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Bioinspired flexible microfluidic shear force sensor skin

Jianzhu Yin[a], Veronica J. Santos[b], Jonathan D. Posner[a,c,d,*]

[a] Mechanical Engineering, University of Washington, Seattle, WA, USA
[b] Mechanical and Aerospace Engineering, University of California, Los Angeles, CA, USA
[c] Chemical Engineering, University of Washington, Seattle, WA, 98195, USA
[d] Family Medicine, University of Washington, Seattle, WA, 98195, USA

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ABSTRACT

There is a need to gather rich, real-time tactile information to enhance robotic hand performance during haptic exploration and object manipulation. Measuring shear forces is useful for grasping and manipulating objects; however, there are limited effective shear sensing strategies that are compatible with existing end effectors. Here, we report a bioinspired and flexible, resistive microfluidic shear force sensor skin. The sensor skin is wrapped around a finger-shaped end effector and fixed at the location of the nail bed. When the skin is subjected to shear force, one side of the skin experiences tension while the other side experiences compression and bulges similar to a human fingerpad. The tension and compression are measured by liquid metal strain gauges, embedded in PDMS, that are strategically placed adjacent to the nail bed, away from regions of direct finger-object contact. We present the sensor design, a finite element analysis static mechanical characterization model, as well as static response experiments. The resistive shear sensing skin exhibits greater than 10-bit dynamic range (up to 5 N) that is insensitive to the applied normal force. The resistive shear sensing skin is intrinsically flexible and immune to fatigue and other problems of solid-state sensors when subjected to repeated, large strains.

1. Introduction

Human fingertips are equipped with mechanoreceptors to collect tactile information so that we can precisely control muscle coordination during tasks such as haptic exploration and object manipulation [1]. This information enables humans to deduce some object properties that cannot be inferred from other modes of sensing, such as vision [2]. Despite the importance of tactile sensing, it is not widely implemented in robot hands or prostheses [3]. A robot hand equipped with a deformable multimodal tactile sensor has been used to demonstrate the ability to perceive local shape, which could be used to advance robot autonomy and provide haptic feedback to human teleoperators [4].

Haptic exploration and object manipulation benefit from rich, real-time tactile feedback through physical contact [3,5–7]. It has been shown that human operators tend to exert more gripping force than needed when using visual feedback alone [2]. Damage of the manipulated object and/or the end effector itself due to overloading is also of concern when tactile feedback is not available [8]. Restoring the sense of touch may be valuable in delicate and precise manipulation applications such as tele-operation of minimally invasive surgery [5]. Several tactile sensors and algorithms have been developed to pick up objects of varying mass and texture [9], estimate the contents of a container [10], and distinguish light and firm touch [11].

Spatially and temporally resolved normal and shear stresses are critical mechanical measurements that need to be resolved on artificial fingertips. Sensor design criteria are typically task-specific; however, general sensor specifications can be guided by physiological properties of human mechanoreceptors [6,12]. Within the scope of in-hand manipulation, normal and shear forces up to 10 N should be resolved with an optimal dynamic range of 1000 [6]. In practice, sensing ranges of 0.3–50 N have been demonstrated in engineered tactile sensors according to their target application [3,5,13,14]. A normal force spatial resolution of 1.25 mm has been suggested to properly resolve object geometric features [3,6,15]. Kyung et al. have shown that humans have high normal force spatial resolution for interactions below 32 Hz [16]. It is less clear how well shear forces need to be spatially resolved, spurring further research of desired resolution during in-hand manipulation. Low latency temporal response contributes to better control stability, faster reflex-like responses, and can enable inference of surface properties such as roughness, shape, or coefficient of friction during

* Corresponding author at: University of Washington, Mechanical Engineering Building, Stevens Way, Box 352600, Seattle, WA 98195, USA.
E-mail address: jposner@uw.edu (J.D. Posner).

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haptic exploratory motion [17–21]. Humans can detect vibrations as high as 700 Hz although frequencies such as 100 Hz, 250 Hz or 1000 Hz have been proposed for vibration sensors for specific applications [3,6,13–15].

A wide variety of tactile sensors have been demonstrated including whole finger [22] and artificial skin based sensors that are compatible with existing robotic and prosthetic hand actuators [23–36]. Sensor skins that can be wrapped conformally around robotic manipulators minimize the need for modification of the end effector. Skin based sensors have been fabricated with liquid-metal-based transducers embedded in elastomers. Polydimethylsiloxane (PDMS) based sensors have been demonstrated as robust, non-toxic, highly flexible, low cost, and easily fabricated [23,28–30], [34,36–39]. Liquid metal filled channels, such as those filled with eutectic gallium indium alloy (eGaIn), are intrinsically immune to cracks and fatigue, suitable for conformal wrapping and large, repetitive strains [37,40–43]. eGaIn is a conductive liquid metal at room temperature and can form microstructures with a 2 μm spatial resolution by injection into micro-channels [23,39,40,44–47]. eGaIn traces that are 200–300 μm wide can be rapidly patterned by microcontact printing, 3D printing, or stencil lithography [48–51].

