A New Method to Extend Applicable Area of Minimally Invasive Neurosurgery by Brain Retract Manipulator

Jun Okamoto[1], Mitsuhisa Iida[1], Kazuya Nambu[1], Masakatsu G. Fujie[1], Mitsuo Umezu[1], and Hiroshi Iseki[2]

[1] Department of Mechanical Engineering, Waseda University
3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555 Japan
okamoto@toki.waseda.jp

[2] Department of Neurosurgery, Tokyo Women's Medical University

Abstract. To extend applicable area of minimally invasive neurosurgery, multi-DOF brain retract manipulator is developed. By inserting this manipulator deeper into the brain as an conductor and then other micromanipulator afterwards, it will be possible to realize new minimally invasive neurosurgery. The brain retract manipulator system is controlled by new safety method with brain retraction pressure monitoring system, Tendon-driven unit which controls lock or free status of each joint of multi-joint spatula, Passive-hybrid control system that assure the system a suitable safety. In evaluation test with a hog, insertion of the multi-joint spatula as deep as the cerebral base was realized, and the possibility of securing the space between the temporal lobe and the cerebral base is verified.

1 Introduction

The introduction of laparoscopic cholecystectomy in 1987 clearly illustrated the potential benefits of minimally invasive approaches to gastrointestinal diseases. Patients suffer less postoperative pain, develop fewer infections, resume oral intake and are discharged sooner than after cholecystectomy performed through a standard Kocher incision. Laparoscopic cholecystectomy's tremendous success stimulated surgeons to apply laparoscopic techniques to treat heart or lung disease. However, endoscopic surgery requires a surgeon with special training and a lot of experience, so master-slave robotic arm have recently been introduced into the operating theatre to enhance the surgeon's dexterity in endoscopic surgery[1][2] .

Nowadays, minimally invasive robotic surgery has been expected to apply strongly to various surgical field. Especially in neurosurgery, robotic operation supported by navigation system will become very effective method, because brain tissue keeps solid structure in rigid cranial bone, so affected area is easily and precisely comprehended in 3D coordinate system. But, on the other hand, neurosurgery has an aspect of incompatibility of minimally invasive approach, because brain tissue is filled densely in cranial bone, there is almost no space where it is possible to insert or manipulate surgical equipments even micro-forceps. Because of this restriction, mini-

R.E. Ellis and T.M. Peters (Eds.): MICCAI 2003, LNCS 2878, pp. 190–197, 2003.

mally invasive neurosurgery is not become popular except for neuroendoscopic or pituitary surgery.

We believe that we could extend applicable area of minimally invasive robotic surgery by developing systems that set a course to conduct a surgical manipulator deeper into the body, and secure appropriate workspace nearby the affected area.

By this time we have developed a multi-DOF brain retract manipulator which secure the workspace in the brain[3]. By inserting the brain retract manipulator deeper into the brain as an conductor, then other micromanipulator [4] afterwards treat the affected area, it will be possible to realize new minimally invasive neurosurgery.

To secure the workspace between the soft brain tissues safely and widely, brain retract manipulator should be secured safety by control rather than mechanical constrains. In this paper, we propose the new control method for the manipulator to protect patients from accident in the operating room, breakdown of the controller, and manipulation error of the operator.

2 Brain Retract Manipulator System

The purpose of this study is to secure the intracranial workspace minimally-invasively by one or two brain retract manipulators. Fig.1 shows a enlarged drawing of brain retract manipulators and Fig.2 shows a general view of the manipulator system.

The brain retract manipulator system consists of following mechanisms. 10-DOF multi-joint spatula, Tendon-driven unit which controls lock or free status of each joint of multi-joint spatula, Brain retraction pressure monitoring system, Passive-hybrid control system that assure the system a suitable safety, and 6-DOF SCARA type supporting structure. Lateral fissure or between brain and endcranium are objective clearance as securable workspace by the brain retract manipulator (Fig.3). To insert a spatula from small incision into the deep brain, it is necessary to downsize its dimensions. At the same time, multi-DOF structured design is necessary to follow the complicated shapes of lateral fissure or endocranium smoothly. So, the spatula was designed in 2mm thick, 7mm wide, and 10-DOF multi-joint structure (130mm long) (Fig.4). As for the drive system, we used active universal joint system developed by Ikuta et al.[5].

