Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

M. Pacelli, L. Caldani and R. Paradiso

Textile Piezoresistive Sensors for Biomechanical Variables Monitoring

Abstract— **In this paper is described the study leading to the implementation of two novel classes of textile piezoresistive sensors, for application in the field of post stroke rehabilitation and cardiovascular diseases monitoring. Two different approaches have been used, the first one leading to the realization of knitted transducer fabric to be integrated in bio-clothes for motion activity and respiration monitoring through plethysmography, the other one leading to printed sensing clothes for movement and posture detection. In particular, this work focuses on the optimization of sensors performances in term of sensing properties with the final objective to go towards a mass production.**

I. INTRODUCTION

In the last years, fabrics coated with conductive polymer composites and knitted strain transducers have been investigated as piezoresistive sensors to realise wearable sensing systems. 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 [1]. This paper describes two new classes of sensors, one made by industrial serigraphy process of Conductive Elastomer (CE) materials on elastic fabric and the other one made by knitting technology. These novel sensors have been studied and characterised in term of sensing properties, by choosing technological solutions compatible with a future mass production.

Both sensors have been employed to realise intelligent biomedical clothes in the frame of MyHeart, an European funded project, aiming to support citizens to fight major cardiovascular disease risk factors. CE and Knitted Piezoresistive Fabric (KPF) sensors have been implemented for applications aiming to maintain people healthy, as well as for rehabilitation and post acute event monitoring to help patients to live with chronic conditions.

Manuscript received April 21, 2006.

This research has been funded by European Commission through MyHeart (IST 507816) projects.

M. Pacelli is with SMARTEX s.r.l., Prato, Italy. (email: m.pacelli@smartex.it)

L. Caldani is with the University of Pisa, Italy (email: caldani@smartex.it)

R. Paradiso is with MILIOR S.p.A and SMARTEX s.r.l, Prato, Italy (phone +39050754350, fax +39050754351; email: rita@smartex.it)

II. MATERIALS

A. *Knitted piezoresistive fabric sensors:*

Knitted piezoresistive fabric (KPF) sensors are realized with Santoni seamless machines using intarsia technique. The piezoresistive sensors has been realised with conductive yarn (Belltron®9R1), produced by Kanebo Ltd. The shape of KPF samples is usually rectangular with the longest side developed along the knitting course direction. To evaluate the influence of elasticity recover on sensor performance, three kinds of samples have been realised with a different textile structures, named:

- Ny 60, Dim: 20mmx60mm;
- Ny 59, Dim: 20mmx60mm;
- Ny 58, Dim: 25mmx60mm.

B. *Printed piezoresistive fabric sensors:*

Printed Piezoresistive Fabric (PPF) sensors are made by a coating printing process of CE material on textile substrate. In the first experimental phase, the deposition was made by spreading a commercial product provided by Wacker LTD [2], Conductive Elastomer Wacker (CEW), on the fabric that was previously covered with an adhesive mask [3].

The early working prototypes have been produced through a handmade process; this approach, was the only possible, due to the high viscosity of CEW material, as this product has not been designed for application in textile field. In order to go for mass production, different solutions have been evaluated: at the beginning a dilution of CEW material greater of 20% has been adopted, successively a different composition of CE materials, deriving from the original commercial product has been studied. The first solution was rejected, as during the crosslink phase the solvent cannot be completely removed by the heating process. The aim of this study was to select a CE material in term of PPF sensor performance, with a viscosity compatible with the use of industrial screen printing process, known as serigraphy, such as to allow the passage of the right amount of material through the mesh of the screen (Fig. 1).

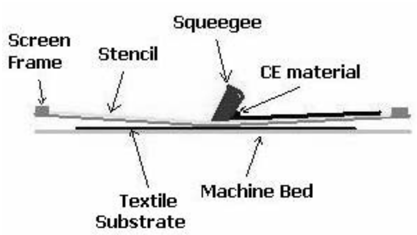

Fig. 1 The principles of screen printing process.

