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CocoStretch: Strain sensors based on natural coconut oil and carbon black filled elastomers

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Abstract

A biocompatible inexpensive strain sensor constituting of an elastomer filled with natural coconut oil and carbon black is presented here. Strain sensors are widely utilised for applications in human activity recognition, health monitoring and soft robotics. Given that these sensors are envisioned to be present in a plethora of fields, it is important that they are low cost, reliable, biocompatible and eco-friendly. This work demonstrates that coconut oil can be used to create conductive percolation network in elastomers, without the necessity for harmful chemicals or expensive machinery. The sensor has a gauge factor of 0.77 ± 0.01 , and the sensing material has a porous morphology filled with an oily suspension formed of coconut oil and carbon black. The results indicate that the liquid filled porous structure can improve the reliability of these resistive strain sensors in comparison to sensors fabricated utilising commonly used nonpolar solvents such as heptane. Consequently, the sensor demonstrates a hysteresis of only 2.41% at 200% strain over 250 stretch/release cycles. Finally, to demonstrate the potential of this fabrication technique, a functionalised glove was developed and used to

detect wrist motion. These easily manufacturable and cost-effective sensors enable wearable on-skin ergonomic intervention systems with minimal impact on the environment.

Introduction

Advancements in flexible and stretchable electronics such as deformable transistors,^[1–3] circuits,^[1,3] sensors,^[3,4] and energy harvesters^[1,5] are currently paving the way towards innovative wearable systems or soft robots.^[6–12] In particular, conformable strain sensors enable a variety of applications such as physical activity monitoring,^[13–17] motion capturing,^[18–20] telemedicine^[21–23] and artificial skins.^[24,25] Moreover, strain sensors have been integrated onto the surface of textiles showcasing their potential to become ubiquitous in smart textile applications.^[16,26] This results in the strain sensors coming into direct contact with human skin. Therefore, there has been a significant drive towards the development of biocompatible strain sensors. For instance, researchers have investigated the effects of ionic liquids and hydrogels to fabricate stretchable strain sensors with low hysteresis.^[27,28] However, most of these sensors have low gauge factors and high impedances, which in-turn complicates the sensors' readout electronics, making them unsuitable for wearable applications. Although resistive strain sensors with high gauge factors have been fabricated,^[29,30] some of these sensors demonstrate a limited strain range of 50%, while others were unable to go back to their original length once stretched. The nature of human motion requires the use of highly stretchable sensors for activity monitoring. This has led to extensive work in developing strain sensing materials and sensors with high sensitivities and wide strain ranges. Most of these sensing materials are fabricated utilizing harmful chemicals,^[31–36] expensive equipment,^[37,38] sophisticated mechanical designs^[36,39,40] or advanced low dimensional materials.^[41–43]

Given the absence of inherently stretchable piezoresistive materials, strain sensors are commonly synthesized by mixing elastomers and conductive materials. In this context Ecoflex is preferred as an elastomer due to its high stretchability, biocompatibility and ease fabrication.

In addition, sensors constructed using Ecoflex showcase a fast response and low hysteresis.^[13,20,44] In the case of conductive fillers, a low cost conductive material is highly desirable for a large scale and inexpensive production of strain sensors. In this regard, carbon black (CB) has been preferred^[13] in comparison to other fillers such as metal nanowire/nanoparticles,^[19,45–47] carbon nanotubes/nanoparticles,^[31,48] and liquid metals.^[49] However, the poor dispersibility of CB in water complicates the formation of uniform and controllable CB conductive networks without resorting to potentially harmful solvents.^[50] In general, nonconductive solvents such as dimethyl dispersion solution,^[31] chloroform,^[32] Toluene,^[33] Heptane,^[34] hexane and acetone^[35] have been utilised during the preparation of CB based elastomer sensors. These solvents increase the dispersibility of the CB particles in the mixture. Nonetheless, most of these solvents are explosive or toxic and therefore are required to be handled with care when fabricating the sensors. Moreover, after the fabrication, traces of these chemicals will be present in the structure, and this could harm the wearer. Shintake et al.^[38] have created strain sensors with a stretchability of 500% and a gauge factor ranging from 1.62–3.37 by mixing CB in Ecoflex without the use of these harmful chemical. However, to synthesize these sensors, expensive equipment such as planetary centrifugal mixers were utilised. Non-toxic but synthetic diluting agents such as silicone oil has been utilized in the synthesis of CB silicone strain sensors,^[51] where the excess of silicone oil was evaporated after the CB particles were mixed in the silicone rubber. The material exhibited limited stretchability of 155%–164% which makes these sensors less preferable for smart textile application where a large working range is required.

