Romano *et al. Soft Sci* 2024;4:31
DOI: 10.20517/ss.2024.24

Soft Science

Supplementary Materials

Tunable soft pressure sensors based on magnetic coupling mediated by hyperelastic materials

Chiara Romano[1], Daniela Lo Presti[1,2], Sergio Silvestri[1], Emiliano Schena[1,2], Carlo Massaroni[1,2,*]

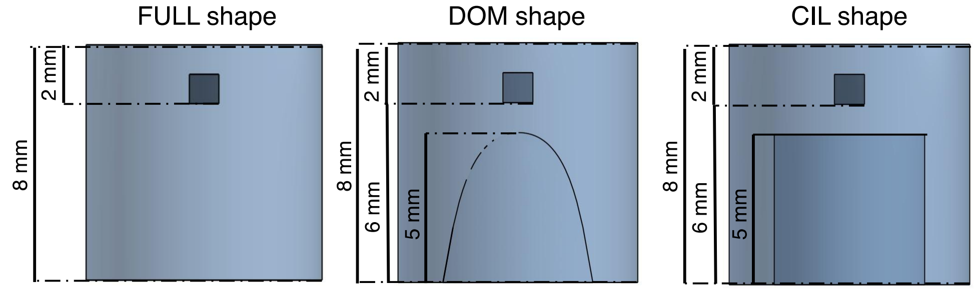
[1]Department of Engineering, Università Campus Bio-Medico di Roma, Rome 00128, Italy.
[2]Fondazione Policlinico Universitario Campus Bio-Medico, Rome 00128, Italy.

[*]**Correspondence to:** Dr. Carlo Massaroni, Department of Engineering, Università Campus Bio-Medico di Roma, Via Alvaro del Portillo, Rome 00128, Italy. E-mail: c.massaroni@unicampus.it

Section 1. Production of soft sensors

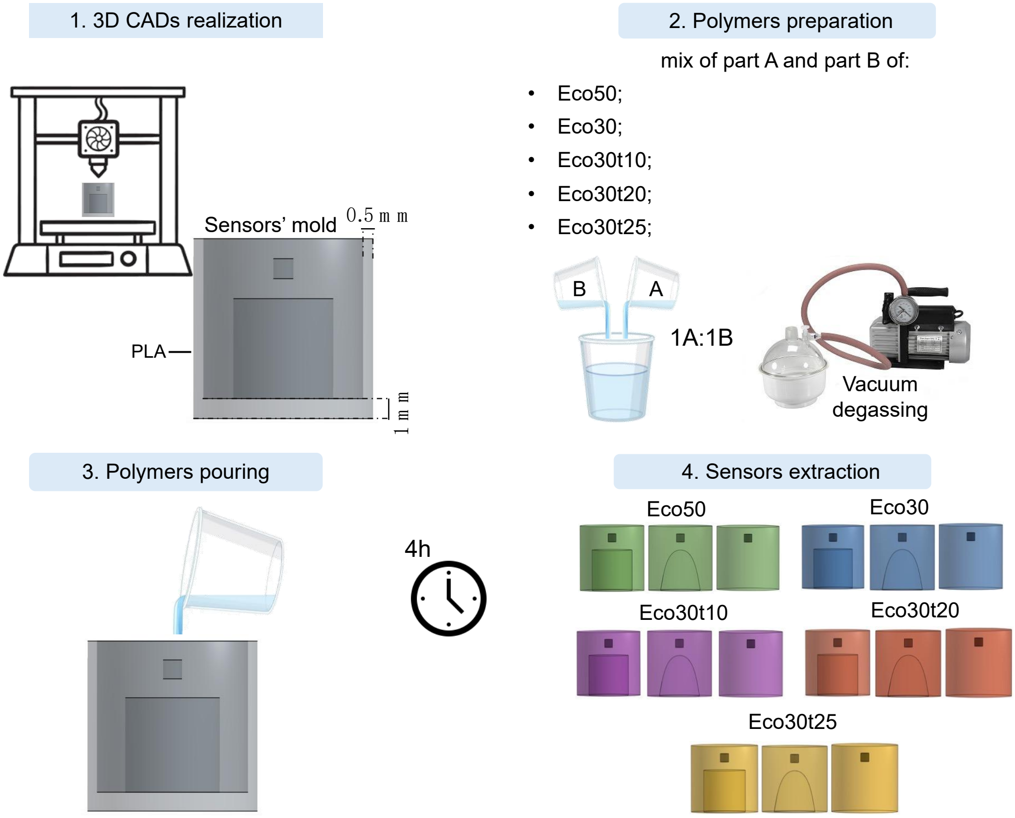
The production of the soft sensors consisted of 3 distinct phases: 1. manufacture of the 3D printed molds; 2. manufacture of the materials; 3. pouring of the materials into the molds.

