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A Preliminary Study on Aerosol Jet-Printed Stretchable Dry Electrode for Electromyography

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Abstract. In the last decade, measurement of physiological signals has been attracting great interest for both health-care and Industry 4.0 applications. In this context, the electrodes used during signal acquisition play a key role. In this work, we propose the development of dry electrodes for electromyography (EMG), specifically exploiting the possibility given by aerosol jet printing to realize electrical pads and interconnections on stretchable substrates. We investigated the materials and geometry of the sensors, characterizing their electromechanical properties at rest and under stretching. Finally, a set of prototypal electrodes for EMG were designed, produced and evaluated comparing them with commercial ones. The described approach resulted to be feasible and promising for different applications considering both health monitoring and human-machine interfaces.

1 Introduction

The measurement of biopotential signals is a common method used to non-invasively track physiological processes [1]. For instance, electromyographic (EMG) acquisition provides information about the muscular activity addressing both health monitoring and human-machine interfaces [2]. The characteristics of the electrodes used in surface recording heavily affect the signal quality and the reliability of their applications. Nowadays, silver/silver chloride (Ag/AgCl) wet electrodes are the gold standard [1]. The conductive gel reduces the contact impedance and acts as an electrolyte for current flow, but it dries with the use affecting the performance and may lead to skin irritation or allergic reactions, preventing their long-term application [3]. To overcome these limits and reduce motion artifacts, dry flexible electrodes have been introduced [4]. In stretchable electrodes, the interfacing and contact impedance improves due to their better adherence and conformability during motion. Stretchable electrodes can be fabricated through both additive and subtractive approaches; the former are indeed a great compromise to develop fast, reliable and cost-effective devices. Among them, aerosol jet printing (AJP) represents an emerging method that reproduces patterns with resolutions up to 10 μm generating and collimating an aerosol flux, which contain a functional ink, onto a substrate [6]. AJP does not require masks to realize a specific pattern, unlike screen printing [1], it allows depositing a variety of materials [7], with ranges of viscosity and density much wider than inkjet printing [8] and it is suitable for printing on non-planar surfaces [6]. This paper presents a preliminary study on dry electrodes fabricated through AJP on stretchable substrates. The electrode is the result of a study in which different ink/substrate combinations were tested to find the optimal solution in terms of both ink/substrate adhesion and their electromechanical characteristics. Then, the obtained solution is tested in an EMG application.

2 Materials and Methods

2.1 Sample Fabrication

The samples were fabricated by using an aerosol jet printer (AJ 300-UP, Optomec Inc.), according to specifically designed patterns. We used a stretchable silver-based ink (PE873, DuPont™) deposited on thermoplastic polyurethane (TPU, TE-11C DuPont™ Intexar™) and polydimethylsiloxane (PDMS). TPU was selected for its high elasticity, good tensile strength, excellent resistance to fatigue, and biocompatibility, while PDMS for its chemical inertness, thermal stability, high mechanical properties and good adhesion capabilities. The main AJP process parameters were: sheath gas flow 55 SCCM, exhaust flow 1300 SCCM, atomizer flow 1260 SCCM, speed process 2 mm/s, plate temperature 60 °C and nozzle tip 200 µm. After the printing phase, all the samples were cured at 130 °C in a dry oven for 15 minutes. Four types of samples with different geometric configurations were investigated. In fact, besides straight segments (type C), we evaluated also samples with "U" shape (type A) and horseshoe shape (type B), which proved to be optimal solutions for the design of circuit connections, in terms of induced mechanical stresses, reduced damage, and increased stretchability [9].

2.2 Characterization

We printed different type C samples using different ink/substrate combinations to select the one that best fits our application. We performed different tests to evaluate several characteristics including ink/substrate characterization and electromechanical behavior. The adhesion of the ink on each substrate was assessed on a 0 to 5 scale using the cross-cut tape test, which is described in the standard ASTM D3359 [10]. The electromechanical characterization was performed in compliance with protocols commonly followed to characterize polymeric materials [11].

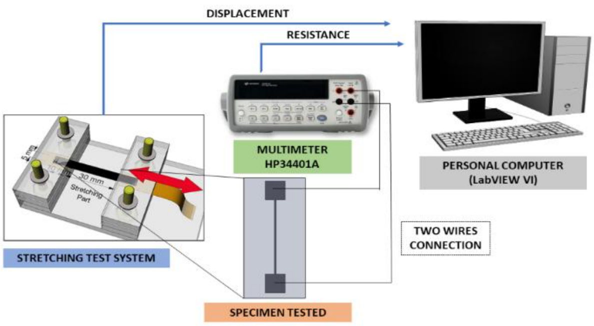

Fig. 1 The experimental setup used during the tests for the electromechanical characterization

Briefly, we employed the measurement system shown in Fig.1 to apply on the samples two deformation protocols. At first, a constant rate (0.5 mm/s) strain ramp was applied until sample failure. Then, we applied different strain levels, maintaining the reached position for 10 minutes after each step.