Another important factor that effects the performance of elastomeric strain sensors is the constant friction between the solid-state conductors and the elastomeric molecules.^[47,52,53] This leads to slippage and detachment among the conductors resulting in low repeatability of the sensor measurements. This can be addressed by utilizing liquid state conductors, due to the ability of liquids to undergo virtually limitless and instantaneous deformation.^[12,52] Therefore,

we utilize eco-friendly coconut oil (CNO) instead of volatile solvents to create a partially liquid and conductive percolation network in Ecoflex when mixed with CB. CNO is an inexpensive, non-hazardous and environmentally friendly natural polymer. It is recognised as a cooking oil fit for human handling and consumption, which is why it is widely used across the food and cosmetic industries.^[54] This oil, as with most of the other natural esters, consists of triglycerides.^[55] These triglycerides contain different fatty acids that make the CNO comparatively conductive to other oils.^[55] Previously, CNO mixed with grape seed oil was used to fabricate a temperature sensor.^[56] Large stretch-ability ($\geq 100\%$) and great stability are also important factors for sensors that require wide strain detection range and long-term repeated usage.

An easily manufacturable, ecofriendly and cost-effective fabrication technique for producing strain sensors with a large strain detection range and great stability, is presented in this work. This fabrication technique is well-suited for environments where standard, yet expensive, electronic and chemical fabrication facilities are not available, as is the case of schools and developing countries. These biodegradable devices are easily customisable and can be utilised to develop ergonomic intervention systems that can be used by everyone. Here, CNO was used to disperse CB and create conductive pathways encased in an Ecoflex structure, as shown in **Figure 1**. Furthermore, scanning electron microscopy (SEM) images and energy-dispersive X-ray (EDX) spectral analysis of the fabricated sensors demonstrated that high CNO density areas displace the Ecoflex, resulting in interconnected tunnel-like CNO/CB pathways. These conductive liquid pathways lead to more reliable measurements for different strains, when compared to sensors fabricated using heptane. Moreover, the sensors demonstrated a hysteresis of only 2.41% at 200% strain over 250 stretch/release cycles. The response time and resistance drift with time and temperature of the sensor were also investigated. In addition to the characterisation, a coconut strain sensor was attached to a textile glove and utilised to monitor wrist motion.

Results

The composite sensing material created by mixing Ecoflex, coconut oil (CNO) and carbon black (CB) has a porous morphology, as shown in Figure 1b. CNO replaces conventional solvent based methods to create CB conductive pathways within Ecoflex. Unlike solvents, the CNO does not evaporate and remains in the structure when the Ecoflex solidifies. This creates a porous structure with a porosity of 35.3%. The pores were filled with an oily suspension containing CB particles. To further clarify this, the sensing material was pressed to get the oily suspension out. Then an Energy-dispersive X-ray (EDX) spectral analysis was conducted on the oily suspension to identify its composition. The results given in Figure 1c1 illustrate that the material contained mainly carbon and oxygen. In comparison the EDX analysis of the frame shown in Figure 1c2 displays high concentrations of silicon. Hence it can be said that the CB and CNO were left in the pores of the material. Furthermore, it was also vital to identify if the porous structure without the oily suspension contained CB particles. For this reason, the material was pressed and thoroughly cleaned with IPA and water to remove the oily suspension. Afterwards the sample was dried, it consisted of only the porous Ecoflex structure without any oil or solvent. This dried sample was dissected, and a high-resolution SEM image of the cross-section was obtained which is displayed in Figure 1d. As shown in Figure 1d, the structure contains well dispersed CB particles. This indicates that during the fabrication process some CB particles were also dispersed in liquid Ecoflex and once it cured these CB particles were trapped in the porous Ecoflex structure.