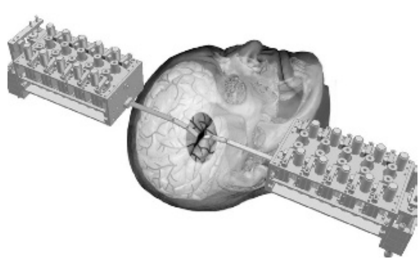

Fig. 1. Brain retract manipulators

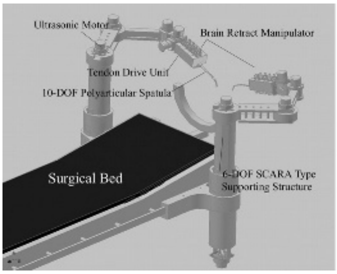

Fig. 2. Brain retract manipulator system

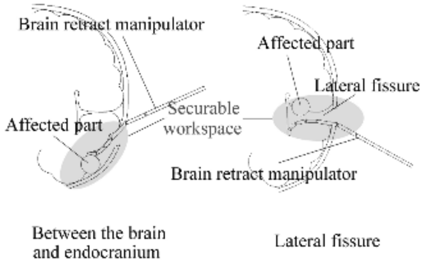

Fig. 3. Securable workspace in the brain

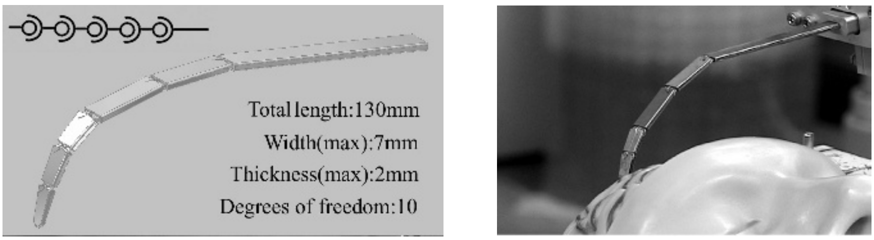

Fig. 4. Mechanical design of multi-join spatula

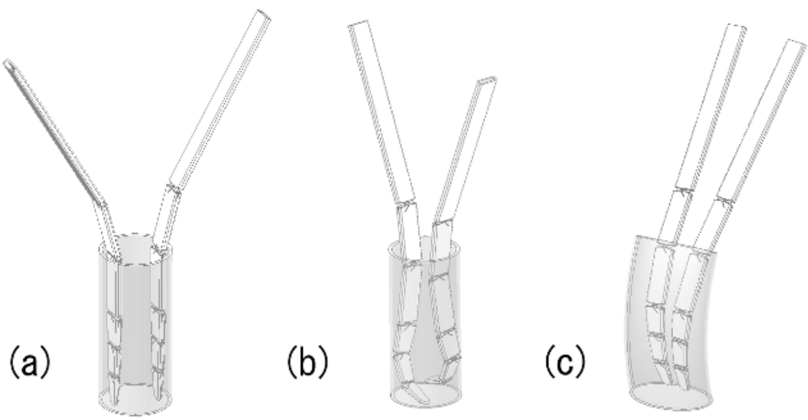

Fig. 5. The Method to secure the workspace in the brain

2.1 Extend Applicable Area in the Brain

Fig. 5. shows that three examples of the method to secure the workspace in the brain.

(a) Manipulators make a linear workspace (assumption of lateral fissure) from opposite direction to conduct another micro manipulator or micro forceps.
(b) Manipulators bear down brain tissue around a affected area to treatment easily for a micro manipulator.
(c) Manipulators make a curved workspace(assumption of between between brain and endcranium) from same direction.

