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Integrated soft sensors and elastomeric actuators for tactile machines with kinesthetic sense

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ABSTRACT

Human skin contains highly specialized deformation receptors that allow us to intuitively and effortlessly interpret our surroundings. These sensors help us to localize touch and determine the degree of contact pressure. In addition, the innate understanding of our own body posture is also due to these mechanoreceptors. This work demonstrates a synthetic sensory–motor analog that can be 3D printed, using direct ink writing (DIW) onto soft, fluidic elastomer actuators (FEAs). This 3D printing technique uses two inks – one that is an ionically conductive hydrogel and another that is an electrically insulating silicone – which is then patterned and photopolymerized into stretchable capacitive sensors. In this paper, these sensors are used to enable tactile sensing and kinesthetic feedback in a pneumatically actuated haptic device. This capacitive skin enabled the device to detect a compressive force from a finger press of ~ 2 N, and an internal pressurization of as low as ~ 10 kPa.

1. Introduction

Human development, intelligence, and survival are intimately linked to tactile (i.e. touch and pressure) and kinesthetic (i.e. position and movement) feedback we receive from millions of mechanoreceptors embedded in our skin [1,2]. These highly specialized receptors are capable of transmitting signals through ionically conducting nerve fibers at rates of up to 70 m s^{-1} [2]. When these sensors are deformed mechanically – perhaps by compression of the skin or contraction of a muscle – an action potential is transmitted along afferent pathways then processed in the central nervous system [2]. An appropriate response to the input stimulus is then returned along efferent neuronal pathways [2]. This sensory–motor coupling allows us to effortlessly perceive and interact with our environment, enabling the performance of complex tasks such as avoiding furniture in the dark or playing the piano. Due to skin's significant role in learning, tool manipulation, and gross motor coordination, the development of a synthetic analog will enable new methods of feedback control in robotics, medical monitoring, and human–machine interfaces. Wearable [3] and implantable electronics [4] have been developed to integrate with human tissue, which is soft, three-dimensional, and mechanically dynamic.

Along with the development of stretchable electronics, the field of soft robotics has been gaining traction as a result of their ability to (i) interact gently with biological

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organisms [5,6], (ii) easily conform to their surroundings [7–9], and (iii) achieve complex motions using simple modes of actuation [10–13]. These robots are typically composed of hyperelastic materials (e.g. silicones) with large ultimate strains, $\Upsilon_{ult} \sim 400\%$–$700\%$, that have embedded networks of pneumatic channels (PneuNets). These pneumatic actuators are powered through inflation, similar to a balloon. A critical limitation of soft robots is the availability of compliant and extensible sensors [14] that can (i) reliably detect external stimuli and internal actuation, (ii) be easily integrated with current manufacturing processes, (iii) function at the high strains encountered throughout actuation, and (iv) tolerate many actuation cycles without delamination.

To address these sensing deficiencies many groups have developed flexible and stretchable sensors that use changes in resistance [15–17], capacitance [18,19], light [20], or resonant frequency [21,22] to detect deformation. Specifically, for soft robots that undergo large deformations, shape sensing is a critical need for feedback control (communicating with a central computer to ensure a machine task is being completed accurately). Therefore, we focus on sensing techniques using stretchable capacitors due to their high precision and sensitivity over large ranges of strain and pressure [23,24].