2.2 Results

The adhesion test result rated 5B, top of the scale, the combination PE873 ink and Intexar TE-11C, while both the PDMS substrates demonstrate poor adhesion with this ink. According to these preliminary results, we chose to further characterize and use only the first combination of ink and substrate. The strain ramp test permitted to identify the relationship between applied stress and the relative change of resistance of the sample. We evaluated the resistance at rest (0% strain) to be 32.91 Ω with a relative change in resistance of 11.7% at failure under a strain of 12.25%. The overall sample behavior can be seen in Fig.2 (*left*). The static strain test depicted in Fig.2 underlines a maximum change of 0.13% at 5% strain in 10 minutes. It is worth noting that this strain-induced variation in the interconnection resistance does not affect the overall signal quality, because its value at zero strain is almost negligible if compared to the resistance of skin-electrode interface (around 150-200 kΩ) and the typical input resistance of the electronics frontend (usually higher than 1 GΩ).

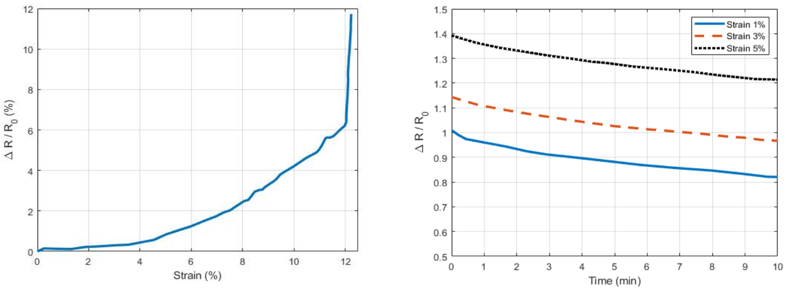

Fig. 2. Sample characterization: strain ramp test (left), static strain test (right)

3 Application to EMG

3.1 Electrode Fabrication

For the development of the EMG electrode, the configuration DuPont™ Intexar TE-11C substrate and the conductive ink DuPont™ PE873 stretchable silver were selected. We designed our electrodes to be similar in shape to the commercial ones used during the validation step to reduce variability due to geometrical factors. Briefly, we designed two parallel electrodes spaced by 15 mm with a 10 mm diameter active area. Each electrode was provided with a 30 mm long horseshoe (type B) interconnection to a set of medical snap buttons as test equipment interconnection. The active area was later coated with a layer of silver chloride (AgCl) to ease the signal retrieval.

3.3 Application Setup

Considering that the high variability of the surface EMG signal produced by voluntary activations may hamper the comparison of the performance between different electrodes, the main characterization was performed in controlled conditions by electrostimulation. A single subject, seated in a firm chair, was connected to an electrostimulator (Globus Genesy 1500), which was configured – as standard protocol - to deliver a 300 µs current pulse followed by a ramp-up stimulus on the peroneal nerve thus to activate tibialis anterior muscle. The recording electrodes were placed over the tibialis anterior, approximately 10 cm from the ankle and fixed in place by adhesive tape. To acquire the signals, we used a FREEEMG (BTS Bioengineering) wireless acquisition system. The custom electrodes were employed both applying electrolytic gel (EG) and in dry conditions. The signals retrieved were then compared with the ones obtained using commercial pre-gelled EMG electrodes (Kendall). For each test case, the same waveform was applied and acquired many times to average repeated measurements and reduce the intrapersonal variability of the stimulus response.

3.4 Results and Discussion

In Fig.3 we report both the validation setup and the averaged waveforms that we acquired during the measurement sessions. In general, the amplitude of the first peak (initial stimulus spike) recorded by using the printed electrodes in dry conditions is the 34% of the one recorded by commercial electrodes, while in wet conditions it is the 84%. However, the following peaks amplitude for the printed electrodes was comparable to the one obtained with the commercial type. Even if our flexible dry electrodes present these limitations, they have important advantages like their reduced encumbrance and thickness that can improve its overall wearability and conformity during motion.

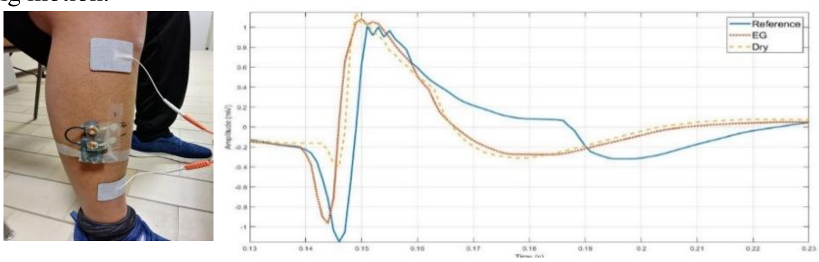

Fig. 3 Validation setup (left) and average stimulus response for different electrodes (right)

Moreover, even though EG based electrodes have lower contact impedance, the gel dehydrates over time unpredictably changing the signal making them unreliable for continuous monitoring.

4 Conclusions

In this work, the development of stretchable EMG electrodes through AJP and tested in an EMG application was reported. Several samples were fabricated in order to better characterize the proprieties of different ink/substrate combinations, but the PE873 ink on Intexar TE-11C was found the most suitable. The electrodes were then designed and produced through AJP and validated through an electrostimulation-based protocol. The validation process consisted of comparing the signals acquired by using the printed electrodes in dry and wet conditions with the ones retrieved with a commercial electrode. As regards the amplitudes, the results are promising with all the electrodes performing in a similar way, even though there some differences in the signal form. This solution can be easily introduced in wearable solutions, thus to address both health monitoring or human-machine interfaces applications.

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