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INNOVATION

Design, fabrication and metrological evaluation of wearable pressure sensors

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Abstract

Pressure sensors are valuable transducers that are necessary in a huge number of medical application. However, the state of the art of compact and lightweight pressure sensors with the capability of measuring the contact pressure between two surfaces (contact pressure sensors) is very poor. In this work, several types of *wearable* contact pressure sensors are fabricated using different conductive textile materials and piezo-resistive films. The fabricated sensors differ in size, the textile conductor used and/or the number of layers of the sandwiched piezo-resistive film. The intention is to study, through the obtaining of their calibration curves, their metrological properties (repeatability, sensitivity and range) and determine which physical characteristics improve their ability for measuring contact pressures. It has been found that it is possible to obtain wearable contact pressure sensors through the proposed fabrication process with satisfactory repeatability, range and sensitivity; and that some of these properties can be improved by the physical characteristics of the sensors.

Keywords

Metrological properties, pressure sensors, wearability

History

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1. Introduction

Pressure sensors are valuable transducers that are necessary in a huge number of medical applications [1,2]. Examples include mammography [3,4], tourniquets [5], gait analysis [6,7] and rehabilitation [8], among others. However, the state of the art of pressure sensors with the capability of measuring the contact pressure between two surfaces is very poor. In this paper this group of pressure sensors will be called contact pressure sensors. Some commercial contact pressure sensors are available, but their price is high. In the last years, a simple and low cost method for contact pressure sensors fabrication has been proposed thanks to the development of a novel piezo-resistive material that consists of a polymeric foil impregnated with carbon black. This fabrication process involves the piezo-resistive material sandwiched being between two sheets of conductive material [9–11]. Some authors have fabricated this kind of sensors and have used them in different applications [12,13]. However, an exhaustive analysis of their metrological properties has not been found in the bibliography.

Since the polymeric piezo-resistive material is flexible, thin, light, washable and reusable, the resultant pressure sensors could be used in smart garments or wearable devices for measuring the interaction between them and the body, the movements of the person under study and some physiological parameters such as breath or muscular activity, among others [1,14,15]. These wearable pressure sensors would require that the conductive material to be used has similar characteristics of wearability and comfort. In this context, a wide variety of textile materials with electrical properties similar to those of solid metals is commercially available. These textile materials present the characteristics of interest.

In this work, several types of wearable contact pressure sensors are fabricated using different conductive textile materials and piezo-resistive films (Velostat, 3M, Saint Paul, MN). The fabricated sensors differ in size, the used textile conductor and/or the number of layers of the sandwiched piezo-resistive film. This work aims to study the metrological properties of these custom-made wearable contact pressure sensors in order to evaluate which of them performs better and to determine which physical characteristics improve their ability for measuring contact pressures. The metrological properties under study are: repeatability, sensitivity and range, and they are assessed through a calibration process that allows one to know the sensor

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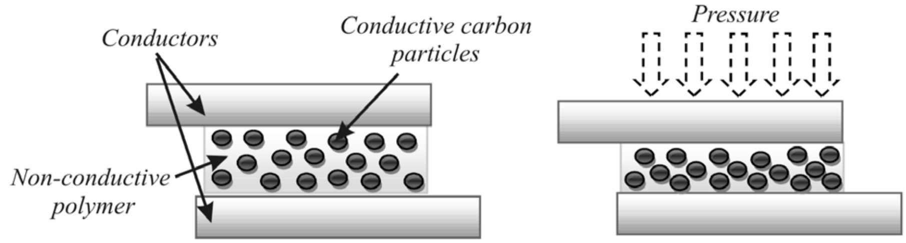
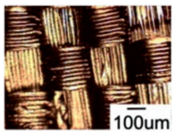
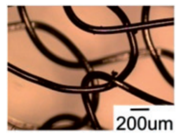
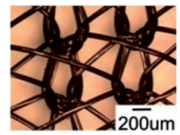
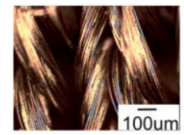


Figure 1. Behaviour of the piezo-resistive foil under stress. Conductive carbon particles get closer together when a pressure is applied. Conductors are necessary in order to take advantage of this situation and obtain a pressure sensor.

Table 1. Commercially available conductive textile materials and some important features (provided by the supplier (LessEMF, Latham, NY).

