Concentric Tube Robots for Minimally Invasive Surgery

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INTRODUCTION

The human body was not designed to facilitate surgical repair. Thus, in order to minimize collateral damage to healthy tissue, many interventions require following complex curved paths through tissue and body lumens to reach surgical targets. The smallest existing instrument technologies utilizing this approach are comprised of catheters and endoscopes for passing through body lumens and flexible needles for steering along curved paths through tissue.

While these technologies provide substantial benefit to the patient, they also possess limitations on the types of interventional tasks that they can perform. For example, steerable needles rely on tissue reaction forces to bend and so cannot steer inside a body cavity. Catheters can be designed to steer inside a cavity, but their flexibility limits the forces they can apply to tissue. Thus, both types of devices have similar interventional capabilities – they can deliver a drug or device (e.g., stent) and perform ablation, but they are limited in terms of the surgical tools that they can use and the tissue manipulations that they can perform.

Recently, a new class of robots for minimally invasive surgery has been developed called concentric tube robots [1,2]. These robots are comparable in diameter to steerable needles and catheters, but differ in construction since they are formed from concentric, telescoping, curved superelastic metal tubes. The shape of these robots is a smooth three-dimensional curve that can be controlled by rotating and translating the individual tubes with respect to each other. While their construction makes these robots significantly stiffer than conventional catheters, the ability to precisely control robot shape enables safe navigation through either tissue or body lumens. Tools and devices are deployed through the central lumen of the robot that serves as a working channel. Consequently, this robotic technology has broad potential for clinical use throughout the body including cardiac surgery [13-15] and neurosurgery [8]. This paper provides a brief summary of our progress to date in developing this technology.

MATERIALS AND METHODS

The family of shapes that a concentric tube robot can assume is determined by the curvatures, stiffnesses and lengths of the individual tubes that comprise it. Three fundamental principles in designing tube sets are illustrated in Fig. 1 [1]. First, each telescoping section is designed to be substantially stiffer than all distal sections. This principle decouples the motion of each section from all of the others. The second principle is for each section to be of piecewise constant curvature. This shape is selected so that the robot can be telescopically extended in a follow-the-leader fashion to avoid producing unnecessary lateral forces either when steering through tissue or when passing through a body lumen. The third principle is to make each telescoping section to be of either fixed curvature or variable curvature (typically varying between straight and a maximum value. This principle is intended to produce the largest workspace with the fewest tubes.

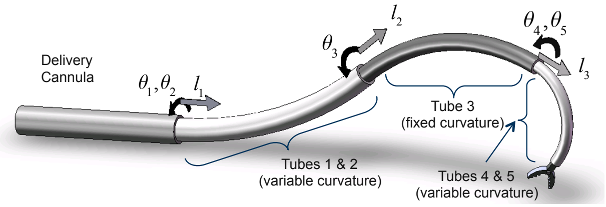

Fig. 1. Concentric tube robot illustrating design principles.

RESULTS

Design algorithms: Concentric tube robots are sets of tubes designed for a specific procedure or set of procedures that mount in a common motorized drive system. These tube sets can be made either for single use or for repeated use with sterilization. As illustrated in Fig. 2(a) for a beating-heart intracardiac intervention, many procedures can be decomposed into two parts, (1) navigating through tissue or body lumens to a surgical site, and (2) holding proximal sections fixed while distal sections articulate independently to interact with tissue.

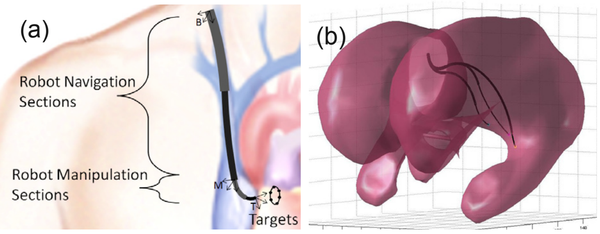

Fig. 2. Algorithmic robot design. (a) Design decomposition for intracardiac beating heart patent foramen ovale closure. (b) Robot design example for intraventricular neurosurgery.

Using this approach, robot design algorithms have been developed utilizing image-based models of the anatomy together with geometric descriptions of the procedure to compute the appropriate lengths, shapes and stiffnesses of individual tubes for procedures in cardiac surgery and neurosurgery [7,8].

