# Soft dielectrics for capacitive sensing in robot skins: Performance of different elastomer types

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# Abstract

In a capacitive tactile sensor the dielectric layer plays an important role: both its electrical and mechanical properties affect the capacitance variation and the sensor response in terms of sensitivity, since the deformation ability of the dielectric layer allows for the detection of small pressures, and spatial resolution, since the dielectric layer acts as a low-pass spatial filter decreasing the spatial resolution. In this work we comparatively evaluate the effect of different elastomers on the performance of a capacitive sensor designed to cover large areas of a robot body. In particular, we compare the sensitivity, the spatial resolution and the durability of the sensor using foams, bulk elastomers and high permittivity composites.


## 1. Introduction

In the past decades, the role of tactile sensing in Robotics has received steadily increasing attention [1]. Tactile sensing is expected to broaden the perceptual capabilities of robots and to enhance their cognitive and motion capabilities in unstructured environments. In recent years, thanks to technological advancements on the miniaturization of electronic components, a renovated interest is being focused on *robot skins*, i.e., large-scale tactile surfaces able to cover wide areas of a robot body [2–5]. A fundamental design aspect is to precisely characterize the response of tactile elements (i.e., *taxels*) with respect to design choices related to geometrical sensor layout and employed materials. On the basis of this characterization, the sensor can be customized to better address robot tasks.

The mechanical characteristics of the dielectric layer impact on the overall skin performance and, in particular, on sensitivity, spatial resolution, and weight. Elastomers are selected as dielectric layers in capacitive sensors for their high compliance, their ability to act as a protective cover and, in case of manipulation tasks, for the increased friction they enable. The choice of the most appropriate elastomer is not an easy task. In this article we present the response of a capacitive sensor designed to cover large areas of a robot body, comparing different elastomers as dielectric layer. We analyse the sensor sensitivity obtained from foam and bulk elastomers, and high-permittivity composites. The aim is to investigate how the mechanical and electrical properties of the dielectric layer affect the sensor performance.

## 2. Related work

### 2.1. Piezo-capacitive sensing principle

Capacitance-based tactile sensors have been widely used for large-scale robot skins [1]. Forces exerted on a robot skin produce variations in the capacitance values of tactile elements (i.e., taxels). The differential capacitance measurement relies on an estimate of the difference between the capacitance values in the nominal and contact cases:

$$\Delta C = C_p - C_n = \epsilon_0 \epsilon_r A \frac{d_n - d_p}{d_p d_n}, \tag{1}$$

where $C_p$ and $d_p$ are, respectively, the capacitance value and the elastomer thickness in the *contact* case (i.e., when a pressure is exerted over the taxel), and $C_n$ and $d_n$ correspond to the *non contact* or nominal case. In order to exploit capacitance-based transduction, it is necessary to maximize the sensor response range. According to Eq. (1), the dielectric constant, taxel area, the nominal thickness of the dielectric, and its mechanical properties are fundamental design parameters.

Much work has been carried out to correlate specific robot tasks with the physical properties characterizing tactile sensors [6–10]. However, the analysis has been mainly focused on identifying materials whose response characteristics resemble at best that of human fingertips [11]. According to [8–10], four are the main desirable properties of dielectric materials for robot skin in fingertips: *compliance* allows the dielectric material to yield elastically when even small forces (e.g., less than 1 N) are applied, thereby enhancing the robot performance when executing force-controlled tasks [6,7]; *hysteresis* enforces the capability of the dielectric material to absorb energy generated when big forces are applied as the result of impact or catching events [9,7]; *conformability* allows the robot to reach more stable grasping configurations, since the amount of fingertip surface in physical contact with the grasped object is maximized on average [7]; *friction* maximizes the likelihood of avoiding slippage [12,13].

The above considerations tend to neglect the employed transduction mode, the thickness and dielectric constant of the dielectric as well as the actual taxel area. In a piezo-capacitive sensor, the hysteresis can seriously affect the repeatability of the measurements, since the force distribution is usually estimated from the deformation of the elastic medium [14].

Shimojo et al. [15] analysed the low-pass spatial filtering characteristics of the elastic cover of a tactile sensor, arguing that its spatial resolution depends on the cover's thickness and stiffness. Vásárhelyi et al. [16] analysed the mechanical information-coding effects of a rubber layer applied on single-crystalline silicon 3D force sensors capable of detecting normal and shear forces. Their work refers only to a specific elastomer and is focused mainly on the correlation between the performance of the tactile sensor and the geometrical characteristics of the elastic medium (e.g., on the use of ridges to detect tangential force components).

The literature in this field does not offer well-defined procedures and commonly accepted benchmarks on how the mechanical, geometrical and electrical properties of different layers can affect the *overall* response of a tactile sensor. Taking inspiration from [17], here we characterize the sensor's overall performance using the following sensitivity function:

$$S = \frac{\Delta C}{\Delta P}, \tag{2}$$

where $\Delta C$ is the measured variation in capacitance between the *non contact* and *contact* cases (Eq. (1)) and $\Delta P$ is the related variation of the applied pressure. The main difference with respect to the definition proposed in [17] is the lack of the coefficient inversely weighting $C_n$. Since, in our case, $C_n$ differs for each taxel, we prefer to characterize an independent measurement of the capacitance variation in response to a given pressure.

### 2.2. *Increasing the dielectric permittivity*

As shown by Eq. (1), the dielectric permittivity can be thought of as a sensor design parameter [18]: the sensor response range (i.e., the difference between the largest and smallest possible values of the quantity measured by the sensor) depends on the taxel area. If a reduction of the taxel area is required to increase the spatial resolution, a high value of dielectric permittivity allows for maintaining the same sensor response range.

In general, elastomers are characterized by a low dielectric permittivity. In the literature, different methods have been discussed to increase it [19], namely the composite approach [20,21], the blend approach [22,23] the electric-field structuring approach [24,25] and the synthesis of new macromolecules [26]. Of particular interest for our purposes, are the composites obtained by loading an elastomer matrix with high dielectric permittivity fillers, such as titanium dioxide ($TiO_2$), strontium titanate ($SrTiO_3$) and lead magnesium niobate-lead titanate (PMN-PT).

