

University of Wollongong

Research Online

Australian Institute for Innovative Materials -
Papers

Australian Institute for Innovative Materials

1-1-2016

Fabrication and characterisation of highly stretchable elastomeric strain sensors for prosthetic hand applications

Solen Kumbay-Yildiz

University of Wollongong, solen@uow.edu.au

Rahim Mutlu

University of Wollongong, rmutlu@uow.edu.au

Gursel Alici

University of Wollongong, gursel@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/aiimpapers>



Part of the [Engineering Commons](#), and the [Physical Sciences and Mathematics Commons](#)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Fabrication and characterisation of highly stretchable elastomeric strain sensors for prosthetic hand applications

Abstract

This study reports on the fabrication and response characterisation of highly stretchable strain sensors made of two commercially available silicone rubber substrates (EcoFlex 0010, and Shin-Etsu KE-441-T) engraved with microchannels, which are filled with two conductive liquids; carbon nanofibers (CNF) in poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) dispersion (PEDOT:PSS) and liquid carbon black (CB). We experimentally quantified the electromechanical response and strain sensing performance of the sensors using the metrics of linearity, hysteresis, resolution, transient properties and repeatability. We conclude that while changing the conductive liquid mainly affects the overall resistance of the sensors, the sensors made of EcoFlex have (i) overall much faster response characteristics during both loading and unloading cycles, (ii) less hysteresis, and (iii) a smaller time constant, that makes them more suitable to applications in which the input stimulus changes at a fast rate.

Disciplines

Engineering | Physical Sciences and Mathematics

Publication Details

Kumbay Yildiz, S., Mutlu, R. & Alici, G. (2016). Fabrication and characterisation of highly stretchable elastomeric strain sensors for prosthetic hand applications. *Sensors and Actuators A: Physical*, 247 514-521.

Fabrication and characterisation of highly stretchable elastomeric strain sensors for prosthetic hand applications

Solen Kumbay Yildiz^{a,c}, Rahim Mutlu^{a,b}, and Gursel Alici^{a,b,*}

^aSchool of Mechanical, Material and Mechatronic Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

^bARC Centre of Excellence for Electromaterials Science, University of Wollongong, Wollongong, NSW 2522, Australia

^cDepartment of Electrical and Electronics Engineering, Hacettepe University, 06800, Ankara, Turkey

Keywords: Elastomeric strain sensor, sensor fabrication, sensor characterization, EcoFlex, Shin-Etsu, CNF, PEDOT:PSS, Carbon black

Abstract

This study reports on the fabrication and response characterisation of highly stretchable strain sensors made of two commercially available silicone rubber substrates (EcoFlex 0010, and Shin-Etsu KE-441-T) engraved with microchannels, which are filled with two conductive liquids; carbon nanofibers (CNF) in poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) dispersion (PEDOT:PSS) and liquid carbon black (CB). We experimentally quantified the electromechanical response and strain sensing performance of the sensors using the metrics of linearity, hysteresis, resolution, transient properties and repeatability. We conclude that while changing the conductive liquid mainly affects the overall resistance of the sensors, the sensors made of EcoFlex have (i) overall much faster response characteristics during both loading and unloading cycles, (ii) less hysteresis, and (iii) a smaller time constant, that makes them more suitable to applications in which the input stimulus changes at a fast rate.

1. Introduction

Since its emergence, the field of soft robotics continues to draw a significant interest from researchers. As part of this new area, much effort goes into designing and fabricating flexible and stretchable electronic components toward realising soft and human friendly devices for use in various soft robotics applications. One group of such devices are elastomer based sensors, which, in contrast to their rigid counterparts, can accommodate large but reversible deformations without losing functionality or applying additional mechanical constraints on the main system into which they are incorporated.

Soft sensors, the resistive or capacitive properties of which change as the strain or curvature applied to them are varied, have been of particular interest. The change in these electrical properties basically occurs due to the change in the device geometry in response to the applied mechanical stimulus. Recent studies report on such sensors with different fabrication strategies including but not limited to lithography [1, 2], 3D printing [3, 4], laser engraving [5-7] and mould based techniques [8-11]. Various conductive agents such as eutectic Gallium-Indium (eGaln) [4, 5, 8-15], carbon [1, 2, 7, 16-20], silver [1, 9, 16] and ionic fluids [6, 21-25] or combinations of these have been used in conjunction with the fabrication approaches mentioned above. Several base substrates with varying viscosity and softness properties have been employed in the design of these sensors; polydimethylsiloxane (PDMS), soft silicone rubbers and hydrogels are among the most commonly used materials in these studies.

* Corresponding author: gursel@uow.edu.au (G. Alici)

Motivated by the ongoing efforts toward achieving reliable strain measurements in soft robotics applications, the results of a study on fabricating and characterising soft strain gauge type sensors are presented in this paper. In principle, the sensors fabricated and analysed in this work consist of an elastomer structure embedded with strain gauge like patterned microchannels that are filled with a conductive liquid. Similar existing studies mainly focus on fabrication techniques and the strain sensing capabilities of such sensors, while other aspects such as transient characteristics and sensing resolution are usually not characterised. The novelty of this work comes from the fact that it encompasses a series of detailed analyses on the strain sensing performance of soft sensors, as well as linearity of data, provided measurement resolution by the materials and experimental setup, hysteresis phenomenon and transient response parameters. Other metrics such as repeatability of experiments and robustness of the devices are also discussed. Furthermore, the effect of material choice on the sensors' overall performance is investigated by changing the base substrate and the conductive liquid while keeping the sensor geometry unchanged. As explained in the following section, change of base material also calls for a change in the fabrication methodologies which are also compared in terms of practicality and time-effectiveness.