	Ripstop Silver	Stainless Steel Mesh	Silver Mesh	Stretch
				
FT	Ripstop	Knitted	Knitted	Knitted
CP	Whole fabric	Solid-Metal thread	Whole fabric	Whole fabric
BF	100% Ny	100% Surgical Stainless Steel	100% Ny	76% Ny 24% Elastic Fibre
MC	100% Ag		100% Ag	100% Ag
MP	>99%		>99%	>99%
W	$40\,\mathrm{g\,m^{-2}}$	$190\,\mathrm{g\,m^{-2}}$	$40\,\mathrm{g\,m^{-2}}$	$145\,\mathrm{g\,m^{-2}}$
T	2 mm (thread diameter)	0.1 mm (thread diameter)	Not supplied	0.40 mm
SR	$<0.25\,\Omega\,\mathrm{sq}^{-1}$	$2\,\Omega\,\mathrm{sq}^{-1}$	$<0.5\,\Omega\,\mathrm{sq}^{-1}$	$<0.5\,\Omega\,\mathrm{sq}^{-1}$
TR	−30–90 °C			

resistance when different pressures values are applied over it. Besides, the similarity in response of different samples of a same type-variety of sensor is also assessed.

2. Materials and methods

2.1. Piezo-resistive foil

Velostat is a carbon-impregnated polymer with piezo-resistive properties—its electrical resistance decreases when pressure is applied. The Velostat piezo-resistive behaviour is due to a change in the distance between conductive carbon particles that occurs when the material is under stress (Figure 1). When pressure is applied, these particles get closer together. If this material is sandwiched between two conductors, the resultant structure can perform as a pressure or force sensor [9]. If a known current is applied between the two conductors, and the voltage between them is measured, it is possible to obtain the piezo-resistive material resistance variations and, through a calibration process, the applied pressure can be known.

2.2. Conductive textile materials

Nowadays, a wide variety of textile material with electrical properties similar to those of solid metals is commercially available. Four types of conductive textile materials (LessEMF, Latham, NY) have been chosen to perform as conductors in the fabrication of the proposed wearable pressure sensors. Table 1 presents the chosen fabrics and their most relevant properties, as their type (FT), the coating process (CP), the base fabric (BF)—material over which the coating process takes place—the metal used for the coating process (MC), the purity of that metal (MP) and the fabric weight (W), thickness (T), sheet resistance (SR) and temperature range (TR). According to the supplier, all fabrics are hand-washables, but washing will eventually degrade the coating except on *Stainless Steel Mesh*, which is made of pure metal threads.

2.3. Fabrication process

The contact pressure sensors fabrication process involves one or several layers of piezo-resistive foil sandwiched between two layers of conductive textile material. These layers of conductive textile material have an extension for allowing the connection with the external measurement circuit. The layers of piezo-resistive material are always larger than the layers of the conductive textile, this is necessary in order to avoid a short circuit between the conductors (Figure 2). Finally, the resultant structure is wrapped with non-conductive heat adhesive fabric. In this work, several types of squared wearable contact pressure sensors are fabricated using different conductive textile materials and one or more layers of a piezo-resistive film. The fabricated sensors differ in size, the textile conductor used and/or the number of layers of the piezo-resistive foil. The different types of the fabricated pressure sensor and their characteristics are presented in Table 2. It is important to emphasize that the conductive textile material area is considered as the active area of the sensor because here is where the injected current passes through.

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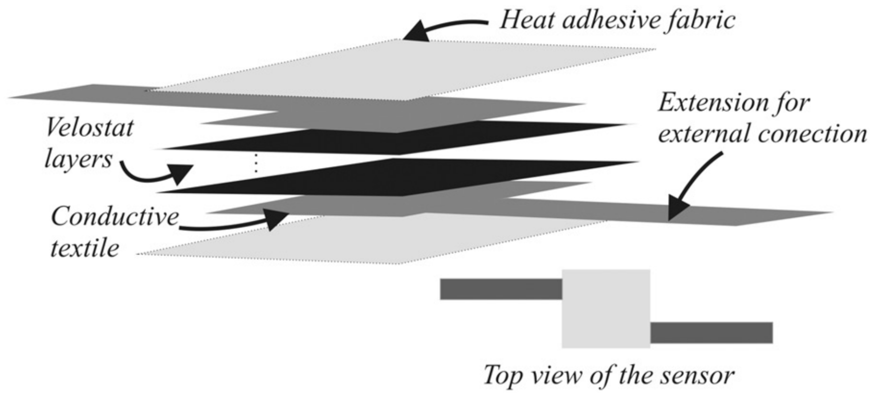

Figure 2. Contact pressure sensors structure. One or several layers of piezo-resistive foil are sandwiched between two conductive textiles and the resultant structure is wrapped with a heat adhesive fabric. In addition, a top view of the sensor is presented.

