Strain-Sensing Fabrics for Wearable Kinaesthetic-Like Systems

Enzo Pasquale Scilingo, Federico Lorussi, Alberto Mazzoldi, and Danilo De Rossi

***Abstract*—In recent years, an innovative technology based on polymeric conductors and semiconductors has undergone rapid growth. These materials offer several advantages with respect to metals and inorganic conductors: lightness, large elasticity and resilience, resistance to corrosion, flexibility, impact strength, etc. These properties are suitable for implementing wearable devices. In particular, a sensitive glove able to detect the position and the motion of fingers and a sensorized leotard have been developed. Here, the characterization of the strain-sensing fabric is presented. In the first section, the polymerization process used to realize the strain sensor is described. Then, the thermal and mechanical transduction properties of the strain sensor are investigated and a geometrical parameter to invariantly codify the sensor response during aging is proposed. Finally, a brief outline of ongoing applications is reported.**

***Index Terms*—Body kinematics, sensors, smart textiles.**

I. Introduction

The integration of electroactive polymeric materials into sensorized garments could enable the development of new instruments in several fields of application, such as man–machine interface technology, teleoperation, virtual reality, ergonomics, rehabilitation engineering, and sports medicine. Strain and temperature sensors based on traditional technology ill befit implementation in wearable devices. The technology based on polymeric conductors is increasingly utilized because they exhibit electromechanical transduction properties suitable for implementing smart fabrics [1]. Moreover, recent developments of "all-polymer" devices are directed toward active electronic components (transistors) [2] and "all polymer" batteries [3] providing essential instrumental functions (power supply, sensor, actuator, and processor) which can be implemented onto fabric substrates. In particular, polymeric conductors are prepared in the form of fiber coatings and spun fibers so as to be incorporated into distributed strain and temperature sensors and contractile actuators [4], [7]. Truly wearable instrumented garments capable of recording proprioceptive maps with no discomfort for the subject and negligible motion artifacts caused by sensor-body mechanical mismatch are crucial for several fields of application [6].

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Sensing fabrics, recently developed by the authors, enable the measurement of shape, detection of posture, and gesture of the human body. In particular, a prototype of a sensorized glove able to detect the position and motion of fingers relative to the palm and a sensorized leotard for upper body movement tracking have been developed. Figs. 1 and 2, respectively, show the mask utilized to produce the glove and the glove with the sensors.

In this paper, we present the results of a series of characterization measurements on polypyrrole (PPy) coated fabrics. In particular, we analyzed the thermal, mechanical, and aging properties of these materials, in order to exploit them in sensorized fabrics. A brief outline of the sensorized glove and leotard will also be given.

II. Materials and Methods

A. Polymerization Process

In our application, sensors are realized starting from conventional textile fibers or fabrics coated by a very thin layer of PPy a $\prod$-electron conjugated conducting polymer [5], [8]. Because of its elasticity, ergonomic comfort, and high piezoresistive and thermoresistive coefficients, we found the combination of PPy as conducting polymer and Lycra/cotton as fabric particularly effective. PPy-coated elastic cotton fabric was prepared using the method developed by Milliken Co. (Spartanburg, SC) as described in U.S. patent 4 803 096 aimed to prepare resistive fabrics for heating and EM shielding. We introduced some variations in the manufacturing process in order to produce a strain sensor suitable for our requirements. In particular, 0.31 g of pyrrole was dissolved in 200 ml of distilled water, and 5 g of the oxidizing agent $Fe(ClO_4)_3$ then added. To this solution, a small piece of cotton-Lycra fabric (3 g) was added. The solution was then placed in a thermostatic cell maintained at 18 °C, and stirred. After the fabric had been in contact with the solution for about 30 min, the coated fabric was taken out, washed with distilled water, and dried in air. Under these conditions, we obtain epitaxial deposition of PPy on the textile substrate. Microscopically a film deposited on the fabric can be observed, with thickness ranging between 0.05 and 2 μ. The formation of the polymeric film is influenced by several factors. If the concentration of the polymeric solution is too high with respect to the amount of textile material or the quantity of water, the polymerization process occurs instantly either on the surface of the fabric and in solution, with the appearance of black particles in solution, termed "black polypyrrole." On the other hand, if the concentration is maintained low, ranging from 0.001 to 0.5 g of polymer for 50 g of textile material in a liter of solution, the

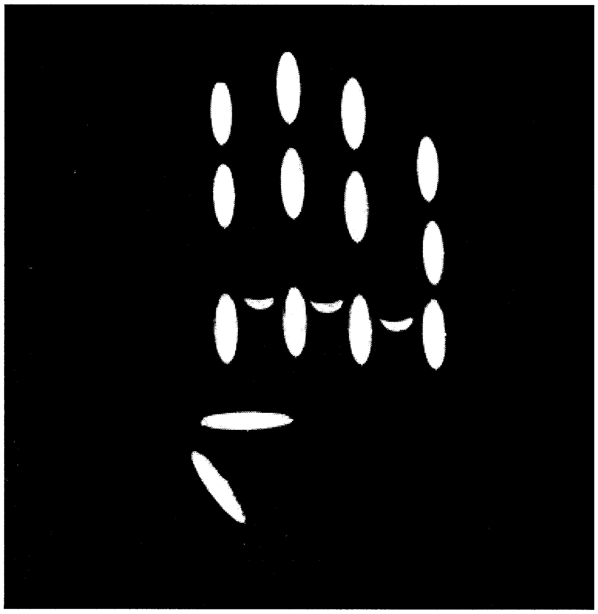


Fig. 1. Screen printing negative mask used to define sensor geometry on the sensorized glove (see Section II-B.).

