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Investigation on the Use of the PE873 Conductive Ink for Surface EMG Measurements

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***Abstract*—Nowadays, wearable devices are part of everyone's life and their popularity is constantly increasing. With diverse applications, spanning from healthcare to fitness tracking, more and more wearable devices are being developed which can send and receive information in real-time.**

To date, electric cables represent the most stable form of communication in terms of reliability and resistance. However, for wearable systems, cables restrict movement and introduce additional noise and movement artefacts on wearable sensing systems. Wireless devices, on the other hand, can be comparatively complicated in design, manufacturing and use. A possible strategy, to improve communications in wearable systems, is the adoption of conductive inks able to conduct electrical signals, these can be printed on fabric without the movement restriction normally associated with traditional wired systems. The use of such conductive inks in wearable sensors may, therefore, lead to a more comfortable method of monitoring health data (heart rate, muscle contraction etc.) throughout the day. In this paper, the properties of the promising conductive ink PE873 (manufactured by DuPont) are tested and analysed. The conductive ink electrical properties are studied in relation to stretching, folding and washing tests. The electrical performance of the ink printed onto the selected fabric is assessed and presented. Furthermore, an optimized printing procedure, aiming at improving the connection performances, is suggested and the development of a novel system able to read muscle contractions, based on PE873, is demonstrated, thus showing that this conductive ink is a promising solution for stretchable electrical connections in the wearable field.

Keywords—Wearable systems; textile electronics integration; conductive ink; interconnections; DuPont.

I. INTRODUCTION

Many of the wearable products currently available on the market have been developed for monitoring of health, well-being and fitness. Such systems, e.g. smart watches and wrist bands, can provide information about physical activity (e.g., steps, calories burned, etc.) and physiological parameters (pulse rate, blood oxygen levels, Blood pressure etc.). The constant monitoring of a subject's health status is a desirable feature for clinical and health-related applications, such as rehabilitation or the management of chronic diseases. This can be clearly observed by the amount of research outputs produced in the wearable field on health monitoring [1]-[3].

In particular, the interest in sensor-embedded clothing is constantly increasing enabled by recent advancements in materials and technology, in particular flexible and printed electronics. For example, biosignals, such as surface electromyography (EMG) or electrocardiography (ECG), can be directly collected from the location of interest (e.g., upper or lower limbs) by means of smart garments, such as fully sensorized shirts or shorts with integrated electrodes [4]-[6].

One of the most attractive features of those wearable devices is the capability to transmit data in real-time without the need of physical connections. On the other hand, wireless communication (e.g., ZigBee, Bluetooth, etc.) can be comparatively unreliable [7], relatively expensive and more complex in terms of design, manufacturing and use. Thus, simpler and less expensive solutions are required to make such systems universally accessible and affordable. To date, electric cables and copper wires have represented the best form of connection in terms of reliability and resistance; however, the presence of cables on wearable devices might restrict body movements and prevent the execution of specific physical tasks, as well as introduce additional noise and movement artefacts.

One of the possible solutions to this problem might come from the new generation of conductive ink [8] which are coming on the market and which are increasingly accessible to system designers. This type of ink can be directly printed on fabrics, and it can be washed and stretched several times while maintaining appropriate electric resistance. Generally, conductive ink is composed by a conductive material, thermoplastic polyvinylbutyral terpolymer binder and a glycol ether solvent [9] and, typically, conductive ink based on silver metal particles, which shows the best conductivity [10].

Although modern inks have an electrical conductivity comparable to copper [11], the reliability of conductive inks in wearable devices is still a critical issue, due to the change in electrical resistance caused by mechanical strain [12].

To address this problem, specific technical aspects need to be considered, such as the relationship between the viscosity of the ink and the porosity of the fabric. For example, viscous inks do not permeate well into porous textile structures [13]. Moreover, the electrical performance is also affected by the different direction of the fabric wires. As shown in [14], when comparing the electrical features under large strains performed in two different directions (e.g., parallel and perpendicular to the fibre bundles), the resistance of the printed line differs of a factor up to 20 between the two scenarios.

At present, the market of conductive inks is still limited, and performances reported by the manufacturers do not take into consideration the electrical properties of such materials under specific mechanical stress, e.g., ink tested on stretchable substrate or textile materials. Therefore, the present work aims at investigating the suitability of a conductive ink available on the market to be used as an electrical connection on both stretchable and unstretchable fabric by testing the electrical performance of the material in both conditions. Furthermore, the opportunity to adopt the conductive ink in a system able to monitor muscle contractions has been also assessed in a practical scenario. In order to investigate the suitability of a conductive ink in creating robust electric connections for surface EMG acquisition with a wearable device, the conductive ink was used to create an electrical connection on a stretchable strip of fabric between a conductive electrode (point A), which transduces the myoelectric signal from the skin, and “snap” connectors (point B) mounted on a custom printed circuit board (PCB), which connects the ink to the EMG measuring device. Moreover, a printing process and associated performance assessment procedures were developed to assess the system.

