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Monitoring Forces in Soft Robotic Brain Retraction via Origami Sensing Modules

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INTRODUCTION

To safely access deeper regions of the brain for procedures like tumor resection, surgeons must displace (i.e., retract) healthy tissues usually through the use of rigid, metal spatulas [1]. However, required retraction forces up to 2.5 N have been shown to increase intracranial pressures beyond the safe range of ≈ 2-3.3 kPa and cause neurological complications when applied over sustained durations [1], [2]. Soft robots have shown the potential to address the need for safer access in neurosurgery by leveraging their inherently safe tissue interactions for tasks such as deploying electrocorticography arrays [3] and navigating brain vasculature [4]. However, there remains a need to quantitatively monitor retraction forces so as not to cause injury to healthy brain tissue. In our previous work, we introduced a soft robotic retractor that distributed retraction forces and generated a surgical workspace through origami-inspired actuation [5]. Here, we present origami sensing modules (OSM) with the ability to monitor tissue interaction forces of the soft robotic retractor via a capacitive sensing modality (Fig. 1). The OSM folds with the elliptical Miura origami pattern of the robot so that contraction/expansion over vacuum pressures and stiffening over positive pressures can retract tissue while monitoring forces (Fig. 1A). By implementing force sensing into the soft robotic retractor, the proposed OSMs seek to reduce unintended trauma and improve the overall safety of tissue retraction in neurosurgical procedures.

MATERIALS AND METHODS

Capacitive sensing is achieved through the use of a layer-by-layer fabrication technique in which laser cut, conductive copper films (Pyralux, DuPont) are stacked with a flexible dielectric so as to act as electrodes. The dielectric comprises a positive pressure stiffening actuator surrounded by Ecoflex 00-50 (Smooth-On, USA) (Fig. 1B). The stiffening actuator is assembled separately using a heat-pressure bonding method in which Teflon acts as a masking layer between thermoplastic elastomer (TPE) layers. Ecoflex is spincoated onto each electrode to achieve consistent dielectric thickness of 0.68 mm.

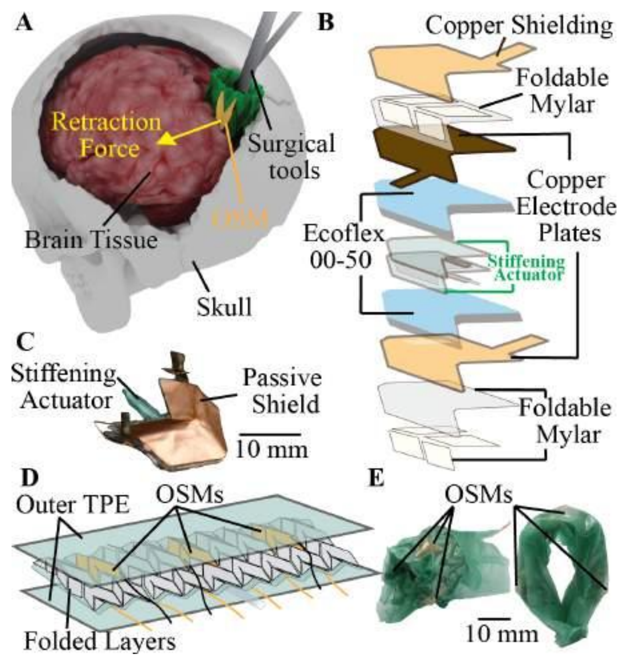

Fig. 1 A) Overview of proposed soft robotic retractor monitoring retraction forces in neurosurgery. B) Schematic of the layer-by-layer manufacturing of the origami sensing modules and materials employed. C) Individual sensing module as a Miura origami unit cell. D) Integration into the soft robotic retractor. E) Final elliptical shape of the robotic retractor.

Laser cut Mylar films reinforce the Miura folding behavior on each side of the OSM via the stacking of Miura-patterned Mylar over unpatterned Mylar. A copper shielding (Fig. 1B) is the outermost layer to mitigate proximity and parasitic effects on the electrodes. All layers attached to the outside of the electrodes are adhered using pressure sensitive adhesive (467MP, 3M, USA). All of the materials used for the soft robot construction are biocompatible. Further, the robot is entirely encapsulated (including sensing wiring) in biocompatible TPE layers (the only material in contact with tissue), making the robot readily translatable into a clinical environment. The complete layering schematic, outlined in Fig. 1B (without the adhesive), results in the OSM shown in Fig. 1C. Through this layering method, the foldable Mylar and stiffening actuation layers are extended into a rectangular sheet with OSMs embedded at three equally-