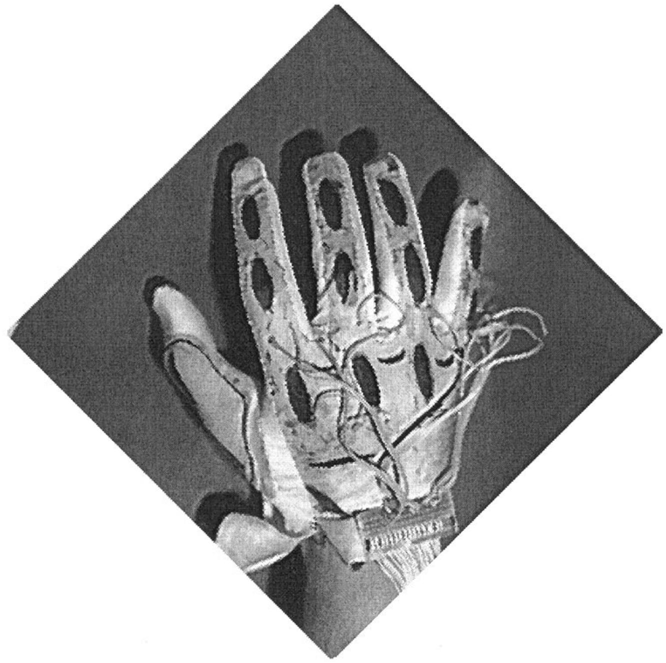


Fig. 2. Prototype of the sensorized glove.

process occurs at low speed and the polymer is deposited on the textile material before the polymerization is complete. Other factors affecting the reaction speed are temperature and the presence of possible additives. Controlling the speed of reaction it is not only important to optimize the correct formation of the polymer on the surface of every fiber, but also to influence the average molecular weight and degree of order of the polymer deposited in epitaxial way.

B. Sensor Geometry Definition

Sensors and conducting tracks on the fabric are obtained by combining the Milliken technique with a screen printing technique developed at Center "E. Piaggio." The combination of the two techniques is based on the observation that the coating of the textiles with particular waxes avoids the deposition of the polymer on the cloth when it is immersed in the polymerization bath.

Briefly, the preparation steps are the following: the first step is the definition of a mask with the position and shape of the sensors and conducting tracks. Using this mask, it is possible to create a negative image of these elements on the fabrics. This is realized on the fabrics by forcing the wax through the mask using a roller and depositing it on the fabric. Subsequently, the polymer is deposited. Last, the garment is washed with soap, solvent and water.

C. Experimental Tests

1) Sensor Aging: The goal of this experiment was to quantify the aging of the sensors, i.e., to evaluate how the rest value of resistance changes with time. In particular, we evaluated the time dependence of the resistance of ten sensors obtained from a single sample of conductive fabric by performing daily measurements with a digital tester, over a period of one month. All of the measurements of resistance reported here are referred to a unit length of 1 cm because the width of the sample used in our experiments is always the same. The dimensions of the samples were 5.8 cm × 2.5 cm.

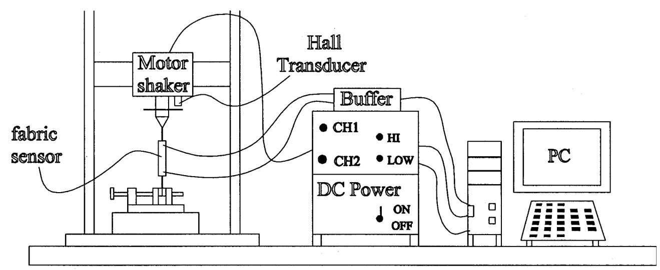


Fig. 3. Instrumental system used for the electromechanical characterization of the fabric sensors.

2) Thermal Characterization: In order to determine how temperature influences the piezo-resistive properties of the sensor, we measured the resistance of a sample having the same size as the previous ones at different temperatures. We located the sensor into an electronically controlled thermostatic cell, maintained at a pre-determined temperature. The thermostatic cell consists of a small metallic container and of a heat pump realized using a Peltier element. Inside the cell, two NTC thermistors were located, one necessary to realize a closed loop PI control of temperature and the other to monitor room temperature through an external digital thermometer. The system was thermally insulated by means of expanded polystyrene.

