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Short communication

A scalable, high resolution strain sensing matrix suitable for tactile transduction

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ABSTRACT

The integration of tactile information, such as contact area, displacement magnitude, velocity, and acceleration, is paramount to the optimization of robotics in human-centric environments. Cost effective embeddable sensors with scalable receptive field size and strain sensitivity are not readily commercially available and would benefit investigations of *in situ* tissue mechanics. We describe the design and performance of a scalable sensor matrix that transduces fine parameters of strain and is made of combinable “modules”. The sensors transduce static and dynamic strains of both uniaxial and multi-dimensional nature. Modules consist of three silicon wafers placed on top of and three on the bottom of a hexagonal collar, wafers are thus positioned 120° to one another to facilitate force vector extrapolation. Analog signals from each sensor can be easily compared to neighboring sensor output to determine mechanical phenomena such as slip or shear. The smallest of our prototype multiunit matrices consisted of seven hexes in a honeycomb orientation of 4.1 mm diameter (containing 42 silicon gauges). Unamplified, unshielded output from this embodiment (3 V_{exc} button cell) yielded 1 mV from 5 µm displacement. Transduction linearity was high ($R > 0.99$ nearest displacement) and exhibited nominal hysteresis. Modules may be placed upon or embedded into a multitude of materials and the size of individual hexagons may be scaled for favorable stiffness to strain ratio and to scale receptive field. Given the scalability of matrix size and resolution, we believe the sensor matrices could benefit the fields of prosthetics, robotics, and physiologic investigation of tissue mechanics.

1. Introduction

Sensors that provide afferent-like information are of particular interest in many fields because, when applied to current technologies such as robotic surgical devices (*e.g.* endoscopy) or prosthetic apparatuses, they would dramatically expand the control available to operators and the information available for development of automated feedback (Eltaib and Hewit, 2003). Recent advances have demonstrated that tactile signals can be transduced to residual limb nerves (Tan et al., 2014), but a biologic-like source of these tactile afferent signals remains difficult to attain or prohibitively expensive.

We describe a scalable honeycomb matrix of strain sensing modules based upon well-established silicon gauge technology (Allen et al., 1980; French and Evans, 1985) that are well suited for integration in current mechanized or robotic devices. Assimilating the biological sense of touch requires an embeddable, distributed matrix of sensors (Beebe et al., 1995) that can transduce static as well as dynamic signals. Our matrices can be used to transduce several types of strain, including displacement at either orthogonal or oblique orientation to their surface, slip and shear across multiple matrices, and three-dimensional displacement over time, with high resolution and fidelity. Moreover, there is nominal hysteresis that can be anticipated by selection of mounting and embedding media. These qualities, together with the durability of solid state sensors and printable circuitry, offer a novel and robust tactile sensing solution.

The fields of surgery, prosthetics, and physiological research have all implemented some form of robotic or mechanically articulated movements (Garcia et al., 2007). However, mechanized devices often suffer from a lack of tactile feedback (Dargahi and Najarian, 2004; Omata et al., 2004; Biddiss and Chau, 2007; Mittendorfer and Cheng, 2013). Integrated sensory feedback can provide error control to a local circuit, which in turn could provide users with more effective and precise control (Pylatiuk et al., 2006)

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Moreover, multi-dimensional strain sensors are overtly uncommon in basic research. Indeed, strain gauges have historically been utilized to measure forces or displacements in one dimension (*e.g.* along the sarcomeric axis; Allen et al. (1980), Full et al. (1998), Ormerod et al. (2013)). This limitation precludes their utility for *in situ* preparations with non-linear geometric orientations. The opportunity to measure strain dynamics across multiple dimensions would allow researchers to better understand the natural function of multi-component tissues (i.e. systems of connective and muscle tissue) and thus provide a useful complement to our knowledge of mechanical tissue properties *ex vivo* (Black, 1976; Woo et al., 1999).

2. Design

We set out to design a sensor system that could mimic tactile sensation. Tactile receptive fields consist of mechanoreceptors arranged in high and low densities depending on the usage of the particular tissue (reviews: Tiwana et al., 2012; Chouvardas et al., 2005). Likewise, our matrices can be scaled to different sizes (Fig. 1) and embedded into or mounted upon substrates of varied stiffness (i.e. greater stiffness yielding lesser sensitivity/voltage gain from the silicon gauges: Fig. 1b). We report on two such embodiments here, one prototype with a resolution ~300 μm^2, and one with sensing resolution ~1 cm^2 (Fig. 1a and a *inset*, respectively). We computed an approximate resolution of ~300 μm^2 in our smallest embodiment from the minimum distance between gages in a single hex, which is 0.7 mm, as well as the extra-hex distance to the nearest silicon gauge (~0.5 mm; Fig. 2c). Strain vectors may be extrapolated such that the functional 'pixel' resolution falls between any pair or triplet of gauges, yielding a 250–350 μm^2 resolution.

The fundamental organization of our sensors consists of several discrete sensing units – silicon gauges – mounted to hexagonal collars arranged in a Fullerene pattern (Fig. 2a and b). Silicon gauges are employed for their high gauge factor and sensitivity to fine strains as well as the simplicity of required circuitry (Fig. 1d) and their solid state robustness. Semiconductor gauges are notably cost effective; they draw very low current (~30 μW. each, Table 1) and provide a high signal to noise ratio.

