Development, fabrication and evaluation of textile electrodes for EDA measurements

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***Abstract*— In this study, textile-based dry electrodes that are integrable to clothing were developed, and their potential and limitations in EDA measurements were characterized. Copper-based and silver-based fabric electrodes and two types of electrodes embroidered from conductive thread were tested for EDA-measurements from fingers, and their performance was compared to that of commercial Ag/AgCl electrodes. Based on the experiment results, stimulus response of skin conductance could be measured with all the electrodes. Copper-based fabric and densely embroider silver electrodes give the best EDA response, which is comparable to that of commercial Ag/AgCl electrodes. The next step is to integrate these textile electrodes into gloves and socks and carry out EDA measurements on female and male adults as well as on children. Our goal is that these EDA measurement clothes would become a part of our everyday life, which would enable versatile health and well-being related applications.**

Keywords*— *EDA, embroidery, conductive fabrics, textile electrodes

I. Introduction

Emotional, physical, and cognitive stress is related to electrode dermal activity (EDA) due to link between sympathetic nervous systems (SNS) and sweating glands. Psychological or physiological arousal affects sweat gland activity resulting change in electrical properties of skin. This phenomenon makes skin conductance a quantitative method to monitor human emotional and sympathetic responses [1].

There has been increasing interest for monitoring different body functions outside laboratory environments [2]-[5]. Skin conductance signal is one of the most measured biosignals, and it can be used as a versatile indicator of a person's health and well-being, e.g., for monitoring sleep quality [6], or as an indicator of neurological health [1], and person's emotional responses to different kinds of stimuli.

The current commercial EDA monitoring devices rely on rigid electrodes. Such devices on the market are, e.g., smart ring from Moodmetrics, wristband from Empatica, and wearable sensor from Shimmer. Rings and wristbands are meant for recording tonic skin conductance, since the sampling rate is too small to gather phasic data. Shimmer sensors can measure phasic component as well. Tonic skin conductance is the slowly varying skin conductance level, which reflects general changes in autonomic arousal. Whereas phasic skin conductance component gives information about short term arousals. For applications that require inconspicuous monitoring, e.g., for patients with increased touch sensitivity or reduced level of consciousness, such devices or even rigid electrodes can be unpleasant or difficult to wear.

Single use Silver/Silver chloride gel electrodes are the most used bioelectrodes. They are reliable, cost effective and non-polarizing electrodes. However, the adhesive and the gel may cause skin irritation [7], thus they are not suitable for all users or for on-going use. In everyday biomeasurements, or when measuring sensory defensive people, seamless non-disturbing dry electrodes are beneficial.

Recently different types of dry electrodes have been studied: Rigid metal electrodes, carbonized rubber electrodes, conductive foam, metal electrodes on soft elastomeric substrates, and different types of textile electrodes [6, 8, 9, 10]. The benefits of dry textile electrodes are their reusability, unobtrusive skin feel, and integrability to clothing. They offer obstruction-free and comfortable setup when monitoring different biosignals.

The aim of this study is to develop dry electrodes that are integrable to textiles and can thus be used as an invisible part of the cloth. The goal was to characterize their potential and limitations in EDA measurements. Thus, we concentrated on conductive textile materials instead of other promising dry electrode materials. In this work, four different textile electrodes, copper-based and silver-based fabric electrodes and two types of electrodes embroidered from conductive thread, were tested for EDA-measurements from fingers, and their performance was compared to that of commercial Ag/AgCl electrodes.

II. Materials and methods

A. Electrodes

In this study four different textile electrodes were investigated; two embroidered and two conductive fabrics based. The structure of textile electrodes is presented in Fig. 1. The bottom layer is the conductive fabric or embroidered patch. To enable electrical connections, a conductor wire is attached to the back side of the electrode textile with conductive copper tape (Copper Foil Tape 1181, 3M). The conductive fabrics or embroidered patches are sewn on 2 mm thick ethylene propylene diene monomer rubber (EPDM) substrate to allow constant electrode to skin contact on the whole electrode surface. The top layer is a Velcro pad, used to attach the electrode to a finger strap for measurements.

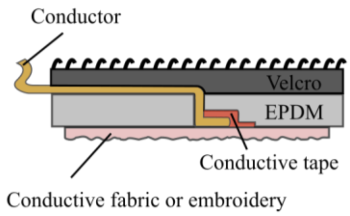

Fig. 1. Schematic of the textile electrode structure.