Table 2. Types and varieties of the custom-made pressure sensors, their sizes, number of piezo-resistive layers and the used conductive textile material. All the sensors are square.

Sensor		Piezo-resistive foil		Conductive textile material		
Type	Variety	Side size	No of layers	Side size	Type	Sensor active area
1	A	2 cm	1	1.5 cm	RS	2.25 cm^2
	B	2.5 cm	1	2 cm	RS	4 cm^2
	C	1.5 cm	1	1 cm	RS	1 cm^2
	D	2 cm	3	1.5 cm	RS	2.25 cm^2
2	A	2 cm	1	1.5 cm	SM	2.25 cm^2
	B	2.5 cm	1	2 cm	SM	4 cm^2
	C	1.5 cm	1	1 cm	SM	1 cm^2
	D	2 cm	3	1.5 cm	SM	2.25 cm^2
3	A	2 cm	1	1.5 cm	SSM	2.25 cm^2
4	A	2 cm	1	1.5 cm	S	2.25 cm^2

RS, Ripstop Silver; SM, Silver Mesh; SSM, Stainless Steel Mesh; S, Stretch.

2.4. Measurement circuit

The measurement circuit used for obtaining the calibration curves of each one of the sensors consists of a constant amplitude alternating current source that delivers the current that passes through the sensor, a voltage meter that senses the voltage generated over the sensor when the current is injected into it and a demodulator that provides a constant voltage value proportional to the pressure sensor resistance. A block diagram of the measurement circuit is presented in Figure 3.

(1) *Current generator*: This generates a 23 kHz constant amplitude alternating current that is injected into the pressure sensor via the contact points P1 and P2. This block is composed of a Wien bridge oscillator, a second-order passband active filter (passband: 10–30 KHz) and a voltage-to-current converter. The injected current has a 3.4 mA constant amplitude.
(2) *Voltage meter*: This block picks up, in the points P1 and P2, the voltage signal generated on the pressure sensor when the current is injected into it. This signal has an amplitude that is proportional to the pressure sensor resistance. This block consists of an instrumentation amplifier with variable voltage gain and a second-order high pass active filter (cut frequency = 16 KHz).
(3) *Demodulator*: This provides a constant voltage signal whose amplitude is directly proportional to the electrical resistance of the pressure sensor. This is achieved with a full wave rectifier, an envelope detector and a second order low-pass active filter (cut frequency = 4 Hz). The voltage signal is then visualized using a digital oscilloscope (Tektronic, Beaverton, OR).

As mentioned, the gain of the voltage amplifier is variable and it is modified according to the pressure sensor under study. This is necessary since some sensors have a high initial resistance—resistance with no load applied—which leads to a saturation of the amplifier. This is sorted out by means of decreasing the gain of the voltage meter.

2.5. Calibration

The pressure sensors calibration curves, which are necessary in order to obtain the metrological properties of the sensors, are obtained using a set of standard weights. These weights are applied over the sensor under study through a rigid surface that leads to an homogeneous distribution of the weight over the entire surface of the sensor. The weights values are: 0, 2, 10, 20, 30, 50, 70, 136 and 200 gf (gram-force). These weights values produce a range of pressure values (expressed in Pa) that go from 0–19 613 Pa when the sensor active area is 1 cm^2, from 0–8717 Pa when the sensor active area is 2.25 cm^2 and from 0–4903 Pa when the sensor active area is 4 cm^2. For the metrological analysis of the sensors, four samples of each sensor type-variety have been fabricated and five calibration curves have been obtained for each sample.