The manuscript is organized as follows. The methodologies adopted for the system development (ink selection, connection process, 3D printing, etc.) are described in Section II, while Section III shows the results obtained over different test conditions. Section IV presents a discussion of these results and conclusions are drawn in Section V.

II. METHODS

A. *Conductive Ink Characteristics*

Despite the market of conductive ink being still in its infancy, a number of companies have already produced conductive inks and pastes for photovoltaics, power electronics, displays, automotive, antenna design and others, but few products on the market have been developed for stretchable e-textile [15]. For this work, the conductive ink selected for analysis is the Intexar PE873 produced by DuPont (DuPont de Nemours, Inc., Wilmington, Delaware, USA). The selection was mainly made based on the waterproof capability of such ink which, by the time of this work, was a feature available only on a very limited range of similar product. Its physical and composition properties are shown in Tables I-II.

TABLE I. PHYSICAL PROPERTIES

Test	***Properties***
Sheet Resistivity (mΩsq/25μm) (5μm Dried Print Thickness on ST505 PET Film)	< 75
Resistivity After Crease (ASTM F1683, 180 deg, 1 cycle, 2kg)	< 5%
Abrasion Resistance (ASTM D3359 Pencil Hardness)	1 H
Adhesion (Tape Cross Hatch) (ASTM D3359 w/3M Scotch Tape 600)	No transfer
Clean-Up Solvent	Ethylene Diacetate
Encapsulant	PE771 / PE773

TABLE II. COMPOSITION PROPERTIES

Test	***Properties***
Solid (%) @ 150°C	60 - 65
Viscosity (PaS) Brookfield RVT, #14 spline, 10rpm, 25°C	50 - 80
Density (g/cc)	2.0
Coverage (cm^2/g @ 5 μm) Coverage (cm^2/g @ 10 μm)	350 175
Dried Print Thickness (microns)	8 - 12
Thinner	DuPont™ 8260

B. *Ink-Sensor Connection*

Point A of the overall system is represented by the electrode made via a conductive and biocompatible fabric (produced by Swift Textile Metalizing LLC, Bloomfield, CT) and placed on the bottom side of the fabric, which is in contact with the skin, and on the top side. Regarding the connection between the top and bottom side of the fabric electrodes, to ensure a robust connection the conductive ink was sandwiched between the two conductive layers, acting as a glue (Figure 1).

On the other hand, point B are snaps integrated in to the PCB design so as to connect with the MyoWare Muscle Sensor (Advancer Technologies LLC, Raleigh, USA), placed on the top side to monitor muscle contractions. To connect the strips of conductive ink with the reading electrodes of the EMG sensor, a PCB layout with three pads on the top and the bottom layer was designed. The top pads connect the PCB to the MyoWare by the means of snap buttons, soldered on top. The bottom pads, instead, connect the PCB with the ink paths (Figure 2a). As soldering on fabric is not possible, a chemical compound has been identified to connect the PCB and the ink paths (Figure 2b). The conductive epoxy 8331-B (produced by MG Chemicals, Burlington, Ontario, Canada) was chosen due to its suitable characteristics of low electric resistance, high water resistance, and short working life.

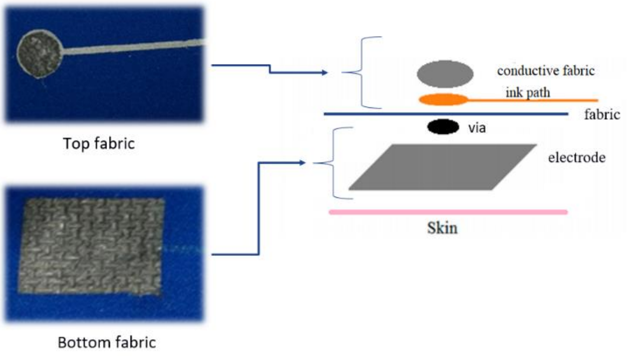

Figure 1. Sandwich structure for collection of EMG signal

Figure 2. a) PCB with snap buttons soldered on top (top). b) Connection between PCB and fabric via 8331-B epoxy (bottom)

C. *3D Printed Support*

From a design methodology perspective, a system designer needs to consider that electronics embedded into clothing can be under significant strain due to body physical movements, thus the use of epoxy on its own does not guarantee a reliable strong grip due to flexing and cracking. To ensure the stability of the communication, a mechanical enclosure was designed to support the electronics. It consists of two 3D printed parts, obtained via fuse deposition model technique using polylactic acid (PLA), which can be screwed together to work as a clamp (red components of Figure 3).

