# Influence of Material Properties on the Performance of Highly Stretchable Pneumatic Strain Gauges

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***Abstract*—A meandering microfluidic channel in a soft elastomeric material works as a pneumatic strain gauge. The channel deforms under external forces, changing its fluidic resistance. This fluidic resistance can be measured by measuring pressure drop over the channel. We made strain gauges by casting four different elastomers of varying stiffness (Sylgard 184, Dragon Skin 30, Ecoflex 00-50 and Ecoflex 00-30) into microfabricated molds. Here we report the effects of material choice on the performance of the sensor under strain and compression. The sensors fabricated from stiffer elastomers proved effective in detecting smaller strains and higher compressive forces, while softer sensors were more suitable for larger strains and smaller compressive forces.**

***Keywords—soft strain sensor; silicone elastomers; soft devices***

## I. INTRODUCTION

The development of soft devices has gained increasing interest in recent years for applications such as wearable monitoring systems [1]–[3], soft robotics [4]–[6], and human-machine interfaces [7], [8]. Soft devices are made from stretchable and conformable materials that can tolerate mechanical deformations and conform to irregular shapes without compromising the functionality of the device. In soft devices, fluidic actuators are often employed to generate mechanical motion. This choice is attributed to the advantages of fluidic actuators: their actuation is fast [9] and they can generate high grasping forces [10]. As fluidic actuators are used in soft devices, the sensors integrated into the device could also output fluidic signal, eliminating the need of transducers shifting signals from energy domain to energy domain. By directly utilizing fluidic signals throughout the system, the overall complexity of the device can potentially be reduced, as heterogenous materials and transducers are not needed.

In our previous work [11], we demonstrated that a meandering microchannel in extremely soft material (Shore hardness 00-50) can be used as a pneumatic resistive strain gauge. Like in an electrical resistive sensor, elongating the soft strain gauge increases the pneumatic resistance of the channel. We integrated the pneumatic strain gauge into pneumatic actuators to detect their deformation and used the sensor for controlling the closing motion of a pneumatic gripper.

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Soft fluidic actuators and soft devices can be fabricated using a wide range of materials. Elastomers, such as poly(dimethylsiloxane) (PDMS), are particularly popular due to their softness, stretchability, ease of processing, and ability to replicate even nanoscopic structures with high fidelity. In particular, Sylgard 184 (Dow Corning) is commonly used to fabricate soft devices [2], [12], [13]. Softer alternatives include commercial Ecoflex (Smooth-On), ExSil (Gelest) or Elastosil (Wacker) product families. The choice of elastomer for a soft device or its components depends on the mechanical requirements of the application. For instance, highly stretchable elastomers may be favored when the application demands extreme flexibility [9], while higher durability is desired for parts where deformability must be restricted [14].

In this work, we fabricated the stretchable pneumatic strain gauges (Fig. 1a&b) from several commercial soft elastomers with softness ranging from Shore hardness A50 to 00-30 (Sylgard 184, Dragon Skin 30, Ecoflex 00-50 and Ecoflex 00-30). The aim is to study the performance of the sensors under external forces (Fig. 1c) and the effect of selected materials. Our findings indicate that softer sensors can measure higher strains and detect smaller compressive forces, while stiffer elastomers are better suited for applications involving smaller strains and higher compressive forces. This study presents insights into the performance of the pneumatic strain gauge fabricated from various commercial elastomers, aiding in the selection of appropriate materials for these kinds of strain gauges.

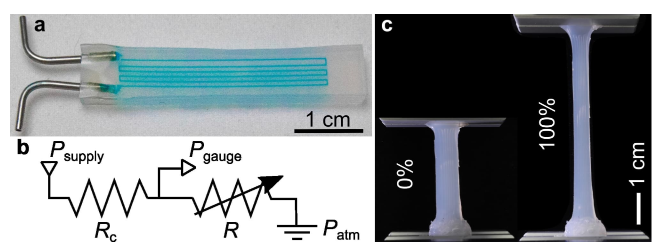


Fig. 1. Soft strain sensors. (a) Photograph of the soft strain gauge. The meandering microchannel is filled with dyed water to visualize it, but in normal operation it is filled by air. (b) Measurement circuit with a costant pneumatic resistor $R_c$ and the pneumatic strain gauge $R$ in series, vented to atmospheric pressure $P_{atm}$. Constant positive supply pressure $P_{supply}$ applied to the circuit while the pressure drop over the strain gauge $P_{gauge}$ is measured. The deformation of the strain gauge changes the pressure drop across it. (c) Photographs of the sensor in relaxed (0%) and in 100% strain.

