Textile Performance Assessment for Smart T-Shirt Development

Mechanical and eletrical study for conductive yarn

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Abstract— **This paper discusses a methodological approach for the metrological characterization of features in conductive textile. One of the outcomes of this paper is an integrated testing protocol aiming to assess the mechanical and electrical specification of conductive fabric. The protocol has been developed focusing on smart garments; this allows for evaluating the conductive features over elasticity, moisture, temperature and washing. The fine characterization of the fabrics allows to use them both as electrodes, sensors or wired connections. In particular, the paper studies the metrological aspects of conductive textile in order to optimize and verify their usage in sensorized t-shirt (as ECG- Electro-CardioGram electrodes, strain gauge, etc.) for continuous non-invasive monitoring in hospital settings, activity of daily living (ADL), sports and fitness. This study looks at optimizing the conductivity of the yarn that follows in minimizing the movement artifacts; this could increase the general performances and reliability of smart garments.**

Keywords-component; conductive yarn characterization, textile sensors, smart t-shirt.

I. INTRODUCTION

The future of healthcare system is based on the development of new and innovative technologies with the purpose of a more accurate, personalized, comfortable and widespread diagnosis and treatment of pathologies [1].

The 2015-2025 decade has been elected the “Wearable Era” for the diffusion and incidence of new miniaturized and wearable products and related services in our life. Most of these systems are related to health and lifestyle. Wearable Biomedical System (WBS) and Wearable Health System (WHS) are probably the most important among these emerging technologies.

The most effective feature of these systems is the non-intrusiveness that is more than non-invasiveness; they can offer solutions for continuous monitoring by measuring non-invasive bio-signal and biomedical parameters without awareness of the user [4]. The non-invasiveness quality of a Wearable Health and Biomedical System is often due to garment embedded sensors. These sensors usually are built on conductive textile sensor. One of the best example for these systems are the smart t-shirts. Smart t-shirts are garments with embedded textile sensors which can record different biomedical signals: ECG (Electro-CardioGram), Heart-rate, Breath-rate, skin temperature and other parameters [5]. All the signals are recorded by means of conductive textiles allowing for several measurements based on different metrological characteristics.

Moreover, this kind of conductive yarns, due to their intrinsic features, could be also used as light wire, antenna or electromagnetic shield. For this reason, the characterization of the yarn and textile becomes mandatory in order to increase the capability of this fabric.

In the last two years, different companies launched different types of sensorized garment, from socks (Sensoria®) [8] to Bra (OM-Signal®) [9]. Despite this, the main purposes of these products are focused on sport monitoring, which is mainly a one-spot measure. These devices/garments are not developed for medical continuous monitoring, which requires to match and respect strict specifications for the medical applications. In order to improve the performance of these smart garments and increase the application field of these conductive tissues, this paper reports a study on the performance and reliability of different fabrics. The metrological characterization and the study of stability over usage, time and washes, allows for developing new sensors, applications and approaches which can be used for sensorized garment. The rest of the paper is structures as follow. In Section II, we defined the system underling all the features that need to be validated; Section III describes the metrological issues defining the proper measuring. Section IV proposes the experimental setup for each measures. Finally, we conclude with Sessions V and VI which show the experimental results and some considerations on these.

II. MATERIALS

Electrocardiogram (ECG) is one of the most used exams for assessing the health status of the cardiovascular system. Moreover, a few parameters extracted from ECG could also be very useful in sport monitoring to detect the fatigue stages and the athletes’ performances. Usually, these studies are conducted by means of ambulatory ECG with standard Ag-AgCl electrodes or chest belt based heart rate monitors. In the first case, the use of electrodes and conductive gels could modify the results due to the invasiveness of the procedure. In the second case, the use of the chest belt requires the electrodes to be well moistened and the belt fits snugly around the chest; this could cause discomfort to the users. Moreover, in some sports, the use of these system is prevented by continuous impacts and displacements, caused by the athletes' gestures, which can cause noise and errors on signals detected by the belt.

The study proposed in this paper starts from an already validated sensorized t-shirt for sport [6]. One of the goals of this study is the characterization of conductive textile in order to optimize the capability and the reliability of this fabric developing a new concept of sensorized t-shirt which could be applied for non-invasive continuous medical monitoring. The sensing t-shirt for medical application consists of I-lead embedded ECG electrodes (Figure 1) and a conductive strain gauge for respiratory activity monitoring. Both ECG and respiratory signal are recorded by an ad-hoc device which is connected to the sensing part by means of snap buttons. As visible in Figure 1, snap buttons receive the signal from ECG electrodes via conductive fabric. According to the hereof description, studying the conductivity, mechanical features and reliability of the yarn is mandatory.