3) Mechanical Characterization: Since Ppy-Lycra/cotton fabric is employed to monitor mechanical strains, a prerequisite condition is to determine how the sensor responds to external stresses. To do this, we performed several mechanical tests, where sensors were submitted to step strain in stretching with increasing amplitude and the induced variation of resistance was recorded. In Fig. 3, the block diagram of the system used to characterize the sensor fabric is reported. An electromagnetic shaker is driven and controlled by an electronic

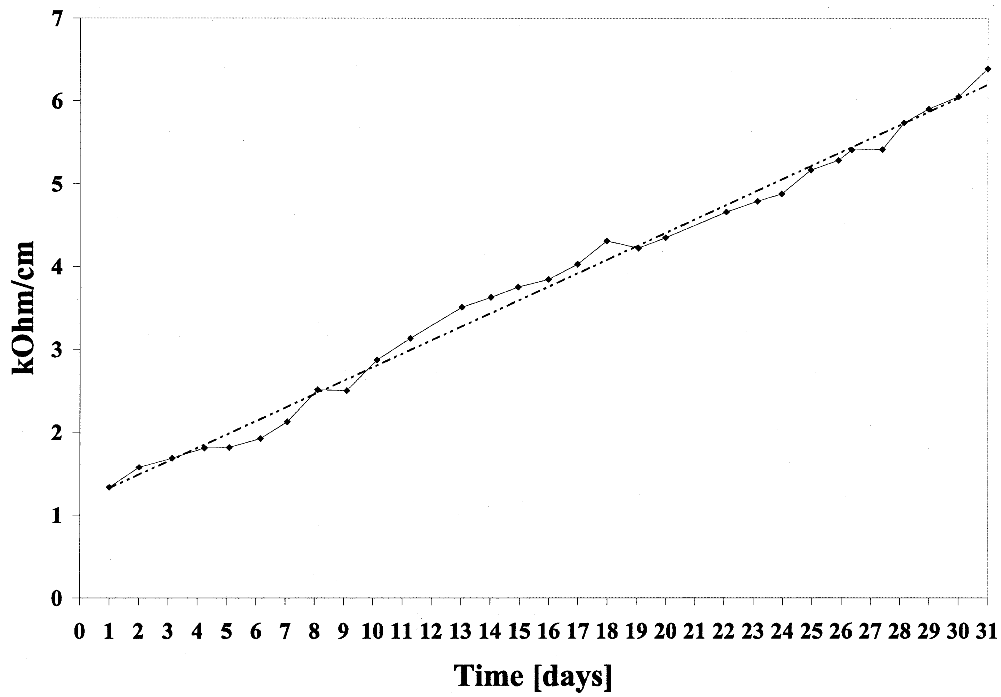


Fig. 4. Resistance per unit of length versus time.

interface connected to a computer. The displacement function imposed on the motor can be input through the computer's keyboard. A sensor strip of known dimensions (the same of the Sections II-C-1 and 2) was attached to the motor imposing displacements. Two metallic electrodes wired to an electronic circuit were applied to the terminal sides of the sensor and the output of the resistance reading and acquisition system sent to a computer. The sensor resistance Rs is connected in series with a reference resistance Rf (300 $\mathrm{k\Omega}$) in voltage divider configuration and to a voltage buffer to minimize the load effect. The output voltage was wired to a channel of an A/D converter and sent to a computer. A Hall effect transducer was used to measure displacements.

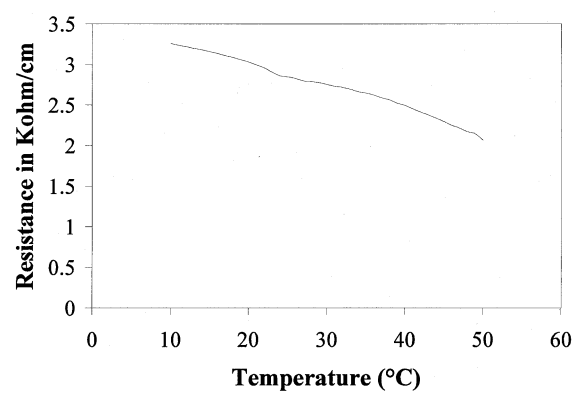


Fig. 5. Resistance per unit of length versus temperature.

III. Experimental Results and Discussion

A. Sensor Aging

The resistance of fabric sensors changes if maintained in open air. To quantify the phenomenon we used two sensors (5.8 cm $\times$ 2.5 cm) with an unstrained initial resistance of 0.9 $\mathrm{k\Omega/cm}$ and put one inside a sealed container and the other in a tray in open air. At the end of a 60-day test period, the sensor in contact with open air exhibited a higher resistance per unit length (8.8 $\mathrm{k\Omega/cm}$) than the other sensor (2.3 $\mathrm{k\Omega/cm}$).

In Fig. 4, we report the average resistance per unit of length versus time. As shown in the figure, the behavior of the resistance with time is fairly linear. Least-square linear regression resulted in the following equation:

$$r = 0.13 \cdot t + 0.90$$

where r is the resistance per unit of length expressed in $\mathrm{k\Omega/cm}$ and t in days. To confirm this trend, we measured the same sensors after 60 days and we ascertained that the average deviation between the effective values and those ones predicted by the linear equation was 10%.