## II. Materials and Methods

### A. Materials and Fabrication

Four different silicone elastomers Sylgard 184 (Dow Corning, Shore hardness A 50), Dragon Skin 30 (Smooth-On, Shore hardness A 30), Ecoflex 00-50 (Smooth-On, Shore hardness 00-50) and Ecoflex 00-30 (Smooth-On, Shore hardness 00-30) were used to fabricate the sensors.

The design and fabrication of the soft strain sensor was similar as in our previous work.[11] The sensor has a meandering microchannel (width: 200 µm, height: 200 µm) with total length of 183 mm embedded in a 40 mm × 7 mm × 4 mm elastomer piece. As the microchannel had five turns, the sensing area of the sensor was 30 mm × 3.84 mm. The channels were fabricated by casting the elastomers into microfabricated molds (photolithography: negative photoresist SU-8 3050, Microchem). Before casting, the molds were treated with trichloro(1H,1H,2H,2H-perfluorooctyl)silane to ensure easy demolding.

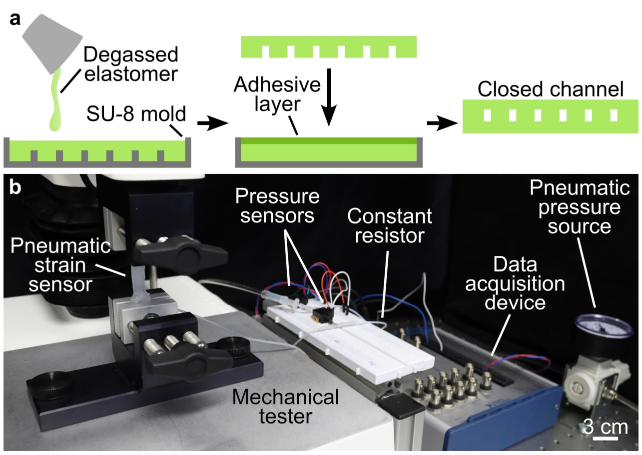


Fig. 2. (a) Fabrication of the soft strain gauges. (b) Experimental setup.

All used elastomers were two-component products, with 1:10 or 1:1 mixing ratio by weight. The fabricated channel structures were demolded and bonded to a flat elastomer piece to create closed channels. With the Ecoflex and Dragon Skin elastomers, the bonding was done by spin-coating a thin adhesive layer of uncured elastomer on the flat elastomer piece gluing the two parts together (Fig. 2a) while for the Sylgard 184 the bonding was conducted with oxygen plasma (Pico, Diener electronic GmbH + Co. KG for 20 s at 30 W and 0.3 mbar pressure). Metallic connections were sealed to the inlet and outlet with a silicon glue (Sil-Poxy, Smooth-On).

### B. Experimental Setup

The strain gauge ($R$ in Fig. 1b) was linked in series to a constant pneumatic resistor $R_c$ (Teflon tube, inner diameter of 0.2 mm) and pressure sensors (015PDAA5, Honeywell, 15 PSI Differential 5V). A constant positive pressure $P_{supply}$ of 60 kPa (relative to atmospheric pressure) was applied to the circuit. The pressure sensors measured both the $P_{supply}$ and $P_{gauge}$, the pressure before the pneumatic strain gauge. Data from the pressure sensors were captured using a data acquisition device (USB-6356, National Instruments). During the tensile tests, the strain gauge was clamped at its ends to a mechanical tester (TA.XT Plus, Stable Micro Systems). The mechanical tester with a spherical probe (TA-18A, Ø 19.05 mm ball, Stable Micro Systems) was used to generate the compression on the sensors for compression tests.