A variety of miniaturized microelectromechanical system soft sensor skins with liquid metal that use capacitive, resistive and inductive sensing modalities have been developed [23,38,39,44,45,47]. Capacitive sensors are typically composed of two flat-plate electrodes separated by a dielectric material and benefit from high sensitivity, ease of array fabrication, and high spatial resolution [23], [36,44]. We previously developed a light touch microfluidic normal force sensor that achieved a spatial resolution of 1 mm with a 5 by 5 array of deformable parallel plate capacitors and was calibrated from 0 to 2.5 N [23]. Roberts et al. presented a soft sensor that used differential measurements in multiple parallel plate capacitor taxels to detect shear deformation in two orthogonal dimensions [44]. Capacitive based sensors are susceptible to electromagnetic interference, crosstalk, and parasitic capacitance.

Resistive sensors, including strain gauges and piezoresistive sensors, convert deformation to change of resistance, which can be easily measured by 4-wire sensing or a Wheatstone bridge circuit. Resistive sensors generally have good sensitivity over a large sensing range, high scanning rate, and are easy to design and implement. Their weaknesses include lower repeatability, high power consumption, and sensitivity to temperature. Park et al. presented an artificial skin capable of measuring uniaxial strain in three directions constructed with serpentine and spiral eGaIn channels; however, the minimal normal force that could be sensed was 7.4 N [47]. Majidi et al. developed a single microfluidic channel resistive sensor skin that measures curvature and could be useful in applications such as angular position feedback of an articulated joint [46].

There are only a few strategies to measure shear force, such as pairs of planar strain gauges [27], vertical cantilevers [49], or clusters of normal force taxels that are strategically positioned in pairs or quadruples such that shear force acting at the center of the sensor cluster results in combinations of normal force readings [36,40,41,50]. Sensor sensitivity can be enhanced by adding a bump or ridge on the sensing surface or adding rigid force-posts embedded in the media over the sensing elements [40,41,50], although this approach suffers from reduced spatial resolution since it takes several taxels to construct a single sensing unit. Using a combination of normal force sensors could falsely generate shear force readings from normal forces that are non-uniform or localized on an individual taxel. Previous reports on shear force sensors collectively demonstrate calibration under a single normal force level and rarely discuss the influence of pre-applied normal force. Shear sensors typically measure forces at the point of physical contact between the sensor and object, but, in robotic applications, the location of contact may be arbitrary and would necessitate a large number of distributed sensors. Tactile sensors that resolve shear forces away from the point of contact may be advantageous, especially when faced with constraints on space, such as the small region of a fingerpad. Sensing modalities that do not require localized sensing for direct measurement of stimuli can be displaced to make room for other sensing modalities, such as normal force.

In this paper, we develop a bioinspired, thin and flexible liquid metal filled resistive PDMS microchannel shear force sensing skin. The sensor skin is wrapped around a finger-shaped effector and fixed at the location of the nail bed. When the skin is subjected to shear force it results in one side of the skin in tension and the other side in compression that buckles and bulges similar to a human fingertip. The tension and compression are measured by embedded liquid metal strain gauges that are strategically placed adjacent to the nail bed, away from the point of finger-object contact. We present the sensor design, a finite element analysis (FEA) static mechanical characterization model in addition to an analytical approach, as well as static response experiments. We show that the resistive shear sensing skin exhibits large dynamic range that is insensitive to the applied normal force over a range of shear forces. The resistive shear sensing skin is intrinsically flexible and immune to fatigue when subjected to repeated large strains.

2. Sensor design and theory of operation

The shear sensing skin design is inspired by the layered structure of the human fingertip. Skin consists of epidermis (outermost layer), dermis, and subcutaneous fat tissue. While all of these layers are soft relative to the underlying bone, the subcutaneous fat tissue is much softer than epidermis and dermis, thus, skin tends to shear and slide with respect to the underlying bone when shear force is applied to the finger pad. This deformation results in tension on one side of the fingerpad and compression on the other side. We can resolve shear force by leveraging the asymmetry in the strain that occurs across the fingerpad, provided there is little to no Poisson's effect at the shear sensing taxels. The Poisson's effect is negligible when normal forces are not applied directly to the shear force sensing taxels.

Fig. 1 shows a schematic of the resistive shear sensing skin and mode of operation. The sensor skin wraps around a rigid artificial fingertip and is fixed with two mounting brackets on the radial and ulnar aspects near the perimeter of a human finger nail bed, as shown in Fig. 1A. The eGaIn-filled microchannel strain gauges are embedded in the skin, adjacent to the fixed mounting brackets. The interface between the rigid fingertip and flexible skin is lubricated so that the skin can slide easily relative to the fingertip. The skin slides relative to the rigid finger, when subject to a radioulnar shear force, putting the opposing sides of the sensor skin in compression (buckling) and tension (Fig. 1B). The measured asymmetric strains across the pair of gauges are used to determine the shear force applied on the fingerpad in the radioulnar direction. The shear force sensor is insensitive to shear force in z-direction because both gauges will experience the same strain due to the symmetry of the system with respect to z-direction. The long strips in the gauge are aligned with the principal direction of circumferential strain, with the goal of maximizing sensitivity to shear forces. The gauge placement is designed to be insensitive to the normal force applied at the point of contact. This shear sensing skin design may be compatible with a range of artificial fingertip geometries, when appropriately calibrated to address variations in finger surface geometry as well as friction between the sensor skin and the end effector.