<u>*Modeling and Control*</u>*:* A motorized drive system, compatible with all tube sets, is used to control the motion of the individual tubes while the surgeon commands the overall motion of the robot using a joystick or keyboard commands. As illustrated in the block diagram of Fig. 3, robot control involves rapid computation of the forward and inverse kinematics. Furthermore, owing to robot compliance, implementing stiffness or force control also requires rapid computation of the relationship between applied loads and robot deformation. Kinematic and quasistatic force models have been developed from Cosserat rod theory and used to implement numerically efficient position and stiffness controllers [1-5,9].

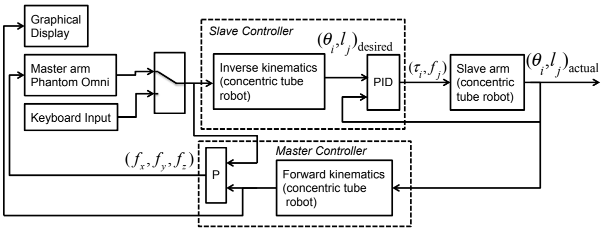

Fig. 3. Block diagram of position controller.

<u>*Surgical Tools*</u>*:* To enable the use of concentric tube robots for surgery inside body cavities, we are creating a tool set that is matched to both the dexterity of the robots and to the workspace available inside the confines of such cavities. Our tool set encompasses the two fundamental surgical tasks of approximating tissue and removing tissue. Given the challenges of manufacturing at the millimeter scale, we are utilizing a metal MEMS fabrication process that produces fully assembled devices with micron scale features [14,15].

Fig. 4 depicts two of our devices. The first is an implant for approximating two layers of tissue [14]. It is comprised of two pairs of expanding spring-loaded wings that are used to pull the tissue layers together. The wing pairs are attached by a ratcheting mechanism that enables the tissue layer approximation distance to be adjusted with submillimeter accuracy. As described below, we have used this device to successfully demonstrate percutaneous beating-heart patent foramen ovale (PFO) closure in a porcine model. Fig. 4(c) depicts a robot-deployed 2 mm microdebrider for tissue removal [15]. The robot lumen is used to power the rotating tool as well as to provide both irrigation and aspiration for entrainment and removal of cutting debris.

<u>*3D Ultrasound Imaging*</u>*:* Real-time high-resolution imaging is necessary for the surgeon to navigate to the target, perform the required task, and then confirm adequate and accurate completion of the repair. Recently, real-time 3D echocardiography has been gaining acceptance for guiding interventions given its relatively large field of view and its ability to image the surgical tool and the tissue structures simultaneously. Metallic instruments, such as concentric tube robots, produce a variety of image artifacts when ultrasound waves interact with their surfaces, however, and can make it difficult to clearly visualize the instrument as well as nearby tissue.

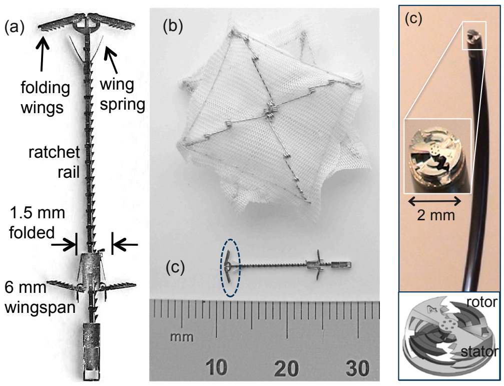

Fig. 4. Metal MEMS surgical tools. (a) Tissue approximation device. (b) size comparison of CardioSeal® catheter-delivered occlusion device and MEMS device. (c) Tissue removal tool.

To address these issues, we have developed echogenic coatings that increase absorption and reduce the specularity of reflections [10]. We have also developed image processing algorithms that reduce artifacts and are tuned to detecting curved tubular objects using as prior information the known robot diameter and the fact that the robot surface facing the ultrasound probe provides the most accurate image (Fig. 5) [11,12].

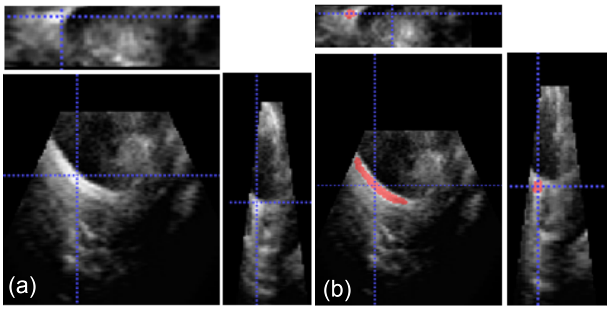

Fig. 5. Robot detection inside the left atrium of an ex vivo porcine heart. (a) Front, top and side views of acquired volume. (b) Corresponding views showing detected robot [12].