The ultimate motivation is to utilise these strain sensors in future studies to measure joint and tip positions of the fingers of a soft and underactuated prosthetic hand without using externally placed sensors for feedback information of the actual positions [26]. To that end, two strategies can be executed; mounting a single larger sensor on the entire finger, which is usually the preferred method in existing studies with flex (also known as bend sensors) or stretchable sensors [3, 5, 17, 25, 27-29], and placing one smaller sensor on each joint and extrapolating the tip position as well as individual joint positions from the acquired data.

The outline of this paper is as follows: Following the Introduction section, Section 2 gives a detailed description of materials and the fabrication steps of the sensors. The setup used for the experiments and the results obtained from the various tests the sensors are subjected to, are presented in Section 3. Conclusions drawn from the studies and future work are discussed in Section 4.

2. Description of materials and fabrication method

In this study, two groups of sensors were fabricated using different substrates as base material. The first substrate is Smooth-On's EcoFlex 0010, which is an extremely soft, low-viscosity two component, addition cured room temperature vulcanising (2 RTV) silicone rubber, while the second one is a one component room temperature vulcanising (1 RTV) liquid silicone rubber (Shin-Etsu KE-441-T, shore a hardness 15). The fabrication methods with these two substrates differ greatly from each other, as explained below.

For the first layer of EcoFlex sensors, EcoFlex is mixed 1A:1B by weight, and poured into a 3D printed (UP Plus 2, 3D Printing Systems) mould with the microchannel pattern and a total height of 650 μm . The mould is put in a vacuum chamber and degassed for 15 minutes in order to remove any air bubbles trapped inside the mixture. Before the sensor part can be demoulded, it is left to cure at room temperature for two hours. For the second part of the sensor, a thin layer (350 μm) of EcoFlex is cast onto a smooth PET surface using a micrometre film applicator and allowed to partially cure for 10 to 15 minutes. The first layer is carefully placed onto the thin layer with the patterned surface facing down, preventing the channels from being filled by the semi-cured silicone, and the sensor is left to cure at room temperature for another hour.

The fabrication of Shin-Etsu sensors, on the other hand, consists of a combination of casting, laser engraving, cleaning and plasma bonding. First, a 650 μm thick layer of silicone is cast onto a clean and smooth PET surface and left to cure for two hours. Upon curing, the silicone layer is peeled off the PET surface. The microchannels along with the contact points are patterned using a laser engraver (Universal Laser Systems, VLS 2.30). Prior to being treated with the laser, the surface of the

silicone is covered with a thin film (LDPE) to prevent it from being contaminated during laser engraving. By altering the speed and power settings of the laser engraver, the width and the depth of the channels can be controlled (2% power and 2.5% speed are used). The microchannels are then gently cleaned with a small and soft brush and the remaining thin film is peeled off. A second silicone layer of 350 μm thickness is prepared. This layer and the patterned surface of the first layer are treated with oxygen plasma (Harrick Plasma, PDC-002, 2mins) and then brought into conformal contact in order to obtain the sandwiched microchannel structure.

The last step of sensor fabrication is filling the microchannels with a conductive liquid. The channels are filled using a syringe fitted with a 30G needle, dispensing the liquid through one of the contact points while the air trapped inside the channels is removed through the other contact point with the help of another syringe. Finally, wires are inserted into the contact points and droplets of uncured silicone are used to cover the needle holes as well as to fasten the wires.

The fabrication processes for both types of sensors described above are depicted in Figure 1. Figure 2 shows the dimensions of the gauge pattern as well as the overall resulting soft sensor fabricated by either method. The total thickness of the sensor is 1 mm and the width and the length of the pattern are 6.5 mm and 15 mm, respectively. The resulting microchannels are 500 μm wide and 400 μm high.

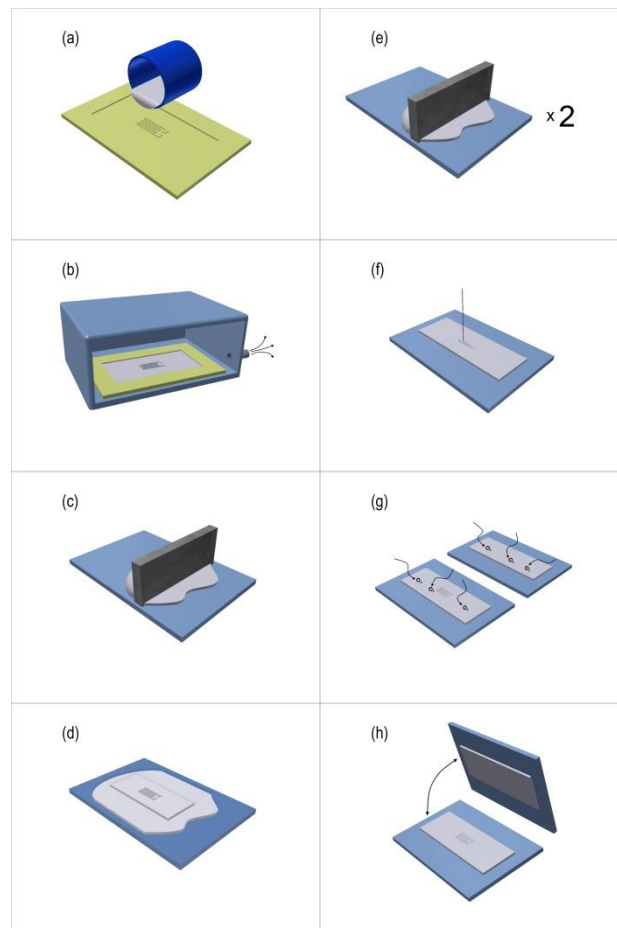


Figure 1 A schematic illustration of the sensor fabrication processes. (a) EcoFlex poured into the mould, (b) degassed in a vacuum chamber, (c) a thin layer cast using a micrometre film applicator, (d) patterned layer placed on a semi-cured layer with its patterned side facing down, (e) a thin layer of Shin-Etsu cast using a micrometre film applicator, (f) layer patterned with a laser engraver, (g) both layers treated with oxygen plasma, (h) layers brought into contact with microchannels trapped inside.