In particular, Carpi and De Rossi [27] showed that the dispersion of titanium dioxide powder in a silicone dielectric elastomer resulted in a lower elastic modulus within certain range of strain and a higher dielectric permittivity. Paik and colleagues [28] discussed the effects of barium titanate ($BaTiO_3$) and $SrTiO_3$ powders on the dielectric constant of epoxy/$BaTiO_3$($SrTiO_3$) composite for embedded capacitor films. Gallone et al. [29] showed that a PMN-PT ferroelectric powder can be used to develop a composite based on a silicone elastomer matrix with improved dielectric permittivity. In this work, we exploit the same approach reported in [27,29] for the production of different composites, as described later in the paper.

## 3. Target scenario and requirements

### 3.1. *Reference robot skin*

In this work we considered the reference robot skin technology described in [3,4], which is based on a tactile sensor consisting of a 3-layer structure (Fig. 1a). A bottom layer (made of a flexible Printed Circuit Board – fPCB) was divided in a number of interconnected 3 cm side triangular modules that enforce coverage compliance with respect to robot body parts with varying curvatures (Fig. 1b and c). Each module hosted 12 circular taxels of a 4 mm diameter as well as (on the opposite side, not shown in the Figure) the read-out electronics for converting capacitance values to 16 bit digital signals (this was accomplished by the Capacitance to Digital Converter chip AD7147 from Analogue Devices, excited at 250 kHz). An intermediate layer constitutes the compliant dielectric medium for the capacitive sensor. Different candidate elastomers were compared, as detailed later on. A top layer, made of a ground plane, forms the second electrode of the capacitor. In particular, an electrically conductive Lycra fabric was glued to the elastomer and connected to ground. This configuration allowed us to assume the same sensor response when objects with different electrical conductivity were in contact. Furthermore, a reduction of the electronic noise was achieved.

When a pressure was exerted on the tactile surface, the conductive Lycra layer got closer to the taxel pads on the fPCB. The CDC chip of each module measured the variation in capacitance of all the taxels in the module. Each measurement was then sent to a central processing unit through a serial $I^2C$ bus.

### 3.2. *Requirements*

Human–robot interaction tasks involving the robot sense of touch require the detection of contact events involving both people and the environment surrounding the robot. It is possible to identify two different broad classes of contacts on the basis of pressure range [18]: on the one hand, the *gentle touch* class is characterized by contact pressures in the 0–10 KPa range; on the other hand, the *manipulation-like touch* class involves pressures in the range 10–100 KPa. Therefore, any tactile sensor to be used in real-world robot tasks must be (i) compliant enough to detect gentle touch contact events, i.e., be responsive to forces whose magnitude is less than 1 N, and (ii) characterized by a $\Delta C$ such to allow for the detection of manipulation-like forces.

In tactile sensors employing the capacitance-based transduction principle, the *tendency to be elastically deformed* as a consequence of the application of a force depends solely on the employed

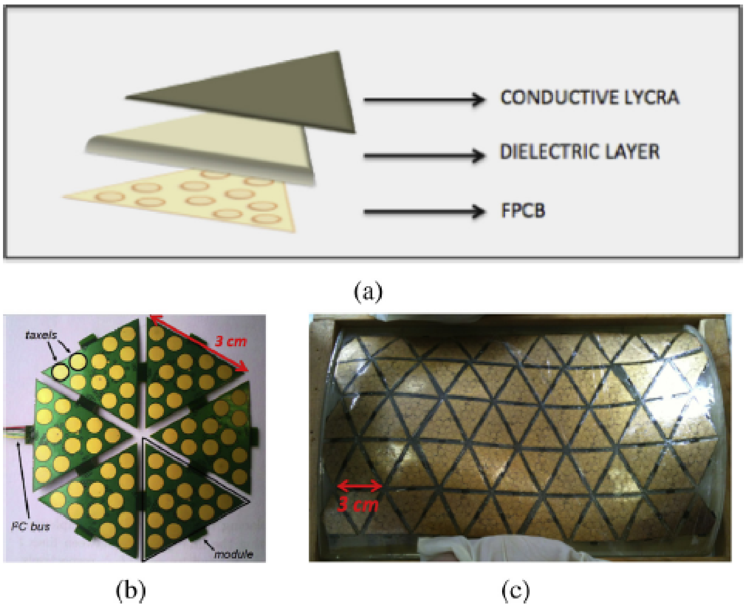



**Fig. 1.** The reference robot skin: (a) An exploded view of the tactile sensor prototype; (b) a simple skin *hexagon*; (c) a large robot skin *patch* conformed to a curved surface.

dielectric material. Such tendency is identified by the elastic modulus *E*, which is higher as long as the material is stiffer.

Elastomer visco-elastic properties, showed generally both by pure and composite elastomeric matrices [20,30], determine the arising of such phenomena like hysteresis (which leads to dissipation of mechanical energy in a loading-unloading cycle), creep (i.e., if the stress is kept constant, the strain increases with time) and relaxation (i.e., if the strain is kept constant, the stress decreases with time). Since, according to the capacitance-based transduction principle, contact events are detected through the deformation of the elastomer layer and contact forces can be estimated through the corresponding stress–strain relationship [14], then visco-elastic phenomena can dramatically affect both the precision and repeatability of the measurements.

It is possible to define a number of general-purpose desired requirements for the overall tactile sensor behaviour in terms of the elastomer mechanical and dielectric properties.

*Sensor response range*. As previously discussed, it is possible to identify two classes of contact on the basis of the pressure range [18]. According to this classification, any tactile sensor to be used in real-world robot tasks must be (i) compliant enough to detect gentle touch contacts, i.e., be responsive to forces whose magnitude is less than 1 N, and (ii) characterized by a sensor response range $\Delta C$ such to allow for the detection of manipulation-like forces.

*Low elastic modulus*. The elastic modulus must be as low as possible, which allows for a higher compliance, enforcing skin softness and thus allowing for a more precise localization of the contact [15].

*High accuracy*. Elastomer visco-elastic properties, showed generally by both pure and composite elastomeric matrices [20,30], determine such phenomena as hysteresis, creep and stress relaxation, which can affect the accuracy of measurements. So it is necessary to minimize the viscous component of the elastomer.