<u>*Beating-heart Intracardiac Surgery Animal Trials*</u>*:* To validate our design algorithms, models, controller, tools and imaging techniques, we performed a series of successful percutaneous beating-heart PFO closures in a swine model. Following the schematic of Fig. 2(a), we designed the 3-section robot of Fig. 6(a) to enter the right internal jugular vein and navigate to the right atrium. Once inside the atrium, section 1 is locked and sections 2 and 3 are used to approximate the septum secundum and primum by first piercing the secundum and then stretching it laterally to achieve the desired overlap with the septum primum (Fig. 7(a)). The robot then pierces the septum primum and deploys the device of Fig. 4(a) producing the result shown in Fig. 7(b).

The tissue approximation device of Fig. 4(a) possesses several advantages in comparison to occluder devices such as that of Fig. 4(b). First, in contrast with occluders that rely on spring forces to remain in position, the ratchet mechanism of the MEMS device provides the ability to tailor the approximation to the patient’s anatomy. Secondly, to reduce the chance of emboli formation on the left side of the heart, it is desirable to minimize the amount of foreign material exposed there to the blood. While only the distal wings of the MEMS device are present on the left side (Figs. 4(c) and 7(b)), an entire umbrella-like square (Fig. 4(b)) of the occluder is present in the left atrium.

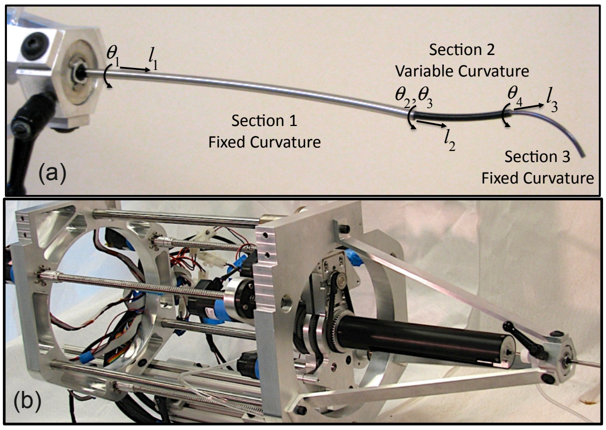

Fig. 6. Robot used for percutaneous PFO closure. (a) Three-section robot design. (b) Motorized drive system.

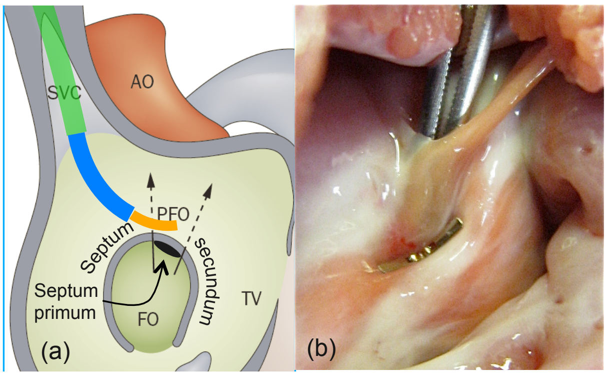

Fig. 7. PFO closure. (a) Robot first pierces septum secundum in depicted location and stretches tissue layer (downward in figure) over primum. (b) Left atrial view showing forceps inserted into PFO channel sealed by device. Visible wings of device are those circled in Fig. 4(c).

DISCUSSION

Concentric tube robots have the potential of filling an important and unexplored niche in instrumentation for minimally invasive surgery. With diameters on the order of 3 mm or smaller, they offer the versatility of steerable needles and catheters with the added potential of performing complex tissue manipulations at their tips. Future progress and successful transition to clinical use hinges on three research areas: (1) developing and integrating new surgical tools, (2) improving imaging techniques for visualizing tools and tissue at the millimeter scale, and (3) developing touch sensing technology that will enable safe navigation of the robot inside the body as well as precise control of tip-deployed tools.

ACKNOWLEDGEMENT

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