Two textile electrodes were fabricated from conductive fabrics: copper-based fabric (Less EMF Pure Copper Polyester Taffeta Fabric Cat. #A1212) and silver-based fabric (Less EMF Stretch Conductive Fabric Cat. #32); and two electrodes were embroidered from multifilament silver-plated thread (Shieldex multifilament thread 110f34dtex 2-ply HC) using a Husqvarna Viking embroidery machine. All the electrodes are presented in Figure 2.

The embroidered electrodes had different surface patterns; densely embroidered (referred as DE Ag), shown in Fig. 2 a), and cross hatched (referred as CH Ag), shown in Fig. 2 d). The idea of this sparsely embroidered electrode is to test if it is possible to save manufacturing time and material (i.e., conductive thread) with this kind of pattern.

All the textile electrodes were circular shaped and had diameter of 15 mm, leading to surface area of approximately 180 mm^2. The reference electrodes were rigid commercial Ag/AgCl GSR electrodes (from Shimmer) with a diameter of 10 mm (Fig. 2 e) and surface area of approximately 79 mm^2.

B. EDA measurements

The EDA measurements were carried out at room temperature (approximately 21 °C). Hands were washed with soap and water before measurements. EDA measurements were utilized for all the five participants in the electrode testing order shown in Table 1. To stabilize the electrodes, the test subjects wore them five minutes before recording started. The participants sat still, with hand placed on the table during the measurement. A test involving six startle-like stimuli was the same in each measurement. Explanations for the stimuli and the approximate time is presented in Table 2. The stimuli time varied slightly between the participants and the measurements since the experimenter waited the signal level stabilization before new stimulus.

TABLE I. EXPLANATION OF THE ORDER OF ELECTRODES USED IN EACH MEASUREMENT SERIES. ELECTRODE 1 AND 2 LOCATIONS IN THE HAND ARE PRESENTED IN FIG. 3.

Measurement series	Electrode 1	Electrode 2
1	Ag/AgCl	Ag/AgCl
2	Ag/AgCl	DE Ag
3	Ag/AgCl	Silver fabric
4	Ag/AgCl	Copper fabric
5	Ag/AgCl	CH Ag

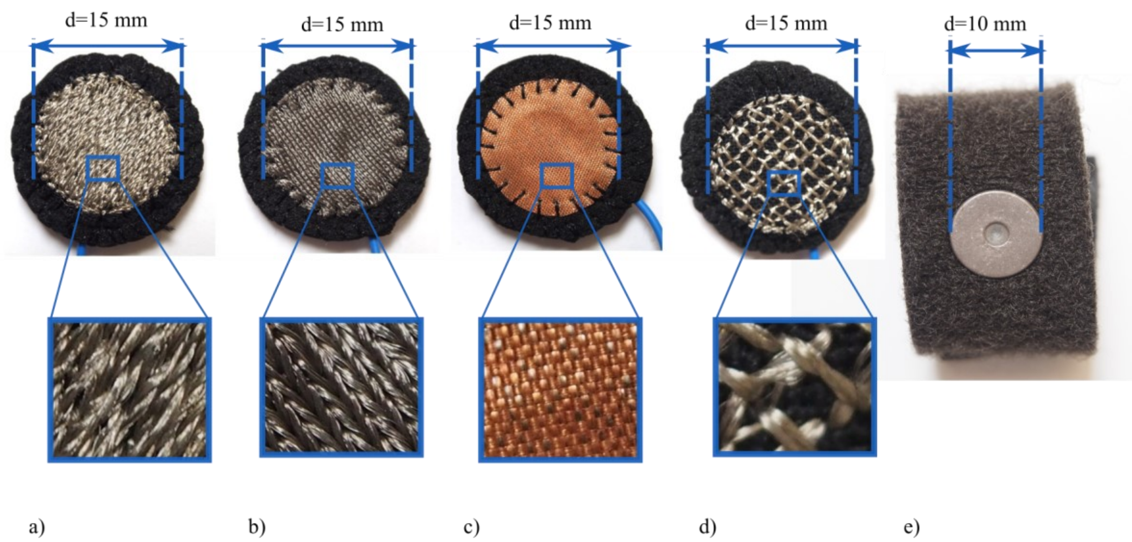

Fig. 2. Photographs of the electrodes and magnified images of the textile electrode surfaces: a) Densely embroidered silver electrode (DE Ag), b) Silver-based fabric electrode, c) Copper-based fabric electrode, d) Cross hatch embroidered silver (CH Ag), and e) Standard reference Ag/AgCl electrode. The structures of textile electrode surfaces are shown in magnified insets.