### C. Pneumatic Resistance

The measured pressures can be converted into pneumatic resistance using the electrofluidic analogy. After making assumptions that the fluid inside meandering microchannel of the sensor is isothermal ideal gas and that the flows are laminar and subsonic, the pressure drop inside the channel can be calculated.[11] When considering all pressures as small pressures relative to the atmospheric pressure, we can calculate the fluidic resistance using the equation

$$R / R_c = \Delta P_{gauge} / (\Delta P_{supply} - \Delta P_{gauge}), \quad (1)$$

where $R$ is the fluidic resistance of the sensor, $R_c$ is the fluidic resistance of the constant resistor, and $\Delta P_{gauge,supply}$ are the gauge and supply pressures relative to the atmospheric pressure $P_{atm}$ ($\Delta P_{gauge,supply} = P_{gauge,supply} - P_{atm}$). This equation represents the pneumatic equivalent of a voltage divider. Both elongating and compressing the sensor leads to a change in its resistance: $R = R_0 + \Delta R$. [11] Using (1), we get $\Delta R/R_c$, which we plot in all our figures.

## III. Results and Discussion

### A. Strain Sensing Experiments

The response of the soft pneumatic strain gauges to varying tensile strains was tested by measuring the relative change in pneumatic resistance of the sensor while elongating or contracting it (Fig. 3b). The results are shown in Fig. 3a. The Sylgard 184 and Dragon Skin 30 sensors broke already at over 30% and 133% engineering strains respectively while the softer Ecoflex sensors tolerate up to 300% strain. The Sylgard 184 sensor exhibited the most modest response, implying that the deformation of the channel is comparatively limited

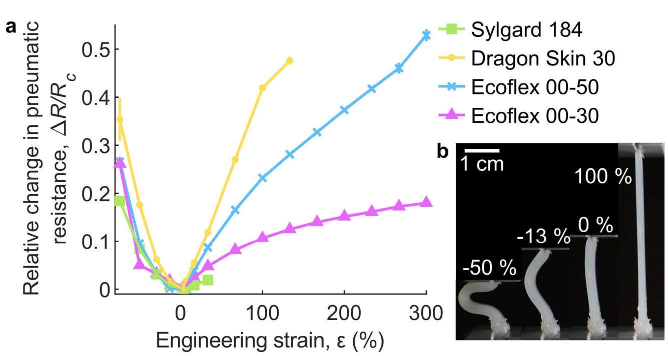


Fig. 3. Soft strain sensors under contraction and tension. (a) Response of $\Delta R/R_c$ to varying engineering strains (0.5 mm/s strain rate) with the four different strain gauges. Each curve is an average of five measurements with one sample. Error bars (almost too small to be seen) represent standard deviation. (b) Photographs of the measurements.

compared to the others. The small slope of the $\Delta R/R_c$–strain curve of Ecoflex 00-30 sensor under tension can be caused by expansion of the embedded microchannel. Elongation of the sensor decreases the thickness of the soft elastomeric walls of the channel, leading to their expansion due to the constant supply pressure. Thus, the decreasing of the cross-sectional area of the channel is restricted. This also explains why the Dragon Skin 30 sensor exhibits a greater response compared to the softer Ecoflex 00-50 sensor at identical levels of strain. Thus, stiffer elastomers can be beneficial for applications with smaller strains while the softer sensors are suitable for larger strains beyond the capacity of stiffer sensors.

The response of the sensors to contraction (Fig. 3a) are closer to each other than under elongation. When contracted, the sensor bends, restricting the fluid flow in the channel. Thus, the increase of the pneumatic resistance may originate from the middle of the sensor where it bends, or near the ends where it was secured to the clamps of the mechanical tester, as bending is present also in those regions. Contraction of the sensor can be roughly compared to bending of a soft actuator that can be measured with an integrated strain sensor. Since there is no significant difference in the performance of the sensors under contraction (Fig. 3a), the sensor material can be selected based on the material used to fabricate the actuator.