Performances of the smart t-shirt depend also on mechanical characteristics of the yarn and the design of the t-shirt [7] and not only on conductive fabric. T-shirt usually is designed as a technical t-shirt developed starting from special yarn which is not only able to constrain electrodes and sensors in the right positions, but it also inserts a certain level of compression and thermoregulation, shaping the body while maintaining the same comfort of a normal t-shirt. The presence of two or more different yarns in the same cloth requires a mechanical study of textures, especially for elasticity which can compromise the stability and the contact of the embedded textile sensors.

Textile electrodes consist into textile containing silver yarn, mixed with cotton, lycra, or other fabric. The composite mixture of conductive and non-conductive yarn changes the features of the textile in elasticity, conductivity, difference of elasticity over length and elongation, etc.

Due to the different composition of the conductive textile, the quality of signals recorded by the t-shirt may differ significantly. For this reason, this work aims to investigate the performances of the different types of conductive textiles in terms of:

- Conductivity;
- Elasticity;
- Measurement repeatability and reproducibility;
- Sensitivity versus disturbances;
- Resistance to washing.

III. METROLOGICAL ISSUES

There are several works in the literature focused on the identification of performances of textile strain gauges, but only few of them focus on the effect of disturbances on the measurement quality. The first step of the sensor characterization is the identification of the textile strain gauge sensitivity. These tests aim to identify the relationship existing between the electrical resistance and the sensor elongation, and the experimental setup usually pairs a displacement measurement system with a 4-wire resistance measurement circuit. In addition to the sensitivity versus the measurand, sensors should also be characterized in terms of sensitivity versus disturbances [2, 3].

The main issues deserving for investigation are:

1) Measurement repeatability, which provides for an indication of a lower boundary for the measurement uncertainty;
2) Measurement reproducibility, that should assess, at least, the change of electrical conductivity after several washing cycles;
3) Contact resistance: in the classical setup for the identification of the strain gauge sensitivity the fabric is usually clamped at its ends so that it can be stretched for the calibration; however, the electrical resistance measured in this way is the sum of the resistance of the fabric and the electrical resistance between the setup and the fabric. The latter has to be measured before the tests.

Figure 1. The smart t-shirt schema and a photo of the prototype.

4) Sensor creep: the creep results in a progressive and slow modification of the electrical resistance in presence of constant sensor deformation and should be quantified with proper tests if sensors are used for long-term monitoring of posture.
5) Sensors' dynamic behavior: often the frequency response function of the sensors is far from the ideal one, i.e. the sensitivity depends on the frequency of the stimulus. The dynamic calibration is therefore needed in order to identify the sensor frequency response.
6) Sensitivity versus temperature and humidity: the sensor behavior may depend on the temperature and on the humidity, thus resulting in a decrease in measurement performance in sports, where the sweating and thermoregulation strongly vary.

IV. EXPERIMENTAL SETUP

Different experimental setups for the complete sensor calibration are mandatory. The first setup is obviously the one for the static calibration, i.e. for the identification of the variation of electrical resistance versus the displacement. We have chosen to measure the sensor elongation with a linear variable differential transformer (LVDT) DC/DC; this sensor has a friction-free core and incorporate oscillator, demodulator and filter providing a self-contained unit accepting a DC input and providing a DC output relative to armature position. The electrical resistance of the textile sensor is measured by a four wire (volt-amperometric) circuit: a stabilized current generator creates a current of 100 mA (to reduce the self-heating). The voltage drop across the tensile sensor is measured by a National Instruments data acquisition board and the electrical resistance is derived using the Ohm law. The experimental setup is shown in Figure 2.

