35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Performances evaluation of piezoresistive fabric sensors as function of yarn structure

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Abstract— **This work focus on the characterization of piezoresistive fabric sensors, realized with conductive yarns that are similar in term of conductive components, but different only in term of geometry, the yarns have been realized according two different production processes while the sensors have been produced following the same process, fabric structure and same materials. The different geometry of the yarns affects dramatically conductivity and functionality of the sensors in term of sensitivity and hysteresis minimization. This result confirms that the functional components can be engineered during the different phases of the process production; to get new properties and new applications. Small changes at fibers level can be fundamental to improve the properties of the fabric sensors.**

I. INTRODUCTION

During the last decade, knitted strain transducers have been investigated as piezoresistive sensors to realise wearable sensing systems for rehabilitation and post acute event monitoring, [1, 2].

A piezoresistive strain sensor provides an electrical response, change in electrical resistance, when submitted to a strain stimulus, the response is reversible when the stimulus vanishes, this property has been used to collect information about body movements. This work focus on the design and optimization of textile piezoresistive strain sensors, aiming at the optimization of the electro-mechanical properties of the fabric sensors that were designed to detect the movements of the body due to respiration activity and joints articulation. Previous authors' works described the influence of the different elastic components of the fabric structure in the electrical response of the sensor [3]. In this work, our attention was focused on the improvement of the conductivity properties to reduce the electrical noise in the sensor and to minimize the hysteresis effect. Keeping constant the amount of charge of the whole sensor structure, by using the same amount of conductive components (i.e. same number of conductive filaments for each yarn) and using a different process to manufacture the conductive yarn, we improved the performance of the textile piezoresistive sensor. This means that a small change in the structure of the fabric, due to a different geometry of the conductive yarn, results in a dramatic change of the functionality, sensitivity of the final fabric sensor.

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II. MATERIALS

Knitted piezoresistive fabric (KPF) sensors were made by knitting an elastic yarn, Lycra®, with a conductive yarn, (Belltron®, produced by Kanebo Ltd), with a circular machine as described in previous works [3], [4]. In order to improve the electrical property of KPF sensor, a new conductive yarn was manufactured in close collaboration with Kanebo Ltd on the base of the first experiments done in the previous work [3]. In the first version of the samples, named Textured KPF sensor (T_KPFs), the Belltron® filaments have been processed by using air blow to tie them together with random tangles, a well known technology used for industrial yarn production. Some interlacing zones have been created in the way to provide a light and reversible ligature. Moreover this yarn has been textured to improve its mechanical properties and allow a better processability during knitting. Texturing affects the behaviour and hand of the fabric in particular drapability, softness, and elasticity. In this work, the new sample of KPF sensor, named Parallel KPF sensor (P_KPFs), has been characterized. The new yarn is realised with the same number of Belltron® filaments (i.e. the amount of charge is kept constant), but with a different procedure, resulting in a parallel structure of the single filaments, with a different charge path that leads to an improvement of the electrical properties and the performance of KPF sensor. Comparing the two conductive yarns, the textured yarn shows a disordered structure and a rough surface. Instead the other one has a parallel structure and a smooth surface [5], as shown in Fig.1.

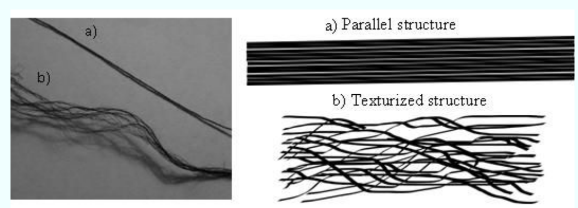

Figure 1. The two kind of structure of yarns: a) the conductive yarn used for P_KPFs sample and b) the yarn used for T_KPFs sample

Samples of both the sensors have been processed with the same circular knitting machine, with the same selection of stitches. The manufactured fabric tubes contain both 75% of electro-conductive yarn and 25% of Lycra®. The samples have been realized cutting the strips with dimensions of 10mmX62mm from the fabric tubes manufactured by using the described yarns.

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

III. METHODS

The samples have been tested using a specially designed electro-dynamic testing system, produced by Fabrica Machinale s.r.l. (Italy) according Smartex specifications. The apparatus is able to apply prefigured strains with controlled amplitude, by using a PLC that controls a linear motor. The system measures the electrical resistance of the samples and the applied strains in synchronous, by sampling at 334Hz.