After the development of the individual wet sensors, a functionalised glove was created and utilised for wrist motion detection. To achieve this, a single sensor was attached using Ecoflex to a wrist glove, as shown in Figure 1e. A volunteer was asked to perform four wrist movements, namely, extension, flexion, ulnar deviation and radial deviation. Each wrist position was held

for thirty seconds and in between each position the hand was returned to its original neutral position and held for thirty seconds. The data was recorded using a battery powered Bluetooth enabled BlueSense microcontroller, making this system completely standalone.^[57] Although these were multi-dimensional movements the results shown in Figure 1f demonstrate that a single sensor can clearly distinguish extension and flexion from radial and ulnar deviations. Therefore, we proved the feasibility of using the wet sensor for wrist motion detection, which is beneficial for activity recognition and preventing carpal tunnel syndrome.

The simple fabrication technique of the CB/CO sensor is shown in **Figure 2a** and this process is explained in detail in the experimental section. In order to characterise the properties of the composite material, the conductivity of the wet composite material for different concentrations of CB ranging from 0 to 12% was investigated and the I/V graphs are shown in Figure 2b. As observed in the graphs the best conductivity is obtained at 12% CB. At higher concentrations of CB the solution was too viscous to be efficiently mixed using a simple magnetic stirrer. For comparison purposes 12% CB was mixed with Ecoflex without CNO and its I/V characteristics are displayed in Figure 2c. This material demonstrated a low conductivity and the material did not have uniform electrical properties throughout its structure. Moreover, the electrical characterisation of the dried sample is given in Figure 2c. The observed conductivity of the dried sample is due to the CB particles dispersed within the porous structure. As demonstrated in the IV graphs (Figure 2a and Figure 2c) the wet sample has a better conductivity in comparison to the dried one. This increase in conductivity is due to the presence of the oily suspension comprising of CB and CNO in the wet sample. The results from the I/V graphs indicate that the 12% CB/CNO wet material has the best conductivity when compared to the rest. Hence, to assess the feasibility of using this CB/CNO wet composite material to measure strain, we fabricated and characterized a CB/CNO resistive strain sensor. The sensors

constituted of the CB/CNO material encased and sealed within an Ecoflex structure as illustrated in Figure 1a. The necessity for the Ecoflex encasement was due to the oily exterior of the sensing material, which comprised of an oily suspension in the porous structure. Since the sensors were fabricated using rigorous stirring, it was important to identify if the resistance of the sensors varied significantly in between different devices. Therefore, three different material batches were synthesised, and from each batch three different sensors were fabricated. The sensors had an average resistance of $235 \pm 181 \text{ k}\Omega$ and the resistance of these sensors could be easily customized by changing the CB concentration as shown in the IV graphs in figure 2b and d. It was important to identify if stretching the CB/CO material brings about any changes in the surface morphology. Therefore, microscopic images were obtained from the surface of the material when it was relaxed and stretched to 100% strain, and they are displayed in figures 2e-f. The images show that there are no cracks in the surface due to stretching. This was further clarified by the SEM image of the stretched material displayed in figure 2g.

Further to the characterisation of the composite material, individual CB/CNO strain sensors were fabricated. **Figure 3a** displays a microscopic image of a cross section taken from a CB/CNO strain sensor. From images of several cross sections we extracted a porosity of 35.3% and figure 3b shows the analysis conducted on figure 3a, where white areas represent the porous regions. In general, for bulk materials water saturation and water evaporation method are more suitable however, for this material we utilized microscopic images because the material contained sealed pockets of CB/CO within its structure. Moreover, to directly compare these strain sensors with those fabricated using heptane as a solvent, we manufactured CB/heptane sensors with similar dimensions to CB/CNO sensors. The microscopic image of the cross section of a CB/heptane sensor is displayed in figure 3c and it demonstrates a less porous structure. The performance of strain sensors is commonly characterised by their gauge factor (sensitivity), stretchability, hysteresis and response time.^[36] The response of a resistive strain