After designing the three shapes for the flexible medium, as shown in Supplementary Figure 1, the negative molds were produced using Onshape computer-aided design (CAD) software. The model of each mold was then exported as an .STL and subsequently imported into the Ultimaker Cura software (Ultimaker Ltd.) to generate the G-code file for printing. For the fabrication process, we used the commercial 3D printing filament PLA eSUN (95A) and the Creality Ender-3 V2 printer. The print parameters were set as follows: print speed set to 30 mm/s, fill density set to 20 per cent.



Supplementary Figure 1. Dimensions of the three shapes of the deformable pressure sensor medium

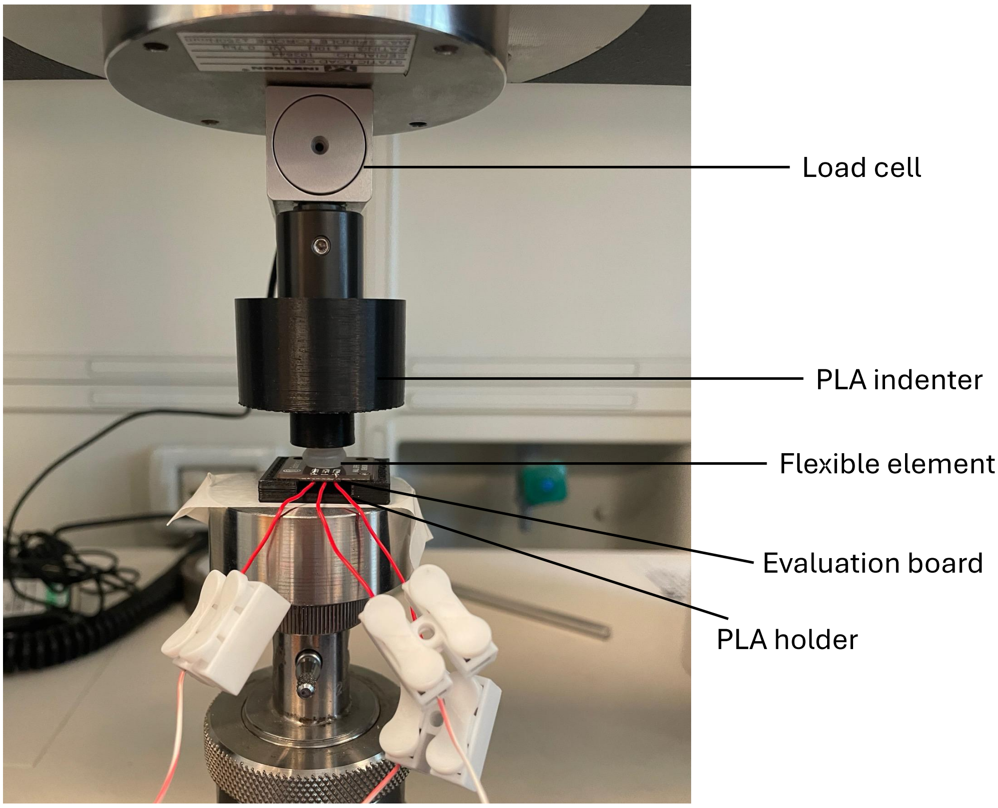
Hence, the negative molds for each sensor were made (5 molds for each mold). Then, the materials for the soft media were prepared. To produce Eco50 and Eco30, part A and part B of the two materials were mixed in a 1:1 ratio to obtain a total weight of 0.5 g. For the Ecoflex 00-30 materials with 10 %, 20 % and 30 % Silicon Thinner (i.e., Eco30t10, Eco30t20, Eco30t25), 0.050 g 0.100 g and 0.125 g Silicon Thinner were added, respectively. After obtaining the mixture, all materials were degassed with a vacuum/pressure pump (mod. VCP 130, VWR International, LLC, PA, USA) for 10 minutes. This last step was fundamental to avoid the presence of air bubbles. Subsequently, the materials were poured into the previously described negative molds. Contextually a neodymium (NdFeB) disc magnet (magnetization: N45) with axial direction of magnetization (dimensions: 1 mm height, 1 mm diameter) was embedded in the soft medium with the south pole of the magnet towards the Hall sensor. The initial gap between the magnet and the Hall sensor is 2 mm. After a waiting time of 4 hours, the soft media were removed and 5 sensing elements for each of the 3 shapes were obtained. A schematic of the sensor production process is shown in Supplementary Figure 2.



