Supplementary Materials for

Using Robotics to Move a Neurosurgeon's Hands to the Tip of Their Endoscope

Karl Price *et al.*

Corresponding author: P.E. Dupont, pierre.dupont@childrens.harvard.edu

This PDF file includes:

Figs. S1 to S3
Table S1
Legends for Movies S1 to S10
Supplementary Data

Other Supplementary Material for this manuscript includes the following:

Movies S1 to S10

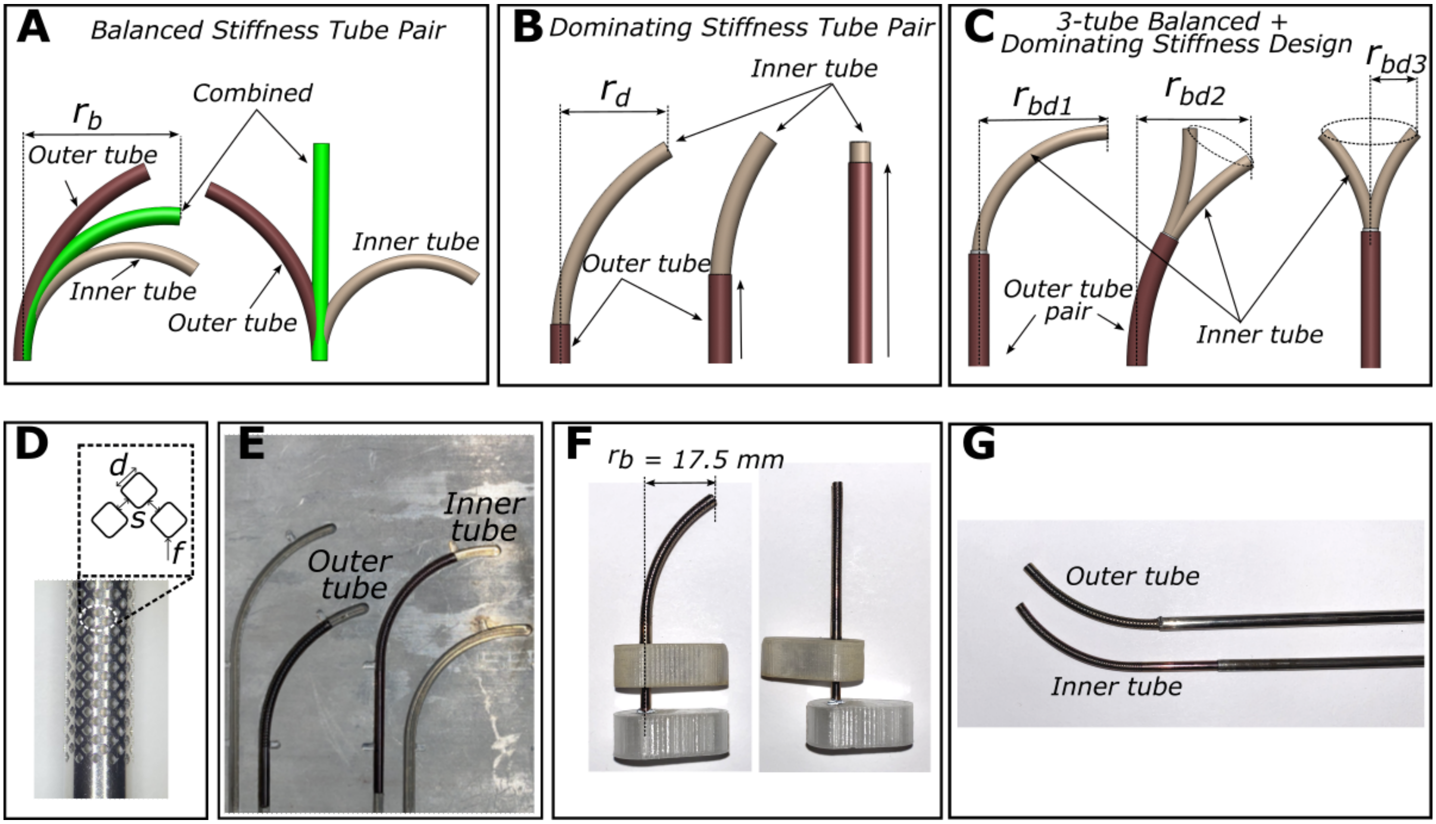

Fig. S1 Robot arm design. (**A-C)** Three designs considered for robotic arms. (**A)** Balanced stiffness design. Concentrically-combined pair of precurved superelastic tubes that are stiffness balanced. When they are rotated such that their precurvatures oppose each other, the tube pair becomes straight. Arm workspace radius is denoted by r_b. (**B)** Dominating stiffness design. Pair of concentric tubes with outer tube straight and much stiffer than inner precurved tube. As outer tube is extended over inner tube, the pair becomes straight. Arm workspace radius is given by r_d. (**C)** Balanced + dominating stiffness design. Three-tube design combining designs (a) and (b). Outer two tubes are stiffness-balanced pair which are much stiffer than inner precurved tube. Workspace radius is given by r_{bd1}. (Note that $r_{bd1} > r_{bd2} > r_{bd3}$.) (**D)** Diamond pattern parameters. Diamonds are square with edge length, *d*, spacing, *s*, and fillet radius, *f*. (**E)** Tubes comprising selected arm design shown in shape setting template. (**F)** Workspace of fabricated robot arms. (**G)** Fabrication of arms from distal precurved NiTi tubes glued to proximal stainless-steel tubes.