By the use of redunancy of the manipulator, a lot of case is applicable during the operation.

3 Safety Control Method

3.1 Feedback Control by Active Controller

Normally, multi-joint spatula is driven by active controller ordinary way. But this manipulator has an unique tendon-driven unit. For dexterous surgery in the clinical field, a compact drive unit to move multi-joint spatula were designed. Fig.6 shows the tendon-driven unit. This mechanism enables one hydraulic cylinder to move each joint of the spatula. This unit provides the system with safety because it isn't able to drive more than 2-DOF at once.

Multi-joint spatula joints are driven by the unit with the following procedure.

1) Select a driven joint of spatula.

2) To engage worm and pinion gear, put compressed air to pneumatic cylinder for transmission (arrow A).

3)To take off the brake, release compressed air from pneumatic cylinder for brake (arrow B).

4) Hydraulic cylinder rotate centre shaft (arrow C), then reel up tendons with feedback control (arrow D).

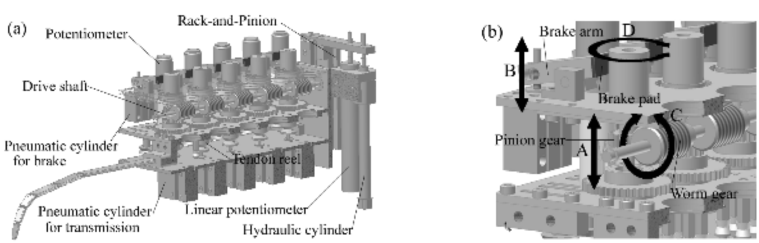

Fig. 6. Tendon-driven unit; (a) Section drawing of the unit. (b) Enlarged drawing of the unit

3.2 Brain Retraction Pressure Monitoring System

In the majority of neurosurgical operations, brain retraction is an essential technique that often influences operative results. If brain retraction pressure exceeds the safe limit, the brain tissue would be seriously damaged from contusion or lack of oxygen caused by the obstruction of blood flow. Hongo et al. reported that when experienced neurosurgeons operates the retractor they routinely used, initial retraction pressure is in the vicinity of 3.3kPa in many cases [6]. But safe limits of retraction pressure was not reported.

So the authors experimented with a hog to measure the limit of retraction pressure on the cerebral base with a conventional brain spatula (Mizuho Ikakogyo Co.,Ltd) and a pressure sensor (Kyowa Electronic Instruments Co.,Ltd PS-05KC) which was mounted on the surface at the tip of the spatula (Fig.7). Determination of the limit of retraction pressure is relied on a neurosurgeon's experience. From the result of the experiment, we decide the limit value vicinity of 4kPa on trial (Fig.8). But After time, this value should be discussed from medical consideration.

To monitor the retraction pressure during the manipulation, the authors developed brain retraction pressure monitoring system using PicoForce (Nitta) that measures the tensions of a pair of tendon that drives each joint of the spatula (Fig.9). Passive controller calculates the average pressure from the brain tissue on a joint of the spatula from the difference of two tensions. With this method, surgeon can monitor the brain retraction pressure constantly, and if the pressure exceeds the safety limit, the method acts as a trigger of passive-hybrid control.

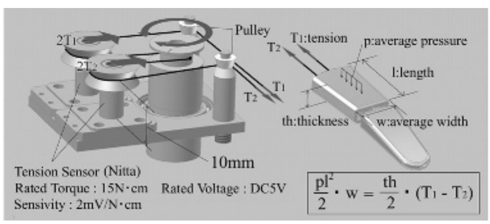

Fig. 7. Brain retract pressure monitoring system

3.3 Passive-Hybrid Control Unit

One of the major approaches to secure safety of surgical robots is to constrain the operation to restrict all working area except for that used for surgical manipulation.