D. Ink-Printing Process

In order to evenly spread the conductive ink only across the conductive paths, namely the narrow strips that connect the fabric electrodes with the PCB, a custom mask was 3D printed. The mask was design to act as a “stencil” to confine the ink only within the designed geometry. The final design of the mask is shown in (Figure 4a). An important element of the 3D printed mask is a small step added on the bottom face (Figure 4b), which allowed more pressure on the fabric surface in order to avoid possible leakage of the ink. The final system is shown in Figure 5.

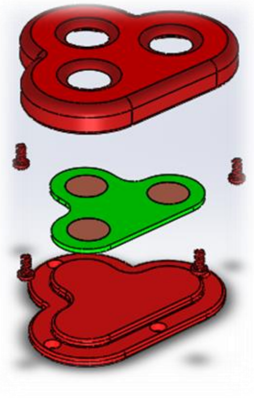

Figure 3. 3D printed support (exploded view)

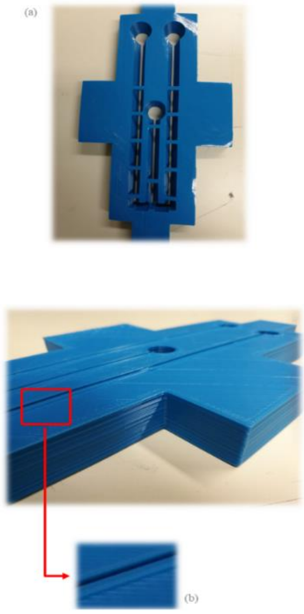

Figure 4. 3D printed mask

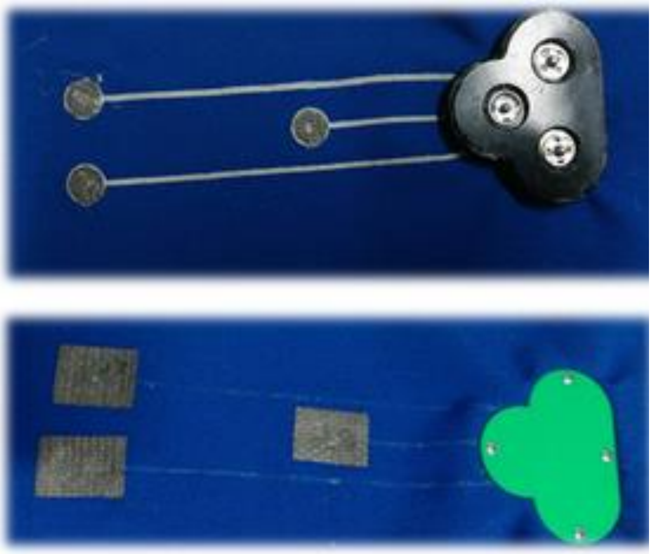

Figure 5. Developed system (top and bottom view)

E. Test Protocol

Three different tests have been carried out on the conductive material once deposited and cured on the textile material in the present investigation: stretching, folding, and washing.

The stretching test was divided in three steps: resistivity measurements in rest position, in a stretched position, and finally in rest position again. The second test investigated the impact of folding the garment along the conductive trace, in which the resistivity was measured after each folding procedure. The washing test consisted in testing the electrical performance of the material after washing at a selected program in a standard domestic washing machine: synthetic garment (2 hours) with a temperature of 30°C and a detergent for coloured garments.

III. RESULTS

To test the performance of the conductive ink, several test samples were made for analysis. The tests were made on two types of fabrics: unstretchable and stretchable materials. Resistance measurements in the following tests were conducted 10 times and the average value is presented with the related standard deviation shown on the graphs as error bars. The ideal condition was to obtain a resistivity near to 1 Ohm, which is comparable to standard cables resistivity.

Stretching results are shown in Figures 6-7, while folding results are illustrated in Figures 8-9, and washing test in Figure 10.

The present work aimed at investigating the suitability of the DuPont PE873 conductive ink to be used as an electrical connection on stretchable and unstretchable fabric by testing the electrical performance in both conditions across different test. This section briefly discusses the results obtained with the implemented experimental protocol.