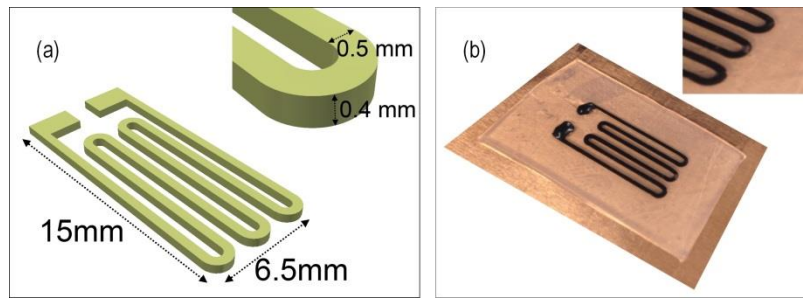


Figure 2 (a) Gauge pattern dimensions; inset shows the dimensions of the microchannel, (b) a finished sensor; inset shows a magnified image of the microchannels.

For the purpose of comparing their performance and characteristics, two different conductive liquids have been used in our experiments. Two groups of sensors are made by filling EcoFlex and Shin-Etsu sensors with carbon nanofibers (CNF) in poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) dispersion (PEDOT:PSS). A third group was obtained by filling EcoFlex sensors with liquid carbon black (CB).

While both fabrication methods described above are similar in terms of complexity, they both come with their own advantages and challenges: The advantage of using a 1 RTV silicone rubber is that the preparation step can be bypassed. During mixing the two part compound, many bubbles form within the mixture which requires another additional step, in the fabrication, i.e. degassing. However, once the mixture is ready, having multiple moulds at hand speeds up the preparation of the patterned silicone layer, while the gauge patterns need to be engraved on the 1 RTV layer one pattern at a time. After demoulding, the sensor parts do not require any cleaning and can be directly bonded with the second layer. The laser patterned layers, on the other hand, require careful handling and a delicate cleaning step as chemical bonding occurs partially or does not occur at all, if the surfaces are not clean. Once plasma bonding is executed successfully, the sandwiched microchannels always have the same geometry, as long as the same settings during laser engraving are used. Bonding of the 2 RTV compound, on the other hand, has to be done manually, since plasma treatment cannot be used with this substrate [6], and the amount of silicone, however small, penetrating the channels cannot be controlled.

Note that the choice of dimensions of a finished sensor may depend on several factors such as the capabilities of the instruments, properties of the materials, cost of fabrication and most importantly on the application where these sensors are to be utilised. For the EcoFlex sensors fabricated during this study, we used a low cost 3D printer to lower the overall fabrication costs. By employing a 3D printer with a higher resolution, it is possible to prepare moulds with microchannel patterns with much smaller dimensions. On the other hand, the methodology described for the fabrication of the ShinEtsu sensors can produce sensors with channel dimensions as small as 50 μm . As pointed out in Section 1, our ultimate aim is to employ these sensors in the control of a soft prosthetic finger. Therefore, the dimensions of the sensors are chosen by taking into account the dimensions of this finger. The resulting sensors are small enough to be placed on the individual joints of the finger, yet large enough to facilitate both fabrication methods described above.

3. Characterisation of the sensor

A series of experiments were conducted to evaluate the electromechanical response and strain sensing performance of the sensors. The performance metrics taken into account are linearity, hysteresis, resolution, transient properties and repeatability. Qualitative measures such as robustness and reliability are also discussed.

3.1 Experimental setup

The sensor to be experimented on is fastened between two plates of the same height. One of the plates is stationary, whereas the other is a precision positioning table equipped with a micrometre (PT1/M, 25 mm Translation Stage with Standard Micrometre, Thorlabs). For convenience, a digital caliper ruler is also fixed on the stationary and moving plates. The sensor is stretched by manually adjusting the displacement of the positioning table. The amount of strain applied to the sensor is calculated by taking the ratio of the displacement of the table, which is read on the micrometre, to the initial length of the overall stretched area.

In order to measure the electrical response of the sensor, a DC voltage source (v_{in}) and a known resistor (R_L) are connected in series to the sensor (R_S). The voltage drop across the known resistor (v_{out}) is recorded (eDAQ, ED821 e-corder) on a personal computer equipped with a data acquisition board (NI 6251). Note that, in order to accommodate for the input impedance of the data acquisition system and the high order of resistance of the sensors, as will be explained in the next section, the load and the input voltage are chosen as $R_L = 50k\Omega$ and $v_{in} = 5V$, respectively. The collected data is later processed and visualised using MATLAB (MathWorks). The circuit representing the measurement setup is illustrated in Figure 3.

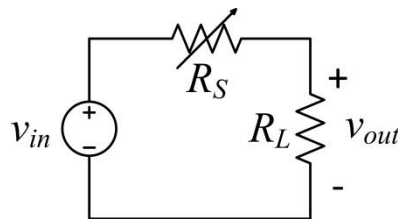


Figure 3 Simple circuit diagram for resistance measurement.

The resistance of the sensor at any given time can simply be found as:

$$R_S = \frac{v_{in} - v_{out}}{v_{out}} R_L$$

The experimental setup described above is presented in Figure 4.

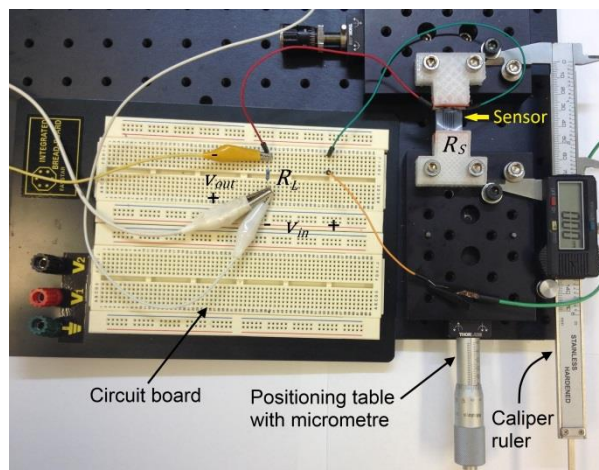


Figure 4 Experimental setup used for strain measurements.

