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Bimanual Endoscopic Robot for Neurosurgery

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INTRODUCTION

In recent decades, improvements in neurosurgical care have been driven by technological advances such as frameless stereotaxy and endoscopy. Endoscopy enables navigation through the clear fluid-filled ventricular system of the brain instead of through healthy brain tissue enabling minimally invasive treatment of tumors, cysts, hydrocephalus and epileptogenic lesions [1]. Twenty percent of brain tumors lie either adjacent to, or inside, the ventricles, and endoscopy has had a major impact in their treatment leading to reductions in morbidity and procedure time [2].

Despite this progress, significant difficulties remain. A major challenge is that most endoscopes force clinicians to perform one-handed surgery even though many neurosurgical tasks require two hands. For example, one hand can retract healthy tissue while the second removes a lesion.

A second challenge is that existing tools are mounted on straight rigid shafts. This forces the surgeon to pivot the endoscope about the burr hole in the skull to move the tool inside the brain. This pivoting motion can damage healthy brain tissue adjacent to the surgical corridor and so limit the size of tumors that can be safely accessed endoscopically.

An ideal system for overcoming these limitations would enable the endoscope orientation to remain relatively fixed during a procedure and allow the surgeon to manipulate multiple dexterous tools within a workspace volume located at the endoscope's tip. The contribution of this paper is to present a robotic two-armed endoscope (Fig. 1) that overcomes these challenges along with preliminary validation results for a bimanual task.

Notable prior results on the design of multi-armed robotic neuroendoscopes include [3-5]. The present work differs from those results in that both the arms and the tools (e.g., forceps, scissors, bipolar cautery, suction) are designed as small, easily-sterilizable and replaceable modules that can be individually swapped during a procedure. This enables intraoperatively exchange of either a tool or a robotic arm without the risk involved in removing and reinserting the endoscope in the brain.

ROBOT DESIGN

The robot design is scalable. Current prototype dimensions are shown in Fig. 2. When fully extended, the 2.8mm diameter arms are 35mm long and trace out circles which are also 35mm in diameter. The arms are delivered with a center-to-center spacing of 8mm through a 10×12mm trocar with an integrated camera and LED illumination. By rotating and translating the trocar about its axis, the overlapping workspaces of the two arms can access a cylindrical workspace shown in red with a diameter of 43mm.

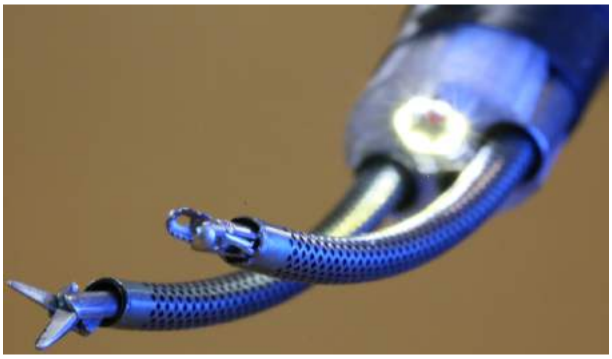

Fig. 1. Bimanual neuroendoscopy robot.

Each arm is constructed from a balanced pair of precurved superelastic tubes such that relative rotation of the tubes causes their curvature to vary between straight and maximally curved [6]. Combined with extension and retraction, each arm possesses three degrees of freedom. Tip-deployed tools, such as the scissors and forceps of Fig. 1, can also roll about the axis of the arm. Arm and tool motion are controlled using haptic interfaces.

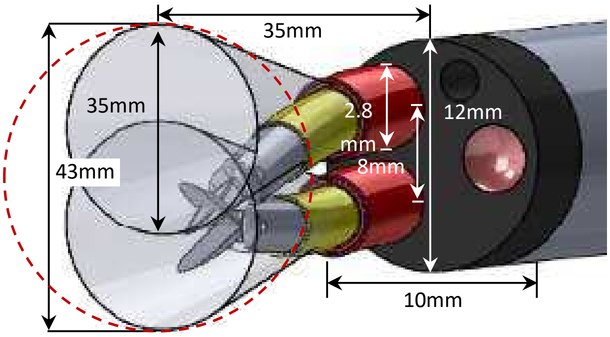

Fig. 2. Dimensions of robot arms, workspace and trocar. Note that arm lengths and workspaces are not to scale. Gray circles show workspaces of individual arms. Red dashed circle shows workspace accessible by rotating the trocar about its axis.