However, it is difficult to place mechanical stoppers on a surgical robot that needs varied working area as in this study. Moreover, it is not completely free from the risk of being out of control. Consequently, as a substitute for active control, It has been researching a system called "passive control" . Taylor et al.[7] developed a passive manipulator for osteotomy and Troccaz [8][9] proposed a passive manipulation control scheme and showed an 2 DOF implementation with motors and clutches. Tajima et al. [10] developed a passive articulated link mechanism compatible to strong magnetic field of openMRI. This system uses only hydraulic cylinder brakes, and controls the movable area of the piston rods the user manipulate by the closing motion of the solenoid valve. These systems are extremely safe as compared to active control, since the system never drives unexpectedly even if the system is uncontrollable. However, at the same time, it is not too suited to behavior for complex minute surgery or minimally invasive surgery.

In order to resolve these problems, we developed a system called "passive-hybrid control" that secures actuator-applied active control not by mechanical structure, but by passive control (Fig.10). Active controller (NS-Geode 300MHz PC/104bus QNX) actuate Closed-circuit hydraulic cylinder to move joints of multi-joint spatula, and passive controller (NS-Geode 300MHz PC/104bus QNX) operate three-port solenoid valves in the closed circuit and monitor the value of brain retract pressure (Fig.11). Two controllers are built and operated individually. If the brain retract pressure monitoring system detect pressure out of the safe limit (4kPa is set as safety value), passive controller judge overdrive of active controller or trouble by some kind of disturbance and close solenoid valves to stop the movement of brain retract manipulator.

Usually, Surgical manipulator systems have emergency stop switch that set under operator's hand or underfoot. Operator is able to stop the system or shut off the power supply to actuators by push the switch artificially and force the manipulator to stop. But the system that has only emergency switch is insufficient to stop the manipulator when the system is overdrive, because operator takes time to awake to the danger.

Passive-hybrid control system also solve the above problem. Passive controller immediately close the solenoid valves if pressure value is above the limit. Moreover, incompressible fluid (water) is applied to the working fluid, stoppage of delivery of fluid to the hydraulic cylinder eliminates the elastic expansion or compression of the fluid in the cylinder, so braking efficiency is more higher as compared with normally hydraulic oil.

The other reasons using hydraulic circuit to passive-hybrid control is as follows:

(a) Consideration of using in the clean area as operating room.

(b) Expandability of using in the MRI environment.

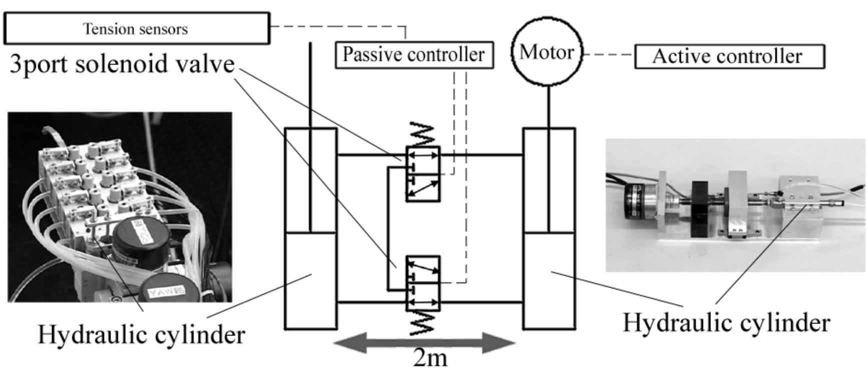

Fig. 8. Passive-Hybrid Control Unit

3.4 Lock and Free Mechanism

In emergency, It is difficult for controllers to judge the optimal solution during the operation. After turn on the passive control, an operator is able to change spatula joints lock or free by cut off the compressed air to the pneumatic cylinder for brake manually (Fig.6). If joints made all free, surgeon can pull up the spatula safely from deep area in the brain.

4 Result

4.1 Bending Characteristic of the Multi-joint Spatula

With the use of a laser range finder and potentiometers, the authors measured the bending characteristic of the all joint of the spatula in no-load. Mean error between actual measurement by laser range finder and measurement value by potentiometer is 7%. This result is considered in practical use, but aftertime, inner friction between wire and spatula structure should be reduced.