TABLE II. DESCRIPTION OF THE STIMULI AND APPROXIMATE TIME AFTER THE START OF THE MEASUREMENT SERIES

Stimulus	Description	Approx. time
1	Single hand clap	10 s
2	Firm touch to shoulder	25 s
3	Test subject pinching themselves	40 s
4	Firm touch to shoulder combined with sudden noise	60 s
5	Single hand clap	80 s
6	Test subject pinching themselves	100 s

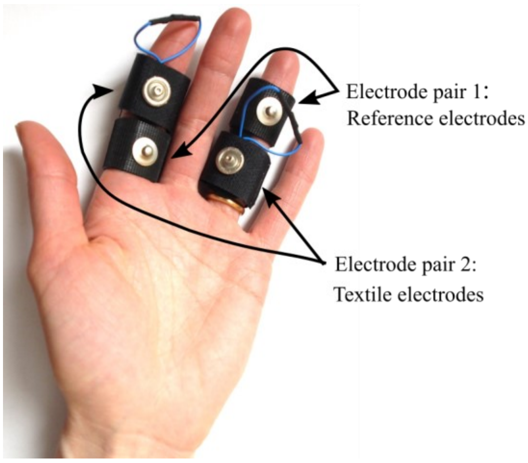

Fig. 3. Location of the electrodes during EDA measurements. The reference Ag/AgCl electrodes are located on the proximal phalange of the index finger and medial phalange of the ring finger, and the textile electrodes are located on the medial phalange of the index finger and on the proximal phalange of the ring finger.

III. RESULTS AND DISCUSSION

In order to clarify the data-analysis of this study, an example of EDA measurement with copper-based textile electrode and Ag/AgCl standard electrode is presented in Fig. 4. The moments of a stimuli are presented as solid black lines in the plot. The actual timing of the stimulus is slightly earlier than presented in the figure, as the experimenter did first the stimulus and after that marked the time stamp. The peak amplitude is a commonly used indication of electrodermal response to stimulus [1], and thus it was chosen as an indicator of the electrode performance. Amplitudes were calculated for all stimuli response peaks from minimum and maximum values of the conductance data. The black arrows show the peak amplitudes in Fig. 4.

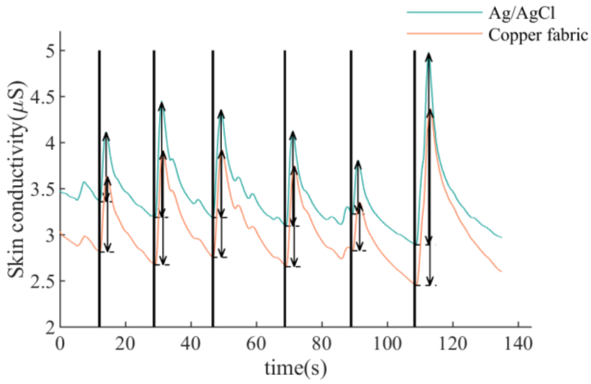

Fig. 4. EDA stimulus response shown for copper-based textile and Ag/AgCl standard electrodes. The times for stimuli are shown with solid black lines. The black arrows show the peak amplitude from the data.

Since the response to stimulus cannot be directly compared between different test persons and experiments, we compared each stimulus amplitude to corresponding amplitude of the reference electrode by diving the amplitude of experimental electrode to the amplitude of reference Ag/AgCl electrode ($A_{norm}=A_{test}/A_{ref}$). From this normalized amplitude, we calculated the mean value and standard deviation from all the peaks for each electrode pair. The EDA response is not identical in all fingers of human hand [10]. Thus, the difference of the EDA response measured with the reference Ag/AgCl electrodes and test electrodes includes the signal difference caused by the position of the electrodes, and the difference of the electrode behavior.

To have an estimation of the effect of the position, the first electrode comparison measurement was done with two Ag/AgCl electrode pair: One pair in the reference electrode position and the other pair in the test electrode position. Furthermore, to get rid of the difference in the response caused by the location of the electrodes, we divided the normalized test electrode amplitude A_{norm} with position factor $S=A_{Ag/AgCl}/A_{ref}$, where Ag/AgCl indicates the Ag/AgCl reference electrode measured in test electrode position (Electrode 2 in Table 1) . The resulting material sensitivity factor $M= A_{norm}/S$.