Supplementary Figure 2. Manufacturing process of pressure sensors with different medium shapes and materials.

Section 2. Characterization of materials

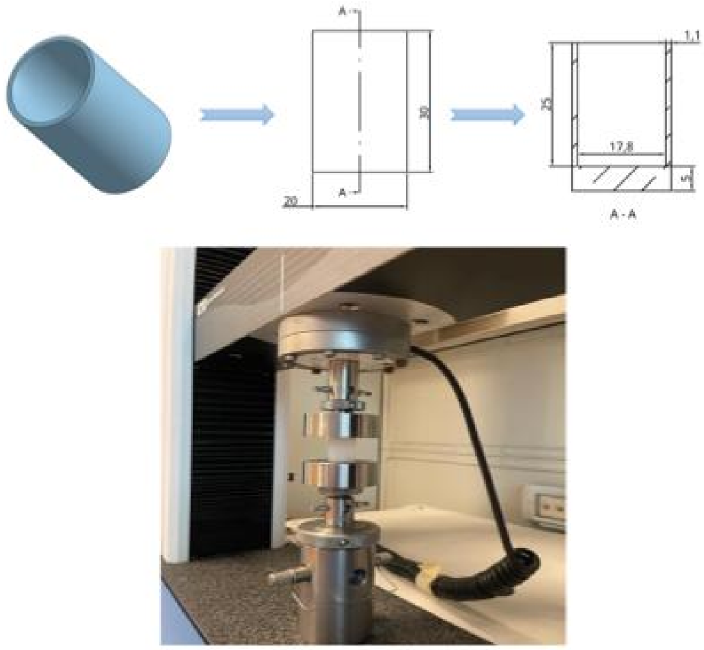
The five materials (Ecoflex 00 - 50, Ecoflex 00 - 30, Ecoflex 00 - 30 with Silicone Thinner at 10%, 20% and 25% respectively) were metrologically characterized by performing both tensile and compression tests. Mechanical experimental tests were carried out using an Instron machine (model 3365) employing a load cell with a full-scale of 500 N and an accuracy of ± 0.25 % of the read value. Photo of the experimental setup is shown in Supplementary Figure 3.



Supplementary Figure 3. Experimental setup employed for the metrological characterization of the sensors

Compression tests

Compression tests were performed to characterize the material behavior under compressive load. The tests were carried out according to ISO 7743:2017, which defines the procedures for characterizing the compressive behavior of silicone rubber. Among the four procedures reported in the document, method C was chosen as it provides results independent of the shape of the test specimen. This method is the most appropriate when the intrinsic properties of the material are to be determined. The standard specimen used is a cylinder with a diameter of 17.8 ± 0.15 mm and a height of 25 ± 0.2 mm. Supplementary Figure 4 shows the dimensions of the mold, which was designed using Onshape software and manufactured using a Creality Ender-3 V2 3D printer.