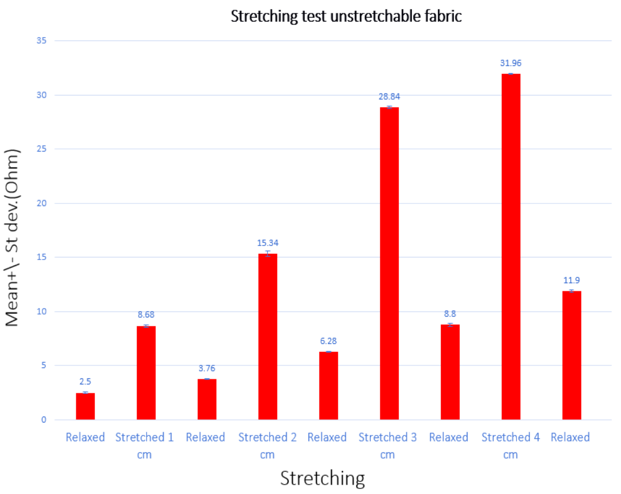

Figure 6. Stretching test results for unstretchable fabric

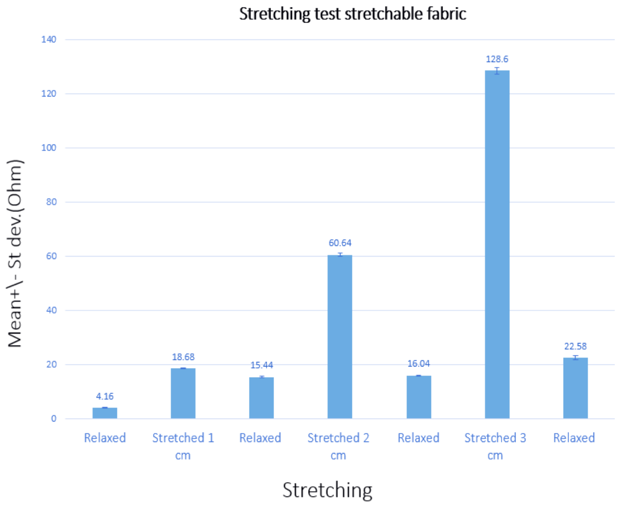

Figure 7. Stretching test results for stretchable fabric

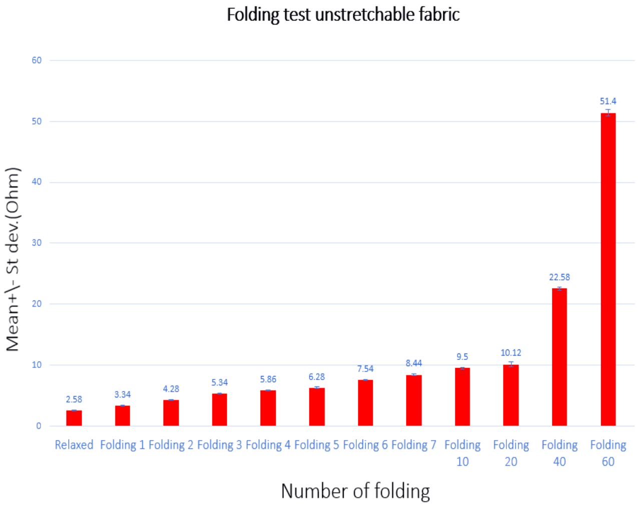

Figure 8. Folding test results for unstretchable fabric

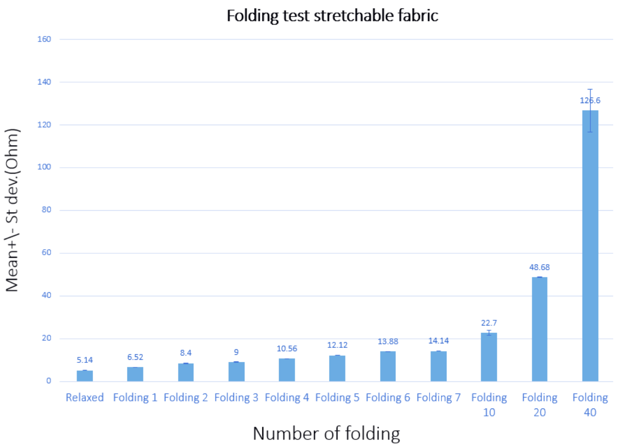

Figure 9. Folding test results for stretchable fabric

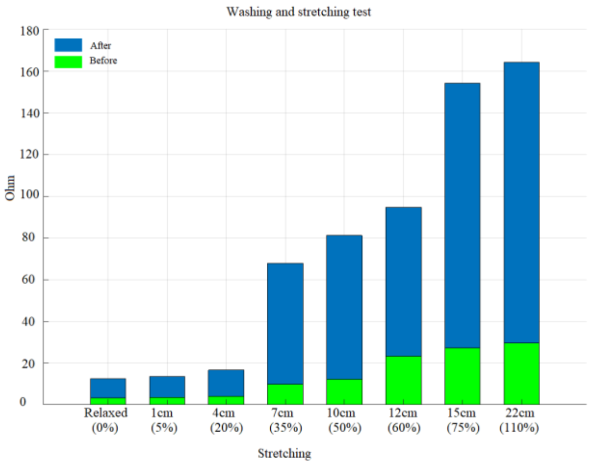

Figure 10. Washing and stretching test results for stretchable fabric

IV. DISCUSSION

A. Stretching Test

Figure 6 illustrates the resistance changes for the stretching test for an unstretchable fabric. Initially, the measured resistivity is 2.5 Ohms in the rest position, which increases to 8 Ohms after stretching the fabric of 5% its length (e.g., 1 cm). However, when returning to a rest position, the resistivity measured is slightly larger than initially obtained. This behaviour is amplified when longer stretching are applied and the measured electrical resistance when applying the maximum stretching of 20% (e.g., 4 cm) is over 30 Ohms.

The same behaviour is shown when performing the test on the stretchable fabric (Figure 7), even though the resistivity values measured are generally higher compared to the previous fabric. It is worth noticing the behaviour of the ink over one day in rest position. Indeed, after 24 hours, the resistivity decreases of 1.08 Ohms and 3.26 Ohms for the unstretchable and stretchable fabrics, respectively, thus showing an adaptation of the textile fibres.

B. Folding Test

The results for the folding test are displayed in Figures 8-9. In both cases, the resistivity measured grows with the number of foldings; however, the unstretchable fabric shows better results. As an example, after the 60th folding, its resistivity (51.4 Ohms) is less than half than the resistivity measured from stretchable fabric after the 40th folding (126.6 Ohms).

C. *Washing Test*

After washing, the stretching test was carried out on the sample according to the previously described procedure.

At the first attempt, the mechanical stress of the washing procedure was enough to cause an open circuit on the conductive track. To this purpose, it is important to specify that every sample analysed was developed with only one layer of ink; therefore, as a possible solution, samples with more than one layer of conductive ink were made [16]. Moreover, to increase the conductivity of the stretchable fabric, it was decided to apply the