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# A Continuum Lung Stapler Leveraging Phase Changing Metal for Dexterity and Stiffness

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## INTRODUCTION

Lung cancer claims over 130,000 lives per year in the USA [1]. For those with malignant tumors requiring resection, minimally invasive thoracic surgery via a video assisted or robotic approach is an alternative to highly invasive open thoracotomy (in which the chest is "cracked" open). This involves the insertion of 3-5 ports through the chest wall and the use of a camera and instruments mounted to rigid shafts, which are used to resect tissue in a deflated lung. One of these tools is typically a stapler which is able to simultaneously cut and seal the lung tissue [2].

Tendon-driven continuum robots (TDCRs) are capable of curvilinear motions, which can add useful dexterity in constrained anatomical regions like the chest [3]. However, the inherent flexibility of TDCRs presents challenges for integrating stapler-type end effectors. Lung staplers today are typically rigid tools because they require large axial forces to be transmitted along the tool shaft to fire staples. Such forces would apply large loads to curved continuum devices, changing their shapes and moving the end effector undesirably during staple firing.

Low melting point alloys (LMPA) have been explored to stiffen substantially soft robots [4] and compliant surgical devices [5], [6]. Here, we propose their use in a TDCR stapler to stiffen the tool shaft before staples are fired. Prior to stiffening, tendon actuation can provide enhanced maneuverability by curving the backbone compared to rigid staplers to position the stapler at the desired location.

## STAPLER DESIGN

We removed the staple head and actuation mechanism (Fig. 1a) from a clinical stapler with a rigid shaft (Fig. 1b: Covidien 30 mm Tri-Staple 2.0), and designed a TDCR upon which to mount it. The TDCR's 10mm diameter matches that of the stapler shaft, and it contains an inner channel to guide the stapler head's actuation mechanism, shown in Fig. 1c and d. To stiffen the manipulator, we use Field's metal, a LMPA with a phase transition temperature of 62° C. The distal 100 mm of the manipulator has a rectangular channel to accommodate the actuation strips that push the staple mechanism through the top and bottom jaws, and an LMPA chamber surrounding the actuation mechanism. The LMPA is heated with embedded nichrome wire (28 gauge) which is electrically insulated with polyimide. The proximal 50 mm of the cross section has a circular LMPA chamber around the inner actuation channel that houses the actuation rod (1.2mm diameter spring steel) to push the actuation strips (see Fig. 1d). As with current clinical staplers, the actuation mechanism closes the jaws in the first few millimeters of its travel, and then advances a

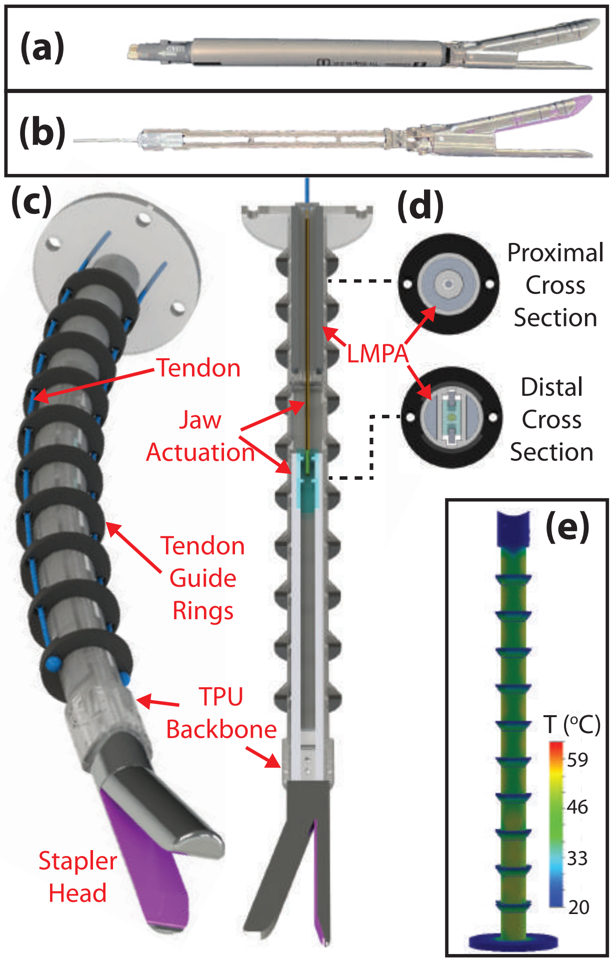


**Fig. 1** (a) The rigid Covidien Tri-staple Reload. (b) Disassembled stapler head is integrated into our design. (c) LMPA continuum stapler. (d) Cross-sectional views show the LMPA which enables switching between flexible (liquid LMPA) or stiff (solid LMPA). (e) Thermal simulation shows that the LMPA will not excessively heat the manipulator's surface.

mechanism that both pushes staples into tissue and cuts tissue between the staple lines along the 30 mm staple length. The tendon guide rings were 3D printed using carbon fiber reinforced Nylon, and contain two holes on either side of the prototype to thread the tendons axially; these parts were embedded in the TPU material as it was printed (*Bambu Carbon X1*). The Field's metal alloy was injected into the channels in the manipulator, and sealed in with flexible epoxy.