Since the sensor were fabricated from elastomers with different mechanical properties, some of them are more stretchable than others requiring less external force to achieve higher straining (Fig. 4b). Thus, when studying the increase of the $\Delta R/R_c$ as function of applied tensile force, the largest responses was obtained with the softer Ecoflex sensors (Fig. 4a) as they stretched more compared to the stiffer sensors (Fig. 4b). For larger forces, the response of the Ecoflex 00-30 sensor is lower than the response of the Ecoflex 00-50 sensor, due to the expansion of the pneumatic microchannel. The results indicate that softer sensors are more suitable for applications with small tensile forces due to their better sensitivity, and that the sensor material does not restrict stretchability of the device.

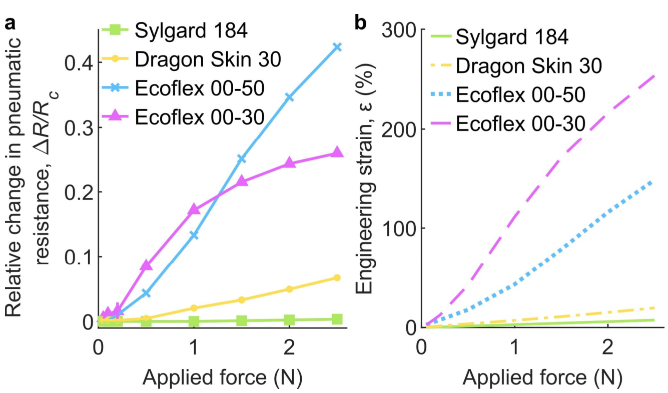


Fig. 4. Response of $\Delta R/R_c$ (a) to applied tensile forces (0.5 mm/s strain rate) with the four different strain gauges and (b) the corresponding strain-force curves. Each curve in (a) is an average of five measurements with one sample. Error bars (too small to be seen) represent standard deviation.

### B. Compression Sensing Experiment

To study the response of the soft strain gauges to lateral compression, sensors made of different materials were compressed by a spherical probe from the center of the sensing area (Fig. 5b) with varying force while recording the relative change in pneumatic resistance. The results are in Fig. 5a. The $\Delta R/R_c$ of all the sensors increased, but the increase was the fastest for the softer Ecoflex sensors when the forces were small. Since the Sylgard 184 and Dragon Skin 30 elastomers are stiffer, more force is required to compress the microchannel and decrease its cross-sectional area. In contrast, the channel fabricated from softer Ecoflex elastomers can be fully closed with less force restricting the maximum force detection range. Thus, stiffer elastomers are more suitable for applications with higher compressive forces involved whereas softer elastomers are more sensitive smaller forces. The depth of the microchannel within the elastomer can also affect to the material selection: channels located closer to the surface are subjected to greater stresses.

## IV. Conclusion

We fabricated highly stretchable pneumatic strain gauges from different elastomers and studied their performance. Overall, employing a softer elastomer allows detecting greater strains and smaller compressive forces whereas sensors fabricated from stiffer elastomers are more sensitive to smaller strains and can tolerate high compression.

One practical challenge in all fluidic devices, including our sensors, is the risk of leaks. Leaks can usually be avoided by careful design of connectors and seals. Another challenge in our sensors is the reproducibility of the fabrication. Bubbles and deformations during elastomer casting can change the geometry of the channels, possibly causing sensor malfunction.

The advantage of the fluidic sensor is that it contributes to the advancement of electronics-free, fluidically operated soft devices. Using the same material for the sensors as the rest of the device enables easier integration, as the sensor can be fabricated using the same process as other fluidic components.