The sample shape used to characterise the PPF sensors was rectangular according to the following dimensions:

- S-Rosso 2.2: 9 mmx70mm;
- S-Beige 1.1: 9mmx 70mm;

where S-Rosso 2.2 has been made with a commercial CEW material and S-Beige 1.1 with the modified CE material.

III. METHODS

To investigate the sensing ability of samples, they have been subjected to different uniaxial mechanical stimuli following signals such as step and trapezium, both of them with variable strain amplitudes and sinusoidal cycles with variable strain amplitudes at selected frequencies. Uniaxial mechanical stimuli have been applied along the length of both kinds of piezoresistive sensors.

They have been imposed by a PC controlled system. Corresponding variations of electrical resistance have been collected through voltage divider, gathered by an acquisition card (National Instruments *PCI-MIO-16E-4)*) with sampling rate of 64 Hz

In order to study the piezoresistive behaviour of several samples made with different structure of KPF sensors and different CE materials for PPF sensors, the output characteristic curves of the fabric sensor have been determined by plotting the fractional increase in electrical resistance value ($\Delta R/R_0$) against the respective value strain ($\varepsilon = \triangle L/L_0$) for each increment. 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, and the correlation coefficient (R^2) has been estimated.

In order to evaluate the performances of KPF sensors for intelligent bio-clothes implementation, the selected sensors have been tested to detect both the respiration signal in function of thorax movement and the elbow bends. KPF sensors signals have been acquired using a voltage divider to convert resistance to voltage, gathered by an acquisition card (National Instruments PCI 6036) with sampling rate of 1000 Hz. The respiration signal of KPF sensor sample has been compared with a respiratory effort transducer, model SSL5B, contained in the BIOPAC® MP30 system. The KPF sensor is sensitive to changes in thoracic or abdominal circumference that occur during the respiratory activity [4]. The elbow bends signal detected by KPF sensors have been compared with a commercial movement tracking system (electrogoniometer by Biometric®). The properties of KPF based system allow the detection of movement index, while the PPF based system showed to be more efficient in the realisation of wearable kinaesthetic systems for gesture and posture monitoring [3],[5].

IV. RESULTS AND DISCUSSION

A. Characterization of KPF sensors

The electrical resistance variation of KPF sensors due to mechanical deformation has been studied. The change in resistance is correlated with the change in strain amplitude. A possible explanation of the observed piezoresistive behaviour of KPF sensors, is that the change of conductive contacts due to local deformation of textile structure affects the charges path, not only for the different interaction among the single filaments inside the yarn, but also for the deformation of the knitted fabric loops during the stretching and relaxing phase [6].

Results have shown that the electrical resistance value increases and decreases with the strain monotonously, in stretching phase and in relaxing phase, respectively for all samples in according to mechanical stimulus applied.

The output characteristic curves for each KPF samples have been reported in Fig. 2

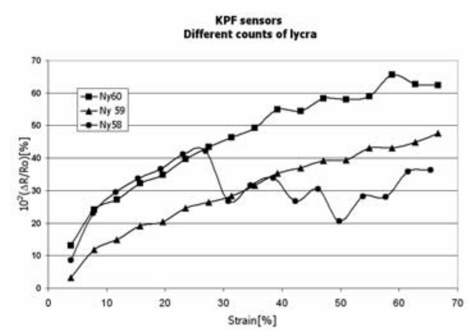

Fig. 2: Output characteristic curves (percentage variation of resistance respect to the initial resistance value versus strain) of Ny60 (square), Ny59 (triangle) and Ny58 (circle).

The different structure and the elasticity recover of fabric significatively affect the strain sensor behaviour as can be seen in Fig. 2.

The output characteristic curves of the samples, Ny60, Ny59 and Ny58, show that there is a linear zone between 7.6% to 26% strain, for all the samples.

In a range from 26% to 55% the electrical behaviour of the sensors begins to diverge, as Ny58 output characteristic curve shows a plastic deformation trend. Ny60 and Ny59 have a comparable behaviour along all linear range, from 7.6% to 55% strain, although the first one shows a higher slope of the linear regression line, which means that Ny60 is the best samples in term of sensitivity.