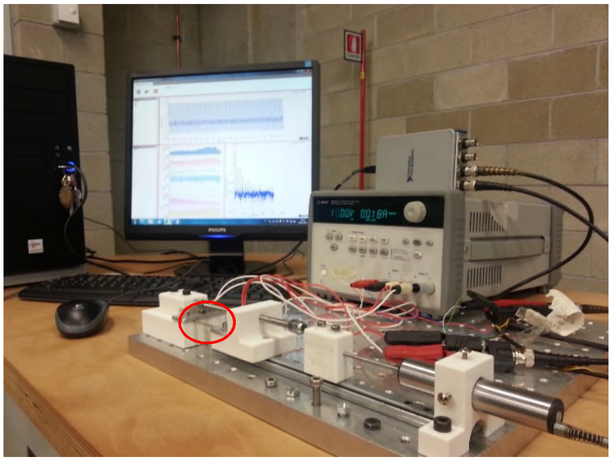

Figure 2. Experimental setup for the static calibration. The red circle shows the sensor

This setup cannot be used to impose quick displacements to the sensors; the textile strain gauge was therefore tested with an electrodynamic shaker, as shown in Figure 3. The upper extremity of the strain gauge and the lower one was moved by the shaker head. The tests to identify the effects of temperature and humidity were performed putting the setup of Figure 2 into a climatic chamber, as shown in Figure 4. The temperature range was between 10 and 40 °C and the relative humidity was not constant during the tests. Further tests were performed by spraying the sensor with water. Tests for resistance to washing were conducted comparing four different conductive fabrics. The composition of the textiles makes them different in conductivity, elasticity and on various mechanical aspects including the characteristics decay after washing. The four fabrics were cut in 2x9 cm patches and were washed for 20 times at 30° degrees with mild soap. The textiles were dried in open air at 22° for about 4/5 hours. The conductivity was measured with the setup used for the static tests.

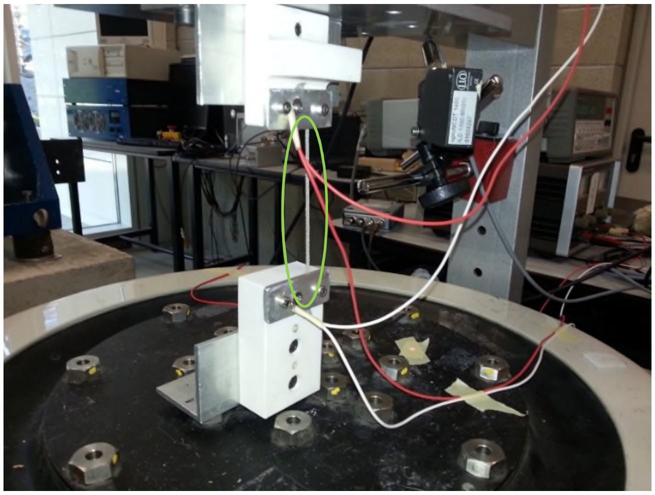

Figure 3. Setup for dynamic tests. The green circle shows the sensor, mounted between the fixed support (upper part of the figure) and the shaker head.

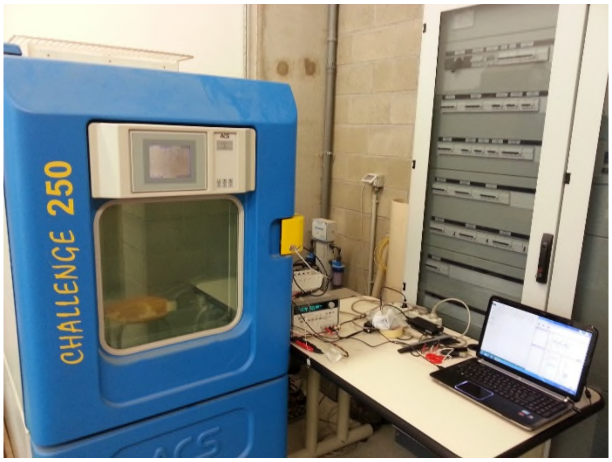

Figure 4. Tests performed in the climatic chamber.

V. EXPERIMENTAL RESULTS

Results of the static calibration on one of the specimens that underwent our tests is shown in Figure 5. The specimen is 24% lycra with 74% silver and 2% polymer. As in many other fabrics of this kind, the sensitivity is not constant and therefore the resistance/length curve is not linear. The approach, in this case, can be the use of a variable sensitivity or the reduction of the useful range (45 to 65 mm) where the linearization is not critical.

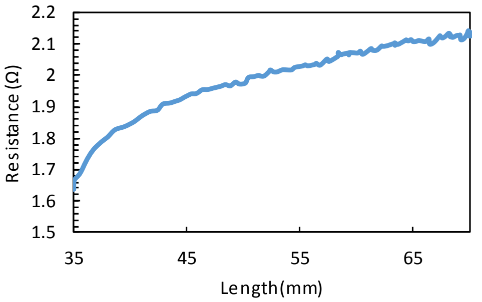

Figure 5. Example of results obtained with the static calibration.