From the five calibration curves obtained for the *i*th-sample of each type-variety of sensor a mean calibration

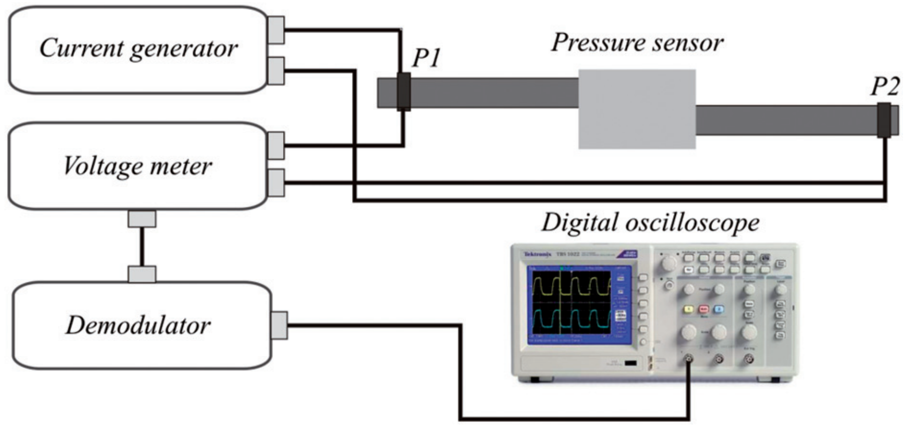

Figure 3. Measurement circuit used for obtaining the calibration curves of each one of the sensors.

curve, $rs_i(p)$, has been calculated for that sample using equation (1). In equation (1), p is the applied pressure, i is the number of the sample under study ($I = 1 \ldots 4$), j is the number of the calibration curve ($j = 1 \ldots 5$) and $rs_{ij}(p)$ is the value of the pressure sensor ith-sample resistance when the jth-calibration process is carried out and a pressure p is applied.

$$rs_i(p) = \frac{\sum_{j=1}^{5} rs_{ij}(p)}{5} \tag{1}$$

Then, from the calibration curves obtained for all samples of a same type and variety of sensor a mean calibration curve, $Rs_{tv}(p)$ has been obtained for that sensor type-variety using (2). In equation (2), tv is the index that indicates the type ($t = 1 \ldots 4$) and variety ($v = A \ldots D$) of the sensor under study.

$$Rs_{tv}(p) = \frac{\sum_{i=1}^{4} \sum_{j=1}^{5} \left[rs_{ij}(p)\right]}{i \cdot j} \tag{2}$$

Besides, the standard deviations of the $rs_{ij}(p)'s$ values with respect to $rs_i(p)$ and of the $rs_{ij}(p)'s$ values from $Rs_{tv}(p)$ are also calculated.

2.6. Metrological properties analysis

2.6.1. Measurement repeatability

The measurement repeatability of the ith-sample of each type-variety of sensor has been studied through the variation coefficients (standard deviation/mean) obtained using the $rs_i(p)$ (mean) and the standard deviations of the $rs_{ij}(p)'s$ values with respect to $rs_i(p)$ (Figure 4). As nine different pressure values have been applied to each sample, nine variation coefficients have been obtained per sample. It leads to 36 variation coefficients for each sensor type-variety (four samples per sensor type).

2.6.2. Fabrication process repeatability

This parameter provides information about how similar are the responses of different samples of the same sensor type-variety.

The repeatability of the fabrication process of each sensor type-variety has been studied using its mean calibration curve ($Rs_{tv}(p)$) and the standard deviations of the $rs_{ij}(p)'s$ values from it. With these values, variation coefficients have been calculated for each applied pressure. Nine variation coefficients are obtained for each sensor type-variety.

2.6.3. Range

In this work, the range of the pressure sensors is considered as the interval that goes from a threshold, which is the smallest input pressure from the zero value that produces a discernible output resistance change, to a maximum pressure value distinguishable by the sensor. This maximum pressure value has been considered as the applied pressure from which a 260 Pa further increase is not enough to produce a sensor resistance variation higher than the 1% of the previous resistance value. In order to calculate the pressure range of each sensor sample, an exponential fit has been applied to its mean calibration curve ($rs_i(p)$) (Figure 4). Then, sensor sample range is studied through the output values of the exponential function when a sequence of 260 Pa input pressure steps is applied.

2.6.4. Sensitivity

For sensor sensitivity calculation, the mean calibration curve of each sensor sample ($rs_i(p)$) is limited to its range and, as they are non-linear in their pressure measurement ranges, they are divided into pressure sub-ranges and several linear fits are performed (as many linear fits as there are pressure sub-ranges). Sensitivity is calculated as a weighted average of the slopes of each linear fit in each pressure sub-range.