In Fig. 3 the KPF sensor response has been compared to the signal obtained with Biopac pneumograph in order to monitor the respiratory activity, and both the signals have been acquired simultaneously.

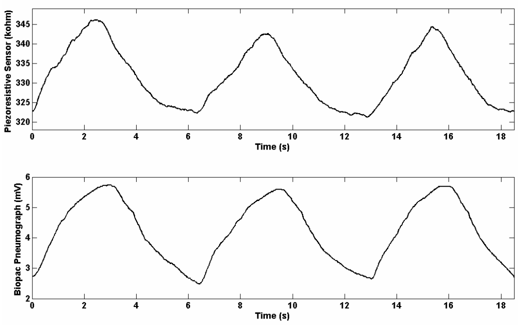

Fig. 3 Signal derived by KPF sensor (upper) and Biopac pneumograph (lower) during normal respiration.

Fig. 4 shows the comparison between the KPF sensor signal during elbow bends, and the response obtained through an electrogoniometer, both the signals have been acquired simultaneously.

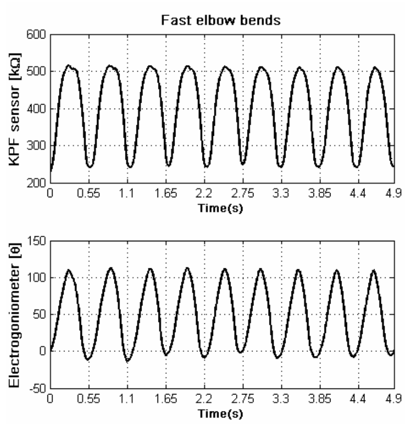

Fig. 4: Signal derived by KPF sensor (upper) and Electrogoniometer (lower) during fast elbow bends.

B. Characterization of PPF sensors.

PPF sensors show piezoresistive properties when a mechanical deformation is applied, as described in several previous works [7], [8]. In according to mechanical stimulus, the piezoresistive behaviour of PPF sensors is similar to that of KPF sensor.

Output characteristic curves have been evaluated for PPF sensors, one made with CEW material and the other one made with the modified CE material, printable through an industrial process.

In Fig. 5 the output characteristic curves of two different material have been compared. The CEW show a linear behaviour on the whole range of strain examined, between 5% and 35% strain, while the output characteristic curve of the modified CE material need to be fit with a polynomial of third degree.

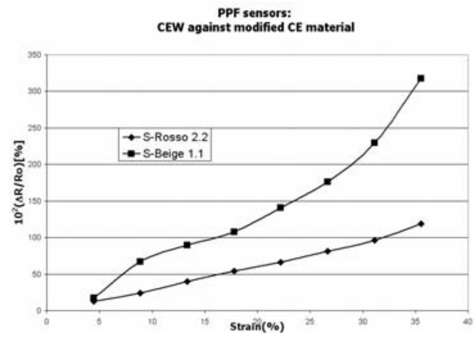

Fig. 5: Output characteristic curves (percentage variation of resistance respect to the initial resistance value versus strain) of S-Rosso 2.2. (rhomb) and S-Beige 1.1 (square).

V. MyHeart Applications

A. Wearable system for cardiovascular diseases monitoring

The implementation of KPF sensors through seamless technology allows the production of wearable systems designed to be minimally invasive for application aiming to monitor cardiovascular diseases from prevention to rehabilitation from critical events.

Cardiopulmonary vital signs can be acquired and monitored by means of seamless clothes where textile electrodes and piezoresistive sensors are knitted in the same production step. Using two piezoresistive fabric sensors for the detection of respiratory activity, both abdominal and thoracic respiration can be detected.

Starting from rate and volume indexes, a number of other respiratory parameters can be computed, such as ventilation, fractional inspiratory time, both inspiratory and expiratory flows over mean inspiratory flow as well as the phase and amplitude relation between abdominal and rib cage respiratory patterns. In addition, the same set of sensors will yield a wide series of respiratory indexes useful for diagnosing several clinical conditions affecting respiratory dynamics.