sensor assuming that the cross-section of the electrode layers is uniform (Poisson ratio ≈ 0) can be expressed as follows^[38]

$$R = \rho(l_0/w_0h_0)(\varepsilon_1 + 1)^2 = \left(\frac{\rho}{\rho_0}\right)R_0(\varepsilon_1 + 1)^2 \quad (1)$$

Where ρ is the electrical resistivity of the conductive elastomer; ρ_0 is the reference resistivity; R_0 is the reference resistance; l_0 , w_0 and h_0 are the length, width and thickness of the electrodes respectively. When strained, the resistivity of CB/CNO material changes as a result of the breakdown and re-alignment of CB aggregates which alters the conductive paths within the material. ^[38,58] This alteration results in a change in resistance and the ratio of this relative change to the mechanical strain is known as the gauge factor GF_R . The GF_R of a resistive strain sensor is given by the following equation.

$$GF_R = \left(\frac{\Delta R}{R_0 \varepsilon_1}\right) = \left(\frac{1}{\varepsilon_1}\right) \left(\left(\frac{\rho}{\rho_0}\right)R_0(\varepsilon_1 + 1)^2 - 1\right) \quad (2)$$

Where ΔR is the change in resistance when compared to the unstrained resistance R_0 . The strain on the sensor is given by ε_1 .

The gauge factor measurements for the presented CB/CNO sensor are shown in Figure 3d. The gauge factor of the sensor ranges from 0.21 ± 0.01 at 20% strain to 0.77 ± 0.01 at 200% strain. The graph also demonstrates the repeatability of $\Delta R/R_0$ for each strain and recovery step over 10 cycles. The average standard deviation for each step is only 0.017. The gauge factors of the heptane sensors are 0.77 ± 0.58 at R_{20} and 0.52 ± 0.05 at R_{200} . The measurements over 10 cycles for the CB/heptane sensors are shown in Figure 3e. The graph demonstrated a lower repeatability of $\Delta R/R_0$ in comparison to the CB/CNO sensors for strain steps over 10 cycles. For the heptane sensor the average standard deviation of $\Delta R/R_0$ was 0.112 for each step. This is significantly larger than the 0.017 obtained from the CB/CNO sensor. The performance of CB/CNO sensors was superior to the fabricated heptane sensors which used hazardous chemicals. The superior performance of the CB/CNO sensor is due to the oily liquid nature of

the material. This reduces the friction in between the CB particles and the elastomer molecules which minimizes the detachment and slippage among these conductive CB particles. [12,47,52]

These sensors when utilized for detecting human motion must be able to withstand large strains. Hence, it is vital to measure the maximum stretchability that the sensor can endeavour. The CB/CNO sensors had a maximum stretchability of $1035 \pm 215\%$ which can be regarded more than adequate for detecting human motion. The change in resistance of a CB/CNO sensor when stretched to its rupture strain is displayed in Figure 3f. In real life applications, strain sensors must also maintain their sensing characteristics without fatigue failure and minimal hysteresis. Therefore, the sensors were subjected to 250 stretch/release cycles at 200% strain to examine their long-term stability. The complete experimental results are presented in Figure 3g. A sample of seven cycles of the test is displayed in Figure 3h. The cyclic test verifies that the strain sensor has a good mechanical durability against repeated stretch/release cycles at 200% strain with no signs of fatigue failure. The change in sensor resistance at R_0 after 200 cycles was only $-0.28 \pm 0.07\%$ and the change in R_{200} was $2.41 \pm 0.06\%$. These percentage changes were similar to the measurements recorded from the CB/heptane sensor, where R_0 and R_{200} changed from $-3.52 \pm 0.08\%$ and $1.26 \pm 0.12\%$ respectively (shown in Figure 3i). Thereafter, a larger cyclic test of 1000 cycles at 200% strain was conducted on a CB/CO sensor to further understand its durability and stability. The results presented in figure 3j indicates that these sensors are even functional after 1000 cycles. An overshoot was also observed during the cyclic tests in both the CB/CNO and CB/heptane sensors, as shown in Figure 3g-j. Therefore, an experiment was conducted CB/CNO sensor to estimate the effects of overshoot on the measurements. As it can be seen in Figure 3k, the sensors' overshoot increases with increasing strain. The average overshoot was calculated as $22.16 \pm 4.51\%$.