## RESULTS

We quantified the force required to fire a staple by directly pushing on the jaw/stapler actuation mechanism; the peak force was 160 N. To demonstrate how the LMPA

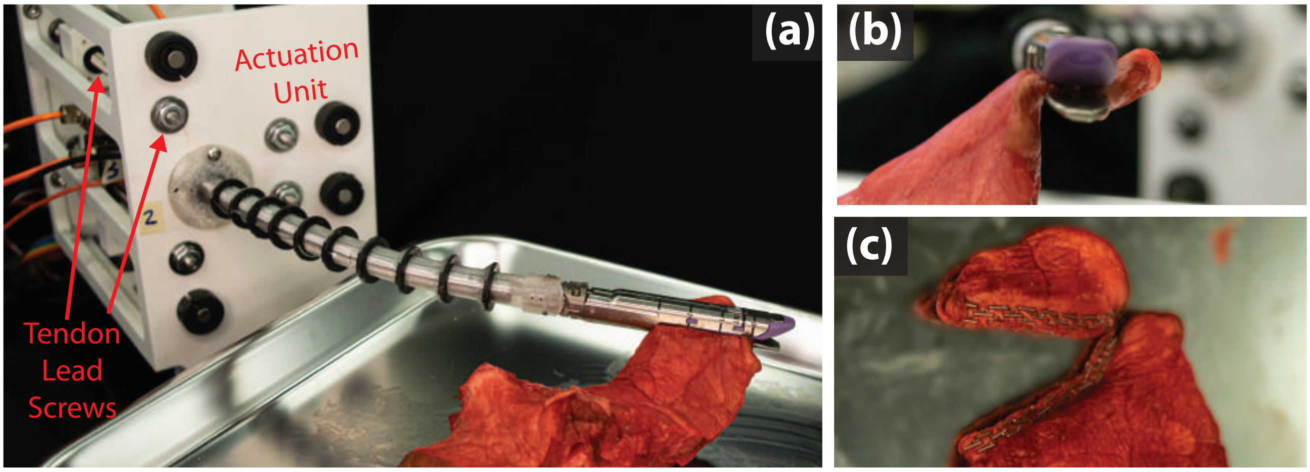


**Fig. 2** (a) The LMPA stapler is solidified in a curved configuration so that it can be actuated without deflecting. (b) Closeup of the stapler head as the jaws close on a sample of porcine lung tissue. (c) Porcine lung sample after staple is applied.

stiffening enables the continuum arm to fire a staple, we actuate the staple mechanism in both the liquid and solid state. First, we use a tendon to bend the manipulator into a curved configuration ($\approx$ 35° tip bending), and lock the tendon displacement. With the metal still liquified, we actuate the jaw mechanism; Fig. 3a shows that the tip deflects significantly, even in the early stages before the jaws close (let alone under the much higher loads needed to fire staples and advance the cutting blade). With manipulator in the nominally curved configuration, we let the metal solidify and then actuated the jaws again. This time the jaws were able to close and advance the blade/staple firing mechanism with minimal tip deflection (Fig. 3b).

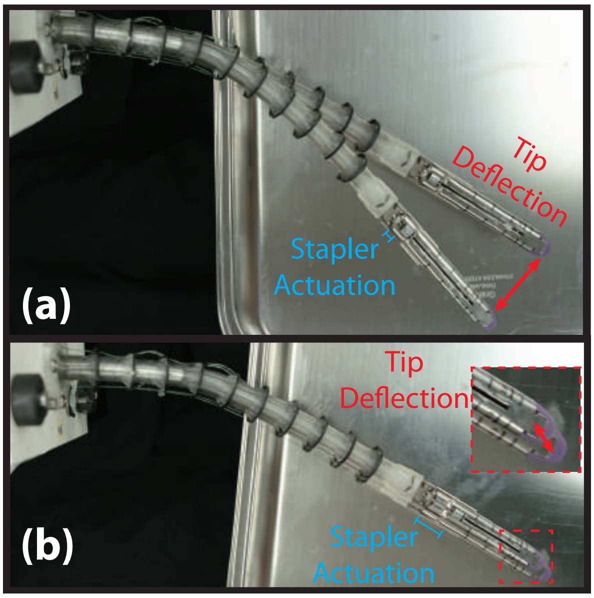


**Fig. 3** Stiffness change between the liquid and solid state. The manipulator was actuated into a curved configuration with LMPA in the liquid state. (a) Actuation of the staple jaws (blue) with fixed tendon displacement, which causes significant deflection (red) and the staples cannot be fired. (b) With the LMPA solid and in the same curved configuration, the jaw can close and fire staples with minimal tip deflection.

We conducted a thermal simulation to verify that the design has the potential to be safe for medical applications. When the metal is heated to 65°C (above its 62°C melting point), the average exterior shaft temperature is predicted to be 43°C, while that of the guide rings (in direct tissue contact) is 34°C; see Fig. 1e.

Finally, we demonstrate the proof-of-concept feasibility of the design by firing a staple into porcine lung tissue. The LMPA segment was melted in 90s with 1.5A (10V) of power applied to the heating wire. The left tendon was actuated to bend the manipulator so the tip was angled 35°. Solidification of the LMPA via ambient cooling took 120s. The actuation rod was manually advanced close the jaws and fire the staple, (Fig. 2a and b), as shown in 2c.

## DISCUSSION

In this work we demonstrated a proof of concept continuum stapler based on LMPA stiffening. We show how the mechanism can be actuated as a conventional TDCR when the LMPA is in the liquid state. The ability to curve the device with tendons can enable surgeons to maneuver tools in new ways. The LMPA can then temporarily stiffen the device, enabling it to withstand the loads required to fire staples. Note that it has been previously shown that fluid heating and cooling can reduce LMPA phase transition time to < 20s [5]. In future work, we plan on integrating more, potentially non-linearly routed, tendons to achieve complex 3D shapes [7] that could be optimized to enhance the device's workspace for the lung surgical workspace requirements.

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