4.2 Pressure Monitoring Characteristic

Pressure monitoring characteristic is measured as well as 5.1. Mean error between actual load value and measurement value by tension sensor is 11%.

This error is related to result of 4.1. So decrease of friction will improve the result of this error.

4.3 Effectiveness of Passive-Hybrid Control

To verification of the effectiveness of passive-hybrid control, the authors make virtual errors to active controller.

After canceling control of active controller, the experiment which applies more than 4kPa on the spatula was conducted 500 times.

As a result of the experiment, passive controller worked out 100%. This system is considered that safety is securable unless active controller and passive controller hung up simultaneously.

5 Conclusions

In this research, we aimed at developing a multi-DOF brain retract manipulator which safely secure the workspace nearby the affected area. This manipulator will dramatically extend the scope of minimally invasive neurosurgery before long.

This research can be applicable not only to neurosurgery but also to other surgical treatments. We will carry on our research as bringing into view the wide range of surgical fields in the future.

References

1. J.P. Ruuda, I.A.M.J. Broeders: Feasibility of robot assisted laparoscopic cholecystectomy, Proceedings of the 15th International Congress and Exhibition, Computer Assisted Radiology and Surgery CARS2001, 159–164 (2001)
2. http://www.computermotion.com/
3. J.Okamoto, M.Iida, K.Nambu, H.Okayasu, M.G.Fujie, M.Umezu, H.Iseki: Development of multi-DOF brain retract manipulator for minimally invasive neurosurgery, Proc. On the 17th International Congress and Exhibition of Computer Assisted Radiology and Surgery (CARS2003), 522–528, 2003
4. K.Kan, M.Fujie, F.Tajima, K.Nishizawa, T.Kawai, A.Shose: Development of HUMAN System withThree Micro Manipulators and Minimally Invasive Neurosurgery, Proc. on the 15th International Symposium and Exhibition of Computer Assisted Radiology and Surgery(CARS 2001), 144–149 (2001)
5. K.Ikuta, S.Daifu, T.Hasegawa, H.Higashigawa: Hyper-finger for Remote Minimally Invasive Surgery in Deep Area, Proceedings of 5th International Conference, Medical Image Computing and Computer-Assisted Intervention-MICCAI 2002, 173–181 (2002)
6. K.Hongo, S.Kobayashi, A.Yokoh, K.Sugita: Monitoring retraction pressure on the brain. An experimental and clinical study, J Neurosurg 66, pp.270–275 (1987)
7. Taylor, R.H., C.B. Cutting, Y. Kim, A.D. Kalvin, D.L. Larose, B. Haddad, D. Khoramabadi, M. Noz, R. Olyha, N. Bruun, and D. Grimm. "A Model-Based Optimal Planning and Execution System with Active Sensing and Passive Manipulation for Augmentation of Human Precision in Computer-Integrated Surgery" in Second Int. Symposium on Experimental Robotics. Toulouse, France. 179–195 (1991)
8. Troccaz, J. and S.Lavalee, “An alternative to actuated robots and passive arms in medical robotics”, Proc.IEEE EMBS, 934–935 (1993)
9. Delnondedieu, Y., Troccaz, J., “PADyC: a Passive Arm with Dynamic Constraints. A prototype with two degrees of freedom”, Proceedings of the 2nd International Symposium on Medical Robotics and Computer Assisted Surgery, 173–180 (1995)
10. F.Tajima, M.Fujie, T.Kanade: PALM-V2:A Passive Articulated Link Mechanism with Variable Viscosity, Proc.of Advanced Intelligent Mechatronics AIM’97, Tokyo, Japan, CD-ROM (1997)
11. H.Okayasu, J.Okamoto, M.Fujie, M. Umezu, H. Iseki: Development of a hydraulic driven flexible manipulator for neurosurgery, Proc. on the 17th International Congress and Exhibition of Computer Assisted Radiology and Surgery (CARS2003), 607–612 (2003)