat have been successfully cannulated for pressure measurement and drug injection using the described manipulator and micropuncture techniques. The targeted vessels ranged in internal diameter from 20 to 130 µm. • Conclusion: This device has applications in microsurgery where tremor and fatigue limit the performance of an unaided hand and where mechanically constrained manipulators are inappropriate due to size and operative constraints.

Introduction

Microsurgical techniques routinely executed in our laboratory require the placement of a 2–3 µm glass micropipette within the lumen of retinal vessels (20–130 µm) of the live anesthetized cat [2, 5, 6]. Once inserted, the micropipette must remain within the vessel for up to several minutes while a pressure measurement is taken or drugs are injected. The size of retinal vessels, the fragility of the micropipette tip and limitations of manual dexterity [3, 4] prohibit this procedure from being performed by hand and has prompted our laboratory to develop several manipulators for positioning and holding the micropipette within the eye. The latest manipulator is a computer-controlled robotic device designed specifically for retinal microsurgery and is capable of placing instruments at the retinal surface with submicrometer precision.

While Cartesian (x, y, z) manipulators are common and commercially available, the geometry of the eye does not easily permit their use [1, 7, 14]. To operate on the interior of the eye, an instrument must be placed through an incision in the sclera. Once inserted, the instrument can no longer be moved in an x, y, z manner but instead must be pivoted about the scleral incision point. Positioning the tip of the instrument along the surface of the retina is accomplished by varying the angular position and insertion distance of the instrument within the eye. This constrained motion requires two rotational degrees of freedom for pivoting the instrument and one translational degree of freedom for moving the instrument through the scleral incision point.

Most existing ophthalmic manipulators use mechanical means to perform the required pivotal motion. This pivotal motion is typically generated using two curvilinear tracks having common centers of curvature or by a single curvilinear track pivoting about a central axis. Attaching an instrument to the device and passing it through the common center guarantees the instrument will pivot about a fixed point [1, 6, 14]. However, prior to operating on the retina the mechanical center of rotation must be set coincident with the scleral incision point. Since the center of rotation of the instrument is fixed with respect to the manipulator, the manipulator apparatus itself must be moved relative to the eye during setup. This initial positioning can be difficult and often requires additional cartesian manipulators to align the mechanical center of rotation with the scleral incision point [6].

The ophthalmic manipulator described in this paper is a computer-controlled robot having the ability to position an instrument with six degrees of freedom. This means that the manipulator can position an instrument at any location (*x*, *y*, *z*) and orientation (roll, pitch, yaw) within the working range of the actuators. The motion of the instrument is not mechanically constrained using linear or curvilinear tracks, and thus it is both versatile in the type of movements it can perform and compact in size.

While one approach for commanding the position of a six degree of freedom manipulator is to mimic the motion of a similar six degree of freedom input device [10], such a design is costly and is neither practical nor necessary for the procedures performed in our laboratory. Instead, a hand-held trackball attached to a computer controller provides a simple operator interface and is used to move the manipulator according to programmed modes of operation. In the particular case of eye surgery, a virtual center of rotation is created in software and set coincident with the scleral incision point during setup. The motion of the micropipette within the eye is thus restricted in software to only pivot about the scleral incision point or move through it, in effect reducing the degrees of freedom from six to three. Allowing the operator to move the micropipette only in the directions required for eye surgery makes the manipulator simple to use and intuitive to operate.

Materials and methods

Manipulator design

The mechanical design of the robotic manipulator (Fig. 1) is based on a variation of the Stewart platform [15] originally presented by Merlet [12, 13] and is detailed elsewhere [8, 11]. Parallel mechanisms are typically used in applications such as aircraft flight simulators and are known for their inherent stiffness, compact construction and ability to provide large angular displacements. These features, when compared with comparable serial manipulators, made a parallel design desirable for the particular case of eye surgery, where size, stiffness and pivotal ability are of primary concern. The manipulator assembly is approximately 12 cm in diameter by 24 cm in length and has an operating range which is dependent on the distance to the center of rotation. For our laboratory setup, the device is capable of operating within a 30° cone inside of the eye.

