Development of a Tethered Epicardial Crawler for Minimally Invasive Cardiac Therapies

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***Abstract*—This paper describes the development of a robotic surgical device to facilitate minimally invasive, beating-heart cardiac therapies that can be performed within the pericardium. The concept we propose is that the device be equipped with the ability to adhere to the surface of the epicardium and locomote to any position and orientation under the direct control of a physician. As compared to current minimally invasive cardiac robotics, our approach obviates cardiac stabilization, lung deflation, differential lung ventilation, and reinsertion of laparoscopic tools. These advantages will result in greater efficiency and reduced trauma for the administration of intrapericardial therapies. This paper describes the current design of the robotic device and presents preliminary results.**

I. Introduction

Laparoscopic minimally invasive devices and techniques have made certain cardiac procedures possible without requiring sternotomy to expose the surface of the heart. Commercially available teleoperative systems now provide a higher level of minimally invasive functionality to the cardiac surgeon by allowing him or her to control robotic manipulators mounted on rigid laparoscopic tools. These systems provide increased dexterity to the surgeon, but are plagued by several drawbacks. They require cardiac stabilization, lung deflation, and differential ventilation, have a limited operative field, and are expensive.

For intrapericardial therapies, we propose a paradigm shift away from these table-mounted laparoscopic manipulators to a Tethered Epicardial Crawler (TEC) that has the ability to adhere directly to the surface of the heart and travel to any position and orientation on the epicardium. This concept will eliminate the previously mentioned limitations of cardiac surgical robotics.

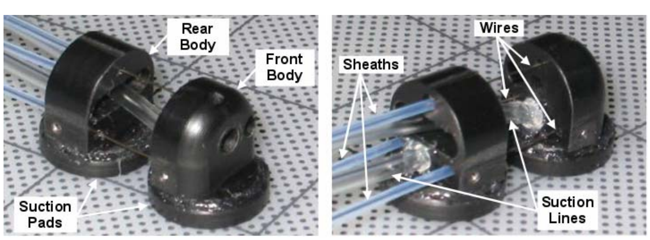

Fig. 1. Photographs of the current TEC prototype.

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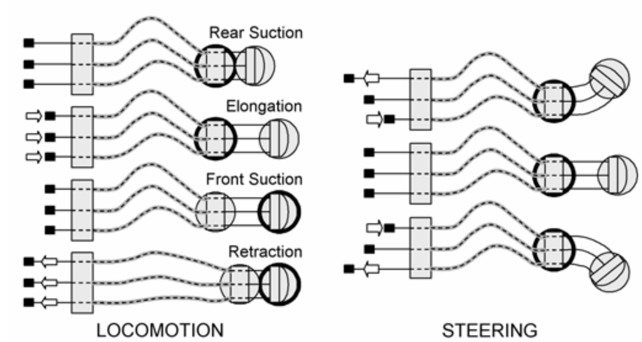

Fig. 2. Illustration of the wire-actuated locomotion and steering of the TEC.

1) Stabilization: Because the laparoscopic manipulators are located in the fixed reference frame of the operating room, the motion of the heart must be suppressed during the procedure. This requires either cardiopulmonary bypass or the use of laparoscopic stabilizers, both of which increase the trauma to the patient and the difficulty of the procedure [1]. The TEC does not require immobilization of the heart because it attaches itself directly to the surface of the beating heart.

2) Lung Ventilation: The rigid laparoscopic tools must be inserted transthoracically through incisions made between the ribs. This entering of the pleural space requires deflation of the left lung, general endotracheal anesthesia, and differential lung ventilation. These preparations eliminate the possibility for outpatient surgery. The locomotive ability of the TEC will allow it to be introduced transpericardially through an incision made below the sternum, thus never entering the pleural space and obviating lung ventilation.

3) Field Limitation: The operative field available after insertion of rigid laparoscopic tools is extremely limited. If a different operative field must be reached during a procedure, the laparoscopic tools must be extracted and re-inserted through additional incisions. Furthermore, some regions of the heart cannot be reached at all with such tools [2]. The TEC can reach any operative field on the epicardium, and can change operative fields easily using locomotion.

4) Cost: Commercially available teleoperative surgical systems cost approximately $1M, and are relatively bulky. The TEC will be far less expensive, and the current design allows the portion of the device that enters the body to be made disposable.

II. Design

This section describes general design elements for the TEC concept, and the details of a prototype that been constructed and tested, as shown in Fig. 1.

A. *Insertion and Retrieval*

The TEC is placed inside the pericardium, directly on the epicardium, using an endoscope. The endoscope is introduced into the thoracic cavity through an incision made just below the xiphoid process of the sternum. Once the treatment is complete, the TEC is retrieved by manually retracting the tether back through the endoscope. This also serves as the recovery method should the device become dislodged.