2.7. Statistical analysis for sensitivity and range

In order to evaluate the effect of the active areas size (factor 1), the fabric type (factor 2) and the interaction between these factors on the range and sensitivity of the sensors, two full factorial experiments are carried out. The factorial experiments are analysed using ANOVA; and all the possible pairs of means of sensitivities and ranges are compared through the Tukey test in order to determine which level of each factor or which combination of them improves these sensor characteristics.

3. Results

First, sensors with a $2.25\,\text{cm}^2$ active area and one layer of piezo-resistive material have been fabricated and evaluated,

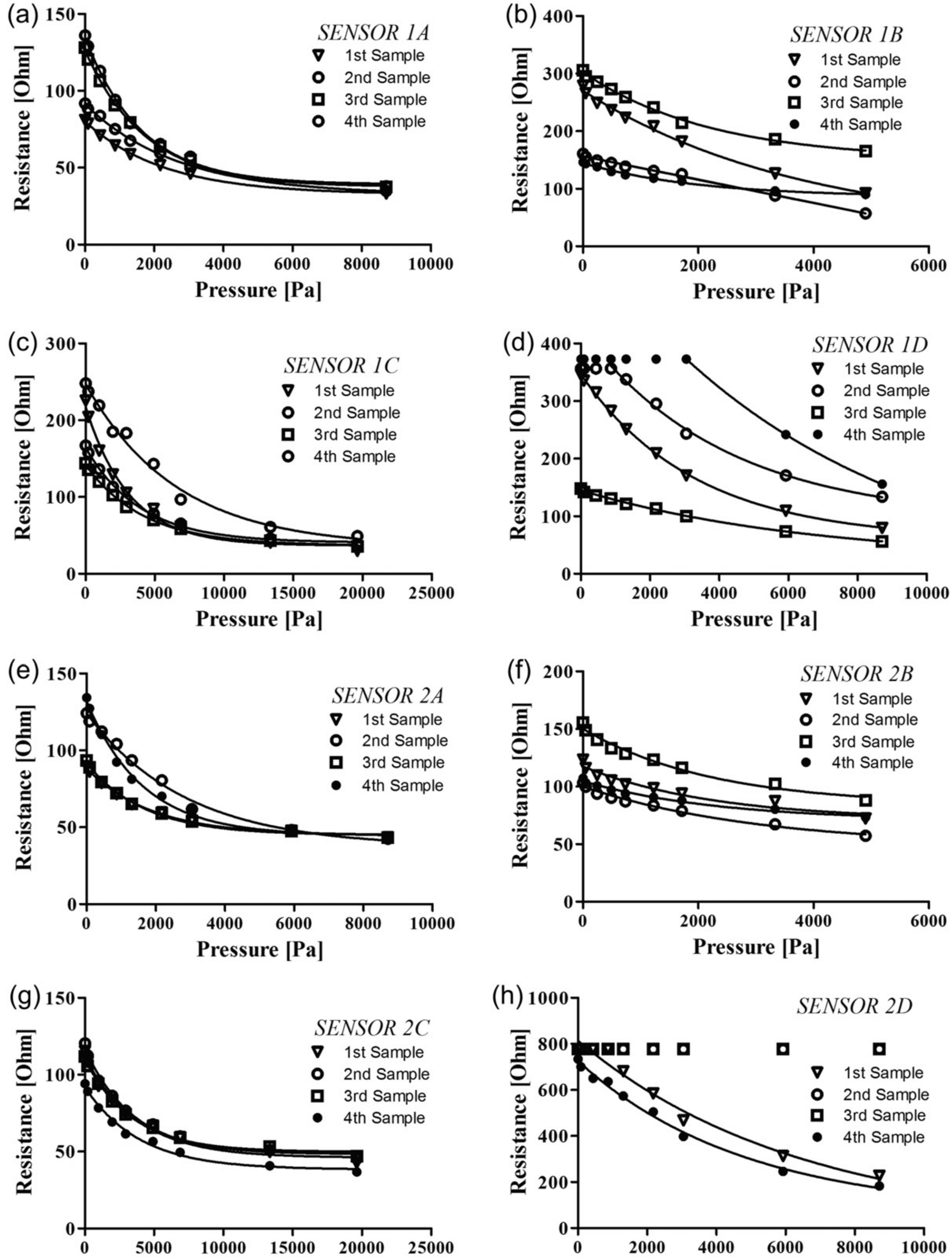

Figure 4. (a–d) Calibration curves obtained for the four samples of type 1/varieties A–D sensors, respectively, and their exponential fits. (e–h) Calibration curves obtained for the four samples of type 2/variety A–D sensors, respectively, and their exponential fits.