3.2 Experimental results and interpretation of data

This section presents the results of various tests to which the sensors were subjected. Each graph given in the figures below provides the data obtained during a cycle of loading and unloading (where applicable) the sensor. However, each particular experiment (cycle) was repeated 10 times with the

same sensor to establish that the sensor shows a similar response in every cycle. Note that these experiments were conducted with different sensors fabricated at different times as well.

The first group of tests aims at investigating the variation of the sensors' resistance as a function of the applied strain. Sensors fabricated using different substrates and filled with different conductive liquids have been tested in the exact same way. The corresponding results are presented in Figure 5. Each data point provided in the plots is obtained by averaging the values recorded with a sampling period of 0.1 s for 5 seconds at each displacement increment during the experiment using the setup described in the previous subsection. Note that R_0 indicates the resistance of the corresponding sensor when it is not stretched, ΔR is the change of resistance and ϵ is the applied strain.

While the vertical axes on the left hand side of the plots show the percent normalised change in resistance ($\Delta R/R_0$), those on the right hand side indicate the sensors' actual resistance values. Recall that all sensors are fabricated targeting the same channel geometry. As expected, the resistances of the sensors filled with the same conductive liquid (CNF in PEDOT:PSS) are quite similar, whereas the sensor filled with CB has overall a higher resistance.

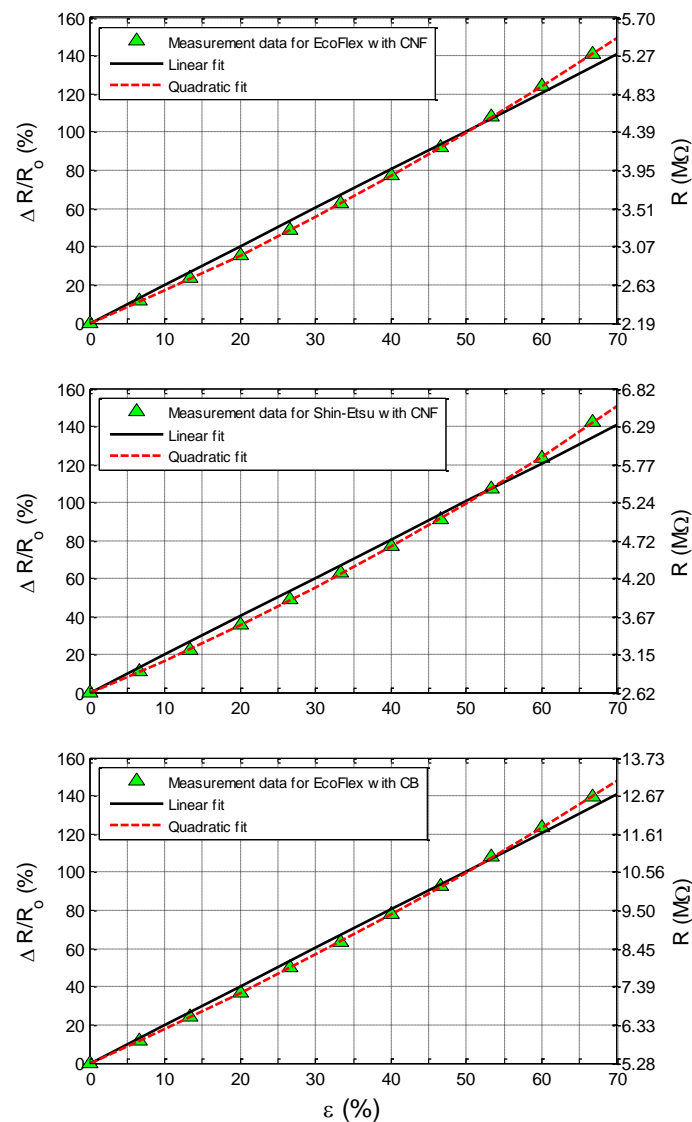


Figure 5 Change of resistance with increasing strain for the sensors made of two different base materials and conductive fluids.

Each data set in Figure 5 is interpolated by two curves; the solid and dashed curves indicate the linear and quadratic interpolation curves, respectively. Since it is known that ΔR is zero at rest (no strain), the curves are manually adjusted to intersect the origin. The relationships between $\Delta R/R_o$ and ε for the linear and second order fits are summarised in Table 1.

Table 1 Interpolation of data in Figure 5.

	Linear	Quadratic
EcoFlex + CNF	$\frac{\Delta R}{R_o} = 2.0098 \varepsilon$	$\frac{\Delta R}{R_o} = 0.7099 \varepsilon^2 + 1.6380 \varepsilon$
Shin-Etsu + CNF	$\frac{\Delta R}{R_o} = 2.0092 \varepsilon$	$\frac{\Delta R}{R_o} = 0.7784 \varepsilon^2 + 1.6015 \varepsilon$
EcoFlex + CB	$\frac{\Delta R}{R_o} = 2.0107 \varepsilon$	$\frac{\Delta R}{R_o} = 0.5530 \varepsilon^2 + 1.7210 \varepsilon$

According to Table 1, all three sensors exhibit a similar behaviour under strain. The gauge factor (GF) of the sensors, given by the formula $GF = \Delta R/R_o \varepsilon$, is found approximately 2 for all sensors, as seen in the first column of the table, indicating that gauge factor remains constant over the applied strain range and does not depend on the substrate material or the conductive liquid used in the sensor. Repeating several experiments with various sensors have resulted in gauge factors within the range of 1.8 and 2.2. Curve fitting and gauge factor of the sensor are included in some existing studies such as [2, 6, 9, 10] and are usually higher; indeed, the values seen in the first column of Table 2 are typically associated with metallic strain gauges [30, 31].