The operating instrument is fastened to the positioning portion of the manipulator called the end effector platform. The pose (position and orientation) of the end effector platform is determined by the position of six linear slides, each of which is attached to the platform through a single leg with ball joints at both ends. A unique combination of linear slide extensions will position and orient the end ef-

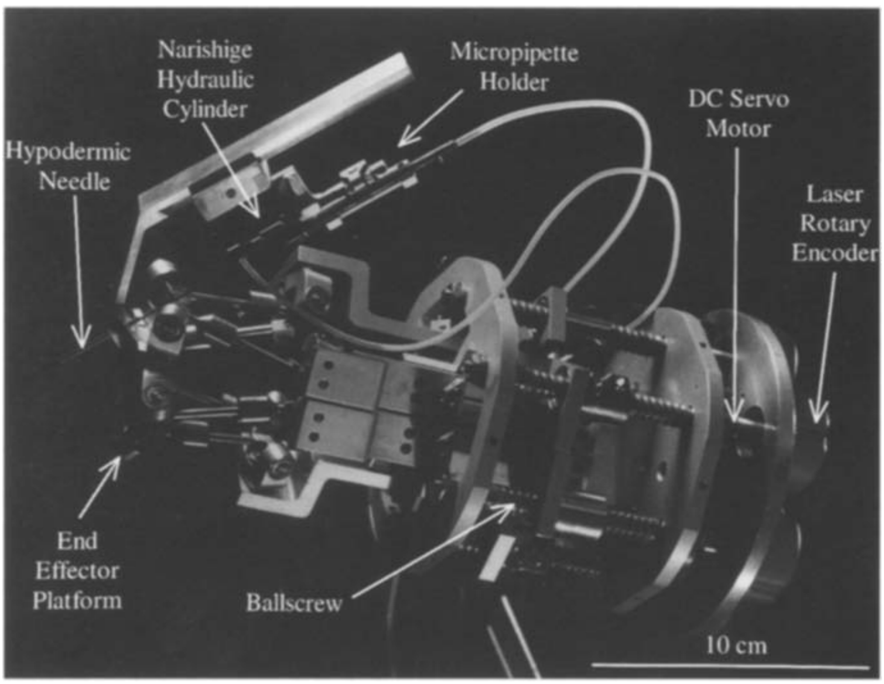

Fig. 1 Photograph of the robotic manipulator. The hypodermic needle and end effector assembly are located to the left of the device. Ball screws attached to linear slides vary the position of the end effector. The ball screws are rotated using DC servo motors and monitored with laser rotary encoders. The micropipette is held by a micropipette holder and moved through the hypodermic needle via the Narishige hydraulic cylinder

fector platform in . unique pose. DC torque motors (model QT-0717-D; Inland Motor, Radford, Va.) driving ball-screw transmissions maintain the position of the linear slides, while laser rotary encoders (model TR-36; Cannon USA, Lake Success, N.Y.) with a resolution of 14400 counts per revolution monitor ball-screw rotation. The linear positioning resolution of the manipulator is 0.2 μm, corresponding to a single laser rotary encoder pulse. The entire manipulator assembly is held by a six degree of freedom microscope stand which provides coarse positioning of the manipulator during surgical preparation.

Computer controller design

Due to the parallel structure of the manipulator, translation of an instrument attached to the end effector platform along a desired path involves a non-intuitive, simultaneous and of all six actuators. Attempting to position the instrument with submicrometer precision by manually adjusting each actuator length would be a difficult, if not impossible task. Instead, a computer controller interprets motion commands from an operator and controls the pose of the manipulator accordingly. The computer controller algorithm is made up of three distinct segments: an operator interface, a motion profile generator and a motor controller. All code was written in C++ version 4.1 (Borland International, Scotts Valley, Calif.) and is executed within a 1-KHz interrupt service routine running on a DOS (MS-DOS 7.0; Microsoft, Redmond, Wash.) based computer (Micron P100; Micron Electronics, Boise, Idaho).

The input device currently used by the operator to control the position of the manipulator is a hand-held trackball (Canon Computer Systems, Costa Mesa, Calif.). The trackball includes a ball which is rolled with the thumb and two buttons which are pressed with the index and middle fingers. One button enables the manipulator and must be held down before the manipulator will move. The other button selects the manner in which the manipulator will move when the trackball is rolled.

The motion profile generator algorithm monitors the trackball for input, converts the trackball information into a corresponding desired pose of the manipulator and then sends the new motor set-point information to the motor controller. Since the trackball can simultaneously control only two degrees of freedom, the motion profile generator must interpret trackball information based on an operator selected algorithm or "mode of operation". Two modes of operation have been developed specifically for eye surgery and are discussed in detail in the following section. Once the trackball information has been interpreted and a new desired pose of the manipulator determined, the motor controller moves the motors to their new location and holds them there using a PID control law until a new set-point is obtained. Since the positioning algorithm is performed 1000 times per second, the manipulator responds to positioning commands from the trackball in a smooth and responsive manner.

