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A Soft Laparoscopic Grasper for Retraction of the Small Intestine

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INTRODUCTION

Laparoscopy can improve outcomes and patient recovery times compared to open surgery. However, the minimally-invasive nature of these procedures deprives clinicians of tactile feedback which, when coupled with pinching graspers that deliver high-stress concentrations, increases the likelihood of inflicting iatrogenic trauma upon tissues, especially the small intestine [1]–[4].

Retraction of the small intestine is often necessary to visualize and access nearby tissues [5], [6]. Commercially-available devices rely on passive structures to hold intestinal segments and do not embed compliance [7]. Prior research on surgical retractors has focused on granular jamming [5], pneumatic balloons [6], and either cable-driven [8] or vacuum [9] graspers. However, these devices are challenging to integrate into surgical workflows, require auxiliary instruments, and do not provide feedback regarding tissue interaction forces.

We introduce a laparoscopic grasper capable of passing through an 18 mm trocar, expanding to a controllable width once inside the abdominal cavity, and safely enveloping the small intestine to enable retraction. Upon entry into the abdominal cavity, the grasper establishes an initial hold on a target intestinal segment by pulling vacuum through the suction unit on its distal tip (Fig. 1[a]); this functionality helps the surgeon isolate the target intestinal segment from surrounding bundles. Once a preliminary suction hold has been established, the grasper envelops the intestine by inflating a pair of pneumatic fiber-reinforced soft actuators (FRSAs) (Fig. 1[b]-[c]), whose separation can be modulated up to 40 mm using a miniaturized scissor lift mechanism (MSLM). This approach distributes the force necessary to grasp and hold the intestine over a large surface area (i.e., the whole surface of the FRSAs) rather than concentrating it in a small region, allowing safe, robust grasps even on dilated intestinal segments. Inflation of the FRSAs and suction are controlled using two buttons (Fig. 1 [d]). The horizontal position of the FRSAs and the separation between them are independently actuated via two linear motors, which the surgeon controls using a rocker switch and trigger, respectively (Fig. 1 [d]). Each actuator is equipped with two soft sensors to interpret 3D interaction forces via a machine learning algorithm.

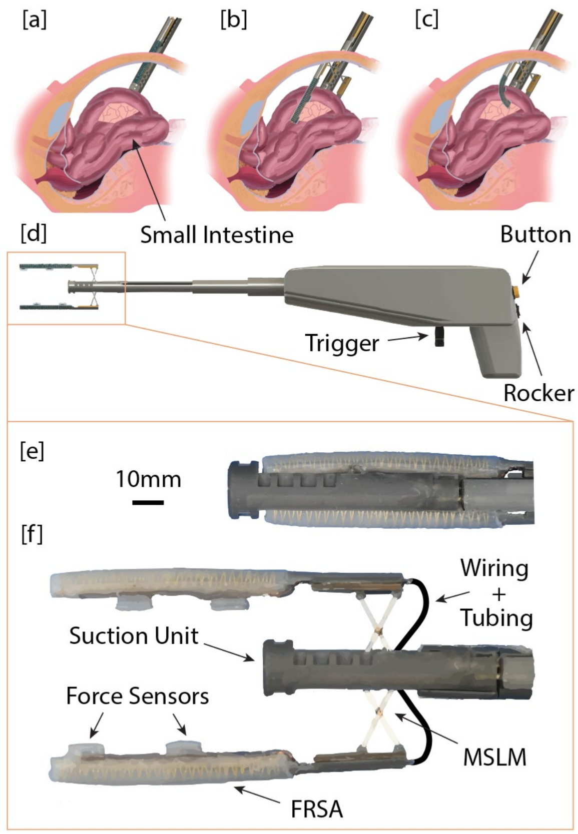

Fig. 1 [a] Activation of suction, [b] deployment of FRSAs, and [c] envelopment of intestine. [d] Complete grasper in [e] closed and [f] deployed configurations.

MATERIALS AND METHODS

The FRSAs are fabricated using Dragonskin 20 (Smooth-On), and are 70 mm in length with a semicircular cross-section of diameter 8 mm. The FRSAs are biased to perform a bending motion when pressurized due to a strain-limiting layer of Muslin fabric and Kevlar fiber wrappings (McMaster-Carr). One end is sealed with additional Dragonskin 20, and a custom pneumatic interface composed of Grey v4 Resin (Formlabs) is partially inserted into the open end for structural rigidity.