As seen in Figure 5, the resistance values of the sensors are in the order of mega ohms. Note that this high resistance allows the sensor to remain insensitive to electrical fluctuations caused by the wires at the contact points due to their motion during the experiments. Moreover, the resistance contribution of the external wires can be neglected. Another advantage of high resistance values is that the change of resistance can easily be observed under strain changes below 1%. Figure 6 provides the results of a similar experiment to the previous one. This time, however, the displacement of the positioning table is increased by 0.1 mm increments, resulting in a resolution of 0.67%; i.e. a change in resistance is observed at every 0.67% increase in the applied strain.

An important performance criterion for stretchable sensors is the amount of hysteresis displayed in the sensor behaviour. In order to show the hysteresis levels, the resistance values are continued to be recorded by gradually decreasing the applied strain at the same increments as in the loading cycle. The results are presented in Figure 7. Similar to the previous two tests, each data point is obtained by averaging the values recorded for 5 s. The plots show the data corresponding to the loading (upwards pointing triangles) and unloading (downwards pointing triangles) sequences of the sensors.

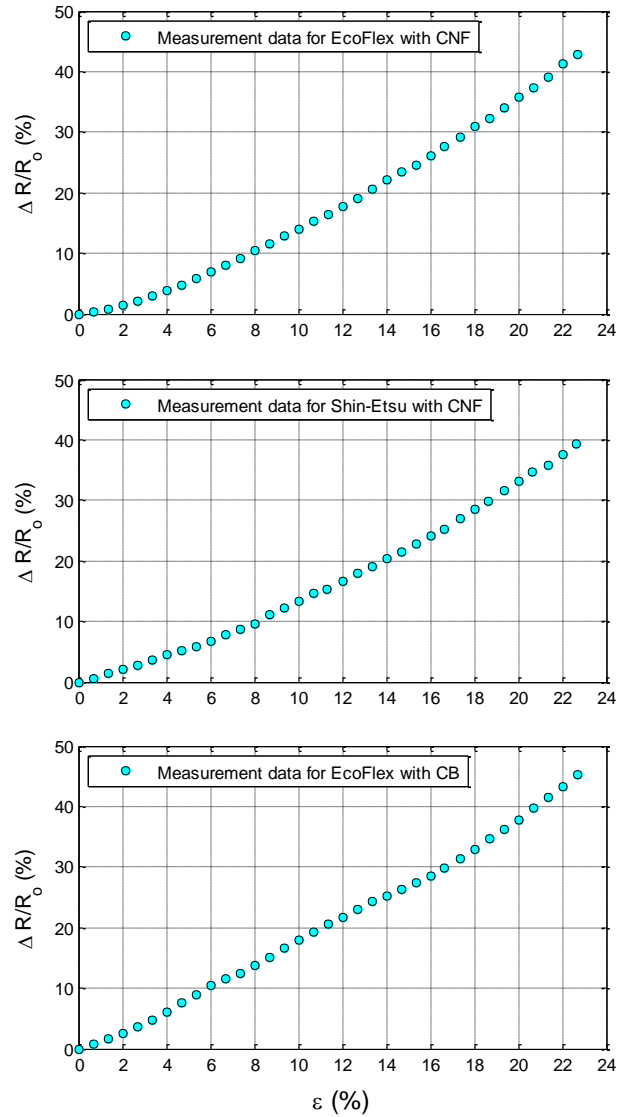


Figure 6 Strain sensing resolution of the sensors.

It is worth mentioning that the silicone compound used in the fabrication determines how much the sensor can be stretched. The maximum strain that can be applied to a sensor also affects how many times the loading and unloading cycles can be repeated over a certain strain range. As Figure 5 indicates, strain amounts above 100% can be applied to EcoFlex sensors without causing any damage. For Shin-Etsu sensors, however, repeating resistance versus strain measurements multiple times over the strain range of 0 - 120% caused the sensors to be torn in two after a couple of cycles. As robustness and repeatable operation are essential factors for the usefulness of the sensors, we limited the applied strain to Shin-Etsu sensors to no more than 70%. We found this value by gradually decreasing the maximum amount of applied strain in our experiments. At this range, the sensors remained undamaged regardless of how many times the experiments were repeated.