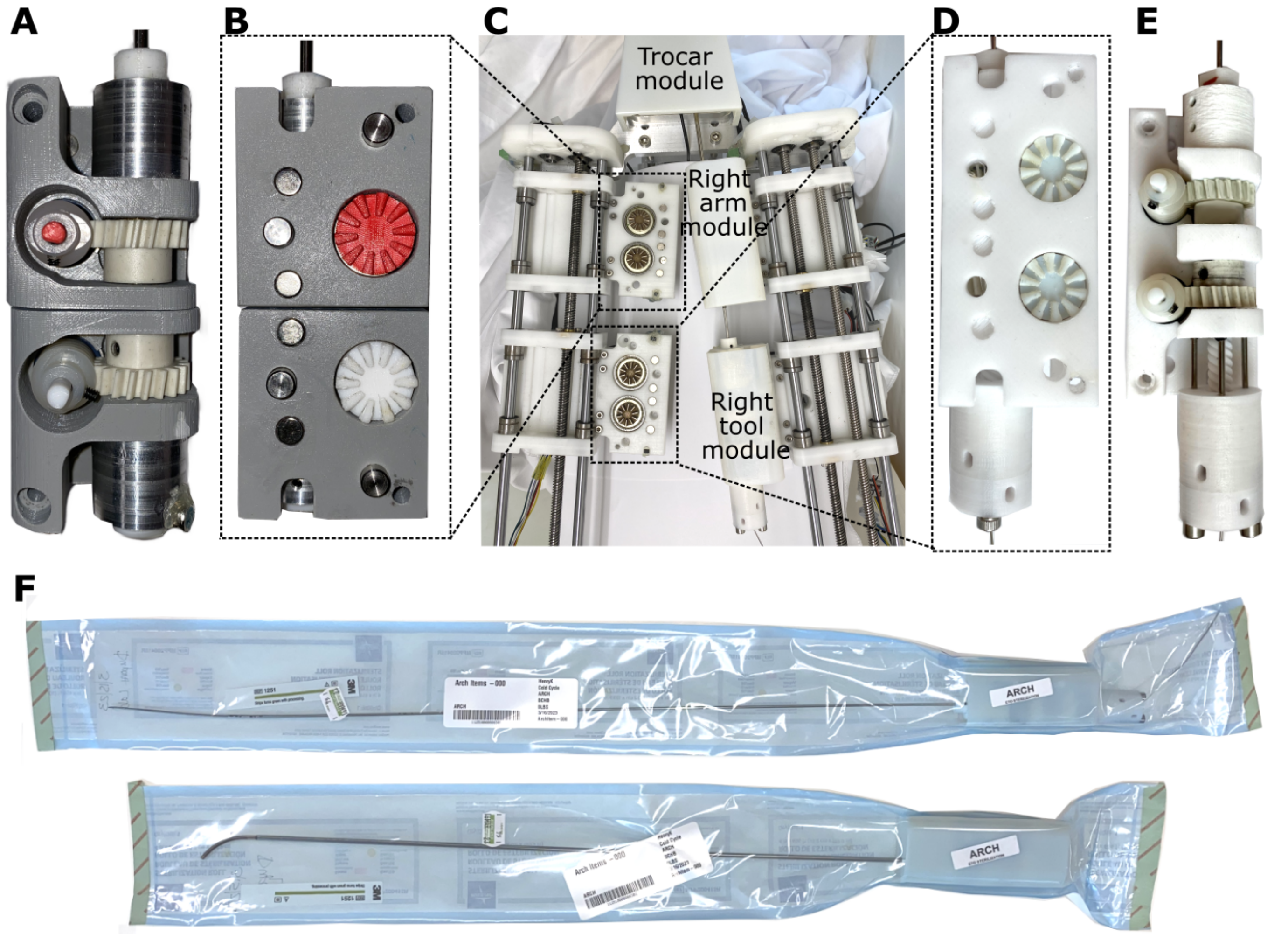

Fig. S2 Arm and tool modules. (**A**) Top view of arm module. Two Screw gear pairs enable independent rotation of two tubes forming robot arm. (**B**) Bottom view of arm module. Screw gears in top view are driven by red and white Hirth gears that mesh with mating gears on drive system coupler in (c). Hirth couplings enable “snap-in” gear mating with virtually no backlash. Pattern of 8 circular magnets align and attract module to drive system coupler. Screws can be used to provide additional mating force. (**C**) Drive system showing coupling components for left arm and tool modules. (**D**) Bottom view of tool module showing Hirth gears that drive screw gear pairs. (Magnets not installed in this image.) **(E)** Top view of tool module. Upper screw gear pair actuates tool roll. Bottom screw gear pair creates linear motion to open / close tools via pull wire by driving hollow linear screw. Pull wire passes through screw and is clamped in thrust bearing. Bearing allows pull wire to rotate along with tool roll. (**F**) Sterile packaged arm and tool modules.

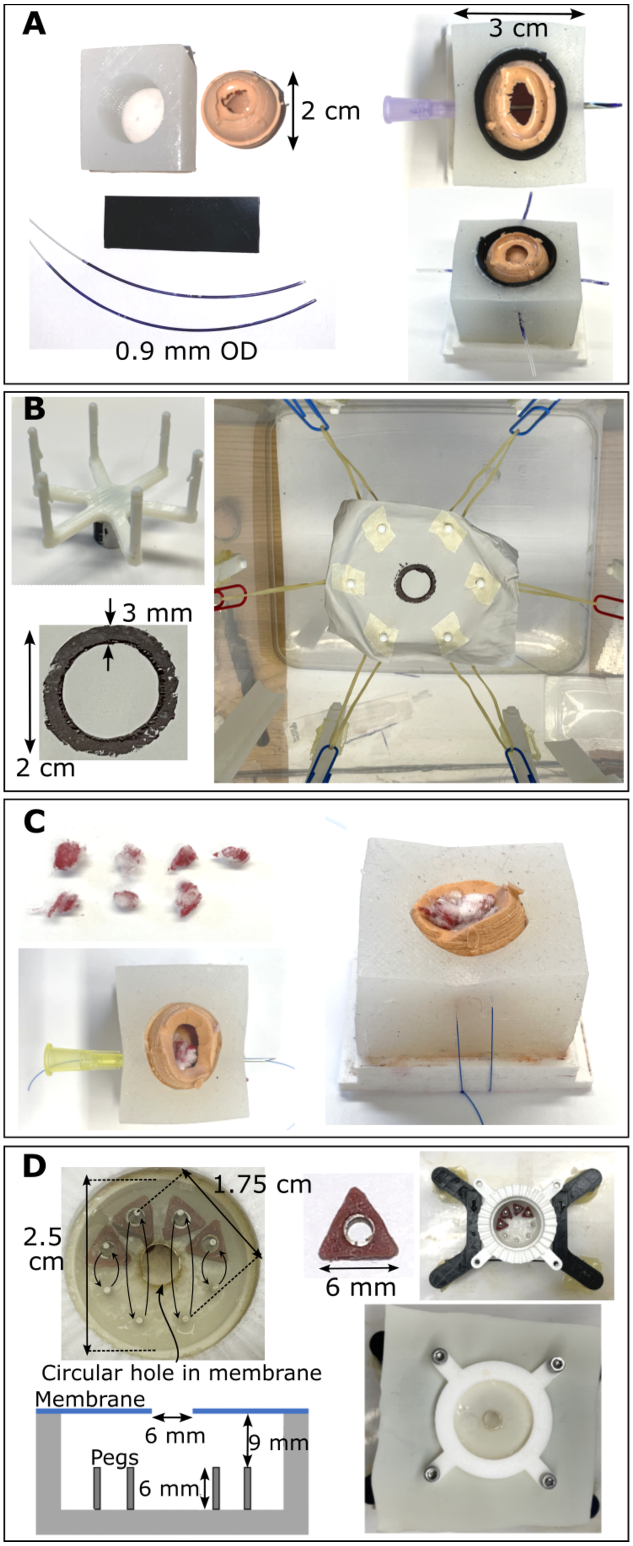

Fig. S3 Fabrication of skill tasks. (**A)** Boundary separation model (Skill task 1). The brain model is made from a block of white silicone with a rectangular piece of adhesive backed conductive polymer placed around the circumference of the tumor cavity. The pink tumor capsule is molded silicone. Four blood vessels are made from two lengths of polymer tubing that are passed through the model using a syringe. (**B)** Capsule cutting (Skill task 2). The membrane is cut from a surgical glove and the circle is stamped in ink on the membrane. A 3d-printed frame with a weight glued to the bottom is used to suspend the membrane using rubber bands from the walls of the water-filled tank. (**C)** Fibrous debulking (Skill task 3). The tumor is comprised of 7 small cotton balls that are suspended on 2 sutures passed through the model using a syringe. (**D)** Hidden ring transfer (Skill task 4). The white well holding the 8 stainless steel pins is 3D printed such that it slides into the black frame that is glued to the bottom of the testing tank. (Skill tasks 1 and 3 also use this frame.) The rings are comprised of an inner stainless steel tubing core glued to an outer silicone triangular prism. The opaque membrane is cut from a surgical glove and 6mm diameter hole is punched in its middle.