A. Electrical resistance

The samples of the KPF sensors, made by using the two different conductive yarns described in the previous section, have been compared in term of conductivity measuring the electrical resistance in rest condition, (R_o). The samples have been positioned between the golden clamps and kept in a not stretched position for a length of 62mm (L_o). The electrical resistances of samples have been measured for a period of 180 seconds by sampling at 334Hz, the final resistance value is the mean of the whole set of resistance values for each sample. This period has been selected according the model equation that has been estimated by fitting the data acquired measuring the electrical resistance of sample in rest condition for a period of 900 seconds.

$$R(t) = a*\exp(b*t) + c*\exp(d*t) \qquad (1)$$

where the coefficients are (with 95% confidence bounds):

a = 454.6 (399.7, 509.4);
b = -0.01401 (-0.01755, -0.01046);
c = 4.675e+004 (4.672e+004, 4.679e+004);
d = -6.066e-006 (-7.263e-006, -4.868e-006).

The goodness of fit was estimated through the correlation coefficient R-square (R^2= 0.944).
The variation of the electrical resistance observed within 180 seconds is around 45% of the variation measured for 900 seconds. Moreover, the Standard Deviation (SD) and the Standard Error of the Mean (SEM) have been calculated; the SD is the measure of the dispersion of a set of data from its mean; and the SEM represents accuracy of the mean.

B. Sensitivity

The sensitivity of a strain sensor is defined as the resistance percentage variation ($(\Delta R/ R_o)*100$) divided by the elongation percentage ($\varepsilon= (L/ L_o)*100$) during the strain. In order to verify and to compare the piezoresistive property of samples, a quasi-static calibration has been done. The samples have been subjected to the uniaxial strain, for the stretching phase, the mechanical stimulus was the ramp in which, each 180 seconds, the elongation increases of 1 mm, until a final elongation of 10mm is reached. Instead, for the relaxing phase, the ramp decreases from 10mm to 1mm with one millimetres step each 180 seconds.

From the output characteristic curve, the linear range is defined as the strain interval in which the resistance behaviour of the sensor is linear. This interval has been calculated by means of a linear regression line; to evaluate the quality of the correlation between the experimental and the theoretical values, the correlation coefficient R-square (R^2) has been estimated.

C. Hysteresis effect

The electrical hysteresis effect was estimated to compare the T-KPFs sample and the P_KPFs sample. This effect occurs when for the same value of the elongation value that has been reached during the stretching phase and the relaxing phase, different outputs are measured. The electrical hysteresis is caused by the friction and by the structural change in a conductive fabric due to the filaments deformation and slippage between the filaments, as well as stretching, bending, twisting and compressing effects that can be observed when the knitted fabric is stretched [6]. Based on this hypothesis, it is possible to evaluate if the different construction of yarns influences in significant way the performances of KPF sensors. The hysteresis effect was evaluated into the linear range of the calibration curves, both for the stretching and relaxing phase. Hysteresis is expressed in term of maximum hysteresis as a percentage of the full-scale-deflection.

D. Repeatability

The repeatability describes the ability of KPF sensors to give the same output for repeated applications of the same input value, keeping constant the measurement conditions. This characterization is necessary to evaluate the stability of the sensor for a long period of time and the reliability of the obtained measures.
To verify the repeatability, the samples have been subjected to the strain of 5 trapezium cycles, of the same elongation; the measure has been repeated by increasing the elongation from 0.5 mm to 8mm, with a step of 0.5 mm. At each step, the percentage resistance change has been calculated for all trapezium cycles. Finally, 5 data sets have been analyzed by using the Analysis of Covariance (ANCOVA) and by performing a regression analysis to evaluate the relationship between the elongation percentage variations with the resistance percentage variations for each group in order to evaluate the affinity of between them. The ANCOVA model with interaction has been used to verify that the regression lines are parallel; in other words, the slopes are not statistically significant different (Test of parallelism). The next step was to draw a common regression line through each group of points, all with the same slope that is a weighted average of the slopes of the different groups. The linear regression equations have been calculated to show the linear relationship between a response, (y), and predictor, (x), [7].