The contact resistance was measured by testing two samples of different length; their electrical resistance is proportional to their length and the measured resistance is the sum of the sample resistance and the contact resistance. The contact resistance with our setup was 0.17 Ω; this value has to be subtracted from the raw measurements obtained with the experimental setup.

The creep of one of the sensors that underwent our tests is shown in Figure 6. In this particular case the displacement was constant but resistance of the sensor increased of approximately 6% after 20 hours. The creep may be critical in all the application where the sensor is used to identify the posture; DC reading is important and therefore a correction procedure similar to that described in ref. [3] should be adopted. In dynamic applications (e.g. breath monitoring) the creep might be not relevant and this issue could be ignored.

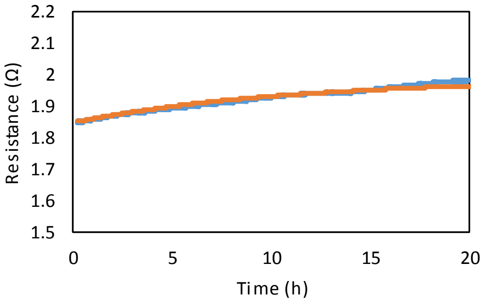

Figure 6. Creep tests of a specimen: resistance variation after 20 hours

Also the frequency response function may significantly differ from the ideal (flat) one. Our tests showed that the response to a sinusoidal excitation contains high order harmonics, as shown in Figure 7. This can be due to the lack of preload of the specimen and can lead to biased amplitude estimation in presence of quick subject movements.

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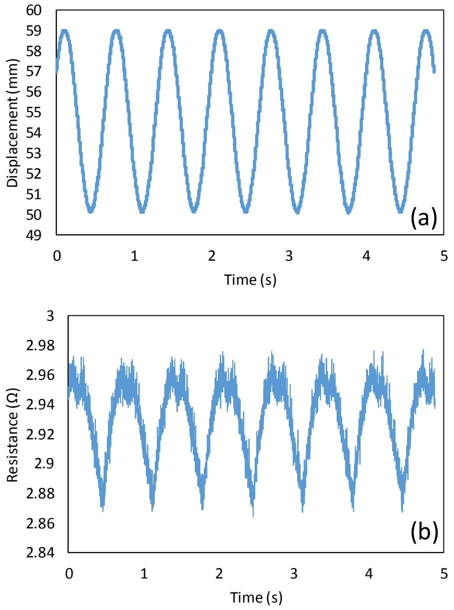

Figure 7. Results of dynamic tests at a frequency of 1.5 Hz. Imposed displacement (a) and specimen electrical resistance (b)

Also, the temperature and the humidity affect the measured electrical resistance: the dependence might be very complex, as shown in Figure 8. In this case, the resistance was influenced not only by the temperature, but also by the humidity, that was not constant during the tests. From this perspective, results were coherent with the ones obtained by spraying the specimens with water.

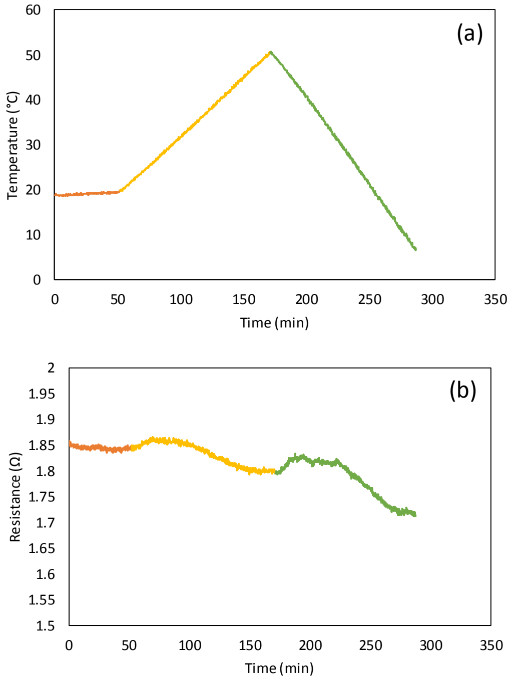

Figure 8. Variation of temperature (a) and of the specimen resistance (b) in environmental tests.