For wearable applications, it is also vital to determine the response time of the sensors when subjected to step changes. The response time of the CB/CNO sensors was measured as 1.11 ± 0.21 s at 100% strain. This response time is sufficient for 3D human body shape reconstruction applications,^[17,59] and ergonomic intervention systems for posture recognition,^[16,60,61] and carpal syndrome detection.^[62–64] Furthermore, the resistance drift of strain sensors can greatly hinder their usability in wearable applications.^[65] Therefore, to observe the drift characteristics, the CB/CNO sensor was stretched to 100% strain and left for 15.0 min. This is shown in Figure 3l. The initial measurements were always obtained 5 min after the step change to ensure that the overshoot was not influencing the measurements. Within a 10 min time window a drift of $2.04 \pm 0.06\%$ was recorded from the sensor. In addition, temperature also has an impact on the performance of most resistive strain sensors.^[38] Therefore, we investigated the influence of temperature on the unstrained sensor. The maximum total change in $\Delta R/R_{25}$ of the sensor was measured as $8.32 \pm 1.58\%$, when subjected to step changes of temperature from 25 to 55 °C at 5 °C increments. The results are shown in Figure 3m. Moreover, since coconut oil has a melting point of 24 °C it was important to identify the functionality of the sensors at lower temperatures. Therefore, the same sensor that was utilised for the stability experiments was positioned within a fridge at 10 °C for 1 h. Then the sensor was taken out of the fridge and immediately cyclic tests at 200% strain was performed on the sensor. The results displayed in figure 3n indicate that cooling the sensor had minimal impact on its performance. The sensor performance is not affected by lower temperatures because CO does not form into a complete solid at 24 °C, it forms into a thick, greasy material. This is due to the triglycerides in coconut oil consist of a mixture of different fatty acids and each of these fatty acids has its own melting point, and at 24 °C only some fatty acids solidify.^[66]

This is the first-time strain sensors have been successfully fabricated using CNO. The strain sensitive material synthesized had a porous structure filled with an oily suspension containing

CB particles. These CB/CNO sensors produced more reliable measurements in comparison to CB/heptane sensors also presented in this work. Heptane is a non-polar solvent that has generally been utilised for mixing CB particles in elastomers.^[34] The sensors demonstrated a superior stretchability compared to the once fabricated using silicone oil.^[51] Moreover, the gauge factor and temperature response were comparable to the resistive strain sensors manufactured by Shintake et al.^[38] using an expensive planetary centrifugal mixer. This paper has demonstrated that CNO can be used to replace harmful chemicals such as heptane and expensive equipment in the creation of strain sensors. These strain sensors can be fabricated using inexpensive easy to get raw materials with minimal effect on the users' health.

The sensors had a gauge factor of 0.77 ± 0.01 , a stretchability of $1035 \pm 215\%$ and a resistance drift in R_0 of only 0.69% and in R_{200} of 2.41% after 250 cycles at 200% strain. Ultimately, the strain sensors were integrated onto a glove and successfully utilized for detecting wrist motion. These sensors are a low cost and easy to fabricate technique that can be utilised in the future to create strain sensors for wearable applications.

Experimental Section

Preparation of the carbon black/coconut oil Ecoflex sensor

The sensors fabricated in this paper comprised of carbon black (CB) and coconut oil (CNO), encased in Ecoflex. The sensing material was fabricated by mixing liquid silicone elastomer Ecoflex (00-30 Smooth-on, Pennsylvania, United States), CNO (Pipkin, London, UK) and CB (Vulcan P, Cabot, Boston, Massachusetts, United States) 10:5:1.2 by weight.