The entire robot is depicted in Fig. 3a with the arm and tool modules shown in Figs. 3b and 3c, respectively. These modules are inserted through the trocar module and clamp to mating drive system components as shown in Fig. 3a. To reduce the complexity and size of the arm and tool modules while making them more easily sterilizable, all the motors for driving the arms and tools are incorporated in the drive system instead of the modules themselves. A sterile drape (not shown) can be used to separate the drive system (all motors and electronics) from the sterile arm, tool and trocar modules.

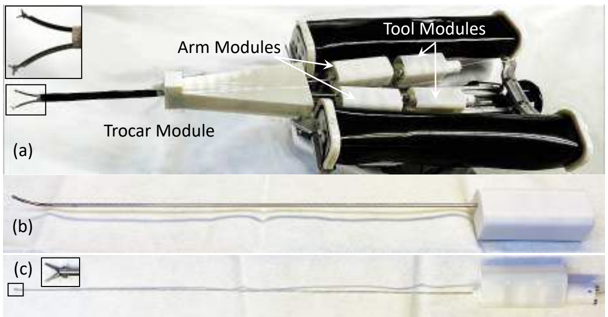

Fig. 3. Modular endoscopic robot. (a) Robotic system with inset showing arms and tools. (b) Removable arm module. (c) Removable tool module.

EXPERIMENTAL EVALUATION

An underwater hidden peg transfer task was used to compare the robotic system with a standard endoscope and a single straight tool. The pegs are hidden behind an opaque elastic membrane (shown semi-transparent in Fig.4a) with a 6mm diameter circular hole. The task is to move the rings between the corresponding top / bottom pegs while minimizing motion of the endoscope – which would create pressure against the surrounding brain tissue during actual surgery. The goal of this task is to explore motions associated with debulking a tumor that is large relative to the diameter of the endoscope trocar.

The challenge of the task is that the elastic membrane, which represents the tumor-encasing membrane, blocks the view of the rings and pegs. In the manual version, the endoscope trocar must be inserted through the hole in the membrane and trocar pivoting about a point located 9.5cm above the membrane (simulated burr hole in skull) is needed to move the rings between initial and destination pegs. This is challenging because the endoscope tends to slip out of the membrane hole as it moves (tops of pegs are 1cm below membrane).

In the robotic version of this task, the trocar can remain stationary while one arm is used to push back the membrane and the second arm grasps and moves the peg. This is shown in Fig. 4b where the right arm has stretched the hole in the membrane up and to the right revealing a peg and ring which can now be grasped by the left arm.

Metrics for comparing robot and manual performance were task time, ring drops and trocar pivoting. For fairness of comparison, a manual endoscope was fabricated using the same camera as the robot. The manual forceps were also identical to those used on the robot. Manual trocar pivoting was measured using an electromagnetic tracking system.

For these initial tests, a single operator performed training trials with both systems until they felt comfortable. Ten trials were then performed with each system. Table 1 lists the results of the experiments. Use of the robot reduced task time by 37% and decreased ring drops by 86%. Furthermore, the robot trocar remained stationary for the entire task while the manual trocar had to pivot about the simulated burr hole by 13deg in both coordinate directions of the peg plane. While not measured by the metrics, the operator indicated a higher stress level using the manual endoscope.

DISCUSSION

This abstract introduces a bimanual endoscopic robot design enabling intraoperative swapping of tools and arms. Initial evaluation on a task modeling tumor debulking demonstrates how the use of two steerable arms can improve task performance. These results suggest that a modular robot system enabling bimanual neuroendoscopy holds the potential to markedly expand the number of intracranial procedures amenable to a minimally invasive approach.

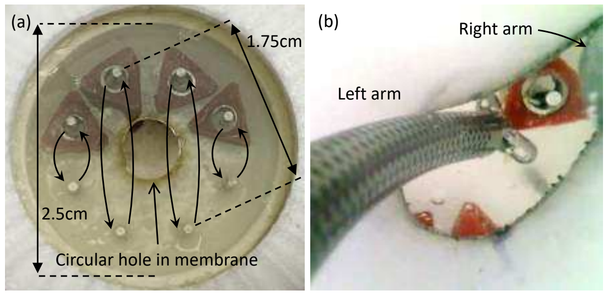

Fig. 4. Hidden peg transfer task. (a) Opaque membrane shown semi-transparent for visualization. (b) Robot endoscope view. Right arm pulls back membrane while left arm reaches for ring.

Table 1. Hidden Peg Transfer Task Metrics (10 trials)

Metric	Manual System	Robotic System
Total task time (min:sec)	2:18±0:45	1:27±0:16
Ring drops	2.1±1.9	0.3±0.5
Trocar pivoting with respect to x and y axes of peg plane (deg)	±6.5	0

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