Table S1. Arm tube parameters		
	Inner Tube	Outer Tube
Outer diameter (mm)	2.5	2.8
Inner diameter (mm)	2.3	2.6
Tube length (mm)	71	56
Patterned length (mm)	35	35
Radius of curvature (mm)	28	35
Diamond edge length, *d* (mm)	0.32	0.40
Diamond spacing, *s* (mm)	0.2	0.3
Diamond corner radius, *f* (mm)	0.08	0.08
Circumferential number of diamonds	12	10

Movie Legends

Movie S1. Manual Boundary Separation (Skill Task 1). The tumor is manually separated from the surrounding brain to locate four blood vessels with the goal of avoiding putting pressure on the brain tissue. The operator used forceps to pull back the tumor capsule. Once a blood vessel tube was located, the forceps were used to squeeze the tube to simulate cautery. The forceps were then exchanged for scissors to cut the vessel. With a single tool, it was extremely difficult to visualize the vessel while cauterizing and cutting it.

Movie S2. Robotic Boundary Separation (Skill Task 1). One arm was used to pull back the tumor capsule while the second cauterized and cut the vessel. Two arms provides excellent visualization while also minimizing contact with the brain tissue.

Movie S3. Manual Capsule Cutting (Skill Task 2). The operator cut out a circular window in a polymer sheet representing the tumor membrane, while staying inside the witdth of the black circle. The operator pivoted the trocar to move around the circle during cutting. Cutting became more difficult as the task progressed because of reduced tension in the circular target.

Movie S4. Robotic Capsule Cutting (Skill Task 2). One arm was used to position and tension the membrane while the second arm cut it. Bimanual tensioning and cutting of tissue are a standard neurosurgical technique.

Movie S5. Manual Fibrous Debulking (Skill Task 3). A single tool is used to debulk a tumor comprised of small cotton balls suspended inside a tumor capsule. The operator tore off each piece and, while grasping it, pulled it out through the trocar. Tumor pieces can be lost if they cannot fit through the trocar. Visibility is also challenging around the periphery.

Movie S6. Robotic Debulking (Skill Task 3). The fibrous tumor is removed using two arms: one arm held open the capsule while the second arm tore off a tumor piece and fed it into the aspiration tube located between the arms.

Movie S7. Manual Hidden Ring Transfer (Skill Task 4). The trocar had to be inserted through the hole in the membrane to enable visualization. The challenge was that the membrane could easily slip off the trocar. Note the ring accidentally knocked off the peg at the end of the movie.

Movie S8. Robotic Hidden Ring Transfer (Skill Task 4). One arm pulled back the membrane to enable visualization while the second grasped and moved the ring.

Movie S9. Manual Pineal Tumor Debulking. Forceps were first used to create a hole in the plastic membrane. Then an aspiration tube was used to debulk the capsule. Note that the left side of the capsule was aspirated blindly because it could not be visualized. This could not be done safely in practice because the region may contain blood vessels.

Movie S10. Robotic Pineal Tumor Debulking. In robotic debulking, the left arm was used to retract tissue and to reposition the capsule enabling continuous visualization during aspiration.

Supplementary Data

These tables include all task trial data used in the paper.

Task 1. Boundary Separation – completion time [sec]		Task 1. Boundary Separation – Contact duration [sec]	
Manual	Robotic	Manual	Robotic
330	110	97	6
294	129	90	15
305	115	99	14
340	102	115	5
257	119	111	9

Task 2. Capsule Cutting – completion time [sec]	
Manual	Robotic
150	96
151	111
139	100
137	106
144	101

Task 3. Fibrous Debulking - completion time [sec]	
Manual	Robotic
154	93
118	122
128	92
151	134
153	134

Task 4. Hidden ring transfer – completion time [sec]					
Manual			Robotic		
Operator 1	Operator 2	Operator 3	Operator 1	Operator 2	Operator 3
133	188	169	85	179	211
106	167	190	86	76	280
137	132	241	115	115	200
91	205	279	76	82	210
146	189	304	75	171	146
139		190	99	182	224
97		159	84	101	141
124		220	108	134	134
158		208	69		166
			73		188
					127
					122
					109
					167
					121
					121

Pineal tumor debulking task – completion time [sec]	
Manual	Robotic
96	80
80	87
103	95
93	
88	