IV. RESULTS AND DISCUSSION

A. Electrical resistance

The measure of the electrical resistance in rest condition is reported in the Table I for the T_KPFs and P_KPFs samples with the dimensions of 10mm X 62mm. The R_o of the P_KPFs sample is reduced about of 77%, the related SD and the SEM values are decreased about of 60% comparing them to the values of the T-KPFs sample.

TABLE I. THE ELECTRICAL RESISTANCE VALUE IN REST CONDITIONS

Samples	Ro (Ω)	SDL(Ω)	SEML(Ω)
P_KPFs	44272.18	147.94	0.6283
T_KPFs	197439.87	372.22	1.5808

B. Sensitivity

The sensitivity of both KPF sensors has been determinate using the slope of linear regression to correlate the resistance percentage variation with the percentage of elongation variation. The piezoresistive effect is due to the change of conductive contacts between the filaments inside the yarn and also to the deformation of fabric loops during the applied strain, [3] and [8]. The output characteristic curves of P_KPFs sample and T_KPFs samples, Fig.2 and Fig.3, show that the resistance value increases when the samples were stretched, and decreases during the relaxing phase.

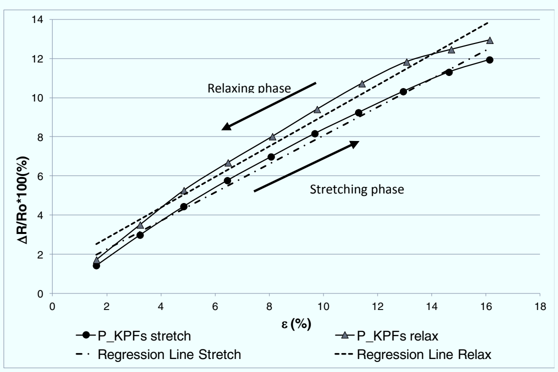

Figure 2. The output characteristic curves of the P_KPFs sample; the experimental data are represented by the markers and the results of linear fit are shown using the dotted lines.

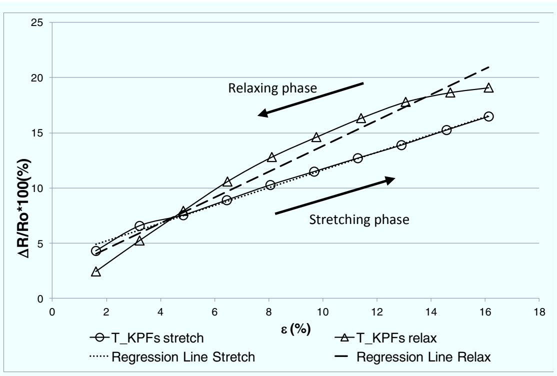

Figure 3. The output characteristic curves of the T_KPFs sample; the experimental data are represented by the markers and the results of linear fit are shown using the dotted lines.

To compare the two output characteristic curves for stretching and relaxing phase, the regression analysis was performed for each sample and the results are shown in the Table II.

TABLE II. THE REGRESSION ANALYSIS RESULTS

Samples	Strain	Linear Range ε(%)	Slope	Intercept	R^2
P_KPFs	Stretch	1.6 ÷ 16	0.7258	0.8106	0.9908
	Relax	1.6 ÷16	0.7830	1.2572	0.9802
T_KPFs	Stretch	1.6÷16	0.8051	3.5878	0.9959
	Relax	1.6 ÷16	1.1623	2.1670	0.9635

The slope values calculated for the P_KPFs samples during the stretching and relaxing phase are very similar and the values of the correlation coefficients, (R^2), confirm the goodness of linear fit. Between the two slopes of P_KPFs sample, the small difference has been estimated by the test of parallelism that confirms that the difference is not statistically significant, ($F=1.929$, $p<0.18$), [7].
The equation of common regression line, (2), has been evaluated for P_KPFs:

$$y = 0.7545*x + 1.03347, \quad R^2=1 \qquad (2)$$

Instead, the slopes related of T_KPFs sample show a slight difference and the test of parallelism confirms that the difference is statistically significant, ($F=23.564$, $p<0.001$), and each group of data have to be analyzed in separated way. The equations of regression line for the stretching, (3), and relaxing, (4), phase are reported below:

$$y = 0.8051*x + 3.5878, \quad R^2 = 0.9959 \qquad (3)$$

$$y = 1.1623*x + 2.167, \quad R^2 = 0.9635 \qquad (4)$$

The linear range is the same for each sample.