An operator interface on the computer console allows the operator to turn the manipulator on and off, move the end effector to predefined positions, change system parameters and monitor system status.

Software constraints for eye surgery

A pose definition and associated modes of operation have been developed that simplify the use of the manipulator during eye surgery. The pose definition uses six variables to define five degrees of freedom as shown in Fig. 2. The sixth degree of freedom would roll the instrument about its own axis and is not currently needed for the procedures performed in our laboratory. However, since the pose definition is defined in software it could be modified at a later time if necessary.

The coordinate variables are split into two groups of three degrees of freedom, each group corresponding to a single mode of operation. The first mode of operation is termed "translational" and is used to move the virtual center of rotation relative to the manipulator base while the orientation of the instrument and location of the center of rotation on the instrument body remain fixed (Fig. 3a). This has the effect of moving the instrument and center of rotation together in cartesian space. Translational mode is used during surgical preparation to locate the scleral incision point and set the instrument's center of rotation coincident with it. When in translational mode, rolling the trackball with only the enable button pressed moves the instrument in the x–y plane, while rolling the trackball with both buttons pressed moves the instrument in the z direction.

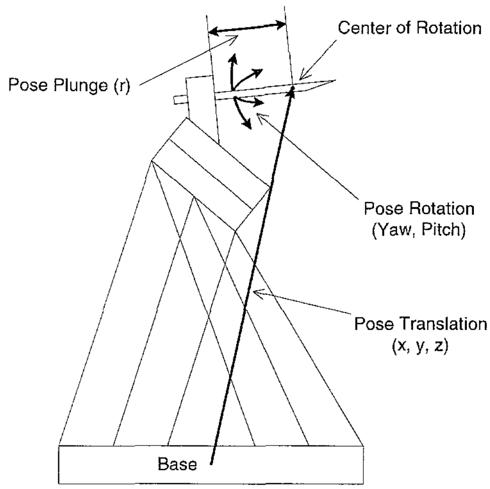

Fig. 2 The pose definition of the manipulator includes six variables to define five degrees of freedom. The pose variables can be grouped into two sets of three variables each. One set locates the center of rotation with respect to the base in cartesian (x, y, z) coordinates. The other set describes the amount of rotation (yaw, pitch) and the plunge distance (r) of the hypodermic needle with respect to the center of rotation

The "rotational" mode of operation fixes the center of rotation relative to the manipulator base and either pivots the instrument about this fixed point or moves the instrument through it (Fig. 3b). This mode of operation guarantees that the instrument will always pass through the scleral incision point by performing the puncture-centered motion typically seen in ophthalmic manipulators. When in rotational mode, rolling the trackball with only the enable button pressed pivots the instrument about the scleral incision point (yaw and pitch) and is used to aim the instrument at the targeted region of the retina. Rolling the trackball with both buttons pressed moves the instrument into and out of the eye (plunge). To place the tip of an instrument at an particular location on the retina, the enable button is pressed and the trackball used to aim the instrument in the desired direction. The instrument is advanced through the sclera and towards the retina by pressing both trackball buttons and again rolling the trackball. Alternating between pivotal and plunging motions is as simple as pressing and releasing a single button, allowing rapid positioning of the instrument within the eye.

The manipulator has been designed to be used with various types of instruments and a schematic drawing of the micropipette end effector is shown in Fig. 4. It consists of a hypodermic needle attached at a 45° angle to the end effector platform, a dovetail slide, a micropipette holder and a Narishige hydraulic cylinder (model HO-22; Narishige, Greenvale, N.Y.). The micropipette holder is attached to the actuation end of the hydraulic cyclinder and the entire micropipette assembly is mounted onto a dovetail slide used for guiding the micropipette tip into the hypodermic needle. The dovetail slide can be locked in place and the Narishige hydraulic cyclinder used