B. Characterization of Temperature Sensitivity

Temperature of fabric sensors was varied from 10 to 50 $^\circ\mathrm{C}$ with incremental steps of 1 $^\circ\mathrm{C}$. Acquired data are reported in Fig. 5. A parameter useful in quantifying the transducing properties of thermoresistive materials is the temperature coefficient of resistance, TCR $= ((R_T - R_{T_0})/R_{T_0})1/(T - T_0)$, where R_T and R_{T_0} are, respectively, the resistance at temperature T and the resistance at reference temperature T_0. Through linear interpolation of the data acquired, the calculated value of TCR is $-$ 0.018 $^\circ\mathrm{C}^{-1}$. The value of the TCR for this coated fabric is high and negative in sign. In fact, the temperature sensitivity of PPy coated fabric is comparable to that of ceramic thermistors with a negative temperature coefficient (NTC thermistors typically have TCR in the range $-$ 0.03 $^\circ\mathrm{C}^{-1}$to $-$ 0.05 $^\circ\mathrm{C}^{-1}$) [9]. In applications related to the monitoring of kinematics of human

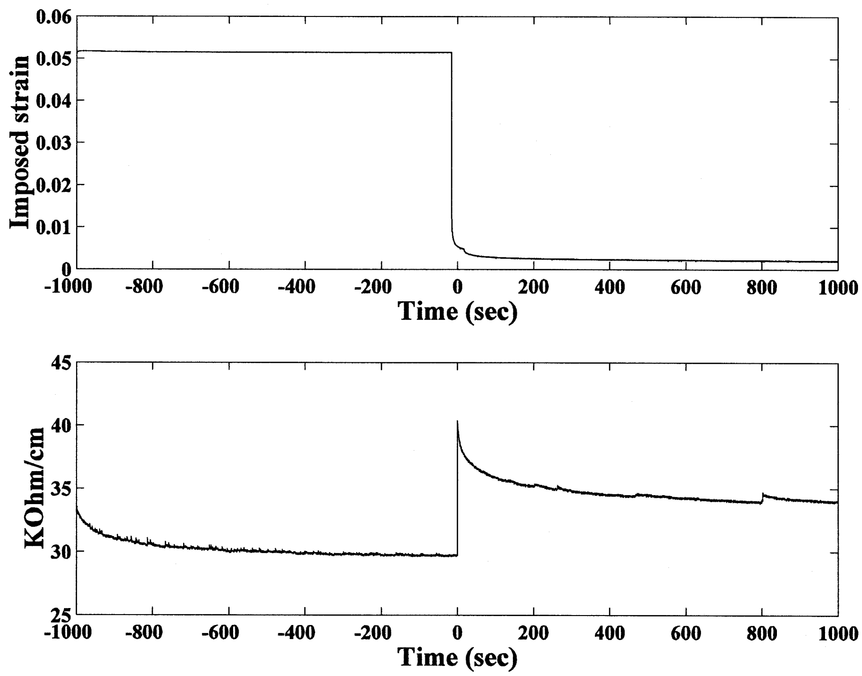


Fig. 6. (Top) Resistance signal per unit of length from the sensor fabric when (bottom) a step function in shortening is imposed.

body segments, temperature variations typically encountered do not significantly affect the acquired data.

C. Data Analysis of Mechanical Tests

Experiments were performed to calculate the fabric gauge factor. To do this, we exerted quasistatic successively small increments of uniaxial stretching along two orthogonal directions in the plane of the fabric. The calculated gauge factors, GF $= (R_f - R_0/R_0)/(L_f - L_0/L_0)$, where R_f and R_0 are, respectively, the final and initial resistance and L_f and L_0 are, respectively, the final and initial sample length, are $GF_{\|} = -$ 13.25 and $GF_{\perp} = -$ 12.5 along the warp and the fill, respectively. It is worth noting that the GF value of this fabric is negative, rather high and very close to that of nickel [9]. We also assessed the dynamic transduction properties of the fabric sensors. Mechanical stresses imposed on fabric sensor were step functions in stretching and always applied in the same direction. The maximum stroke of the electromagnetic shaker was 6 mm; therefore, we divided this interval in ten steps and we imposed ten step functions of strain with increasing magnitude, from 1% to 10%, on the sensing fabric. Our goal was to formulate a relationship between the stretching imposed and the resistance measured. We acquired the rest value of the resistance for 15 min, then we imposed the step strain and we maintained the stretching for an additional 15 min, once more recording the resistance signal. To avoid an excess of redundant data we chose a lower sampling rate (33 Hz) during the first 15-min interval and a sampling rate of 1 kHz for 1 s, during which the step strain was applied. Figs. 6 and 7 illustrate the step function imposed and the relative resistance signal, respectively, for shortening and stretching of the fabric sensor. From a qualitative description of the behavior of the fabric sensor, confirmed by repeating the test, we can affirm that when suddenly stretched, the sensor always responds exhibiting an initial peak and a subsequent relaxation down to the final value. The final resistance is lower than the initial one, i.e., the resistance of the sensor is reduced when stretched and this confirms the negative sign of the gauge factor previously calculated.

Although a more detailed analysis is needed to elucidate this piezoresistive transducing phenomena of conducting fabrics, it is interesting to outline a few observations, which are pertinent to the origin of transduction. In principle, the electromechanical properties of the coated fabric could be ascribed to the intrinsic piezoresistive properties of the conducting polymer layer and/or to the strain modulated resistive contact topology of microfibers and bundles constituting the fabric. To assess the first hypothesis, the strain-gauge factor of a bulk PPy sample in a thick-film (34 mm) form (Lutamer from BASF AG, Ludwigshafen, Germany) was measured using the same methods and techniques described here; the measured values of GF ranged from 0.45 to 0.9 (depending on the degree of doping). Comparing this value of GF with the one of the PPy coated Lycra fabric, we note that it is much smaller and opposite in sign. Therefore, the intrinsic piezoresistivity of the PPy can be excluded from being the cause of fabric electromechanical properties.