*Low skin weight*. The skin weight must be as low as possible. Since a skin-like system is expected to cover large areas of a robot body, a heavy skin has an impact on the torque required to actuate robot links. As a consequence, the elastomer density must be low, which means that the use of heavy insulating fillers must be limited.

*High resistance to ageing*. Ageing is an alteration of the chemical and physical structure of the material leading to a detriment of its mechanical properties. The capability of a material to resist ageing is a desirable feature in order to obtain a stable and durable sensor.

*High dielectric permittivity*. A high dielectric permittivity can allow for a reduction of taxel areas maintaining a high sensor response range (Eq. (1)), thereby allowing for an increment of the skin spatial resolution. This is particularly important for small surfaces, such as robot fingertips, where a reasonable goal is to reduce taxel diameters, in order to increase the capability of the single fingertip to discriminate finer-grained contact shapes. For example, let us assume a taxel diameter of 4 mm, on elastomer with a dielectric constant $\epsilon_r = 2.3$ at 250 kHz and a deformation of 0.1 mm (corresponding to a strain of 5% for a 2 mm thick elastomer). Then, according to Eq. (1) the capacitance variation corresponds to 6.74 fF. To reduce the taxel diameter by 40% while maintaining the same capacitance variation, the necessary dielectric permittivity should reach the value $\epsilon_r = 6.4$ at 250 kHz. This value will be used as a target in the following sections.

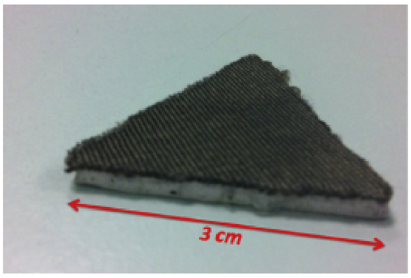
*Dielectric losses*. The dielectric loss can reduce the sensing ability and for this reason it is important to choose a dielectric medium with low losses.

## 4. Materials and methods

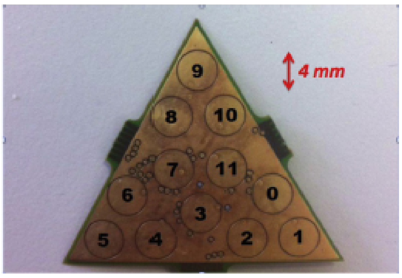
### 4.1. Elastomers

As discussed above, both compliance and lightness are critical constraints in the choice of the dielectric layer. For this reason, we turned our attention to very soft elastomers characterized by low elastic modulus and low weight, as declared by suppliers. Both polydimetilsiloxane (PDMS) and polyurethane-based elastomers are well suited materials, which are available on the market in a large variety of solutions. Availability, ease of processing and low-cost are of the utmost importance in robot applications.

We selected two PDMS products by Smooth-On, Inc., namely the EcoFlex bulk elastomer (up to 00–30 shore A hardness) and the SomaFoama 15 foam elastomer, as well as a Polyurethane bulk elastomer, namely the Polytek 74–20 bulk elastomer (20 shore A hardness) by Polytek. While all the selected materials offer suitable levels of compliance and lightness, they are characterized by




(a)




(b)

**Fig. 2.** Prototype of a capacitive sensor: (a) Sample with the conductive Lycra on top; (b) the fPCB triangular module used for the experiments (a reference number identifies each taxel).

specific advantages and flaws in terms of the overall combination of the relevant properties. For example, the SomaFoama foam (specific gravity 0.24 g/cc, as declared by the supplier) is much lighter than EcoFlex and Polytek bulk elastomers (specific gravity around 1 g/cc) and, possibly, even softer.

Also considering *a posteriori* the experiments discussed in Section 5, SomaFoama has a lower dielectric constant than EcoFlex and Polytek, due to the diffuse porosity which makes it an extraordinary light foam. EcoFlex could be preferable even because PDMS based formulations are usually more resistant to ageing with respect to polyurethanes, which in turn are inclined to react with environmental moisture. Unfortunately, PDMS materials are also usually characterized by low dielectric constant values (at 250 kHz, it is $\epsilon_r = 4.2$ for EcoFlex and $\epsilon_r = 2.3$ for SomaFoama), which can be a drawback for our purposes. To overcome such limitation, we adopt the approach reported in [27,29] to produce new elastomer composites by dispersing high dielectric constant ceramic powders ($TiO_2$, $SrTiO_3$ or PMN-PT) into our PDMS elastomers. Since polyurethanes generally show higher intrinsic dielectric constants than silicones, the choice of Polytek (at 250 kHz, it is $\epsilon_r > 7$) could help reaching our target in robot skin spatial resolution without burdening the dielectric layer with heavy ceramic fillers.

Based on all the aforementioned considerations, it becomes clear that the comparative analysis we present in this work is aimed at finding the best trade-off of properties between the three possible candidates. In order to evaluate the performance of sensors with these different materials, the following experimental tests were performed: (i) mechanical and dielectric characterization of the elastomers; (ii) evaluation of the sensor sensitivity; (iii) evaluation of sensor responses considering the ageing process; (iv) evaluation of the influence of spatial filtering caused by the elastomer on the overall sensor response, with the aim of quantifying the spatial resolution.

### 4.2. Sample preparation

For the preparation of specimens we followed the procedures described in [27]. The two components (A and B, as defined by the manufacturers) for each elastomer were mixed at room temperature (B/A = 1 by weight for Ecoflex, B/A = 0.5 for SomaFoama and B/A = 2 for Polyurethane). As a filler, we used different high dielectric constant ceramic powders: Dioxide Titanate ($TiO_2$) and Strontium Titanate ($SrTiO_3$) by Sigma–Aldrich and PMN-PT by TRS Ceramics Inc. containing 85% of lead magnesium niobate $Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN) and 15% of lead titanate $PbTiO_3$ (PT). The powder was added to the elastomer by hand mixing and air bubbles were extracted with a vacuum pump. For each elastomer, four specimens were prepared and tested. Triangular specimens were obtained using moulds, with a 2 mm thickness and a 3 cm side length; on top of each sample, a conductive Lycra layer was glued (a Sil-poxy glue from Smooth-On Inc. was used) in order to test the sensor response with a non conductive indenter (see Fig. 2a). For the mechanical characterization tests, we prepared cylinder-like specimens, with a 15 mm thickness and a 15 mm diameter, while for the dielectric characterization tests the specimens had a 1 mm thickness and a 11 mm diameter.