Supplementary Figure 4. Experimental set-up for the compression tests carried out for the materials characterization

Subsequently, the specimen realization was carried out. Thus, for the standard specimens of Ecoflex 00 - 50 and Ecoflex 00 - 30, part A and part B of the silicone rubber were mixed in equal weight, the mixture was subjected to a degassing process for 10 minutes, after which it was poured into the mold and cured at room temperature for a period of 4 hours. The same procedure was carried out for the tailor-made materials, by adding the Silicon Thinner of 10%, 20% and 25% of the total weight.
Then, the following steps were performed for compression characterization:

- The standard specimen was positioned between the indenters of the Instron machine.
- A displacement of 80 % of the initial height of the standard specimen was set (i.e., 20 mm).
- A compression rate of 10 mm/min was set.

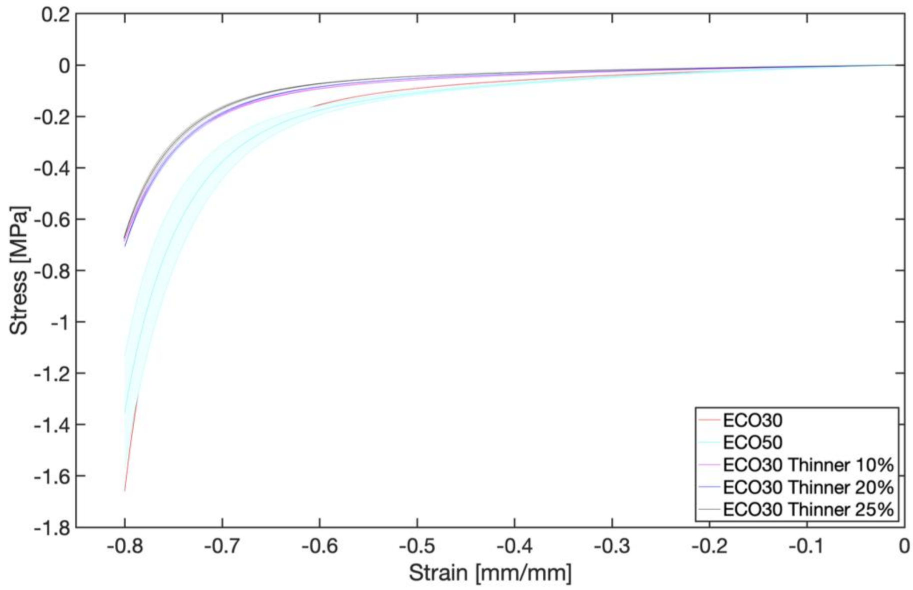
During the test, the Instron machine acquired the force and deformation data applied to the standard specimen with a sampling frequency of 100 Hz. Three tests were carried out for each specimen to enhance data reliability.
The acquired data were then analyzed in the MATLAB environment in order to calculate the stress-strain graph for each material. The nominal stress (σ), was defined as the force (F) applied per area (A0):

$$\sigma = \frac{F}{A_0} \tag{S1}$$

The nominal strain (ε), was defined as:

$$\varepsilon = \frac{l_i - l_0}{l_0} \tag{S2}$$

where l_i is the instantaneous length of the specimen, l_0 its initial length. Supplementary Figure 5 shows the stress-strain graph in which the average of the 3 tests is shown as a solid line and the uncertainty is shown as the colored area. This last was calculated considering a Student's distribution with a confidence level of 95%. The different colors refer to the different materials analyzed.



Supplementary Figure 5. Stress-strain curve obtained for the five materials tested as a result of the compression tests