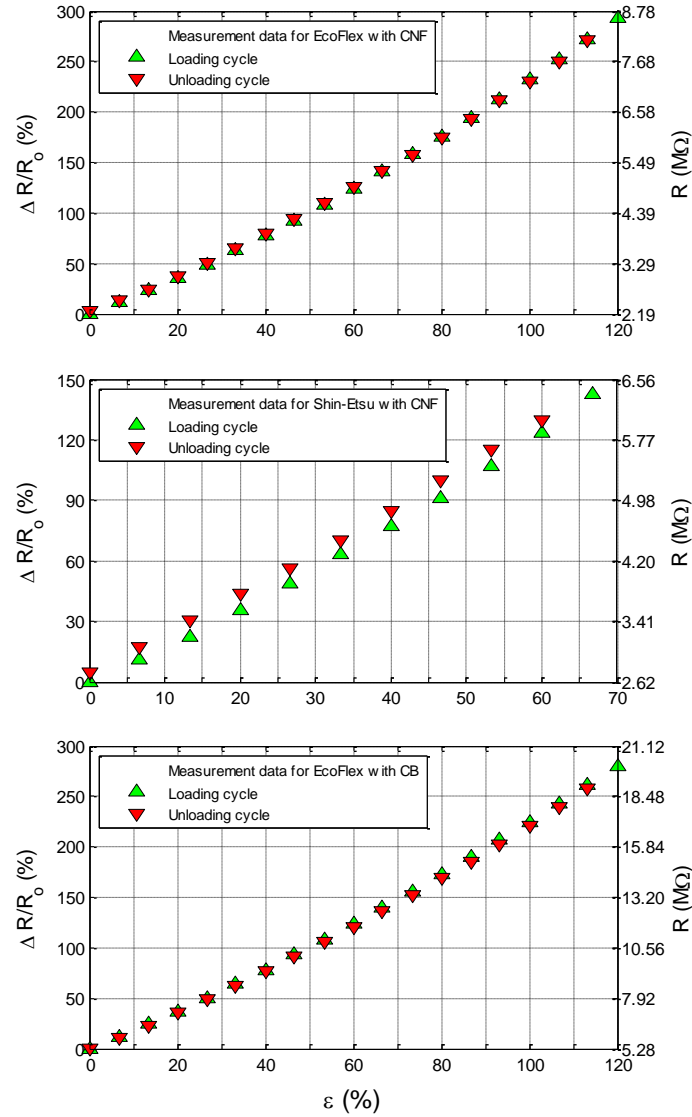


Figure 7 Loading and unloading cycles.

Figure 7 suggests that the sensors display a nonlinear response, as is generally the case in polymer based sensors. The amount of hysteresis observed in sensors fabricated with EcoFlex is less than those made using Shin-Etsu, since EcoFlex sensors can return to their previous states in a shorter time while it takes Shin-Etsu sensors longer to return to their initial length. EcoFlex sensors filled with CNF in PEDOT:PSS and CB remain with less than 3% and 0.2% excess resistance, respectively, when they are back in their unstretched states. The resistance of Shin-Etsu sensors, on the other hand, increases by more than 5% when they are back at 0% strain.

According to our observations, one reason for the hysteresis is that PEDOT:PSS is absorbed from the microchannels into the substrate material, increasing the overall resistance of the sensors over time. This phenomenon appears to occur more slowly in EcoFlex in comparison with Shin-Etsu. Furthermore, the absorption of the conductive liquid is even slower when CB is used, which explains why less hysteresis is observed in the sensor behaviour, as seen in Figure 7. We observed that the time during which seemingly identical sensors stay operational varies from 2 to 6 hours. In other words, our attempts to establish a fixed rate of material loss that occurs inside the sensors over time remained inconclusive. We suspect that the amount of fluid that is absorbed by the base substrate might be related to several factors such as the exact amount of fluid injected in the sensor, amount

of electrical current flowing through the fluid, amount of strain to which the sensor is subjected, how well the silicone compound is degassed and how properly the bonding of the silicone layers has occurred. Similar observations regarding the loss of ionic conductive fluids over time have been reported in [4, 21].

The nonlinear behaviour of the sensors can also be observed in Figure 8, where the step responses of two sensors that are fabricated using either substrate and filled with the same conductive fluid (CNF in PEDOT:PSS) are taken into consideration. The graphs in Figure 8 show the normalised change of resistance of the sensors with respect to time. The amount of the applied strain is instantly increased to 30% and then decreased back to zero in order to observe the sensor response during both the loading and unloading cycles. Note that the sudden increase of strain from 0 to 30% was accomplished by manually pulling the translation stage by 4.5 mm, as quickly as possible. The time needed for the strain increase was not taken into consideration when calculating the transient metrics for either sensor.

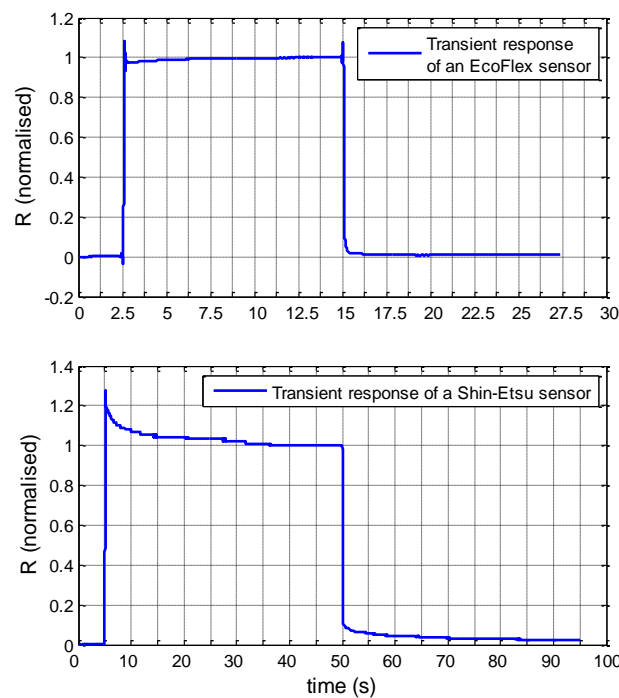


Figure 8 Transient characteristics of the sensors with different base materials.

When the strain is instantly increased, the response of the EcoFlex sensor is very quick and displays both an under- and an overshoot around 8%. The Shin-Etsu sensor, on the other hand, has an overshoot of over 27%; an undershoot is not observed. The two sensors also differ in terms of rise and settling times. The transient characteristics of the sensors during the unloading cycle appear to be significantly different than what they display during the loading cycle. Both their responses are overdamped and faster than the loading cycle. An undershoot is again observed for the EcoFlex sensor.

The transient response parameters of both sensors for loading and unloading cycles, i.e. percent overshoot (PO), rise (t_r) and settling t_s times and time constants (τ) of both sensors are summarised in Table 2. EcoFlex sensors have an overall faster response than Shin-Etsu sensors. This is consistent with the results provided in Figure 7 where more hysteresis is observed with Shin-Etsu, as each data point is calculated from data collected over the same time interval during each experiment. Note that, the rise times for the loading cycles indicate the time required for the response to rise from 0%

to 100% of its final value; whereas for the unloading cycles, the time for the response to fall from 90% to 10% is taken into account, as this is the common approach for overdamped responses [32]. Furthermore, the settling times given for the EcoFlex sensor in Table 2 indicate the time when the response continues to remain within the 2% error band; while the 5% error band definition is used for the Shin-Etsu sensor; the main reason being that the final resistance value for this sensor remains above 2% of its initial value.