The FRSAs are deployed via the MSLM, which can adjust the separation of the actuators anywhere between the closed configuration (Fig. 1[e]) and 40 mm (Fig. 1[f]), sufficient to envelop both healthy and pathologically dilated segments of the small intestine [10].

Each FRSA is equipped with a pair of soft magnetometric sensors (see Fig. 1[f]) to monitor tissue-tool interaction forces during grasping. The soft force sensors consist of a triple-axis magnetometer (Melexis) and a 1.6 mm diameter, 0.8 mm thick N52 NdFeB magnet (K&J Magnetics) embedded in Ecoflex 00-50 (Smooth-On). The sensors transduce a 3D force input into a nonlinear, coupled 3D magnetic field vector output. A TensorFlow dense neural network (DNN) with three hidden layers was used to interpret sensor calibration data, given its simplicity, accuracy, and microcontroller compatibility. Electrical signals are routed using a printed circuit board (PCB) that conforms to the FRSA curvature. This flexible PCB consists of alternating layers of spin-coated Ecoflex 00-10 silicone (Smooth-On) and 500 μm-thick laser-cut copper traces (McMaster-Carr).

The stroke of the FRSAs was determined using an electromagnetic tracking system (Northern Digital Inc., Aurora), and the forces generated at their tips were obtained via a blocked force test using a NANO17 6-axis force transducer (ATI Industrial Automation Inc.). The soft sensors were calibrated using the NANO17 and a U5e Universal Robot, and the ability of the grasper end-effector to hold a tissue sample was assessed using standard weights and an explanted porcine small intestine.

RESULTS

Results of the FRSA stroke and force tests are reported in Fig. 2[a-b]. The FRSAs bend with radius $\approx$ 22 mm, and exert >2.5 N at their tip. When pressurized to 250 kPa, the grasper end-effector can hold 500 g (Fig. 2[c]), and retract an explanted porcine small intestine (Fig. 2[d]).

The DNN uses an 80% training - 20% validation data split and 100 epochs to interpret soft sensor calibration data; the forces recorded by the NANO17 are plotted against the DNN-predicted values in (Fig. 2[e]-[g]). The maximum mean absolute error was found to be 0.16 N in a normal force range of 0–10 N and a shear force range of 0–2 N.

DISCUSSION

We introduce a laparoscopic grasper capable of retracting the small intestine via atraumatic envelopment. The utilization of inherently compliant FRSAs, accompanied by a deployable MSLM and an array of soft sensors capable of transducing 3D forces, enable the proposed device to manipulate intestinal segments safely. Future work will focus on *in-vitro* testing using abdominal phantoms and evaluating grasping of simulated dilated intestines.

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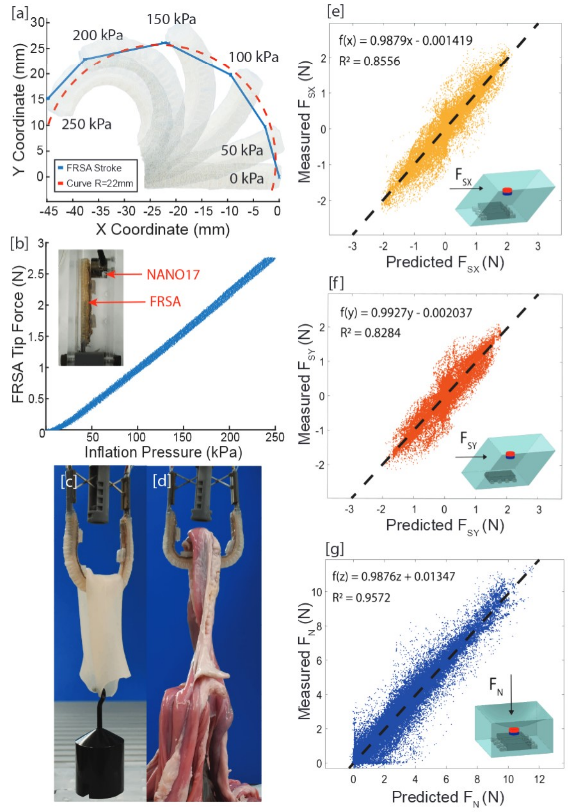

Fig. 2 Plots of FRSA tip [a] position and [b] force during inflation. [c] Grasper holding 500 g silicone tube and [d] explanted porcine small intestine. Measured vs DNN-predicted [e] X shear (F$_{SX}$), [f] Y shear (F$_{SY}$), and [g] normal (F$_N$) forces applied to sensors, with best fit lines.

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