A soft pop-up proprioceptive actuator for minimally invasive surgery

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INTRODUCTION

Surgical robots and miniaturized smart instruments have been developed to overcome limitations of current tools and further reduce invasiveness of surgical procedures [1][2]. This miniaturization effort, as well as the development of more flexible instruments that can navigate the body following complex anatomical paths toward the surgical target, often leads to the loss of sensory feedback and dexterity and increases design complexity. Developing mm-scale robots combining distal dexterity and sensor feedback at the surgical site would increase reliability and controllability, especially in flexible endoscopy, where the procedures are primarily based on visual feedback. However, this introduces several technical challenges because of the lack in viable manufacturing technologies at this scale: current approaches mainly rely on fiber optic based sensing systems [3]-[6]. Recently, a pop-up book inspired manufacturing technique has been utilized to fabricate surgical tools with embedded actuation and sensing [6]-[8]. Furthermore, soft materials and soft fluidic micro actuators have been introduced in this paradigm to fabricate soft pop-up mm-scale sensors and actuators for minimally invasive surgery (MIS) [8]. Advantages of this approach include low cost manufacturing, scalability, and flexibility in material selection. Furthermore, the use of soft material provides a safer interface with biological tissue. In this paper, we exploit the soft pop-up fabrication technique to develop a mm-scale bending actuator with proprioceptive capabilities based on capacitive sensing (Fig. 1).

MATERIALS AND METHODS

The soft fluidic micro actuator (SFMA) is fabricated using soft lithography and is composed of two soft layers bonded together via oxygen plasma treatment. The bottom layer is fabricated by spin coating MED-6033, a biocompatible silicone elastomer (NuSil, CA, USA), on a silicon wafer at 350 rpm for 100 s (resulting in a 500 μm thick membrane). The upper layer is fabricated by spin coating MED4-4220, another biocompatible silicone elastomer at 450 rpm for 100 s (400 μm thick membrane). Due to the different shore hardness of the two materials (50A and 17A respectively), the upper layer will expand when pressurized. The SFMA is integrated in the center of the system (Fig. 2) and bonded irreversibly to the rigid-flex laminate using a chemical surface modification process including oxygen plasma treatment and silanization using (3-Aminopropyl) triethoxysilane (APTES, Sigma-Aldrich Corp., MO, USA). The rest of the laminate is composed of glass-reinforced epoxy laminate sheets (254 μm thick) as rigid material, 9877 (3M, MN, USA) as a biocompatible adhesive (254 μm thick), and DuPont Pyralux copper/polyimide (18 μm copper and 25 μm polyimide) as a flexible layer with conductive electrodes, for a total laminate thickness of 1.83 mm (Fig. 2, left). A secondary conductive trace runs along the main trace to shield possible interference due to capacitance coupling (Fig. 2, right). The laminate is bonded together applying pressure and then laser machined to release the final mechanism. Tubes with an internal diameter of 254 μm (Micro-Renathane Catheter Tubing, Braintree Scientific, Inc., MA, USA) are inserted and sealed (Poxy Pak, Loctite, USA). The SFMA is pressurized with deionized (DI) water and its expansion causes the bending of the soft pop-up mechanism (Fig. 3a and b). The soft pop-up proprioceptive actuator is characterized using an experimental setup consisting of a programmable syringe pump (11 Elite, Harvard Apparatus, MA, USA), a pressure sensor (BSP B010-EV002-A00A0B-S4, Balluff, USA) connected to a NI USB-6002 board (National Instruments, Austin, TX, USA), and a capacitance-to-digital converter (AD7746 Analog Devices, MA, USA).

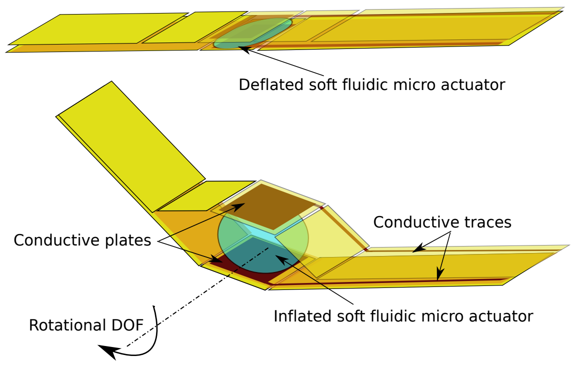

Fig. 1 Soft pop-up proprioceptive bending actuator with embedded capacitive sensing: top, flat configuration (actuator not inflated) and bottom, bent configuration (actuator inflated).