### 4.3. Experimental test protocols

In order to perform the dielectric characterization of the specimens, wideband dielectric spectroscopy was carried out at 20 °C in the 10 Hz–100 MHz frequency range, by means of a vector network analyser (model ZVRE by Rohde and Schwarz). The procedure followed the guidelines proposed by Pelster [31] and was based on measuring the transmission coefficient of a capacitive cell, filled with the sample, placed inside a coaxial air line and connected in series with the central conductor. The complex dielectric permittivity was extracted at each frequency by comparing the material response to that of other two standard loads. The cell was a plane capacitor with stainless steel circular electrodes of 15 mm diameter, between which disk-shaped specimens of 11 mm diameter and 1 mm thickness were sandwiched.

Composites and pure matrices were mechanically tested by means of a dynamometer (model EPLEXOR 100N by GABO Qualimeter Testanlagen GmbH), used for measuring visco-elastic sample properties at variable strains. Both the real (i.e., the storage modulus $E'$) and imaginary part (i.e., the loss modulus $E''$) of the compressive complex elastic modulus $E$ were characterized. Specimens were compressed in the static strain range of 5–30% at 20 °C along the

**Table 1**
Dielectric permittivity of the elastomers at 250 kHz and increase of the permittivity of the composites (50%wt.) with respect to the pure matrix.

| Elastomer | Pure | With $TiO_2$ | | With $SrTiO_3$ | | With PMN-PT | |
|---|---|---|---|---|---|---|---|
| | $\epsilon_r$ | $\epsilon_r$ | Increase (%) | $\epsilon_r$ | Increase (%) | $\epsilon_r$ | Increase (%) |
| SomaFoama | 2.3 | 3.9 | 69 | 4.8 | 107 | 3.1 | 34 |
| Ecoflex | 4.2 | – | – | 5.2 | 22 | 5.3 | 24 |
| Polytek | 8.2 | – | – | – | – | – | – |

**Table 2**
Storage modulus of the tested elastomer for a compressive stress in both pressure ranges.

| Elastomer | Pressure range (kPa) | Pure | With $TiO_2$ | | With $SrTiO_3$ | | With PMN-PT | |
|---|---|---|---|---|---|---|---|---|
| | | $E'$ (MPa) | $E'$ (MPa) | Increase | $E'$ (MPa) | Increase | $E'$ (MPa) | Increase |
| SomaFoama | 0–10 | 0.13 | 0.36 | 176 % | 0.39 | 200 % | 0.16 | 23% |
| | 10–100 | 0.13 | 0.49 | 276% | 0.45 | 246% | 0.21 | 61% |
| Ecoflex | 0–10 | 0.18 | – | – | 0.33 | 83% | 0.25 | 50% |
| | 10–100 | 0.20 | – | – | 0.49 | 145% | 0.32 | 60% |
| Polytek | 0–10 | 0.19 | – | – | – | – | – | – |
| | 10–100 | 0.46 | – | – | – | – | – | – |

cylinder's axis direction. A dynamic compressive strain of 2% was superimposed during the test at a frequency of 10 *Hz*.

With respect to the experimental tests aimed at evaluating the performance of sensors with different dielectrics, the procedure is outlined below. A skin triangular module was used for the test (see Fig. 2b) and differential responses (Eq. (1)) for each taxel at a sampling rate of 50 ms, were collected. The test was performed for each dielectric sample. Each sample was mechanically excited with a non conductive 3 mm diameter indenter, which was actuated by a linear motor (from Faulhaber GmbH & Co). A gradually increasing deformation (with 0.14 mm steps) was induced to reach the maximum desired pressure range. A load cell was connected to the indenter to measure the force. Each deformation was held for 10 s and the material was let to relax for other 10 s before inducing a further deformation. In order to control the position of the indenter, we used linear motor stages allowing for a translation along the $x$ and $y$ axes and for a rotation around a vertical $\theta$ axis (Thorlabs Inc.).

In order to characterize the effects of ageing, we left the elastomer specimens in an open box in a lab environment for approximately 6 months. Then, we performed again the experimental tests as described above and compared the results. The ageing rate depends on the chemical structure of the polymer and on the particular environment in which it operates. We decided to leave samples to age in a typical environment when robots may be installed, which is exemplifying very common conditions faced by robots provided with skin. The use of different environments or accelerated lifetime techniques could possibly result in different ageing rates and final properties. It is noteworthy that varying the relevant conditions in which the materials are exploited would require to carry out specific ageing tests.

Finally, in order to evaluate the filtering effects of the elastomer on the taxel response, we performed two different tests: one with a 3 mm circular indenter (i.e., smaller than the taxel area), and another with a 12 mm indenter (i.e., greater than the taxel area).

## 5. Results and discussion

### 5.1. Dielectric permittivity and mechanical properties

The dielectric permittivity of any material varies with the frequency of the applied electric field, which was, in this case, the excitation frequency of the read-out electronics. For the reference robot skin technology, the excitation frequency is 250 kHz. Fig. 3 and Table 1 present the measured values of dielectric permittivity.

Although fillers with high dielectric constant were added to the selected elastomers, the obtained dielectric constant did not reach the target value of 6.4 (see Section 3.2). The best result was obtained from the dispersion of PMN-PT in the Ecoflex matrix, with a resulting dielectric permittivity $\epsilon_r - 5.3$. The best percentage increase was obtained from the composite made by dispersing $SrTiO_3$ in the SomaFoama matrix, with $\epsilon_r - 4.8$ (percentage increment of 107%). The Polyurethane matrix showed a higher dielectric permittivity (i.e., $\epsilon_r - 8.2$), without the need for dispersing fillers. Regarding the dielectric loss (see Fig. 3b), all the tested samples showed very low dispersion (less than 0.5) throughout the considered frequency ranges, except for Polyurethane, which is prone to show dissipative behaviour, due to absorption of air moisture and impurities. Further investigation is required to assess whether Polyurethane represents the most suitable choice for our application.