Table 2 Transient response parameters.

	Loading cycle				Unloading cycle		
	t_{rl}	PO	t_{sl}	τ_l	t_{ru}	t_{su}	τ_u
EcoFlex	0.11s	8.1%	1.21s	0.3s	0.07s	0.45s	0.11s
Shin-Etsu	0.08s	27.6%	9.47s	3.16s	0.33s	8.35s	2.78s

4. Conclusion and future work

Fabrication and characterisation of various soft strain sensors are presented in this work. Their strain sensing capabilities, as well as the linearity of their response, the resolution they provide and their transient characteristics are also investigated.

The sensors are composed of microchannels trapped between two thin layers made of two different commercially available silicone compounds in order to observe the differences in characteristic properties that arise as a result of these two different substrates. Due to their distinct softness properties of these two compounds, separate strategies are used for the fabrication of the sensors. While one group of the sensors are fabricated by using a 3D printed mould, laser engraving and plasma bonding are the chosen steps for the fabrication of the other group. The two fabrication methods used in this study are found to be comparable in terms of practicality and time-effectiveness.

The microchannels within the silicone compounds are filled with a conductive liquid. Toward investigating the effect of the chosen liquid on the sensors' performance, two sensors fabricated using the same substrate are filled with two separate conductive liquids having different conductivities. By doing so, three groups of sensors that are composed of different base materials and conductive fluids are obtained for comparison. An experimental setup consisting of a simple electrical circuit and a data acquisition system was created which allows data to be collected at various sampling intervals.

The sensors' strain sensing capabilities are investigated by examining the changes in sensor resistances under varying amounts of strain. First and second order relations that represent the collected data over a range of 0% - 70% strain are given. A first order relation appears to represent the data well for the given strain range; that is the output received from the sensor is nearly linear with respect to strain, thus strain can easily be predicted from the change of resistance. The results also indicate that, over the strain ranges taken into account during the experiments, the gauge factor of the sensors does not depend on the amount of applied strain and is also not affected by the choice of the base material or the conductivity of the liquid used. As commonly encountered in soft stretchable sensors, hysteresis levels are observed between the loading and unloading cycles of the sensors. The amount of hysteresis observed in Shin-Etsu sensors is larger than those in EcoFlex. The Shin-Etsu silicone compound also enforces a limit of 70% on the maximum amount of strain that can be applied to the sensor, whereas EcoFlex sensors can easily be stretched over 100% many times without being damaged.

Changing the conductive liquid mainly affects the overall resistance of the sensor; the relation between resistance change and strain over the loading cycle is not affected. Sensors filled with either liquid have resistances in the order of mega ohms, thus providing a high strain sensing resolution even without complicated microchannel patterns; both fabricating and filling long and complex patterned channels can be impractical. This is the main advantage of these liquids over the preferred conductive eGaN in recent studies in which the resistance of the sensors is usually in the order of mere ohms. However, the liquids injected to the microchannels are absorbed by the substrate over time which is the main disadvantage of the conductive liquids chosen for this study. Moreover, the rate of absorption of PEDOT:PSS occurs at a faster rate in Shin-Etsu than in EcoFlex silicone rubber. Although the use of liquid CB increases the overall resistance of the sensor further, the rate of absorption of this liquid occurs at a slower rate than PEDOT:PSS.

One of the main contributions of this study is the inclusion of the detailed and comparative analysis of the transient response parameters in order to better explore the nonlinear behaviour displayed by the sensors. To that end, two sensors fabricated with either substrate with the same channel geometry are tested and compared. The only similarities observed during this test is that both sensors exhibit an underdamped response with similar rise times when the applied strain is suddenly increased and an overdamped response when the sensors are released to their original states. Sensors made of EcoFlex have overall much faster response characteristics during both loading and unloading cycles; having a smaller time constant makes them more useful for applications in which the input stimulus changes at a fast rate.

The current experiment and sensor designs enable repeatable readings in strain sensing. The reliability of these measurements depends to a large extent on the durability of the sensors which is directly affected by the choice of materials used in their fabrication. Taking into account the test results obtained in this study, the combination of EcoFlex as the base substrate and liquid carbon black as the conductive fluid appears to be the logical choice for the reasons summarised in this section for use in our intended application; the position control of a prosthetic finger made of a soft material. The main future effort in this regard will go into obtaining a mathematical model by recording the change in the resistance of the sensors that relates this information to the position of the fingertip and the positions of individual joints of the prosthetic finger. The operating point of the sensors, i.e. the amount of strain the sensors will be subject to is foreseen to not exceed the 0% - 20% range. Furthermore, the resolution provided by the sensors fabricated with the principles and techniques reported in this study is considered to be sufficiently high for this application.

Designing a proper strategy to successfully control the position of the underactuated finger without physical feedback of the actual tip position will be the ultimate goal of the study. Our future work will establish how the major disadvantage of these sensors, i.e. the absorption of the liquid over time, will affect the accuracy of the position estimation and the overall control performance. Therefore, much focus will also be given to exploring other conductive inks in the hopes of finding more suitable liquids with similar advantages provided by the materials used in this study. In an effort to improve linearity, different sensor geometries and microchannels with different dimensions are being experimented on as well. Improving the wire connections and their positioning is another ongoing effort.

Acknowledgment

The author S. K. Yildiz acknowledges the support provided by The Scientific and Technological Research Council of Turkey (TÜBİTAK) under the 2219 - Postdoctoral Research Scholarship Programme. The authors thank Dr Holly Warren and Mr Reece Gately for supplying carbon nanofibers (CNF) in poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) dispersion (PEDOT:PSS) and liquid carbon black (CB) used in this study. This work was supported in part by the

Intelligent Nano-Tera Research Systems Laboratory and by ARC Centre of Excellence for Electromaterials Science (Grant No. CE140100012).