Here we present a highly extensible sensing skin that we integrated with soft, pneumatic actuators via a 3D printing technique called direct ink writing (DIW; Fig. 1). This skin enables soft machines to sense external stimuli as well as their own shape, thus creating a device that has both tactile and kinesthetic sense. Central to our approach is the development of two viscoelastic fluids—one that is ionically conductive (hydrogel elastomer precursor) and another that is electrically insulating (silicone elastomer precursor). We directly patterned these inks by extruding them in alternating layers through micronozzles of two different diameters, $d_{hydr} = 330\ \mu\text{m}$ and $d_{sil} = 250\ \mu\text{m}$, on our custom dual-head 3D printer. The two inks are yield-stress fluids that flow through our print heads at high shear rates and retain their shape after exiting the nozzles due to their viscoelastic properties. After extrusion, we used in-situ photopolymerization of the inks to chemically crosslink them into conductive hydrogels and insulating silicones with large ultimate strains, $\gamma_{sil}^{ult} > 350\%$ and $\gamma_{hydr}^{ult} > 300\%$ (Fig. 2, S2). When patterned into alternating conductive and dielectric layers, these composite skins behave as stretchable capacitors, capable of transducing low mechanical stresses and large strains into electrical signals. We printed these stretchable capacitors onto soft, Pneumatically-powered Haptic Displays (PHD; Fig. 1, S1) to provide sensory feedback control. We characterized the ability of the PHD to (i) detect touch (tactile sense), (ii) detect its own actuation (kinesthetic sense), and (iii) integrate these two senses for sensory–motor coupling.

2. Experimental design

2.1. Ink preparation

We chose to use DIW because it offers material flexibility, rapid design iteration, low cost [25–27], and facile integration with previously established soft robot fabrication methods (i.e. replica molding [8] and rotational casting [9]). In addition, the rheological properties of many polymeric inks can be modified to enable this printing technique [28–30]. Specifically, both the shear thinning and yield stress properties of these complex fluids can be adjusted so the inks flow smoothly out of micronozzles and retain their shape after being printed. The shear thinning exponent (n), storage (G') and loss (G'') moduli are primarily controlled by the high molecular weight polymer constituents [30].

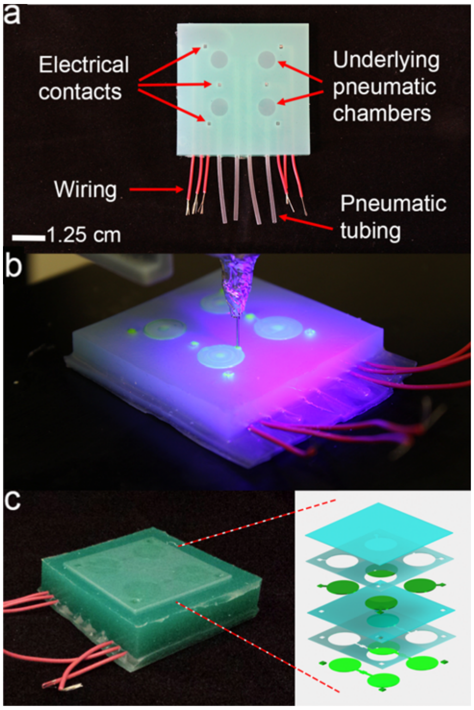

Fig. 1. (a) Image of pneumatic haptic display with wells where electrical contacts will be formed, underlying pneumatic chambers, tubing and electrical wiring. (b) Image of printing stretchable sensors onto pneumatic haptic display. (c) Fully printed sensor on surface of pneumatic haptic display; (inset) Schematic of printed layers of conductive polyacrylamide (green) and insulating silicone (blue).

To tailor the rheology of the silicone elastomer precursor, we prepared blends of high and low molecular weight silicones (60 wt% Nuvasil® Loctite 5039, 40 wt% Wacker® Semicosil 912) together into a homogeneous melt (details in supplemental information, SI (see Appendix A)). In this system, the high molecular weight polymer serves to adjust the yield stress, while the low molecular weight one polymerizes into a resilient matrix. We chose silicones because they have very high electrical resistivity (on the order of $10^{13}\ \Omega$ m), low leakage currents [31], high strain to failure, and high resilience [18,32].

We chose hydrogels because they can be made highly conductive, transparent, biocompatible, and stretchable [18,33]. We formulated the hydrogel elastomer precursor analogously to the silicone by combining high molecular weight polyacrylamide (PAAM 5–6 million