Sand Blasting Inside a Patient: A CRISP Robot for Spraying Powder inside the Chest Cavity to Preclude Lung Collapse

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INTRODUCTION

We present a novel clinical application for a new kind of robot that self-assembles inside the patient. It is made of multiple needles that capture one another with snares at their tips. Each needle bends continuously, making the entire system a continuum, reconfigurable, incisionless surgical parallel (CRISP) robot, as shown in Fig. 1. It is incisionless because its needle-diameter (<3mm) tools are so small that no sutures are required after surgery.

The CRISP robot moves as robot arms outside the patient apply movements to the base of each needle. The robot motions are coordinated using mechanics-based models of the needles and the constraints imposed on one another when coupled [1] [2]. This enables the system to achieve tool tip motions specified by the physician.

In this paper, we explore using the CRISP system for pleurodesis, a medical procedure to which surgical robots have never previously been applied. Pleurodesis prevents lung collapse by intentionally introducing an irritant (e.g. talc powder) that causes the visceral pleura and parietal pleura to adhere to one another through scar formation. It is used for patients with recurrent lung collapse, buildup of fluid around their lungs (e.g., due to cancer), or who have had a first lung collapse and work in jobs in which subsequent collapses could be catastrophic (e.g., as an airplane pilot). Without pleurodesis, patients suffering a spontaneous lung collapse have a 20% chance of recurrence after their first episode, 60% after the second, and 80% after the third [3].

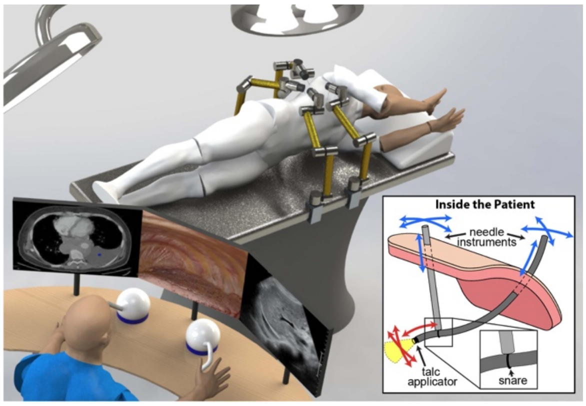

Fig. 1: The CRISP robot gives the surgeon percutaneous access to the pleural space. Robot manipulators outside the patient control each needle in a coordinated manner.

Pleurodesis is improved by an even distribution of powder applied to the surface of the pleurae (see Fig. 2). Pleurodesis can fail if there is a "patchy distribution of talc" [4], and fails up to 57% of the time when attempted using an indwelling pleural catheter that cannot be actively aimed inside the body [5]. The alternative, if the physician wishes to aim the powder delivery tube, is currently thoracoscopic surgery, which requires larger incisions to admit endoscopes and other tools [6].

In this paper, we propose the CRISP robot as a new and less invasive way to deliver the powder to the pleura. We hypothesize that the CRISP robot approach will enable surgeons to more thoroughly cover the pleural surfaces with powder during pleurodesis and do so solely through needle-sized openings that produce no scarring and do not even require sutures after surgery. This promises to enable better pleural adhesion and a lower recurrence rates of lung collapse for patients.

MATERIALS AND METHODS

Our CRISP robot prototype system is shown in Fig. 3a. To enable the needles to attach to one another within the patient, a snare made of a Nitinol wire basket is inserted through a needle made of superelastic Nitinol tubing (OD: 1.17 mm, ID: 0.85 mm). This needle is used to grasp the powder deployment tube inside the chest cavity, which is made from PEEK (OD: 1.70 mm, ID: 1.00 mm). The base of each needle is controlled by a robot manipulator (AUBO Robotics). The insertion length of each needle is controlled by a linear actuator consisting of a motor driving a lead screw.

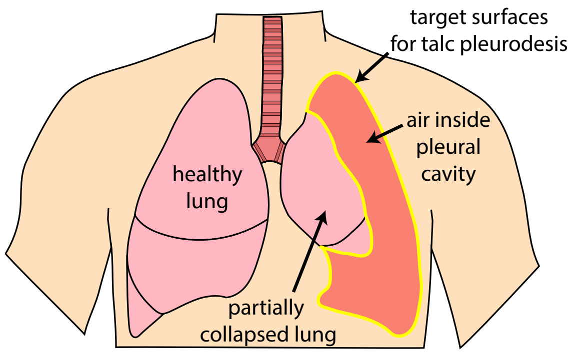

Fig. 2: Pleurodesis prevents recurrent pneumothorax (collapsed lung) by using chemical agents (e.g., talc powder) to irritate and adhere the pleural surfaces outlined in yellow.