i.e. sensors 1A, 2A, 3A and 4A. They differ in the conductive textile material used. The only sensors that present output resistance variation during the calibration process are the sensors 1A and 2A; this suggests that the *Stainless Steel Mesh* and *Stretch* fabrics were not suitable for pressure sensors fabrication. These fabrics are discarded at this stage and no other variety of these sensor types is fabricated.

Once determined the most suitable fabrics for pressure sensors fabrication (these are *Ripstop Silver* and *Silver Mesh*), sensors 1D and 2D have been fabricated and evaluated. They have been elaborated with *Ripstop Silver* and *Silver Mesh*, respectively, and have the same size of sensors 1A and 2A, but they have three sheets of piezo-resistive foil instead of one. The evaluation of the four samples of these sensors showed a

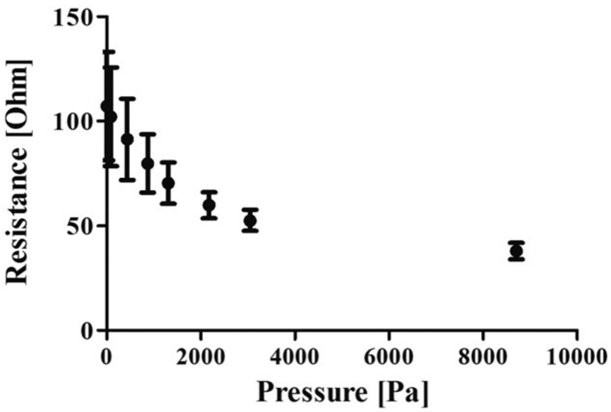

Figure 5. Calibration curve obtained for sensors 1A. The ends of the whiskers represent standard deviations.

wide response variability. Some samples presented acceptable output resistance variation during the calibration process, while others did not present variation at all or a high input pressure was necessary in order to observe any change in the output resistance (Figure 4). It is believed that the response variability between samples of these sensors types-varieties can be a consequence of a poor contact between layers of the piezo-resistive foil. Because of that, multi-layer sensors are no longer considered for fabrication.

3.1. Calibration

Calibration curves of all samples of all sensors types-varieties and their fits are shown in Figures 4a–4h except those obtained for sensors 3A and 4A, since they did not present output resistance variation during the calibration process. Exponential fits of the calibration curves of some samples of sensors 2D are not presented, since these calibration curves do not follow an exponential distribution. Also, as an example the mean curve of the sensor 1A (Rs_{1A} (p)) is presented in Figure 5.

3.2. Measurement repeatability

The 36 variation coefficients (VC [%]) obtained for the four samples of each sensor type-variety are presented in a box plot in Figure 6. They are grouped per sensor type-variety. As can be observed in Figure 6, the mean VC, which is represented by a cross symbol inside the box, is ~5% in most cases. The worst performance is presented by the 1C-pressure sensor, but, even in this case, the mean variation coefficient is less than 10%. These results show that all samples of the custom-made pressure sensors present a very repeatable response which makes them suitable for pressure measurement.

3.3. Fabrication process repeatability

The nine variation coefficients obtained for each sensor type-variety are presented in a box plot in Figure 7. In this case, the mean variation coefficient, which is represented by a cross symbol inside the box, goes from 9.5% (sensors 2c) to 32.8% (sensors 1B). This parameter indicates that, if several samples of a same type-variety of sensor are custom-made following