For the preparation of the material initially the CB was added to the CNO and heated over a water bath to 30 °C. It was crucial to maintain this temperature since the melting point of CNO is 24 °C. The solution was stirred for 0.5 h to ensure the release of the agglomerated CB particles. Then part B of Ecoflex was added to the solution and it was stirred rigorously for 3 h. Thereafter, the heating was turned off and the solution was left to cool at room temperature

over the course of 1 h, during this time the solution was continuously stirred. This was done to ensure the solution was cooled when part A was added, since higher temperatures cause the Ecoflex to cure faster. Afterwards, part A was added and the solution was stirred for 1-2 min. Then the solution was degassed and poured into an Ecoflex mould for curing. The mould had dimensions of length 20 mm by width 5 mm by height 2 mm. Moreover, copper contact wires were inserted into the structure before it was fully cured. The wires were later used to connect the sensor onto the readout electronics. Thereafter a layer of Ecoflex was added on top to fully encase the sensing material.

Preparation of the carbon black/heptane Ecoflex sensors

The materials utilised for the CB/heptane sensors were heptane, Ecoflex and CB (10:10:1.2). These samples were fabricated by stirring CB with heptane for 0.5 h. Afterwards, part A of Ecoflex was added and stirred for 3 h. Finally, the part B of Ecoflex was added and stirred for an additional 3 h. As in the previous sample, the structure was degassed and encased in Ecoflex.

Porosity estimation of the carbon black/coconut oil Ecoflex sensor

The porosity of the material was estimated by quantifying the area of the dark spots in the microscopic cross-sections of the CB/CNO sensors using the image analysis software tool Image J, as shown in **Figure S1**.

Conductivity experiments on the composite materials

The conductivity experiments were conducted using a Keysight B1500A parameter analyser. The samples tested were positioned on top of two copper tapes positioned 5 mm apart attached onto a glass slide. The copper tapes were utilized as contact pads for the probes instead of the oily material. The thickness and width of the samples were both 5 mm.

Experiments to measure the performance of the strain sensors

For these experiments we utilised a stretch system comprising of a stepper motor and a MCDC 3006 motion controller (Faulhaber, Schönaich, Germany). Here one representative sample from each of the two types of sensors (CB/CNO and CB/heptane) was utilised. The measurements

from the sensors were recorded using a digital multimeter (34465A, Keysight, Santa Rosa, CA, USA). The sensors were stretched every 10 min by 20% to 200% to determine the gauge factor. Measurements were taken every second. The average resistance measured by the sensor for each step was calculated from the average of the measurements obtained in between 9.5 min to 10 min after the previous step. This was done to ensure a steady state was reached before the measurements were obtained. For the experiment to obtain the maximum stretchability, six devices were stretched until there was complete rupture and infinite resistance between the two ends of the sensor. In the case of the cyclic tests the stretch system was utilised to stretch the sensor to 200% and it was left at that position for 60 s thereafter it was released to its original length and left for 60 s. The total time for the completion of a single cycle was 131 s. The process was repeated for 250 cycles and the measurements were measured every 0.5 s utilising the Keysight multimeter. The same procedure was utilised for the durability and stability experiments. In this case a CB/CO sensor was cycled for 1000 cycles at 200% strain. For the response time and drift experiments the stretch system was utilised to stretch the sensors by a step of 100% and relaxed. As in the previous experiment the measurements were measured every 0.5 s using the Keysight multimeter. The response of the sensors to different temperatures was evaluated using an EchoTherm IC50 digital Chilling/Heating Dry Bath (Torrey Pines Scientific Inc., Carlsbad, CA, USA). The temperature of the surface of the dry bath was changed from 25 °C to 55 °C in steps of 5 °C. For the experiment to evaluate the performance of the cooled sensors, the sensor used for the durability and stability experiment was put inside a fridge at 10 °C for 1h. Thereafter it was taken out and a cyclic test was performed on the sensor at 200% strain. In each step the temperature was maintained for 10 min. The average measurement was calculated from measurements obtained in between 9.5 min and 10 min after the previous step. This ensured that a steady state had been reached when the measurements were obtained. For the wrist motion detection experiment the sensor was connected to the ADC channel of a bluesense microcontroller.^[57] The change in voltage was measured using an