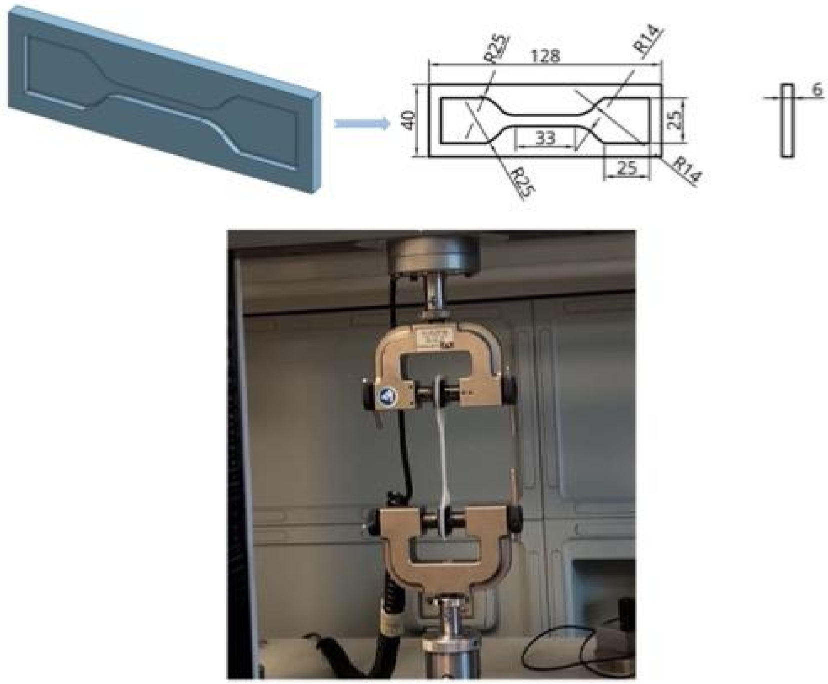
Tensile tests

For the tensile tests, the specimens were made considering ASTM - D412 of 2006. Method A was chosen with the dog-bone shape with dimensions shown in Supplementary Figure 6 (section 'Die C' of the document). The molds were designed using Onshape software and 3D printed with the Creality Ender-3 V2 3D printer. Then, the standard specimens were prepared using the five different materials, according to the same procedure adopted previously for the compression tests.

Following the production of the standard specimens for each material, the specimens were placed between the two clamps of the tensile testing machine (see Supplementary Figure 6) and the following parameters were imposed:

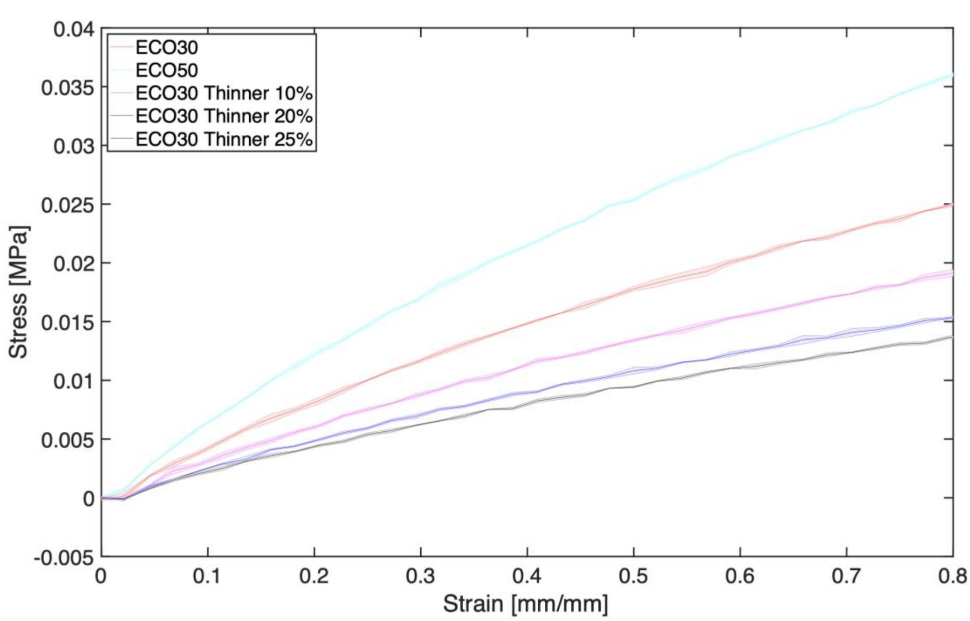
- a deformation of 80% of the initial length of the standard specimen.
- a tensile rate of 450 mm/min.

Three compression tests were carried out for each material.