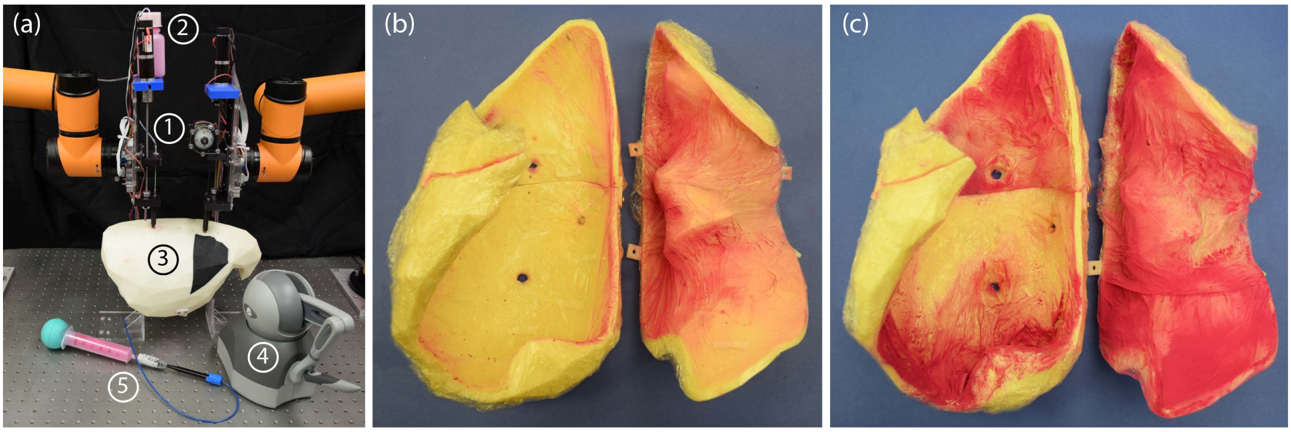

Fig. 3: (a) Experimental setup showing (1) CRISP robot, (2) powder container, (3) phantom model, (4) haptic control device, and (5) manual powder applicator. (b) Powder spraying results using manual method. (c) Powder spraying results using CRISP robot.

Our CRISP robot prototype is teleoperated with a 3D Systems Touch haptic device. The user controls the pose of the distal end of the powder spray tube using resolved rates control. The points along the needle shafts that coincide with the chest wall are programmed to remain at remote center of motion points, as described in [2].

Experiment Design: To evaluate the surface coverage improvement enabled by our robot, we compared it to the current manual approach. The manual approach consists of deploying the powder applicator through or attached to a rigid endoscope and tilting it to aim the powder. We simulated this by tilting the powder delivery tube through all possible angles through the entry port while spraying powder. To perform these experiments, we created a phantom model of the lung cavity by segmenting a CT scan of a patient with a partially collapsed left lung. We segmented the air in the pleural space and 3D printed an anatomically accurate volume. The phantom interior was lined with a transparent film layer covered with slow tacking spray adhesive to enable powder to adhere to the film. To facilitate these experiments, the phantom was made in two halves, so that the top half of the cavity could be sprayed while viewing through the bottom, and vice versa. Both the robotic and manual experiments were conducted in this manner.

The powder was colored red to enable easy visualization of surface coverage. After spraying the powder onto the surface, the film covering the interior of the lung cavity was removed and photographed. Coverage percentages were computed in MATLAB by thresholding HSV images to segment colored regions and converting pixel dimensions to physical dimensions using a ruler that was included in each image.

RESULTS

The results of the manual spraying are shown in Fig. 3b. Since the tube could only be tilted, and not bent to aim at all surfaces, it could achieve good coverage only on the side of the cavity opposite to the one where it entered the chest (i.e., the right-hand side of Fig. 3b). In contrast, the CRISP robot enabled the tube to be aimed in many directions, as shown by the greater coverage visible in Fig. 3c. In particular, notice the improved coverage of the surface of the cavity through which the spray tube was introduced. Quantitatively, image processing revealed that the robotic method covered 860 cm^2 of the interior area, while the manual method achieved 513 cm^2.

DISCUSSION

As seen in Fig. 3, more complete coverage of the pleural surface was achieved with the CRISP robot, due to its ability to aim the powder applicator within the chest cavity. This illustrates the feasibility of delivering better coverage less invasively than can be done by current manual techniques, which seems likely to improve the success rate of the procedure. We believe this is just one of many potential interventions that may be enabled in the future by the CRISP approach. The ability to access the lung cavity with a teleoperated system through needle-size openings that do not scar and require only a simple band-aid to close after surgery opens up new possibilities in less invasive lung biopsy and intervention, that may one day improve outcomes for many patients.

REFERENCES

[1] Mahoney, et al., "Reconfigurable Parallel Continuum Robots for Incisionless Surgery," in *IEEE/RSJ IROS*, 2016.

[2] Kuntz, et al., "Motion Planning for Continuum Reconfigurable Incisionless Surgical Parallel Robots," in *IEEE/RSJ IROS*, 2017.

[3] Chan, et al., "Efficacy study of video-assisted thoracoscopic surgery pleurodesis for spontaneous pneumothorax," *Annals of Thoracic Surgery,* 71(2):452-454, 2001.

[4] Massard, et al., "Minimally Invasive Management for First and Recurrent Pneumothorax," *Annals of Thoracic Surgery,* 66(2):592-599, 1998.

[5] Bhatnagar, et al., "Outpatient Talc Administration by Indwelling Pleural Catheter for Malignant Effusion" *N. Eng. J. Med.* 378(14):1313-1322, 2018.

[6] Viallat, et al., "Thoracoscopic talc poudrage pleurodesis for malignant effusions: a review of 360 cases," *Chest,* 110(6):1387-1393, 1996.