analogue input of the microcontroller and transmitted through Bluetooth onto a computer. The data was processed and analysed in Python.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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P.L., N.M., and J.C.C. conceived and designed the experiments; P.L. performed the experiments; P.L. and J.C.C. analysed the data. N.M. provided expertise in flexible electronics; D.R. provided expertise in data analysis; P.L., J.C.C., L.A.G.-G., and A.P. wrote the paper with input from all authors; D.R. and N.M. supervised the work. All authors have read and agree to the published version of the manuscript. This work was partially funded by EPSRC, GCRF, and NIHR, under the contact number: EP/R013837/1 (SmartSensOtics).

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Figure 1. Carbon black dispersed in coconut oil can be used to fabricate sensors for smart textiles. a) Concept figure of a CB/CNO strain sensor encased in an Ecoflex structure. b) SEM image of the cross-section of a CB/CNO sensor material. Here the regions with a higher carbon concentration is presented in yellow and cyan shows the regions with a higher silicon concentration. c1) Energy-dispersive X-ray (EDX) spectral analysis done on the oily material present within the pores of the composite material. c2) EDX analysis done on the surface of the sensor. d) Closeup image of the dried material where carbon is shown in green and silicon in red. e) The strain sensor integrated onto a textile glove and utilised for flexion, extension, ulnar deviation and radial deviation. f) Results from wrist motion experiment where the response due to flexion, extension, ulnar deviation, radial deviation and neutral position are shown in the red, blue, yellow, green and white regions of the graph respectively. The graph was utilised to distinguish between flexion and extension

Figure 2. The fabrication technique and I/V characteristics of the CB/CO composite material along with microscopic images of the material when it is relaxed and stretched. a) Simple fabrication technique of the CB/CO sensors. b) I/V graphs for different concentrations of CB in CNO and Ecoflex material, from 0-12%. c) The I/V characteristics of the dried sample that

contained 12% CB and the I/V characteristics of a mixture containing only 12% CB and Ecoflex without CNO. d) The resistance measurements from the different materials compositions. Microscopic images of a surface of the CB/CNO sensor material when e) it is relaxed, f) when it is stretched to 100% strain, captured using a Dino-Lite premier digital microscope (New Taipei City, Taiwan). g) A SEM image of the stretched CB/CNO sensor material at 100% strain.

Figure 3. Microscopic images of the CB/CNO and CB/heptane sensors along with their performance. a) Closeup of the CB/CNO sensor material using a Dino-Lite premier digital microscope f (New Taipei City, Taiwan). b) Image analysis conducted on a) utilising Image J,

where white areas represent the porous regions. c) Closeup of the CB/heptane sensor material using the digital microscope. d) Change in resistance with response to strain over 10 cycles for the sensor fabricated using CNO. e) Change in resistance with response to strain over 10 cycles for the sensor fabricated using heptane. f) Resistance change recorded from a representative CB/CNO sensor when stretched up to its rupture strain of 1130%. g) Cyclic tests conducted on the CB/CNO sensor for 250 cycles at 200% strain and h) presents a section of the cyclic test. i) Cyclic tests conducted on the CB/heptane sensor for 250 cycles at 200% strain. j) The first and the last five cycles from the stability and durability experiment where a CB/CO sensor was cycled at 200% for 1000 cycles (the complete experimental measurements are given in **Figure S2**) k) Increase in strain in steps of 20% up to 200% to identify the overshoot in the sensor. l) Drift measurements from the sensor where the sensor was kept stretched for fifteen minutes. m) Temperature response of the CB/CNO sensor. n) Cyclic measurements at 200% strain from a CB/CO sensor that was cooled to 10 °C.