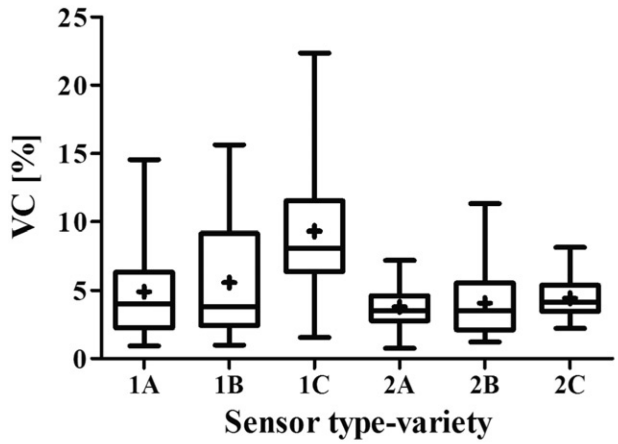

Figure 6. Variation coefficients (VC [%]) obtained for the four samples of each sensor type-variety. The bottom and top of the box are the first and third quartiles and the band inside the box is the second quartile (the median). The ends of the whiskers represent the minimum and maximum of all of the data.

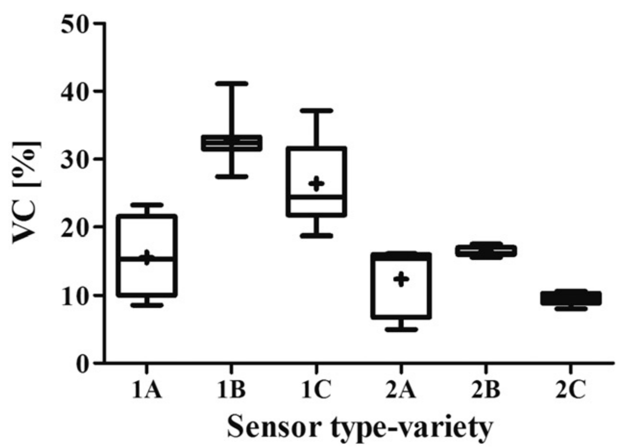

Figure 7. Variation coefficients (VC [%]) obtained for each sensor type-variety. The bottom and top of the box are the first and third quartiles and the band inside the box is the second quartile (the median). The ends of the whiskers represent the minimum and maximum of all of the data.

the fabrication process described above, their response to the same applied pressure will vary between 8.9–10.2% (95% CI) in the best case (sensors 2C) or between 30.0–35.5% (95% CI) in the worst one. The high VC (%) values of this parameter obtained for some sensors are not worrying since they mean that, once a sensor type-variety sample is fabricated, a calibration process must be carried out for it. On the other hand, it indicates which pressure sensor type-variety must be fabricated if the intention is to obtain samples with very similar response between them (sensor 2C).

3.4. Range

The range obtained for each sample of each sensor type-variety is presented in Table 3. How good a pressure sensor type-variety is, regarding this parameter, depends on the application.

As it has been mentioned above, the sensor range is evaluated through the equation obtained from an exponential fit applied to the mean calibration curve of the sensor sample

Table 3. Ranges and weighted average sensitivities (Ω//Pa) of pressure sensors samples.

Sensor sample	Range [Pa]	Sensitivity [Ω/Pa]	Sensor sample	Range [Pa]	Sensitivity [Ω/Pa]
$1A_1$	0–5980	−0.00644	$2A_1$	0–8060	−0.00923
$1A_2$	0–5720	−0.01295	$2A_2$	0–4160	−0.00923
$1A_3$	0–5980	−0.01227	$2A_3$	0–5460	−0.01415
$1A_4$	0–4940	−0.00652	$2A_4$	0–4420	−0.01208
$1B_1$	0–4900	−0.03409	$2B_1$	0–4160	−0.00816
$1B_2$	0–4900	−0.0206	$2B_2$	0–4900	−0.00669
$1B_3$	0–4900	−0.02628	$2B_3$	0–4420	−0.01158
$1B_4$	0–3900	−0.01218	$2B_4$	0–3380	−0.0072
$1C_1$	0–11 180	−0.01460	$2C_1$	0–7800	−0.00688
$1C_2$	0–10 920	−0.00989	$2C_2$	0–7540	−0.00754
$1C_3$	0–10 920	−0.00832	$2C_3$	0–6760	−0.00706
$1C_4$	0–18 720	−0.01022	$2C_4$	0–7800	−0.00551

under study ($rs_i(p)$) (Figure 4). The mean determination coefficient (R^2) obtained for the exponential fits is 0.99 ± 0.012.

