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A Fluidic Actuated Soft Robot for Improving Bronchoscopic Biopsy

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INTRODUCTION

Lung cancer has long been one of the deadliest forms of cancer in large part due to the difficulty in diagnosis when at its earlier stages [1]. Because of their large diameter (i.e., ≈ 6 mm) preventing them from navigating in the peripheral lung, traditional bronchoscopes used in minimally invasive biopsy encounter difficulty when trying to reach smaller, deep-seated lesions [2]. Robotic solutions have been developed to address these limitations in surgical navigation. Commercial robotic bronchoscopy systems, like the Auris Monarch™ and Intuitive Ion™, consist of tendon-actuated continuum robots which focus on navigation and biopsy deeper into the lung periphery [3]. Soft robots present a promising alternative to these commercial robotic systems due to their scalability, inherent flexibility, and potential for safer interactions with biological tissue, making them well-suited for procedures in the peripheral lung [4]. Furthermore, the materials used in soft robotics are generally more economical and allow seamless integration of soft robotic actuation and sensing mechanisms. Exploration of various actuation methods, such as magnetic and fluidic, have demonstrated navigation capabilities in hard-to-reach areas of the lung and the ability to integrate useful tools, such as needles and cameras [5], [6]. However, with miniaturization, the ability of soft robots to transmit forces and interact with the surrounding biological tissue diminishes.

We propose a 3.5 mm diameter soft robot with embedded degrees of freedom (DOFs) for tip steering, tip stabilization, and needle deployment for tissue biopsy in bronchoscopy procedures (Fig. 1). Via soft actuators in its continuum body, the robot can navigate through the lung branches to the target lesion and anchor itself within an anatomical channel by pressurizing each respective actuation chamber. After anchoring, a needle may be deployed using a bellows shaped chamber from the robot tip using an origami-inspired soft actuator to puncture the target lesion and take a biopsy. The fluidic actuated DOFs embedded in the proposed robot seek to reach deeper into the lungs, actively increase force transmission at the millimeter scale, and distally control the biopsy needle laying the framework for enhanced surgical capabilities in minimally invasive bronchoscopy procedures.

MATERIALS AND METHODS

The continuum body, seen in Fig. 2A, holds two actuation chambers, one off-center along its axis for steering and one circumferential around its tip for stabilization via radial expansion. The tip needle deployment DOF of the robot consists of a 3 mm diameter bellows actuator with a mounted needle, as shown in Fig. 2B. The robot is fabricated using a series of molding processes for the continuum body and a heat-pressure based method for the needle deployment DOF. The base of the continuum body, made of DragonSkin 10, is molded with the axial chamber and base of the circumferential chamber. The stabilization membrane is subsequently molded using Ecoflex 00-30 to promote the radial expansion of the stabilization DOF, as seen in Fig. 2C. The axial chamber, shown pressurized in Fig. 2D, is sealed at the tip of the continuum body to complete the steering DOF. The needle deployment DOF is fabricated by the heat-pressure induced bonding of thermoplastic elastomer (TPE) (Stretchlon 200, FiberGlast USA) and masking of fluidic chambers via PTFE films. Each layer of TPE and PTFE is laser cut with a circular pattern and layered such that the resulting bellows are connected in series, as seen in Fig. 2B. The resulting actuator is fitted with stainless steel plates to mount a biopsy needle and fixed to the robot tip using Sil-Poxy adhesive. These inexpensive, soft materials make the robot disposable after a procedure.

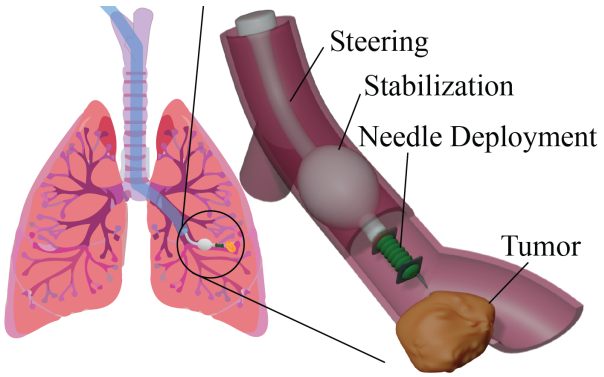

Fig. 1 The fluidic actuated soft robot with steering, stabilization, and needle deployment DOFs to take a lung biopsy.