So, to explain a possible cause of sensors behaviors, changes in quasistatic resistance of carbon fiber felts under tension and compression have been considered as reported in literature [10] and shown in Fig. 8. They appear to be qualitatively very similar to our data in Fig. 9. In accordance with the given explanation for the decrease in resistance of carbon fiber bundles under load. We suggest that the piezoresistive properties of the PPy/Lycra fabric arise from a progressive increase in the number of contacts marked on the Fig. 8 with 1, afterwards from the area contacting the microfibers marked with 2, and, finally, the bundles themselves as the applied load increases marked with 3. This

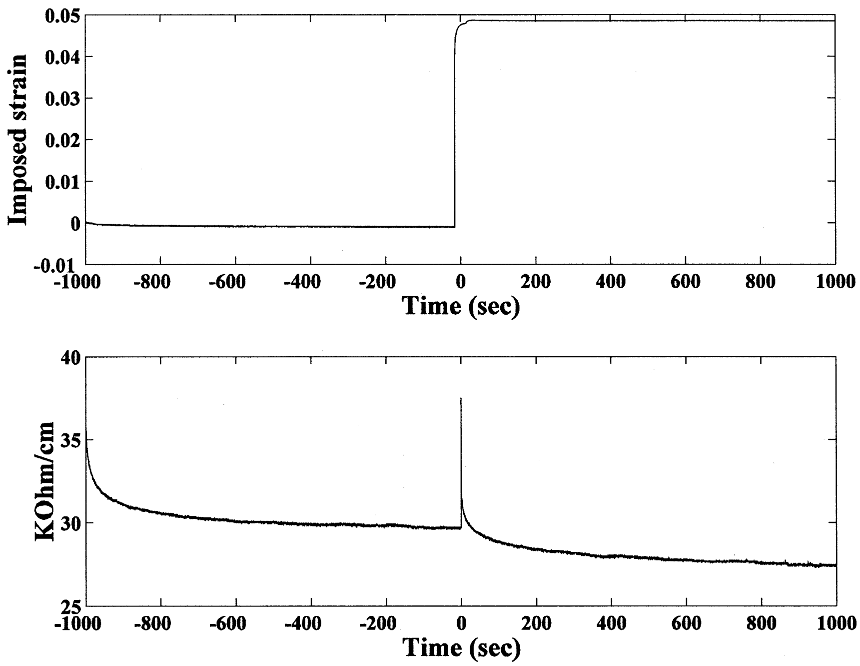


Fig. 7. (Top) Resistance signal per unit of length from the sensor fabric when (bottom) a step function in stretching is imposed.

progressive increase in conduction path with strain is thought to account for the decrease in electrical resistance.

In Figs. 10 and 11, the relaxed and strained appearance of the fabric is shown through low magnification electron microscopy (35×).

Observing Figs. 6 and 7, we can make the following remarks.

- The final value of the resistance depends on the degree of stretching and it decreases as the stretching increases.
- It is reasonable to hypothesize that there exists a linear zone of the sensor response, i.e., in which the stretching is linearly proportional to the equilibrium resistance variations.
- The peak of resistance subsequent to the application of the step of strain, both in extension and in shortening is always positive.
- The sensor is more sensitive to shortenings, in terms of maximum excursion of the peak of resistance immediately following the step.
- The aging of a sensor subjected to cyclic stress is $+2\ \mathrm{k}\Omega/\mathrm{hour}$, with respect to the aging of an unstrained sensor, $+125\ \Omega/\mathrm{h}$.

From this preliminary analysis, it is evident that the main disadvantage of fabrics coated with conducting polymer is that settling times are too long and this makes the fabrics unusable in most applications. For this reason, we focused our attention on the study of the resistance response in the time range of 1-s, immediately after imposition of a step-wise deformation. In particular, we tried to obtain information relevant to the applied strain in the initial peak. In Fig. 12, the resistance relative to a given stretching in the first second after application of a deformation is reported. From the analysis of these graphs, we deduced several significant parameters. What is needed is to find a relationship between them being invariant with aging phenomena.

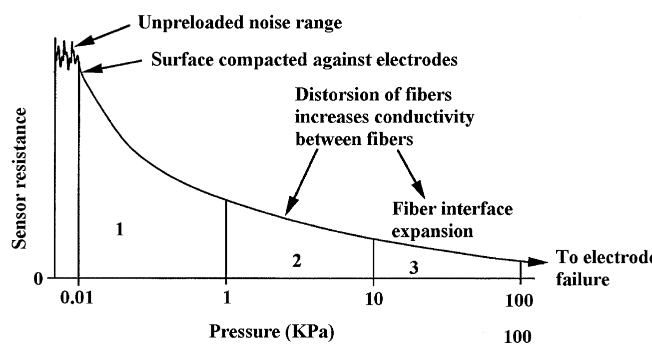


Fig. 8. Graph of percent relative variation resistance versus stress for a sample of carbon felt (adapted from [10]).