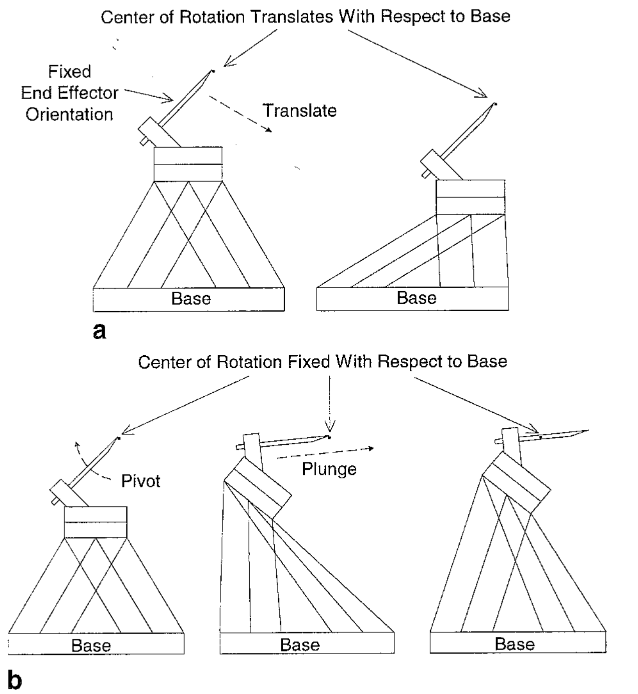

Fig. 3a, b Splitting the pose variables into functional groups allows an input device with fewer degrees of freedom than the manipulator to be used intuitively for micropuncture. **a** The translational mode of operation translates the enter of rotation using cartesian coordinates while maintaining a fixed tool orientation. This is used to place the center of rotation of the tool coincident with the scleral incision point prior to tool insertion. **b** The rotational mode of operation fixes the center of rotation at the scleral incision point and pivots the tool about that point or moves the tool through that point

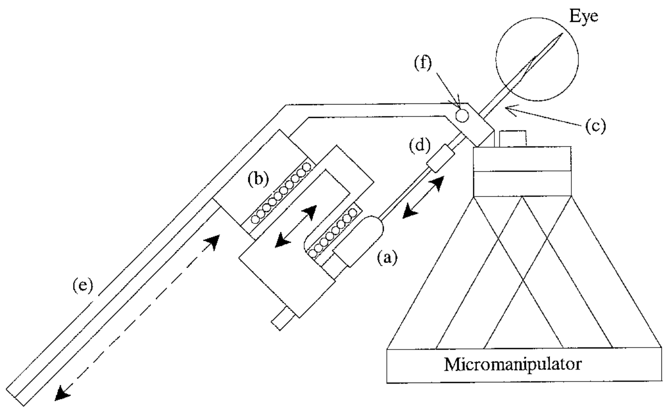

Fig. 4 Schematic view of the end effector used for retinal vascular micropuncture. A micropipette holder (*a*) provides a pressure-tight interface to the glass micropipette. The micropipette assembly is attached to a Narishige hydraulic actuator (*b*) which advances and retracts the micropipette relative to the hypodermic needle (*c*). A silicon rubber boot (*d*) provides a seal between the micropipette and hypodermic needle to prevent the leakage of vitreous. A dovetail slide (*e*) guides the micropipette during initially insertion through the hypodermic needle. The hypodermic needle is held in place with a locking cam mechanism (*f*)

to move the micropipette through the needle. The hypodermic needle provides a passageway for the micropipette through the sclera and into the eye. A silicon rubber boot placed over the micropipette and hypodermic needle prevents the leakage of vitreous.

Experimental use

The manipulator has been used extensively in our laboratory to make physiolocial measurements in the retinal circulation of the live, anesthetized cat. All animal experiments were performed in accordance with the *Principles of laboratory animal care* (NIH publication No. 86-23, revised 1985). Details on our experimental setup and micropuncture can be found elsewhere [2, 5, 6].

To prepare the manipulator for use, a hypodermic needle was loaded into the end effector such that the tip of the needle was at the software-generated center of rotation. A microscope stand holding the manipulator was used to position the tip of the needle near the sclera and aim the needle in the general direction of the targeted vessels. Once approximate positioning was complete, the "translational" mode of operation was used to place the tip of the needle (and virtual center of rotation) at the desired scleral incision point. The center of rotation was then fixed at the scleral incision point by changing the mode of operation to "rotational," guaranteeing that the micropipette assembly would always pass through this selected point.

The needle was filled with normal saline to prevent the introduction of air into the vitreal chamber, rotated using the manipulator until it was normal to the surface of the eye, and pushed through the sclera. With the hypodermic needle successfully inserted into the eye, a micropipette was filled with either a solution to be injected or 2M saline for making pressure measurements. The micropipette was placed in the holder and attached to the Narishige hydraulic cylinder. Using the dovetail slide as a guide while viewing the back of the hypodermic needle with an operating microscope (Zeiss OPMI1; Carl Zeiss, Thornwood, N.Y.), the micropipette was carefully inserted into the needle so as not to break the tip. After the initial insertion, the micropipette was advanced further while the operator observed the tip of the hypodermic needle through the pupil using the operating microscope and a plano-concave lens over the cornea. The interior of the eye was illuminated through the pupil using a white light source from the operating microscope. When the micropipette tip emerged from the tip of the hypodermic needle, the dovetail slide was locked which rigidly fixed the micropipette to the manipulator.