Fig. 4, Tables 2 and 3 show the outcomes of the mechanical characterization of the elastomers. The dispersion of fillers produces in the elastomer a significant variation of the storage modulus with the applied strain, whereas pure matrices are characterized by an almost *flat* response. This does not hold for the Polyurethane, which shows a more dynamic behaviour with respect to compression strains.

The increase of the dielectric permittivity via insulating fillers is known to lead to an increase of the elastic modulus of the compounds. For a stress in the gentle touch range there are increments of the storage modulus between 23 and 200%, whereas for a stress in the manipulation-like range there are increments ranging from 61 to 246%. In the case of SomaFoama, and in particular in the composites based on $TiO_2$ and $SrTiO_3$, the increase of the storage modulus was 176 and 200% for a gentle touch and 276 and 246%, respectively, in case of manipulation-like touch (Table 2).

The dispersion of fillers led, on average, to an increase of the mechanical loss modulus, which means a more viscous behaviour of the overall composites (Table 3. However, for the SomaFoama filled with PMN-PT, the loss modulus decreased.

The increasing elastic modulus and the change in viscosity must be considered in the choice of the elastomer to be used. The increase of dielectric permittivity allows the designer to reduce the taxel radius (Eq. (1)) and to increase the overall robot skin spatial

**Table 3**
Loss modulus of the tested elastomer for a compressive stress in both pressure ranges.

| Elastomer | Pressure range (kPa) | Pure | With $TiO_2$ | | With $SrTiO_3$ | | With PMN-PT | |
|---|---|---|---|---|---|---|---|---|
| | | $E''$(MPa) | $E''$(MPa) | Increase (%) | $E''$(MPa) | Increase (%) | $E''$ (MPa) | Increase (%) |
| SomaFoama | 0–10 | 0.010 | 0.053 | 459 | 0.042 | 341 | 0.010 | 0 |
| | 10–100 | 0.010 | 0.065 | 550 | 0.050 | 400 | 0.014 | 39 |
| Ecoflex | 0–10 | 0.019 | – | – | 0.067 | 252 | 0.031 | 63 |
| | 10–100 | 0.024 | – | – | 0.101 | 321 | 0.042 | 75 |
| Polytek | 0–10 | 0.065 | – | – | – | – | – | – |
| | 10–100 | 0.092 | – | – | – | – | – | – |

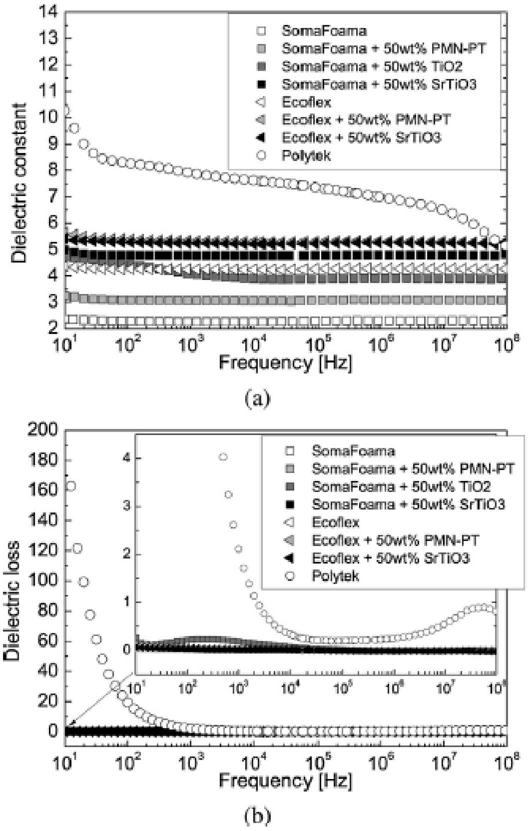



**Fig. 3.** The characterized values of the dielectric permittivity: (a) dielectric constant; (b) dielectric loss.

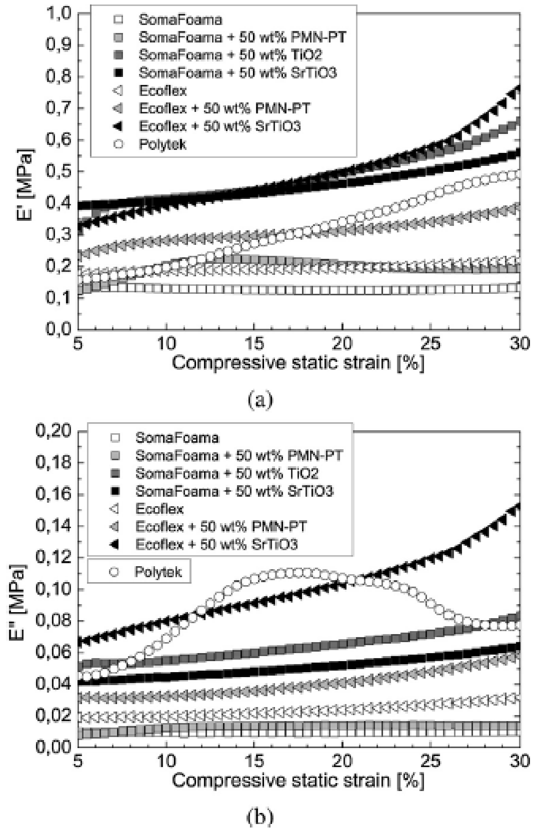



**Fig. 4.** Storage (a) and loss (b) modulus as a function of the applied compressive strain.

resolution maintaining the same detectable sensor response range. The increase of the material stiffness may significantly reduce the overall sensor sensitivity due to mechanical filtering, as argued in [15], especially for low forces.

The use of ceramic fillers leads to an increase of the elastomer weight. We computed the average weight increase of the elastomers filled with ceramic powders with respect to the pure matrix. Table 4 shows that, for the SomaFoama the increase is 59% with $TiO_2$, 58% with $SrTiO_3$ and 54% with PMN-PT, when using Ecoflex the increase is 37% with $SrTiO_3$ and 31% with PMN-PT. In Table 4, the apparent density values of pure elastomers and their composites is reported. Note that Polyurethane had a density of 1.44 g/cm$^3$, lower than the other composites. For large-scale robot skins, this fact may significantly affect motion performance.