Fig. 6: Wearable interfaces: on the left a system to monitoring thorax and abdominal respiration signal; on the right the last generation of bio clothes, a female model. .

B. *Neuronal rehabilitation garment model and realization*

A special process has been set up to realize biomechanical monitoring garments, from the design perspective, as sensors and connections are realized with the same CE materials, due to the necessity to guarantee a continuous conductivity of sensors and tracks network, a special pattern has been designed to avoid any interruptions on the circuit, (see Fig. 7).

Another critical issue was the connectivity between the coated circuit and the electronics, for this reason printing and cabling was realized before the cut and sew phase, by using an hybrid solution (coating on the sewing done with conductive flexible yarns that are used as conductive cables). A special wood frame for handmade printing has been designed and realized to coat the elastic fabric.

Fig. 7: Examples of garments for biomechanical monitoring.

A second fabric layer has been coupled with the printed one, as first approach, to insulate the conductive circuit from the external side. The cables have been protected and insulated by means of PE membranes, a prototype realized according this methodology is shown in Fig. 8.

Fig. 8: Wearable interface to monitor movement and posture for post stroke rehabilitation: on the left handcraft prototype, on the right a prototype for industrial implementation.

The use of a second layer to insulate strain sensors, give rise to several difficulties in term of manufacturing process as well as in term of final garment weight, to preserve the breathability and the comfort a new approach has been exploited. Sensing patches of fabrics have been coupled with a basic conformable garment, that is designed to cover user needs. Strain sensors are printed on elastic textile patches, that have been sewn with the printed faces on the internal side (see Fig. 8 on the right).

VI. CONCLUSIONS

One of the main requirements to develop strain gauge sensors is related to response linearity. The correlation between the applied strain and the resistance change needs to be linear to allow to identify the resistance value with the measured variable. According to the results of this work, there are novel textile sensors that exhibit a large range of linearity. These results are very promising in view of future mass application, as this new material have been developed to be processed by means of industrial technologies.

In the variety of sensing interfaces that have been presented, one of the most significant result is the reduction of the gap to be covered in view of mass production. The results achieved have clearly shown that intelligent bio-clothes based systems are ready for the market. These systems answers user needs in term of comfort, as well as , market needs in term of industrial feasibility.

REFERENCES

[1] Chung D L L , *Smart Mater. Struct*,1995.

[2] “Elastosil lr3162”, www.wacker.com.

[3] A. Tognetti, F. Lorussi, R. Bartalesi, S. Quaglini, M. Tesconi, G. Zupone, and D. De Rossi, “Wearable kinesthetic system for capturing and classifying upper limb gesture in post-stroke rehabilitation,” Journalof NeuroEngineering and Rehabilitation, vol. 2, no. 8, March 2005.

[4] G.Loriga, N.Taccini, D.De Rossi and R.Paradiso,”Textile Sensing Interfaces for Cardiopulmoranary Signs Monitoring”, Proceedings of the 2005, IEEEEngineering in Medicine and Biology 27th Annual Conference, Shanghai, China, September 1-4, 2005.

[5] F. Lorussi, W. Rocchia, E. P. Scilingo, A. Tognetti, and D. De Rossi,“Wearable redundant fabric-based sensors arrays for reconstruction ofbody segment posture,” IEEE Sensors Journal, vol. 4, no. 6, pp. 807–818, December 2004

[6] R. Wijesiriwardana, T. Dias, S. Mukhopadhyay, "Resistive Fibre-Meshed Transducers," *iswc*, p. 200, Seventh IEEE International Symposium on Wearable Computers (ISWC'03), 2003.

[7] M. Taya, W. Kim, and k. Ono, “Piezoresistivity of a short fiber/elastomer matrix composite,” Mechanics of Materials, vol. 28, no. 3, pp. 53–59, 1998.

[8] W. Peng, , D. Tianhuai, X. Feng, and Q. Yuanzhen, “Piezoresistivity of conductive composites filled by carbon black particles,” Acta Materlae Compositae Sinica, vol. 21, no. 6, 2004.