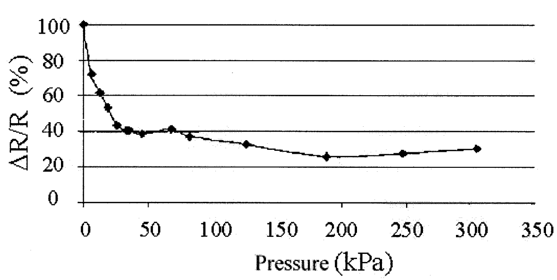


Fig. 9. Graph of percent variation of resistance versus stress for the PPy-Lycra/cotton fabric.

From our observations, we can affirm the following statements.

- The magnitude of the peak of resistance is always positive, and it is almost proportional to the amplitude of the step strain externally imposed, both in stretching and shortening. This is true until the saturation of the sensor fabric response is attained. With our sample, the value of the maximum strain corresponding to the upper limit of the linear zone is around 6%. Indeed, the aging of the sensor,

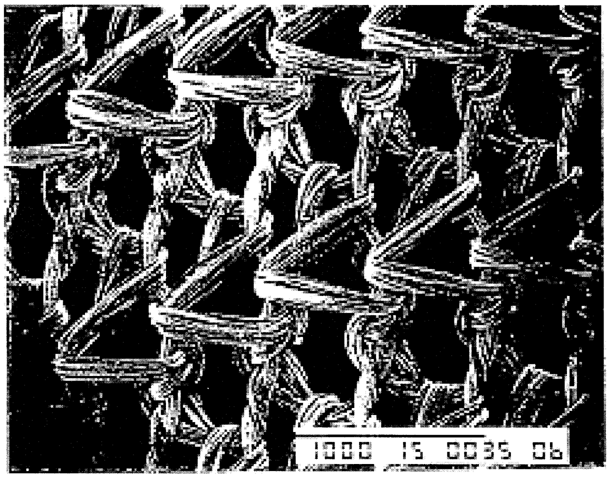


Fig. 10. Unstrained fabric (Lyrca/cotton coated with PPy); low magnification electron microscopy (35×).

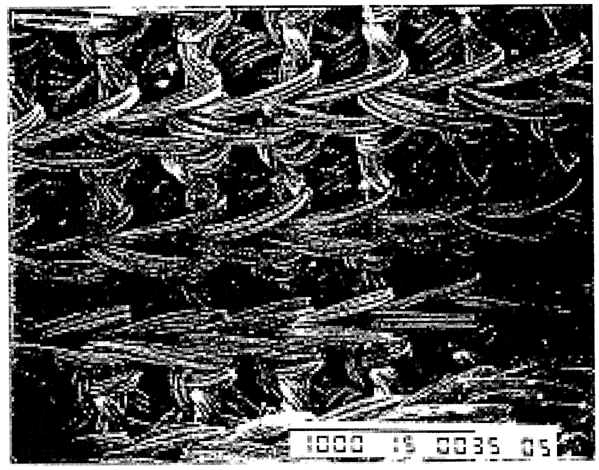


Fig. 11. Strained fabric (Lycra/cotton coated with PPy); low magnification electron microscopy (35×).

in addition to an increase of the rest value of the resistance, induces a reduction of the sensitivity of the sensor.

- The time derivative of the resistance in the descending phase of the response curve, soon after the peak, increases in absolute value with the amplitude of the strain imposed in stretching.

In order to take into account the aging of the sensor, we repeated the same experiments three times at weekly intervals. All the parameters identified above were subject to variations, hence our efforts were devoted to find an invariant correlation between them. Fig. 13 reports the amplitude of the excursion of the initial peak of the resistance versus the magnitude of the step strain imposed in stretching. Fig. 14 reports the value of the time derivative of the descending part of the resistance curve calculated at the point at which the resistance is half the difference between the maximum value and the final value (1 s), for various strain amplitudes. Both graphs report three series of data relative to the same experiment repeated at weekly intervals. Two zones can be distinguished: before saturation of the sensor (occurring at about 6% of strain imposed) and after saturation. Before achieving saturation, we can verify that the excursion of the peak changes in a significant way with the strain imposed, whereas the time derivative remains constant. After saturation, the excursion loses significance, while the time derivative changes in a pronounced way. This is due to the fact that for strains higher than 6%, although the initial point of the relaxation is the same, the final steady value changes with the strain imposed and, thus, the time derivative in the initial tract enables a prediction of this final value.

These observations induced us to argue that a combination of these parameters could codify for the magnitude of the applied strain. We, therefore, conceived a right-angled triangle, traced in Fig. 12, where the cathetus height is equal to the excursion of the initial peak and the slope of the hypotenuse is equal to time derivative of the resistance calculated at the middle point between the peak and the final value. In Fig. 15, we report the area of this triangle as a function of the magnitude of the strain and we can see that it is almost independent of aging. Since the curve has a non-monotonic behavior, we have to distinguish the zone before saturation from that after saturation. To do this, before acquiring the signals from the sensor, we can impose a step strain higher than 6%, that is, the limit of saturation, and we can record the value of the resistance. The magnitude of this value enables us to determine whether the sensor is in pre or post saturation conditions.