### 5.2. Sensitivity

We computed the sensitivity as defined in Eq. (2) for all the values in the gentle-touch (0–10 kPa) and in the manipulation-like ranges (10–100 kPa). We averaged the sensor response with respect to the applied pressure for all the specimens of the same elastomer. The need for averaging emerged because the sensor response varied on a sample basis as reported in Fig. 6 where the average and the standard deviation of the sensor response of the different speciments for each material is shown. This variation is due to the presence of air bubbles or varying distribution of the filler within the matrix (Fig. 5).

Fig. 7 shows for each elastomer the averaged sensitivity values (i.e., the slope of the dotted lines consisting of a linear interpolation of the data) in the considered contact ranges. The lines labelled as "0 months" correspond to newly made samples, whereas the lines labelled as "6 months" refers to the same samples tested after 6-months. Ageing effects are discussed in the next Section. The sensitivity curves show similarities among the tested materials. We observe that the gentle-touch range was usually characterized by a higher sensitivity (i.e., the slope was higher), whereas in the manipulation-like range the response was less dependent on pressure variations. This is a useful feature, as for smaller pressures a higher resolution is usually preferred to discriminate the contact event at a finer level of detail.

The SomaFoama filled with 50% of PMN-PT elastomer showed the best sensitivity in the gentle touch range ($S_g = 3.24$ fF/kPa), whereas SomaFoama filled with 50% of $SrTiO_3$ is best for the manipulation-like range ($S_m = 0.68$ fF/kPa). The worst sensitivity value for both the contact ranges was obtained with the SomaFoama filled with 50% of $TiO_2$, namely $S_g = 0.72$ fF/kPa for the gentle touch and $S_m = 0.21$ fF/kPa for the manipulation-like touch. From this sensitivity analysis important design choices emerge. On the one hand, if the sensor is to be used in tasks where contacts in the gentle touch range are expected, SomaFoama filled with 50% of PMN-PT is the best choice. On the other hand, manipulation requires the use of SomaFoama filled with 50% of $SrTiO_3$. This suggests that skins for robots must be purposely tailored in order to obtain an appropriate tactile performance level in various parts of the robot body. It is noteworthy that, since the resolution of the CDC was 0.32 fF, sensitivity values lower than this resolution could not be detected.

**Table 4**
The apparent density values of pure elastomers and their composites.

| Elastomer | Pure | With $TiO_2$ | | With $SrTiO_3$ | | With PMN-PT | |
|---|---|---|---|---|---|---|---|
| | g/cm$^3$ | g/cm$^3$ | Increase (%) | g/cm$^3$ | Increase (%) | g/cm$^3$ | Increase (%) |
| SomaFoama | 0.96 | 1.53 | 59 | 1.52 | 58 | 1.48 | 54 |
| Ecoflex | 1.28 | – | – | 1.76 | 37 | 1.68 | 31 |
| Polytek | 1.44 | – | – | – | – | – | – |

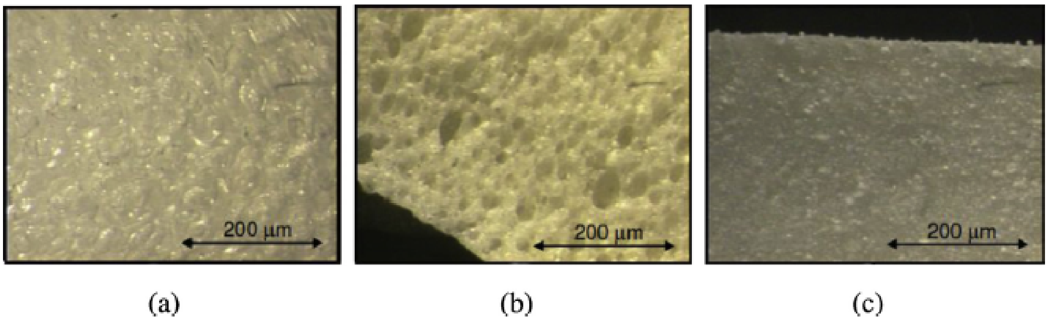



**Fig. 5.** Pictures of elastomer samples: (a) SomaFoama; (b) SomaFoama filled with PMN-PT; (c) Ecoflex filled with PMN-PT.

## 5.3. *Ageing*

As shown in Fig. 7, ageing significantly altered the sensitivity. After 6 months for all the evaluated elastomers, the sensitivity decreased in both the pressure ranges. The gentle touch range was more affected. Furthermore, it is possible to observe a generalized flattening of the response, likely due to an increase of the material stiffness.

The Polyurethane exhibited the worst detrimental effect of ageing in terms of sensitivity and sensor response range. The sensitivity varied from 1.63 to 0.10 fF/kPa for the gentle touch, and from 0.50 to 0.06 fF/kPa for the manipulation-like touch. The data suggest that the elastomer lost its *deformation capabilities*, since the difference between the sensitivity values in the two pressure ranges became very small, i.e., 0.04 fF/kPa. The SomaFoama filled with 50% of PMN-PT showed the best resilience to ageing in the gentle touch