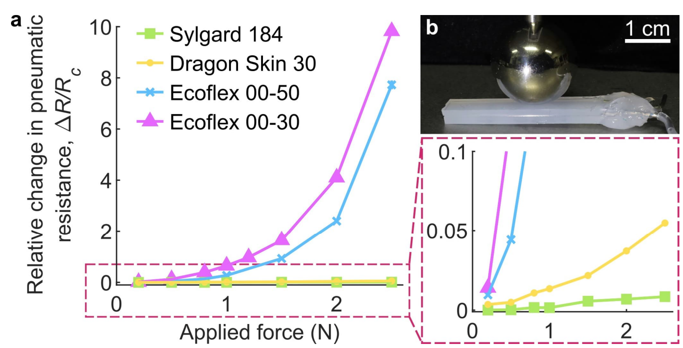


Fig. 5. Soft strain sensors under compression. (a) Response of $\Delta R/R_c$ to varying compression force (0.1 mm/s compression rate) with the four different strain gauges. Each curve is an average of five measurements with one sample. Error bars (almost too small to be seen) represent standard deviation. (b) Photograph of the compression force measurement.

## References

[1] S. Xu *et al.*, “Biocompatible Soft Fluidic Strain and Force Sensors for Wearable Devices,” *Adv. Funct. Mater.*, vol. 29, no. 7, p. 1807058, 2019.

[2] A. Koh *et al.*, “A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat,” *Sci. Transl. Med.*, vol. 8, no. 366, p. 366ra16, Nov. 2016.

[3] Y. Mengüç *et al.*, “Wearable soft sensing suit for human gait measurement,” *Int. J. Robot. Res.*, vol. 33, no. 14, pp. 1748–1764, Dec. 2014.

[4] N. W. Bartlett *et al.*, “A 3D-printed, functionally graded soft robot powered by combustion,” *Science*, vol. 349, no. 6244, pp. 161–165, Jul. 2015.

[5] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, “Soft robotics for chemists,” *Angew. Chem. - Int. Ed.*, vol. 50, no. 8, pp. 1890–1895, Feb. 2011.

[6] H. Wang, M. Totaro, and L. Beccai, “Toward Perceptive Soft Robots: Progress and Challenges,” *Adv. Sci.*, vol. 5, no. 9, p. 1800541, Sep. 2018.

[7] S. Robla-Gómez, V. M. Becerra, J. R. Llata, E. González-Sarabia, C. Torre-Ferrero, and J. Pérez-Oria, “Working Together: A Review on Safe Human-Robot Collaboration in Industrial Environments,” *IEEE Access*, vol. 5, pp. 26754–26773, 2017.

[8] W. Heng, S. Solomon, and W. Gao, “Flexible Electronics and Devices as Human–Machine Interfaces for Medical Robotics,” *Adv. Mater.*, vol. 34, no. 16, p. 2107902, 20222.

[9] B. Mosadegh *et al.*, “Pneumatic Networks for Soft Robotics that Actuate Rapidly,” *Adv. Funct. Mater.*, vol. 24, no. 15, pp. 2163–2170, Apr. 2014.

[10] S. Zaidi, M. Maselli, C. Laschi, and M. Cianchetti, “Actuation Technologies for Soft Robot Grippers and Manipulators: A Review,” *Curr. Robot. Rep.*, vol. 2, no. 3, pp. 355–369, Sep. 2021.

[11] A. Koivikko, V. Lampinen, M. Pihlajamäki, K. Yiannacou, V. Sharma, and V. Sariola, “Integrated stretchable pneumatic strain gauges for electronics-free soft robots,” *Commun. Eng.*, vol. 1, no. 1, pp. 1–10, Jun. 2022.

[12] F. L. H. Iii, R. K. Kramer, Q. Wan, R. D. Howe, and R. J. Wood, “Soft Tactile Sensor Arrays for Force Feedback in Micromanipulation,” *IEEE Sens. J.*, vol. 14, no. 5, pp. 1443–1452, 2014.

[13] M. Amjadi *et al.*, “Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review,” *Adv. Funct. Mater.*, vol. 26, no. 11, pp. 1678–1698, Mar. 2016.

[14] M. Yurugi, M. Shimanokami, T. Nagai, J. Shintake, and Y. Ikemoto, “Cartilage structure increases swimming efficiency of underwater robots,” *Sci. Rep.*, vol. 11, no. 1, pp. 1–12, 2021.