The last step to be investigated is the sensor aging: the setup for static tests was used to compare the aging after 20 washing cycles of four different conductive textiles:

- 3D conductive textile: the silver yarn is mixed with a 3d static filament which give to the fabric a thickness of 2mm. It consists in two different layers (one on the top and one on the bottom) connected in the middle by another more rigid conductive yarn which contributes to thickness.
- High elasticity textile: This fabric is composed by 76% of nylon covered silver and 24% of elastic yarn. Thanks to the nylon and elastic yarn, this textile is very elastic in one direction (65% elongation), and less elastic (30% elongation) in the perpendicular one.
- Low elasticity textile: It consists in 99,9% silver yarn coupled with a polymer. It is elastic in only one direction (about 20% elongation).
- Cotton/silver textile: This last textile is structured into two layers: the firs layer is composed by 100% cotton while the second layer consist in 50% silver and 50% cotton. It has an elasticity that is intermediate between the two previous ones.

The results are shown in Table 1 and Figure 9. The measures were not taken in a controlled environment in order to simulate the normal aging of an article of clothing. Results show that the largest resistance variation occurs for cotton and silver textile; this is due to the fact that this yarn is very fragile and rupture of conductive fibers causes a considerable increase of the resistance. Moreover, the result outlining that the percentage of silver yarn in the textile is not directly correlated to the high conductivity of the fabric.

TABLE I. VARIATION OF ELECTRICAL RESISTANCE OVER WASHING

ELECTRICAL RESISTENCE (OHM) OF FABRICS VS WASHING NO.	3D TEXTILE	LOW ELASTIC TEXTILE	HIGH ELASTIC TEXTILE	COTTON AND SILVER TEXTILE
0	0.553	8.411	1.721	3.130
1	0.536	8.525	1.917	3.420
2	0.526	9.873	2.544	4.498
5	0.526	10.828	3.337	9.943
10	0.759	19.491	4.942	26.032
20	0.930	37.040	5.171	46.687

All the measure are in ohm

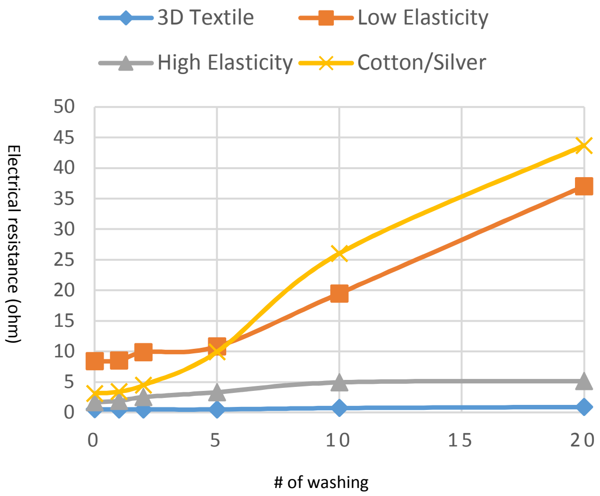

Figure 9. Variation of resistance over washing.

VI. CONCLUSION

In this work we have described the tests that should be performed for a complete metrological characterization of a textile sensor. The setup is based on a classic voltamperometric circuit but allows performing static and dynamic tests on the different specimens. The contact resistance was approximately 0.17 Ω; this value is small, but is of the same order of magnitude of the resistance of specimens that underwent our tests. The static calibration outlined that the behavior of some sensors is not linear, similarly with what was evidenced in studies already published. The creep was also relevant but could be compensated using a first order regression model. Dynamic tests are also mandatory in the sensors' characterization, given that on different specimen families the frequency response function decreased above 1 Hz, mainly because of the harmonic distortion due to the lack of elastic preload of the sensor. Also the temperature, the humidity and the washing affected the electrical resistance, thus showing that a proper calibration and a pre/washing are mandatory to obtain reliable results. Washing tests shows also that the conductivity is not directly related with the percentage of silver (conductive) yarn, but it is related with the knitting technique.

In order to optimize the performances and the reliability, all these aspects need to be taken into consideration when developing a smart t-shirt for medical purposes. The proposed set of measurements is one of the first proposals to build a "standardized" protocol in this directions. Future work will go in the direction of testing other fabrics and eventually to identify other parameters and a related testing methodology.

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