C. Hysteresis effect

To evaluate the hysteresis effect between the two samples, the equations of obtained regression lines, (2) for the P_KPFs samples and (3) and (4) for the T_KPFs samples have been used. The results are shown in the Table III.

TABLE III. THE HYSTERESIS (%) VERSUS ELONGATION(%)

Samples	Elongation (%)	Hysteresis (%)
P_KPFs	1.6÷16	0
T_KPFs	16.13	25.72

Sinusoidal stimulations have been used to simulate the real conditions of use for body movement sensing. The typical hysteresis behaviour of the sensor is reported in Fig.4, the sample was strained to a maximum elongation of 1mm at 0.25Hz; the maximum percentage of the measured hysteresis error is 8%.

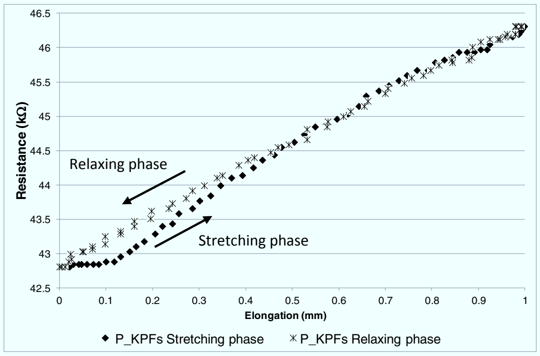

Figure 4. The hysteresis behaviour of the P_KPFs sample when it is strained to a maximum elongation of 1mm at 0.25Hz

D. Repeatability

For both samples the regression lines of 5 data sets were carried out and the results are shown in the Table IV.

TABLE IV. THE REGRESSION LINES RESULTS FOR EACH DATA SET

Samples	Data	Linear Range ε(%)	Slope	Intercept	R^2
P_KPFs	Set I	0.8 ÷13	1.6387	3.9829	0.9665
	Set II	0.8 ÷13	1.6131	3.7419	0.9711
	Set III	0.8 ÷13	1.5726	3.7832	0.9697
	Set IV	0.8 ÷13	1.5583	3.6059	0.9656
	Set V	0.8 ÷13	1.5144	3.7776	0.9622
T_KPFs	Set I	0.8 ÷13	2.5508	3.0076	0.9791
	Set II	0.8 ÷13	2.5098	2.5600	0.9836
	Set III	0.8 ÷13	2.4793	2.4351	0.9856
	Set IV	0.8 ÷13	2.4698	2.1532	0.9849
	Set V	0.8 ÷13	2.4776	1.9278	0.9867

The slopes related to each sample are similar and the test of parallelism confirms that differences are not relevant. In fact, the F-statistic results are $F=0.404$ with $p<0.806$ for P_KPFs sample and $F=0.156$ with $p<0.96$ for T_KPFs sample. Also, in this case the common regression lines have been elaborated for each sample, as shown in Table.V.

TABLE V. THE COMMON REGRESSION LINES RESUTLS

Samples	Regression line	R^2
P_KPFs	y=1.5796*x+3.7781	1
T_KPFs	y=2.4974*x+2.4171	1

The repeatability is verified by demonstrating that a common regression line exists for each group of data, since all the responses (y) of each data set have the same linear relationship with their respective predictors (x).

V. CONCLUSION

It is important to underline that a small change in the structure of the yarn influences the electrical properties of the final conductive fabric. Sensors have been realized by using the same textile structure with the same amount of conductive and elastic components. Results from the characterization tests show that, it is possible to modify the range of linearity of the sensor response by changing the organization of the single conductive filament of the yarns. A diversified geometry of the conductive components affects dramatically the sensors performance, in term of conductivity, sensitivity, linearity and hysteresis. In our study a different process in the yarn realization leads to a reduced resistance value of the knitted sensor, while the sensitivity and repeatability were not affect. Instead, the hysteresis effect was minimized leading to a new class of sensors that is under use in several biomedical applications. In this work we have shown that the properties of fabric sensors can be improved and optimized at different levels, not only in term of materials and fabric macro structure but also in term of yarn and fiber geometry.

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