IV. Applications

The fabric sensors described here can be utilized in the realization of wearable devices able to record and control human posture and gesture, which could be worn for long time with non discomfort. A correct interpretation of sensor resistance data enables the use in different fields. Monitoring body kinematics and analyzing posture and gesture is an area of major importance in bioengineering and several other discipline connected. We integrated sets of sensors into a glove telemetrically linked to a electronic unit which treats the prefiltered data obtained by the sensors and reconstruct the mutual position between consecutively bones into a kinematic chain, when it is possible, expressed by sets of angles. These idea has been validated by proofs obtained by several prototypes already realized. Two methods of sensor location has been adopted. The first one consists in intuitively setting a certain sufficient number of sensors in correspondence of the joints. Each joint requires a number of sensors equal to its degrees of freedom, placed in independent way. In particular, for the glove, each interphalangeal joint has to be covered by a sensor, while at least two sensors are required to detect position of each metacarpal–phalangeal joint and the carpal–metacarpal joint of the thumb. We placed the sensors, which record flexion–extension on the back of the hand, in correspondence of the tendon, which realizes extension. Starting from the flat hand position, the sensor modifies its resistance in correspondence of a flexion of the finger or thumb. To read adduction–abduction of the finger, we placed sensors on the side of fingers, in correspondence of the interdigital webs. Thumb opposition is detected by reading the output of a sensor which crosser the carpal–metacarpal joints on the radial side [11].

We also constructed a sensorized leotard to monitor trunk and upper limbs position and motion. By modeling the spine by a

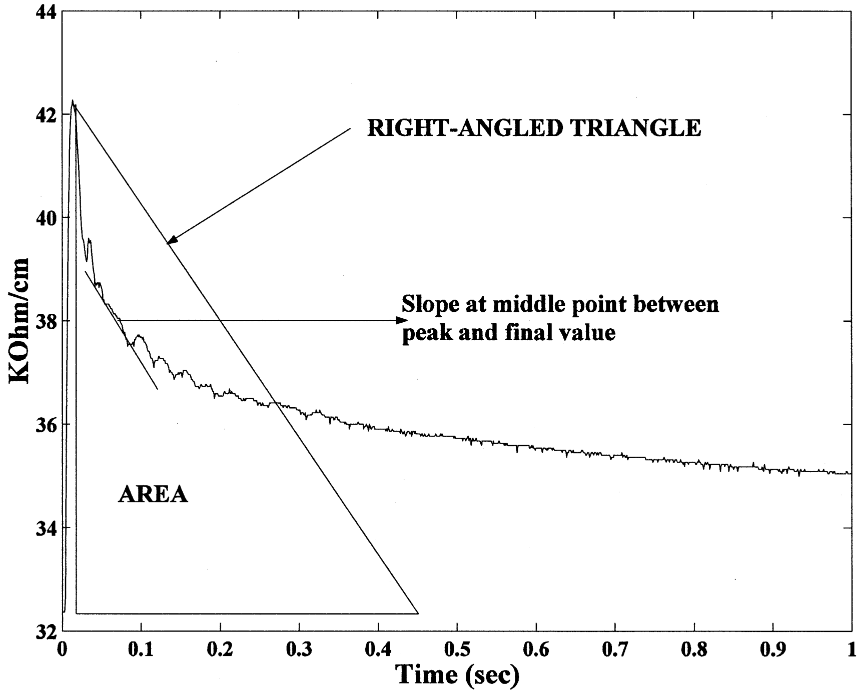


Fig. 12. Resistance per unit of length versus time after the application of the mechanical strain. The triangle we considered to be useful in data treatment is also traced. The initial value of resistance is relative to an unstrained resistance per unit length.

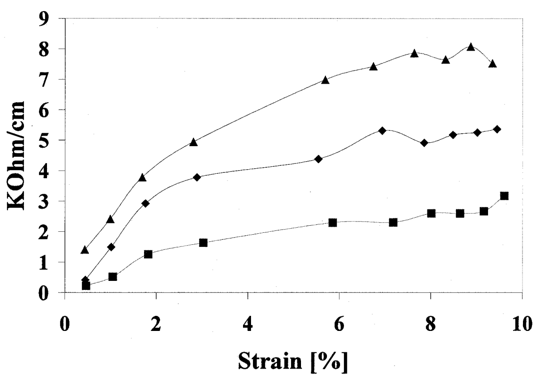


Fig. 13. Initial excursion of the peak of the resistance versus the magnitude of the step strain function imposed in stretching at weekly intervals (△ = first week; ◇ = second week; □ = third week).

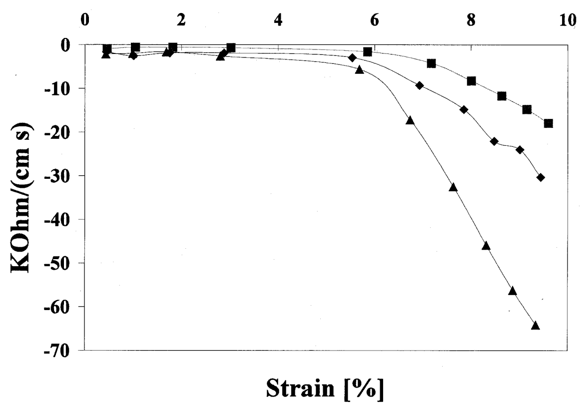


Fig. 14. Middle point slope of resistance versus amplitude of the step strain function imposed in stretching at weekly intervals (△ = first week; ◇ = second week; □ = third week).