RESULTS

The experiment consisted of pressurizing the actuator by increasing the volume of DI water (0.012 ml for each step) at a flow rate of 0.01 ml/s, measuring the corresponding capacitance variation and resolving the relative bending angle visually. Images are taken by placing a camera on a tripod parallel to the system and analyzed in Matlab (Mathworks Inc., Natick, MA, USA). The capacitance measured during actuation is reported in Fig. 3c. Prior to actuation, the soft pop-up proprioceptive actuator is pre-bent of an angle of 17 °. This is due to intentional compression in the laminate to pretension the mechanism. The max pressure reached during testing is 200 kPa, corresponding to a maximum reached bending angle of 78°. Pressures in the same range have already been tested in devices for MIS safely [9]. The system response is compared with a linear fit and the results are reported in Fig. 3c.

DISCUSSION

In this paper, we integrate SFMA into rigid-flex laminates to achieve a soft/folded proprioceptive actuator based on capacitive sensing. Capacitance variation with relative bending angle is characterized showing a linear trend for a bending range from 17 ° to 78 °. According to [8], soft pop-up actuators are able to generate forces in the newton range and can withstand up to 500 cycles before failure. This soft pop-up proprioceptive actuator can be applied as a building block (i.e., a rotational joint) for developing novel mm-scale endoscopic robotic platforms or it can be combined with current flexible instrumentation, e.g., to steer a gripping tool during endoluminal tissue manipulation. The prototype is fabricated entirely with biocompatible components: all materials have been previously applied in disposable medical devices. The maximum measured speed that the actuator is able to achieve is 8.7 °/s with a flow rate of 0.12 ml/s. Future work will include analytical modeling of the capacitance response, plus the possibility of combining capacitance data with volume and pressure information in order to improve the motion accuracy. Furthermore, scalability of the system along with the possibility of integrating electronics on-board will be evaluated.

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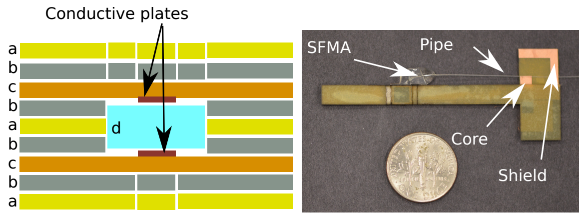

Fig. 2 Left: cross-section of the soft pop-up proprioceptive bending actuator laminate consisting of nine layers: a, b, c, and d the represent rigid, adhesive, flexible materials, and soft fluidic micro actuator respectively. Right: fabricated prototype after lamination and release cuts.

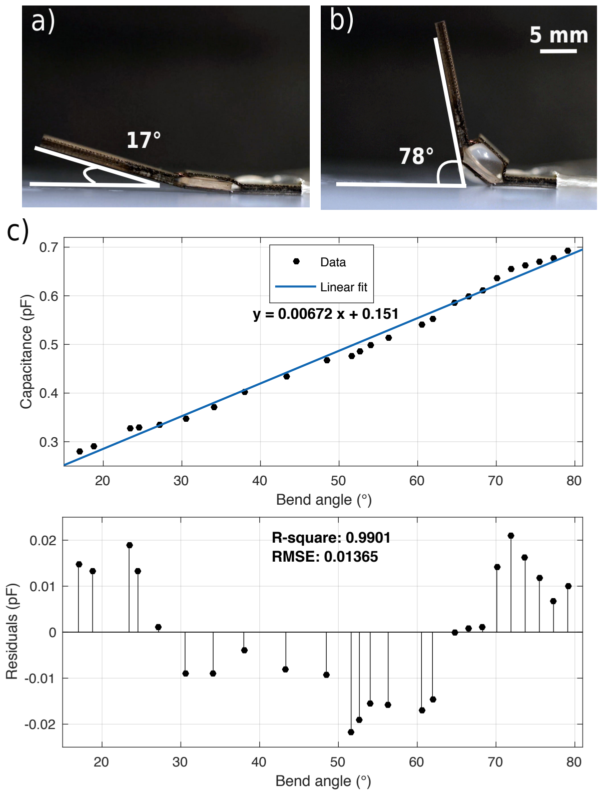

Fig. 3 Soft pop-up proprioceptive actuator characterization. a) Actuator in non-pressurized state. b) Actuator reaching the maximum bending angle. c) Capacitance variation versus bending degrees with linear fit and corresponding residual errors.