References

1. Niu, X.Z., et al., *Characterizing and Patterning of PDMS-Based Conducting Composites*. *Advanced Materials*, 2007. **19**(18): p. 2682-2686.
2. Lu, N., et al., *Highly Sensitive Skin-Mountable Strain Gauges Based Entirely on Elastomers*. *Advanced Functional Materials*, 2012. **22**(19): p. 4044-4050.
3. Muth, J.T., et al., *Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers*. *Advanced Materials*, 2014. **26**(36): p. 6307-6312.
4. Frutiger, A., et al., *Capacitive Soft Strain Sensors via Multicore–Shell Fiber Printing*. *Advanced Materials*, 2015. **27**(15): p. 2440-2446.
5. Kramer, R.K., et al. *Soft curvature sensors for joint angle proprioception*. in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2011.
6. Chossat, J.B., et al., *A Soft Strain Sensor Based on Ionic and Metal Liquids*. *Sensors Journal, IEEE*, 2013. **13**(9): p. 3405-3414.
7. Araromi, O.A., S. Rosset, and H.R. Shea, *High-Resolution, Large-Area Fabrication of Compliant Electrodes via Laser Ablation for Robust, Stretchable Dielectric Elastomer Actuators and Sensors*. *ACS Applied Materials & Interfaces*, 2015. **7**(32): p. 18046-18053.
8. Park, Y.-L., et al., *Hyperelastic pressure sensing with a liquid-embedded elastomer*. *Journal of Micromechanics and Microengineering*, 2010. **20**(12): p. 125029.
9. Park, M., et al., *Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres*. *Nat Nano*, 2012. **7**(12): p. 803-809.
10. Menguc, Y., et al. *Soft wearable motion sensing suit for lower limb biomechanics measurements*. in *IEEE International Conference on Robotics and Automation (ICRA)*. 2013.
11. Park, Y.-L., B.-R. Chen, and R.J. Wood, *Design and Fabrication of Soft Artificial Skin Using Embedded Microchannels and Liquid Conductors*. *Sensors Journal, IEEE*, 2012. **12**(8): p. 2711-2718.
12. Dickey, M.D., et al., *Eutectic Gallium-Indium (EGaln): A Liquid Metal Alloy for the Formation of Stable Structures in Microchannels at Room Temperature*. *Advanced Functional Materials*, 2008. **18**(7): p. 1097-1104.
13. Park, Y.-L., B.-r. Chen, and R.J. Wood. *Soft artificial skin with multi-modal sensing capability using embedded liquid conductors*. in *Sensors, 2011 IEEE*. 2011.
14. Zhu, S., et al., *Ultrastretchable Fibers with Metallic Conductivity Using a Liquid Metal Alloy Core*. *Advanced Functional Materials*, 2013. **23**(18): p. 2308-2314.
15. Majidi, C., R. Kramer, and R.J. Wood, *A non-differential elastomer curvature sensor for softer-than-skin electronics*. *Smart Materials and Structures*, 2011. **20**(10): p. 105017.
16. Chun, K.-Y., et al., *Highly conductive, printable and stretchable composite films of carbon nanotubes and silver*. *Nat Nano*, 2010. **5**(12): p. 853-857.
17. Yamada, T., et al., *A stretchable carbon nanotube strain sensor for human-motion detection*. *Nat Nano*, 2011. **6**(5): p. 296-301.
18. Lipomi, D.J., et al., *Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes*. *Nat Nano*, 2011. **6**(12): p. 788-792.
19. Lacasse, M.A., V. Duchaine, and C. Gosselin. *Characterization of the electrical resistance of carbon-black-filled silicone: Application to a flexible and stretchable robot skin*. in *IEEE International Conference on Robotics and Automation (ICRA)*. 2010.
20. Firouzeh, A. and J. Paik, *Robogami: A Fully Integrated Low-Profile Robotic Origami*. *Journal of Mechanisms and Robotics*, 2015. **7**(2): p. 021009-021009.
21. Cheung, Y.-N., et al., *A novel fluidic strain sensor for large strain measurement*. *Sensors and Actuators A: Physical*, 2008. **147**(2): p. 401-408.

22. Noda, K., et al. *Stretchable liquid tactile sensor for robot-joints*. in *IEEE International Conference on Robotics and Automation (ICRA)*. 2010.
23. Wu, C.-Y., W.-H. Liao, and Y.-C. Tung, *Integrated ionic liquid-based electrofluidic circuits for pressure sensing within polydimethylsiloxane microfluidic systems*. *Lab on a Chip*, 2011. **11**(10): p. 1740-1746.
24. Manandhar, P., P.D. Calvert, and J.R. Buck, *Elastomeric Ionic Hydrogel Sensor for Large Strains*. *Sensors Journal, IEEE*, 2012. **12**(6): p. 2052-2061.
25. Sun, J.-Y., et al., *Ionic skin*. *Advanced Materials*, 2014. **26**(45): p. 7608-7614.
26. Mutlu, R., et al. *Effect of flexure hinge type on a 3D printed fully compliant prosthetic finger*. in *IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*. 2015.
27. Saggio, G., *Mechanical model of flex sensors used to sense finger movements*. *Sensors and Actuators A*, 2012. **185**: p. 53–58.
28. Sajid, M., et al., *Highly stable flex sensors fabricated through mass production roll-to-roll micro-gravure printing system*. *Sensors and Actuators A: Physical*, 2015. **236**: p. 73-81.
29. Michaud, H.O., J. Teixidor, and S.P. Lacour. *Soft flexion sensors integrating stretchable metal conductors on a silicone substrate for smart glove applications*. in *28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*. 2015.
30. Hoffmann, K., *An Introduction to Stress Analysis and Transducer Design using Strain Gauges*. 1987: HMB.
31. *Measuring Strain with Strain Gages*, 2014, National Instruments, .
32. Ogata, K., *Modern Control Engineering*. 3rd ed. 1997: Prentice Hall.