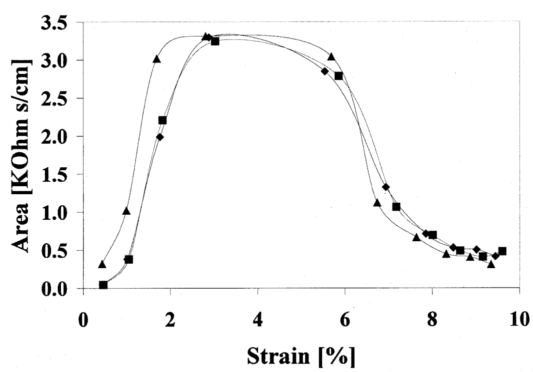
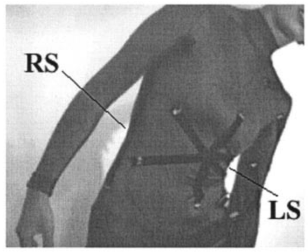


Fig. 15. Area of the right-angled triangle derived from the excursion of the peak (height) and the derivative in time (slope of the hypotenuse) at weekly intervals (△ = first week; ◇ = second week; □ = third week).

continuous curve capable to span a set of configuration parameterized by three variables (two for flexions, one for torsion), we have been able, with only four sensors, to monitor the state of the large set of joints, constituting the spine. The elbow joint, the gleno–homeral joints and the thorax–scapular complex do not need further details with respect to the consideration explained above for the joints of hand.

The second method of sensor placement is based on the assumption that a large set of sensors uniformly distributed on a garment is needed to relieve each modification of the surface covered by the fabric. In both cases, the adopted methodology has been in a certain sense functional, i.e., the final aim of our work is to know which gesture a subject holds, and not which sensor has modified its resistance. From this point of view, redundant sets of sensing zones linked in different topological networks can be regarded as sets of spatial distributed sensors. These interconnections consent to drastically reduce the number of channels of the data acquisition systems, and by comparing simultaneously the entire sets of sensible zones with the value of the joints variables, we are able to reconstruct the posture in

(a)



(b)

Fig. 16. (a) Left flexion of the torso solid model and (b) actual posture.

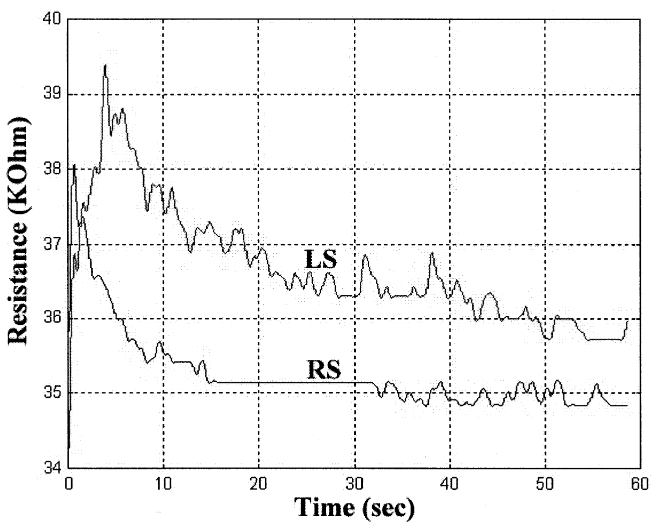


Fig. 17. Time change in resistance of the fabric sensors located on the left side (LS) and right side (RS) of the upper body upon flexion.

acquisition time. An initial kinematic parameters identification phase of the system is necessary to balance the irregularities of operation of individual sensors. In particular, piecewise linear interpolation, multivariate spline interpolation, and a method based on neural network are under consideration, and results will be reported later on. The emphasis of the method consists in the observation of the global status of the system, comparing all the sensors simultaneously. In Fig. 16, a left flexion of the thorax of a subject wearing the leotard is shown. The signals relieved from the sensors respectively placed on the left (LS) and right (RS) sides are reported in Fig. 17.

V. CONCLUSION

We have shown that fabrics coated with conducting polymers, in particular, polypyrrrole, have piezoresistive and thermorestive properties. We investigated these properties showing that they can be used to realize strain sensors, which may have useful applications in the broad area of man–machine interfaces. In particular, these fabrics are easily integrated into truly wearable, instrumented garments capable of recording kinaesthetic maps of human motor functions with no discomfort for the subject. Finally, we have proposed a geometrical parameter useful to codify for the fabric sensor response independently on sensor aging. These results are thought to be important for applications in real time analysis of body gesture and posture.

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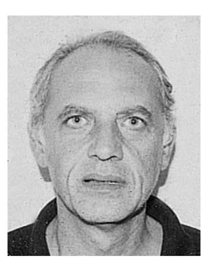

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