RESULTS

To characterize the increase in force transmission due to stabilization, the robot was fixed in a 6 mm diameter tube and a displacement of 2 mm was applied to its tip with an ATI Nano17 force sensor. Force was measured over three repetitions for when there was no stabilization and with stabilization deployed. Force characterization of the stabilization DOF found that the effective stiffness of the

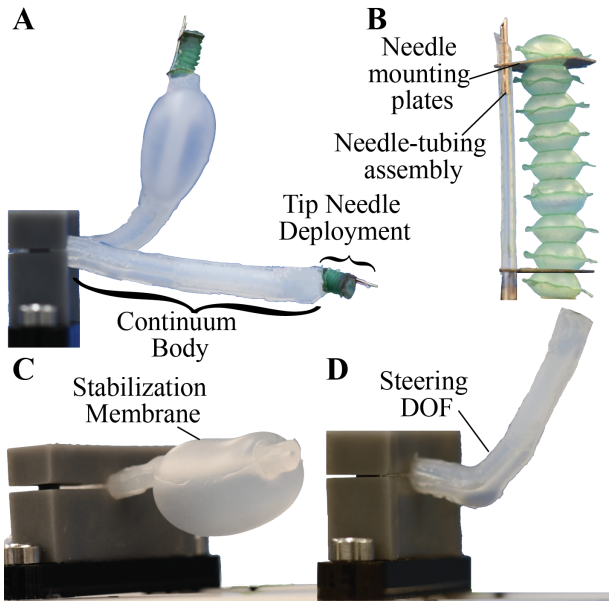

Fig. 2 A) Continuum body DOFs and needle deployment DOF in actuated and unactuated states. B) Bellows actuator for needle deployment. C) Pressurized stabilization membrane and (D) steering DOF on the continuum body.

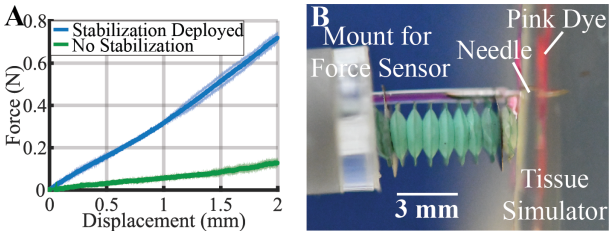

Fig. 3 Force characterization of (A) the stabilization DOF and (B) puncture with the needle deployment DOF.

tip increased by 5×, as seen in the results in Fig. 3A.

To verify the force transmission to the needle, the needle deployment DOF was mounted to the Nano17 force sensor ≈6 mm away from a tissue simulator made of 10% by weight gelatin (Knox Gelatin) and pressurized with air to 100 kPa to puncture (Fig. 3B). Two separate speeds were used to measure force. The slower speed pressurized the mechanism in 5 kPa steps up to 100 kPa over 60 seconds. The faster speed pressurized the mechanism immediately to 100 kPa within 1.75 seconds. Both speeds yielded similar results with the average recorded force necessary to puncture being 0.06 N. The measured result aligns with the previously determined force to puncture lung tissue of 0.088 N [6]. Puncture of the tissue simulator was visually confirmed by injecting pink dye, as seen in Fig. 3B.

An *in-vitro* test was performed by imitating a bronchoscopic biopsy procedure. The soft robot was inserted into a 3D printed lung model (Elastic 50A, Formlabs, USA) to demonstrate the intended surgical workflow of steering to the target (Fig. 4, A-B), stabilizing within the branch (Fig. 4, C), and deploying a needle into the tissue simulator (Fig. 4, D). Pink dye was again injected into the tissue simulator at the end of the lung model for visual confirmation of biopsy. The continuum body was dyed green for clear visualization within the lung model.

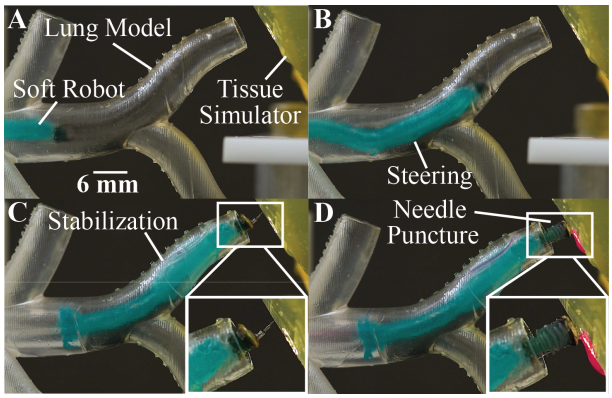

Fig. 4 In-vitro demonstrations for the fully assembled soft robot in a 3D printed lung model.

DISCUSSION

This study demonstrates the potential to give surgeon's greater control over their tools in interventional bronchoscopy by integrating multiple distal DOFs into a mm-scale soft robot. The robot actively increases tip forces during biopsy and distally controls a biopsy needle. At a 3.5 mm diameter, the robot can reach deep into the lungs with the advantages over commercial bronchoscopy systems being high flexibility, safer tissue interactions, and a needle that initiates puncture from the tip. The materials used also make it easily disposable. Further, the robot can achieve these advantages due to the ability to actively increase stiffness by 5×. It uses this greater stiffness to transmit the measured 0.06 N force through the needle from its tip rather than through the body of the bronchoscope as is done in current biopsy procedures. The proposed robot can successfully steer, stabilize, and puncture within our mock anatomical setup demonstrating its ability to operate in a similarly scaled environment. Future work will also focus on ex-vivo and in-vivo animal experiments to validate the robot on biological tissue.

ACKNOWLEDGEMENTS

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