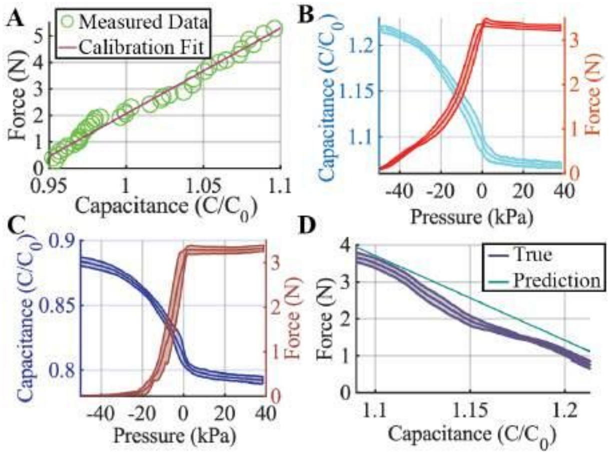

Fig. 2 A) Force calibration of the OSM major axis. B) Capacitance and force varying over actuation pressure in major and C) minor axis. D) Validation of force prediction by the OSM averaged over three trials.

spaced locations (Fig. 1D). This pattern is manually folded to obtain a 9×4 cm Miura origami shape. As seen in Fig. 1D, an outer TPE layer seals the resulting folded layers so that, by applying vacuum, contraction of the robot can be controlled. The robot is sealed into an elliptical configuration (Fig. 1E) with flexible adhesive (Loctite) to allow for the passage of surgical instruments through its opening following the retraction of tissue (i.e., release of vacuum pressure). Integration of the three OSMs into the origami pattern was determined based on the major and minor axes of expansion to monitor forces along each axis independently.

RESULTS

To calibrate the OSMs on the robot, applied forces were measured on the major axis by an Instron and on the minor axis by two ATI Nano17 F/T sensors during immediate expansion of the retractor from -50 to 0 kPa and stiffening up to 40 kPa. A capacitance-to-digital converter (AD7746, Analog Devices) recorded capacitance changes during experiments. Applied force was varied from 0 to 5 N by constraining the robot with the Instron at various heights to achieve 0.1 N increments. The linear trend found in Fig. 2A results in a calibration curve for each axis. From these results, we calculate a sensitivity of 0.032 $N_{\surd}^{1}$ resulting in a resolution of about 0.25 N.

The robot was also fixed in a fully contracted (-50 kPa) state in a rigidly constrained environment to measure capacitance response over varying pressure. Capacitance and force were recorded for major and minor axis as pressure was increased up to 40 kPa in 1 kPa steps as shown in Fig. 2B and Fig. 2C, respectively. In this configuration, a maximum force of 3.3 N is achieved in each axis with the normalized capacitance decreasing linearly with increases in force. The experiment was repeated with the Instron moved 1 mm into the retractor (i.e., force is preloaded) to validate the predicted force (Fig. 2D). This case shows the OSMs predict forces over varying pressure with an average error of 0.38 N.

To test the sensor and prediction method in an *in-vitro* setting, brain tissue was simulated using molded gelatin

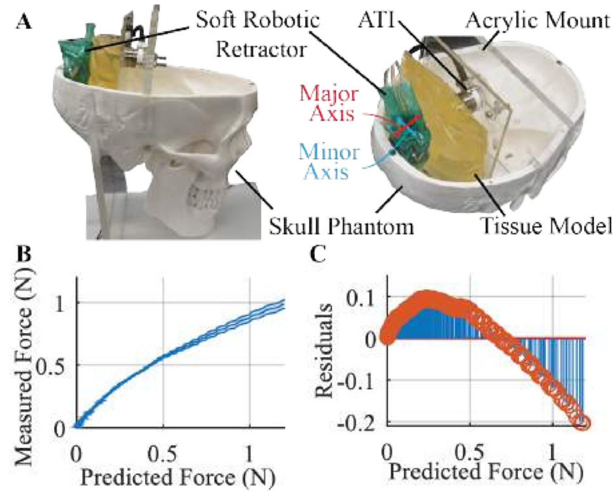

Fig. 3 A) In-vitro experimental setup monitoring the force output on simulated brain tissue. B-C) Predicted force compared with actual measured force averaged over three trials.

(Knox Gelatin) with a thickness of approximately 20 mm. The tissue model was placed inside a skull phantom to mimic the neurosurgical environment, as shown in Fig. 3A. An ATI sensor was mounted behind the tissue model to measure the force output of the robot. The robot was inserted in a fully contracted (-50 kPa) state and expanded/stiffened up to 40 kPa. A predicted force on the brain of up to 1.2 N is measured by the OSMs as seen in Fig. 3B. The average error in these predictions (Fig. 3C) is 0.06 N or 5% of the full measured range.

DISCUSSION

Our soft robot can manipulate brain tissue and monitor force interactions, paving the way for enhanced safety in neurosurgery. Using layered fabrication techniques enables the creation of a folding OSM that measures force based on changes in capacitance. The measurable changes of 0.25 N over the 0-5 N range translates into an equivalent resolution of about 0.5 kPa changes in intracranial pressure. Therefore, potential harmful pressures over 3 kPa [2] may be detected and thus, prevented by the surgeon. *In-vitro* experiments demonstrate the accuracy of the robot in a simulated surgical setting with an average error of 0.06 N. Future work will focus on closed-loop control from the sensor feedback and *in-vivo* validation.

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