Silicon crystals are mounted to the top and bottom of a substrate such that upon strain, one crystal is in tension and the other is in compression, providing a simple mechanism for cumulative estimation of three-dimensionality. The 120° orientation of each silicon gauge pair to its neighbors within a hexagon, or to the neighboring hexagon (Fig. 2), simplifies computation of strain vectors. Silicon fabrication and insulation *via* vapor paralene deposit are established methods and were performed by Micron

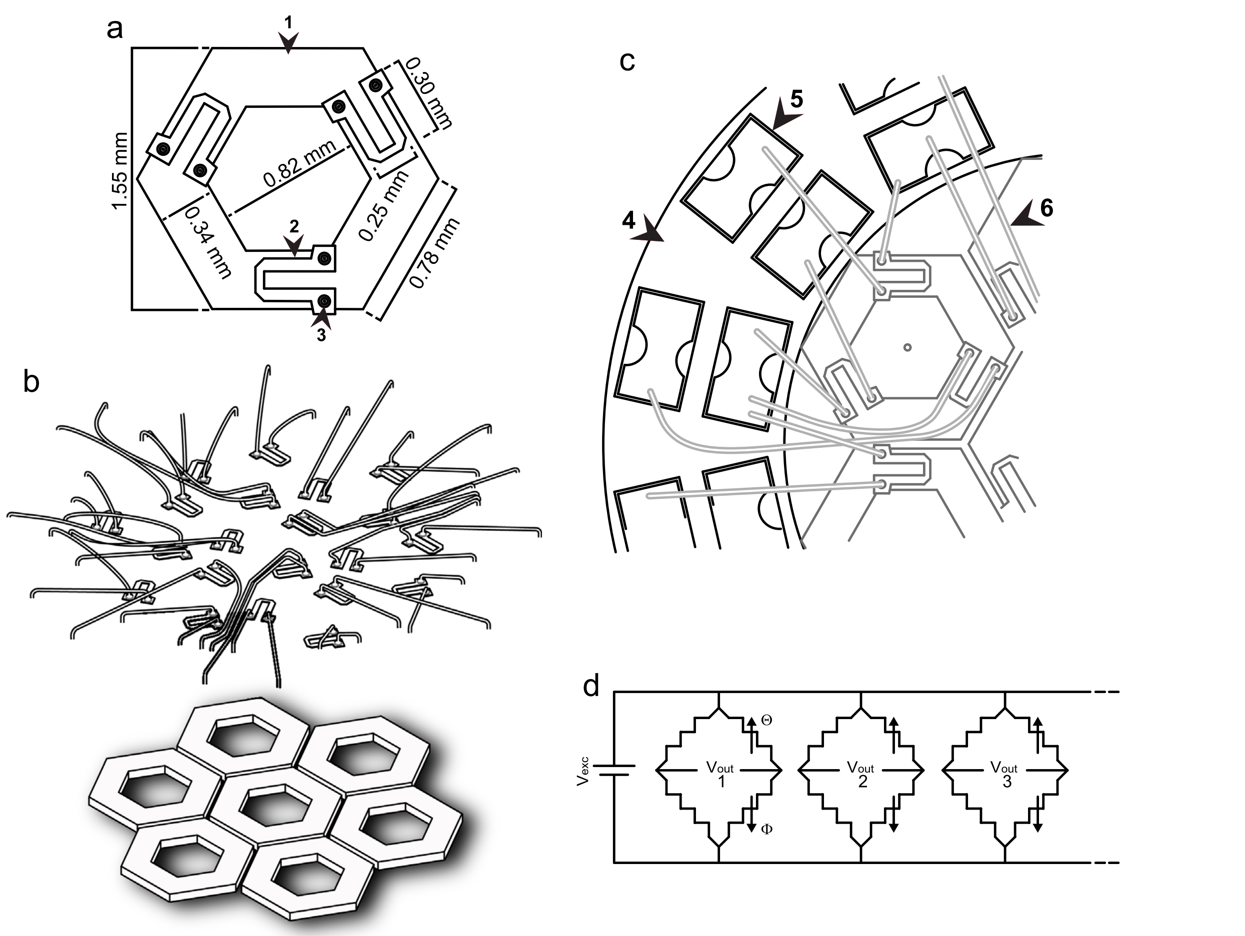

Fig. 1. Scalability of sensor matrices and sensitivity to deflection. (a) Photo of 38 mm diameter sensor matrix consisting of seven hexes (42 silicon gauges) arranged in a Fullerene pattern and embedded in ~6 mm silicon elastomer (Sylgard: note small bubbles in image). *Inset*: our smallest seven-hex matrix, 42-gauge prototype (~5.5 mm), surrounded by a collar utilized for electrical connections in prototyping (total diameter ~8 mm). Each sensor matrix is pictured next to a US penny (9.5 mm radius). (b) Output sensitivity of any sensor within a matrix is proportional to deflections of angle Θ, which are a function of hex diameter given a constant displacement (d_1).This provides a higher resolution voltage signal when a displacement is applied in a higher density receptive field composed of smaller sensor hexagons and/or when sensors are embedded in lower stiffness media.