The results for all electrodes and participant are presented in Fig. 5. In this setup, value one means that the response measured with the test electrode is at same magnitude than response measured with the reference electrode. Smaller values indicate smaller measured response of the test electrode than the reference electrode.

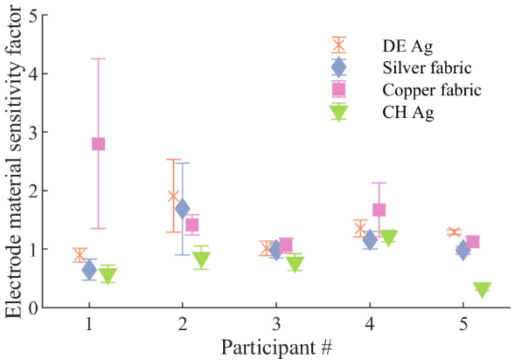

Fig. 5. Average amplitude of the stimulus set for all electrodes and participants, normalized against differences in personal response and position of the electrodes.

Skin conductance measured here is influenced by electrode and wire resistance of both electrodes, electrode to skin contact resistance for both electrodes, and the actual skin conductance. [8] The contact force is one factor having an effect on the electrode to skin contact impedance. In these experiments, the force was not measured and thus it was not constant. This might influence on the results and increase the variance. It is something that requires further consideration in our next study. However, despite the variance, we can find clear differences between the electrode materials.

As a conclusion of the experiment, the copper-based fabric and densely embroider silver electrode (DE Ag) give the best EDA response. Cross hatched embroidered Silver (CH Ag) gives the lowest response, which is likely due to the smallest contact area of the electrode material (see Fig. 2). The smaller the contact area is, the higher is the contact resistance when the electrode materials are identical, as seen in the case of both embroidered electrodes.

The resistance of the electrodes and the wires was for all electrodes less than 1 Ohm. It is negligible compared to the measured skin conductivity, which is µS level (see Fig. 4). Furthermore, the electrodes were located at same position for each electrode measurement, thus we can assume that the skin impedance is roughly constant in all measurement, and thus the difference between the electrode materials is a result of different contact impedances between the skin and the electrode.

The reason why copper-based fabric and DE Ag electrodes perform better than silver-based fabric is not as obvious as in the case of CH Ag. A previous study suggested that the dry electrode behavior of textile electrodes was limited by poor contact caused by the structure of weaved metalized threads [8]. Compared to other dry electrode materials, metals and conductive rubber, textile electrodes also absorb fluids and thus prevent sweat to work as an electrolyte.[8] This might be the explanation in this study as well. Fig. 2 shows that copper-based fabric is rather smooth, and both copper-based fabric and DE Ag form much denser surface than silver-based fabric electrodes, resulting in larger effective contact area and smaller contact resistance.

Copper-based fabric and DE Ag electrodes show higher response than commercial Ag/AgCl electrode. This result is most likely caused by the smaller surface area of the Ag/AgCl electrode than superior performance of the textile electrodes. Ag/AgCl electrode surface area was 79 mm2, whereas the textile electrode surface area was 180 mm2.

As a conclusion, we find these results promising, when considering the next step of our work, which is the integration of the textile electrodes to gloves and socks, to move towards daily-life EDA measurements. An interesting future topic is to test if these measurement clothes can be used for measuring EDA from children, who are often challenging to measure in clinical and experimental setups.

IV. Conclusion

The aim of this study was to develop electrodes for skin conductance measurement that can be integrated as an invisible and obstruction-free part of clothing. We developed and tested copper and silver-based fabrics and two embroidered electrodes having different surface structure. Based on the achieved results, both fabric-based and embroidered electrodes can be considered functional. This is promising, considering their easy fabrication and low cost.

Stimulus response of skin conductance could be measured with all the electrodes, but copper-based fabric and densely embroidered silver thread electrodes showed the best behavior. The data indicated that the most significant factor affecting the electrode behavior was the electrode to skin contact resistance. The best electrodes had the densest surface structure resulting highest contact area and thus lowest contact resistance. All of the tested textile electrodes had consistent response compared to a reference electrode and can be easily integrated to clothing.

The next step is to integrate these textile electrodes into gloves and socks and carry out EDA measurements on female and male adults as well as on children. A larger number of people will be measured to achieve enough data for a statistical analysis. These clothes will have the look and feel of normal clothing, which will enable EDA measurements in the daily life. This would open the door for versatile health and well-being applications, such as monitoring sleep and stress at home and at work.

Acknowledgment

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