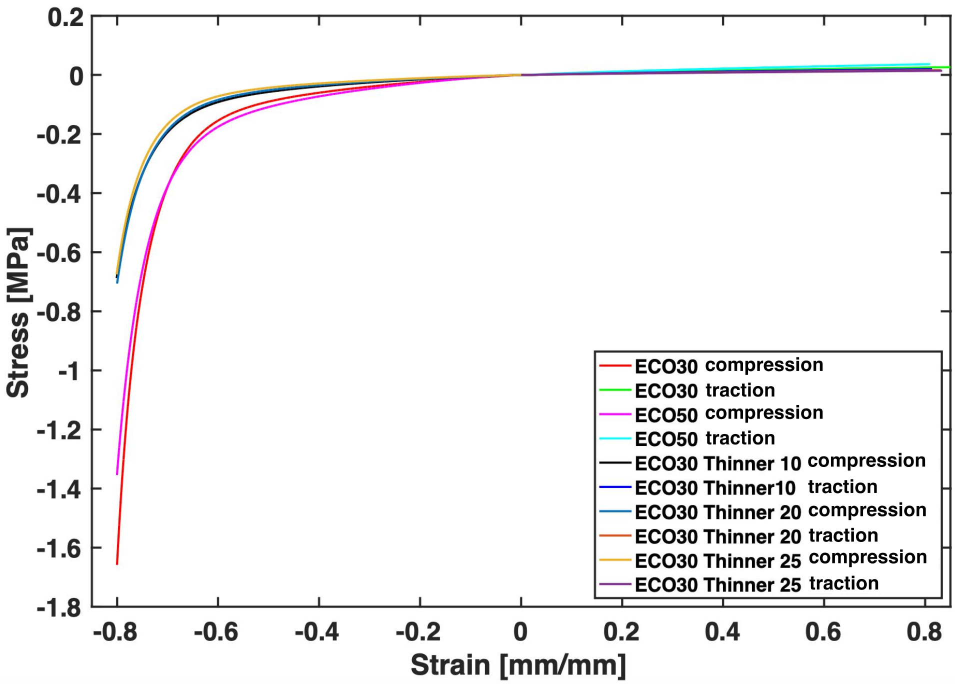
Supplementary Figure 6. Experimental set-up for the tensile tests carried out for the materials characterization

Stress and strain data were acquired by the Instron machine with a sampling rate of 100 Hz. The collected data were analyzed in the MATLAB environment. Supplementary Figure 7 shows the stress-strain graph for the tensile test, in which the average of the 3 tests is shown as a solid line and the uncertainty as a colored area. The different colors refer to the different materials analyzed.



Supplementary Figure 7. Stress strain curve obtained for the five materials tested as a result of the tensile tests.

After obtaining the stress-strain curves separately for tension and compression, these were combined as shown in Supplementary Figure 8. This yields a stress-strain curve describing both tensile and compressive behavior, both evaluated at 80% strain considering all materials investigated. This stress-strain curve obtained for each material will be used below in order to obtain the Yeoh model parameters.



Supplementary Figure 8. Stress-strain curve obtained for the five materials tested as a result of the combination of tensile and compression tests

Section 3. Model of materials in finite element analysis

To establish the finite-element model of the materials used to make the flexible elements, the Yeoh model was used. This model can be used to describe nearly impressible hyperelastic materials and it is more reliable, efficient and accurate than the other models typically used (Neo-Hookean hyperelastic model and Mooney- Rivlin model). The Yeoh model provides the smallest residual sum of squares (RSS) of the three hyperelastic constitutive equations. As with the other hyperelastic models, this model is described in terms of elastic deformation energy functions. The elastic deformation energy function of Yeoh's model is:

$$W = \sum_{i=1}^{3} \left[C_{10}(\overline{I_1} - 3)^i + \frac{1}{D_i} (j-1)^{2i} \right] \tag{S3}$$

where J is the volume ratio after deformation to before deformation. This example assumes an incompressible (J=1) hyperelastic material, then the strain energy density of Yeoh can be simplified, as:

$$W = C_{10}(\overline{I_1} - 3)^1 + C_{20}(\overline{I_1} - 3)^2 + C_{30}(\overline{I_1} - 3)^3 \tag{S4}$$

Where,

$$\overline{I_1} = \overline{\lambda 21} + \overline{\lambda 22} + \overline{\lambda 23} \tag{S5}$$

Where, $\overline{\lambda_i}$ is the deviatoric stretch, with $\overline{\lambda_i} = J^{-\frac{1}{3}}\lambda_i$ and $\lambda_i = \varepsilon_i + 1$; $\lambda_1, \lambda_2, \lambda_3$ are the stretch in principal direction 1,2,3 and ε_i is the engineer strain in principal direction I. It shows only three parameters C_{10}, C_{20}, C_{30} need to be defined for the (incompressible) Yeoh model. Although the order parameter N can be large, in practice we only use order 3 at most.