3.5. Sensitivity

Weighted average sensitivities of the pressure sensors samples are presented in Table 3. It is important to emphasize that the determination coefficients (R^2) are higher than 0.985 in all linear fits.

3.6. Statistical analysis for sensitivity and range

As it has been mentioned, a factorial experiment was carried out in order to analyse the influence of active area size, fabric type and their interaction on the sensors samples ranges. This factorial experiment was analysed using ANOVA. Prior to ANOVA analysis, variances homogeneity and normality of residuals were tested. Raw data did not meet the assumptions, so they were transformed (their reciprocal was used) in order to solve the problem. The ANOVA showed, with a significance level of 0.05, that only the active area of the sensors has influence on their range ($p < 0.0001$) and through a Tukey multiple comparison test it has been found that the smaller the area the higher the sensor range.

Then, another factorial experiment was carried out in order to analyse the influence of the factors and their interaction on the sensors samples sensitivity; this experiment was also analysed using ANOVA. In this case, raw data did not meet the assumption of variance homogeneity so they were transformed using the equation ln(-sensitivity). The analysis showed, with a significance level of 0.05, that both factors (active area size and fabric type) and the interaction between them have an effect on the sensors samples sensitivities ($p = 0.0173$, $p = 0.0031$ and $p = 0.0033$, respectively).

Finally, a Tukey multiple comparison test was used for assessing what active area size, fabric type or combination of them leads to a higher sensitivity. It has been found that sensors made with Ripstop Silver fabric type and a $4\,\mathrm{cm}^2$ active area (sensors 1B) have the highest sensitivity and that there is no statistical difference between sensitivities of the rest of the tested sensors type-varieties.

4. Discussions and conclusions

In this work several types-varieties of pressure sensors have been fabricated and evaluated by means of their metrological properties. Sensors 3A, 4A, 1D and 2D have been discarded before the metrological analysis since, during the calibration process, they did not perform well. This indicates that *Stainless Steel Mesh* and *Stretch* are not suitable fabrics for the fabrication of the proposed pressure sensors; and that multiple layers of piezo-resistive foil deteriorate the sensors behaviour. Other authors have found that pressure sensors fabricated with several layers of piezo-resistive foil present a better sensitivity, but they did not validate the results trying different samples of the same sensor type [11].

The measurement repeatability presented by the rest of the sensors has been very satisfactory, a mean variation less than 10% has been observed in all cases between calibration curves of each individual sample. With respect to the repeatability of the fabrication process, i.e. the ability to obtain—with the proposed fabrication process—different samples of the same sensor type-variety with similar response, it has been very acceptable for some sensor types-varieties (1A, 2A, 2B and 2C) and not as good in other cases (1B and 1C). This situation can be a consequence of the variability of the carbon particles density in the piezo-resistive material, which can be improved by means of a custom-made fabrication of this material. Besides, an automated fabrication process can further improve the fabrication process repeatability. Even so, a poor fabrication process repeatability is not a major problem, since the results only imply that not a unique calibration curve can be applied to all samples of a same sensor type-variety and that each sample must be individually calibrated.

The pressure measurement range of all sensors is acceptable and it has been demonstrated that the smaller the active area of the sensor the higher its range. However, as has been stated, how good a sensor is regarding this parameter depends on the application. Finally, it has been found—using a Tukey test—that the highest sensitivity is obtained with sensors 1B—made with *Ripstop Silver* and a $4\,\mathrm{cm}^2$ active area—and that there is no statistical difference between sensitivities of the rest of the tested sensors type-varieties. However, the fabrication process of sensor 1B presents poor repeatability, so, when fabricating a pressure sensor a choice must be made between obtaining the best sensitivity or a better fabrication process repeatability (i.e. different samples of the fabricated sensor with similar response).

Taking everything into consideration, it can be stated that it is possible to obtain wearable contact pressure sensors through the proposed fabrication process. Also, if the sensors are fabricated with the physical characteristics of sensors 1A, 1B, 1C, 2A, 2B or 2C, a satisfactory repeatability, range and sensitivity will be obtained. Also, the resultant sensors will present the desired characteristics of comfort, size and weight, since they are fabricated using thin and very flexible materials. Therefore, they will be wearable and, thanks to the characteristics of the used materials, they will also be reusable. Finally, it must be noticed that an individual calibration process will be necessary for each fabricated sensor sample.

Declaration of interest

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