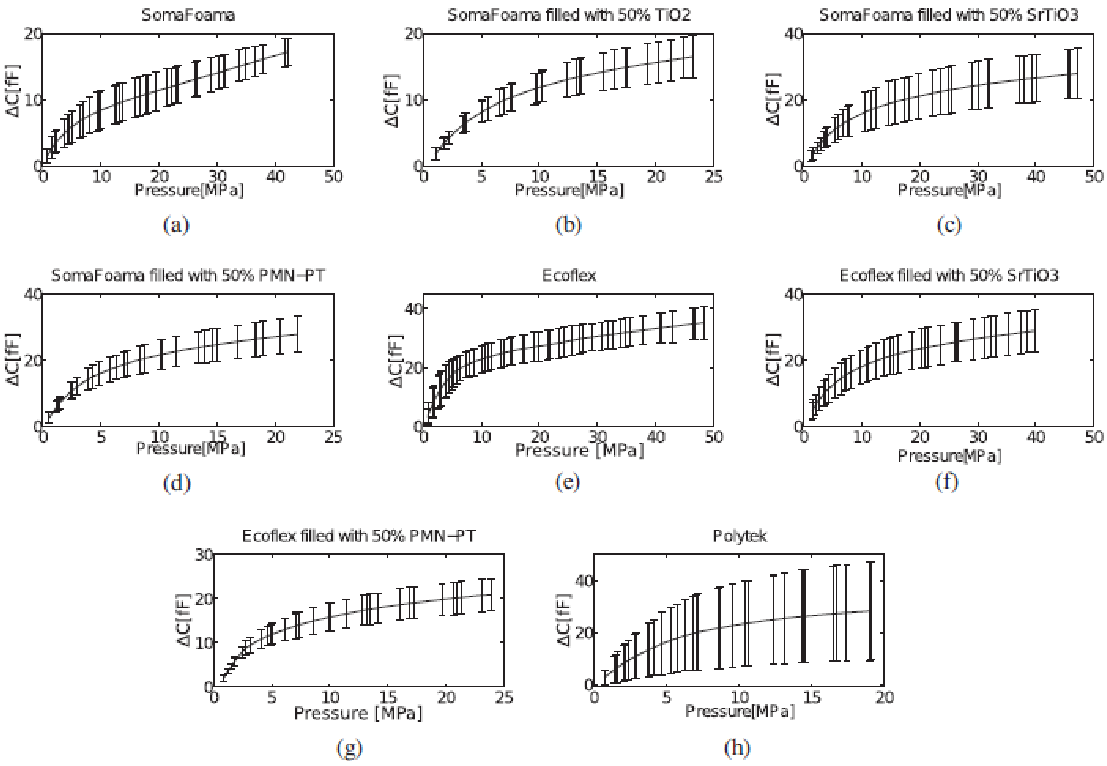



**Fig. 6.** The average and the standard deviation of the sensor response of the different speciments for each material.

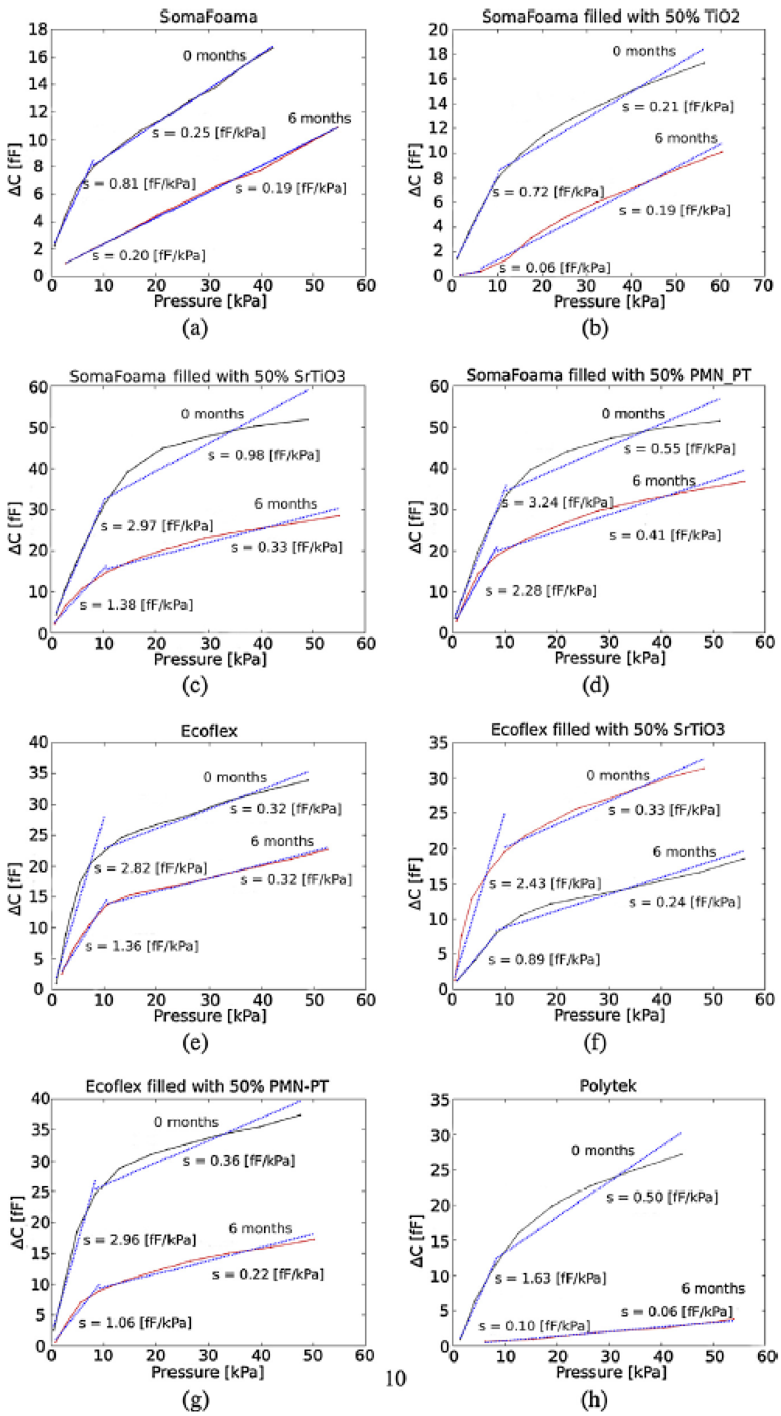



**Fig. 7.** The sensor response for different elastomers as a dielectric layer: for each material, the two plots refer to a newly made sample (0-months) and the same sample measured after ageing (6-months). Dotted lines represent the linear interpolation of the data in the two ranges. The sensitivity values are expressed as the angular coefficients of the interpolating lines.

range, as its sensitivity changed from 3.24 to 2.28 fF/kPa, whereas in the manipulation-like range SomaFoama filled with 50% of $TiO_2$ showed the best behavior: its sensitivity varied from 0.21 fF/kPa to 0.19 fF/kPa.