ink while the fabric was stretched. The results achieved from using this methodology are shown in Figure 10. Using this new ink-printing method, the resistivity value of the conductive trace after washing is still unsatisfactory. However, the resistivity before and after washing is lower than the results obtained in the stretching test. This test was carried out only on the stretchable fabric, which was the worst between the two cases.

Overall, it can be concluded that the performance of the PE873 conductive ink is acceptable only in a small range of mechanical strain, thus conductive ink is still not able to provide results comparable to standard cables in a wearable solution requiring significant stretching capability (such as lycra shorts for instance with integrated sensors for example). One of the biggest issues is the ink penetration in the textile fibres, which deeply impact on the conductivity [16]. DuPont has now made available a new series of conductive inks, which promise better performance, as shown in Figure 11.

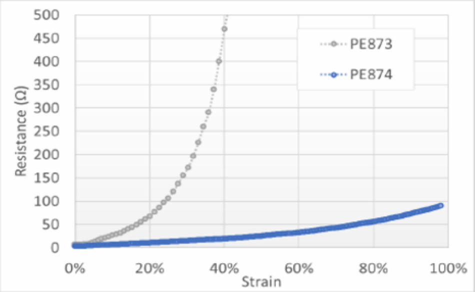

Figure 11. PE874 and PE873 mechanical and electrical performance compared

In the picture, the characteristics of the PE873 and of the new generation ink (PE874) are compared. Furthermore, DuPont has also produced a stretchable TPU (thermoplastic polyurethane) film, which works as a printing surface and is characterized by high recovery and composed of a melted adhesive layer for bonding to fabric.

V. CONCLUSION

Conductive inks have the potential to represent a possible efficient and inexpensive solution for solving the interconnection issues typical of smart wearable garments with embedded sensors and electronics. In this paper, the features of the promising conductive ink PE873 (manufactured by DuPont) were tested and analysed across several experiments (stretching, folding and washing) by measuring the electrical performance of the ink. Furthermore, the methodologies adopted for implementing an optimized printing procedure were discussed.

Even though this investigation presented mixed results, it can be concluded that the performance of the PE873 conductive ink was acceptable in a limited range of mechanical strain. The next-generation conductive inks, and improved printing procedures, can potentially ensure better performance of printed connections, thus making it a desirable technology in the field of wearable devices in the coming years.

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