While continuously observing the tip of the micropipette through the operating microscope, the operator directed the micropipette toward a target vessel using the hand-held trackball. Once the tip of the micropipette was centered over a retinal vessel and just touching the surface of the retina, the enable button was released, fixing the manipulator at that location. Using the Narishige hydraulic actuator, the micropipette was carefully advanced until it just penetrated the vessel wall [6], after which pressure measurements were taken or drugs injected.

Results

A pressure measurement obtained from a 60-μm retinal vein using the manipulator, a micropipette and a servo-null device (model 5A; IPM, LaMesa, Calif.) is shown in Fig. 5. The trace shows the pressure reading as the micropipette was inserted, held steady and then retracted from the lumen of the vessel. Over 50 retinal vessels in the live, anesthetized cat ranging in diameter

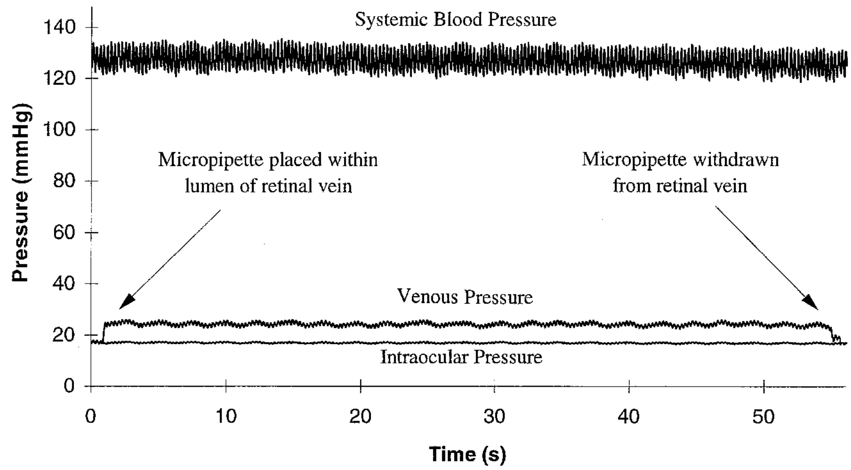

Fig. 5 Pressure measurement in a retinal vein of a live anesthetized cat acquired using the micromanipulator and the micropuncture technique

from 20 to 130 μm have been successfully cannulated for pressure measurement and drug injection using this manipulator-based micropuncture technique [6].

The compact size of the robotic manipulator and the virtual center of rotation made setting up the experiment in preparation for micropuncture significantly easier than with previous manipulators [6]. Since the robotic manipulator takes up less space around the head than similar mechanical manipulators, we were also able to perform experiments requiring two instruments in the eye by holding one instrument with the robotic manipulator and another with an older mechanical manipulator.

Discussion

We have found the robotic manipulator described in this paper to be easy to use and versatile while providing precise, steady placement of an instrument over large areas of the retina. One goal of this research was to develop a manipulator which is easy to set up for retinal microsurgery and essentially transparent to an operator using it. The setup procedure has been simplified in that a virtual center of rotation at the scleral incision point has been established by touching the sclera with the tip of the instrument. Once the scleral incision point has been selected, the motion of the tool is constrained to always pass through that point. Since the motion of the tool is constrained, the operator does not need to worry about damage to the instrument or the eye at the scleral incision point due to an erroneous motion command.

To move the micropipette tip within the eye, an operator observes the tip of the micropipette through an operating microscope and guides it based on visual information. The operator is thus using the manipulator as a tool and always has direct control over how the tool is moving. To make the manipulator as intuitive to use as possible, the computer and robot residing between the operator and the tool should be essentially transparent. This infers that the operator should feel like they are holding the tool and that the tool moves in a manner which the operator expects. Transparent operation was addressed by carefully selecting the mapping schemes which relate a rolling of the trackball to a corresponding notion of the manipulator. When the trackball is rolled in one direction, the back of the instrument follows with a reduction in scale making the operator feel as if this thumb is attached directly to the back of the instrument.

Using the manipulator in a teleoperated manner is only one of many possible applications. The computer controller is also capable of following predefined motion profiles and placing the instrument at a specific location within the eye. This capability could be used to microscopically scan surfaces, move the instrument in a complicated preprogrammed manner or repeatedly visit the same retinal location. By registering the instrument to the eye, the computer controller could also be used to set up additional motion constraints based on eye geometry. An example would be to keep the instrument at least 10 μm from the retina or to allow controlled penetration of the instrument into the subretinal space for the injection of various substances.

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