In Supplementary Table 1 the obtained parameters for the five materials are shown.

Supplementary Table 1. Yeoh model coefficients per each material

Coefficient	ECO50	ECO30	ECO30T10	ECO30T20	ECO30T25
C1	14,781 Pa	115,161 Pa	7,968.4 Pa	6,777.0 Pa	5,716.1 Pa
C2	-473.31 Pa	-150.79 Pa	-350.86 Pa	−120.37 Pa	−104.14 Pa
C3	108.17 Pa	153.62 Pa	56.178 Pa	56.888 Pa	Pa

Section 4. Calculation of Young Modulus and linearity error

To calculate the Young's modulus of the materials, the data obtained in the tensile test were used considering only the linear range (up to approximately 12.5 % of the strain). Then, the stress-strain curve was calculated based on the specimen dimensions. The Young's modulus of each material was then calculated by evaluating the slope of the linear part of the stress-strain curve. The obtained values are reported in Supplementary Table 2.

Supplementary Table 2. Young modulus obtained for the five materials

	ECO50	**ECO30**	**ECO30T10**	**ECO30T20**	**ECO30T25**
Young Modulus	81 kPa	71 kPa	47 kPa	41 kPa	34 kPa

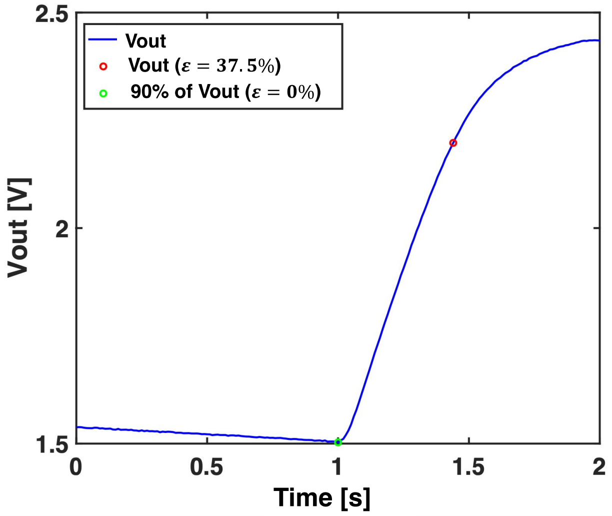
Next, a 1st order linear fitting was performed to find the best fit to the data. The linearity error, LE, was then calculated as the difference between the measured values and the values predicted by the fitting. This error provides a measure of the deviation between the linear model and the experimental data. To further quantify this discrepancy, the maximum linearity error in percent was calculated, as shown in Supplementary Table 3. The latter was obtained dividing LE by the full-scale value of the output.

Supplementary Table 3. Linearity errors for the five materials and the three shapes

Linearity error	**ECO50**	**ECO30**	**ECO30T10**	**ECO30T20**	**ECO30T25**
FULL shape	4.02 %	3.69 %	3.69 %	3.52 %	3.89 %
DOM shape	4.49 %	4.16 %	4.18 %	4.44 %	3.97 %
CIL shape	5.92 %	4.76 %	6.66 %	4.18 %	3.66 %

Section 5. Method for recovery time calculation

The recovery time was calculated as the time it takes for the sensor output to return to 90% of its corresponding value at zero strain, following a displacement of 3 mm (ε = 37.5%). In Supplementary Figure 9 in red is shown the 90% Vout at ε = 0, and in green the value of Vout at ε =37.5%. This evaluation provides a key indication of how quickly the sensor returns to its initial state after being stressed.



Supplementary Figure 9. procedure used to calculate sensor recovery time.