B. *Prehension*

The TEC prototype adheres to the epicardium using two independent suction pads. Suction has proven to be effective in current surgical devices such as the Octopus™ and Starfish™ (Medtronic, Minneapolis, MN), as well as in mobile robotics. The vacuum pressure is regulated by external computer-controlled valves, and supplied to the suction pads via two vacuum lines.

C. *Locomotion*

The TEC prototype has two modules, each consisting of a body mounted on an independent suction pad. Each module has a 13 mm circular footprint and a 13 mm height. Locomotion is achieved by moving these modules relative to one another. Actuation is provided by transmission of forces from three external motors through the tether of the device via lengths of nitinol wire. The reaction forces are resisted by flexible sheaths that cover the portion of wire running between the motors and the rear body. Inchworm-like locomotion is achieved by alternating the suction on the two modules, while changing the lengths of the wires between them (Fig. 2). The configuration of the sheaths and enclosed wires does not affect the locomotion of the device as long as there is slack between the motor and the rear module. Turning is achieved by differentially changing the lengths of the side wires (Fig. 2).

D. *Control Interface*

The locomotion of the device and operation of the surgical end-effector is controlled by the surgeon using a PC-based graphical user interface that provides video feedback. A joystick controls the direction of travel and offers two speeds of travel. The visual feedback is relayed to an external video camera by a fiberscope running through the tether.

E. *Therapy*

By employing a modular design for end-effector attachment, the TEC will be capable of performing a variety of surgical treatments. Epicardial lead placement for resynchronization is an immediate application for which the TEC would prove ideal [3]. More innovative procedures, such as epicardial delivery of myoblasts or stem cells for regeneration of the failing myocardium, could also be facilitated by the TEC as their clinical use increases. The actuation for these end-effectors will either be provided directly by an on-board motor or transmitted from an external motor through the tether.

III. Testing

As an experimental proof of concept, we tested the off-board motor TEC prototype on the surface of poultry tissue. This design has proven effective in both adhering to and traversing the biological tissue, as shown in Fig. 3. With a vacuum pressure of -680 mmHg, the TEC was able to maintain excellent prehension of the tissue without damaging the surface. Turning was successful despite the low resistance of the poultry tissue to shear forces.

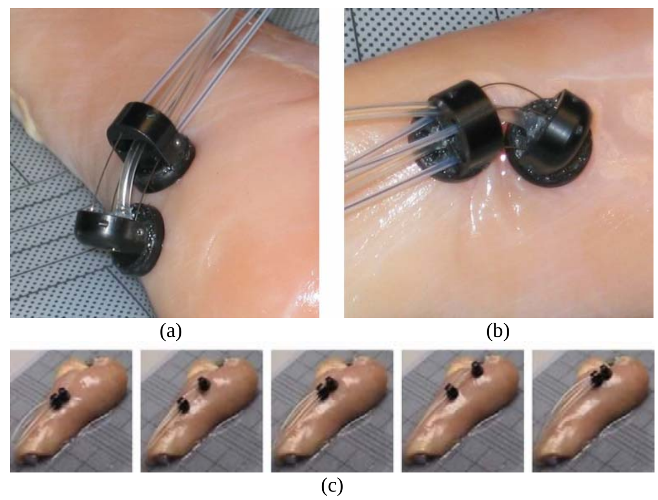

Fig. 3. Photographs of the TEC prototype during the poultry test: (a) adhering to the tissue, (b) turning, and (c) walking.

IV. Discussion

The feasibility of inchworm-like locomotion on biological tissue using the TEC has been demonstrated. In the future we will incorporate pressure sensors at the electronic valves to enable verification of adequate prehension of the surface during locomotion. Future work will also include *in vivo* tests on beating porcine cardiac tissue, and development of surgical end-effectors as described in Section II.E.

References

[1] M. P. R. Watters, R. Ascione, I. G. Ryder, F. Ciulli, A. A. Pitsis, and G. D. Angelini, "Haemodynamic changes during beating heart coronary surgery with the 'Bristol Technique,'" *Eur. J. Cardiothorac. Surg.* 19:34-40, 2001.

[2] V. Falk, A. Diegler, T. Walther, R. Autschbach, and F. W. Mohr, "Developments in robotic cardiac surgery," *Curr. Opin. Cardiol.* 15:378–387, 2000.

[3] H. Mair, J. L. Jansens, O. M. Lattouf, B. Reichart, and S. Dabritz, "Epicardial lead implantation techniques for biventricular pacing via left lateral mini-thoracotomy, video-assisted thoracoscopy, and robotic approach," *Heart Surg Forum* 6(5): 412-417, 2003.