It is well-known that the curing degree strongly influences the ageing properties of a vulcanized rubber. As a matter of fact, during a vulcanization process the unsaturated bonds in the main polymeric chain react with the curing agent in order to make covalent

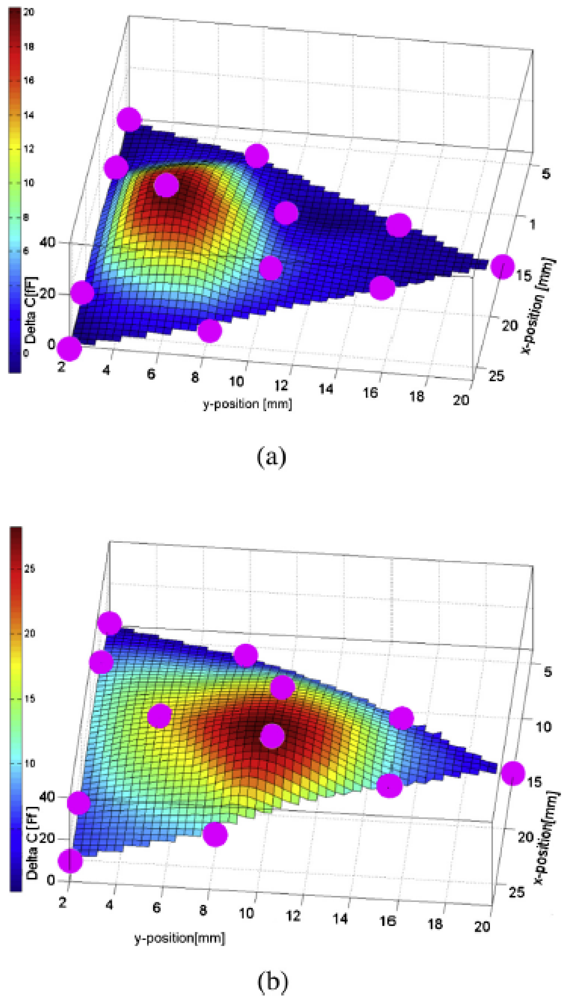



**Fig. 8.** Interpolation of the taxels response in a triangular module sensor, with Ecoflex as a dielectric layer in response to a 40 KPa pressure. Red dots show the position of the 12 taxels. Only the area inscribed by the polygon formed by the outer taxels is reconstructed. In (a) the pressure was exerted with a 3 mm indenter centred on taxel 3; in (b) the pressure was exerted with a 12 mm indenter centred between taxels 3, 7 and 11. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

crosslinks between the various chains. This usually implies that the more bonds become saturated after curing, the harder and the stiffer is the final material. This behaviour can be observed in Fig. 7. Hence, in order to end up with a soft elastomer, only a small fraction of unsaturated bonds in the main polymeric chains must be saturated by the vulcanization process. The many residual unsaturated bonds are thus available for possible further reactions with other oxidizing agents in the environment, which is the main reason that makes vulcanized rubbers destined to ageing over time. In the literature, it is possible to find many ways to extend the life of a rubber. Such improvements are likely to be successful if performed in a strictly controlled industrial environment.

### 5.4. *Spatial filtering*

With "spatial filtering", we refer here on how a single stimulus is mechanically filtered by the elastomer, thereby leading (in principle) to taxel responses outside the contact area [15]. Fig. 8 shows the sensor response to a stress distribution over a triangular module sensor using Ecoflex as a dielectric layer, when a pressure of 40 KPa was applied, specifically with a 3 mm and a 12 mm indenter. The dots correspond to taxel positions on the triangular module and reflect the arrangement of Fig. 2. On the basis of the $\Delta C$ values from all the taxels, the surface represented in Fig. 8 was obtained by interpolation. Even from this simple model, it is possible to observe that the sensor response is properly concentrated underneath the indenter area. This shows that a precise localization of the contact can be obtained. Furthermore, it can be noticed that the mechanical filtering effect of the elastomer *spreads* the pressure in an area actually larger than the excited one. This effect proves very useful when the robot skin is in contact with small objects (i.e., less than 4 mm wide) in a location where taxels are not present (e.g., between taxels): in such a case the contact can still be detected by means of the surrounding taxels.

We did not observe any relevant difference in spatial filtering by changing the tested elastomers. Actually in the most challenging case (i.e., a 3 mm indenter), the different elastomers showed the same behaviour in terms of the stress distribution spreading over the unexcited taxels.

## 6. Conclusions

Different types of elastomers were developed, characterized and tested as candidate dielectric layers for large-scale capacitive tactile sensors. We showed that using various types of elastomers leads to a different sensor, in terms of sensing capabilities. The outcome of this work suggests the need for choosing different elastomers in order to adapt the performance and characteristics of the sensor (based on the same electronics) to different robot tasks. It emerges that it is not possible to identify the best general-purpose elastomer. The choice is determined by the application scenario in which the sensor is used. Each application enforces specific requirements that need a trade-off between desired and required system parameters (e.g., involved contact forces, elastic *vs* viscoelastic behaviour, sensitivity within specific pressure ranges, weight, durability, spatial resolution). Examples include applications related to tactile-based manipulation, physical human–robot interaction (including such cognitive tasks as tactile-based contact reconstruction and classification [14], as well as tactile-based postural control [32]).

With respect to the requirements introduced in Section 3.2, it is now possible to draw the following conclusions.

*Sensitivity.* The SomaFoama filled with 50% of PMN-PT elastomer showed the best sensitivity in the gentle touch range, whereas SomaFoama filled with 50% of $SrTiO_3$ showed the best sensitivity value for the manipulation-like range.

*Dielectric permittivity.* The Polyurethane would allow for a reduction of the taxel radius, thanks to an intrinsically high dielectric permittivity (not requiring any loading with ceramic fillers), ensuring also a low weight of the whole skin.

*Resistance to ageing.* All the tested elastomers were affected by a worsening of their mechanical properties, which led to a reduction of the sensitivity in both pressure ranges. SomaFoama filled with 50% of PMN-PT showed the best resilience for the gentle touch range, whereas in the manipulation-like range SomaFoama filled with 50% of $TiO_2$ showed the best behaviour. However, ageing is unavoidable in very soft elastomers, and by conditioning the mechanical properties of the materials, it also makes their piezo-capacitive response properties to vary over time.

*Spatial resolution.* From the spatial filtering point of view all the tested elastomers were very soft and showed a similar behaviour, allowing for a precise localization of the contact area. The softness also allowed for a good response range of the sensor.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