Flexible and Printed Electronics

Integrated dry PEDOT:PSS electrodes on finished textiles for continuous and simultaneous monitoring of electrocardiogram, electromyogram and electrodermal activity

Integrated Dry PEDOT:PSS Electrodes on Finished Textiles for Continuous and Simultaneous Monitoring of Electrocardiogram, Electromyogram and Electrodermal Activity

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Abstract

Herein, screen printed electrodes prepared from commercially available conducting polymer poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) have been shown to record simultaneous Electromyogram (EMG), electrocardiogram(ECG), and Electrodermal activity (EDA) from a spandex t-shirt sleeve in dry state. Secondly, electrodes printed on an arm sleeve recorded EMG during muscle contraction and were compared to commercial Ag/AgCl electrodes that use hydrogel. Thirdly, the printed electrodes have been shown to be stable to 10 washes with detergent and 10 dry cycles upon treatment with commercially sold fabric protectors with ECG signals being recorded in underwater conditions from wrist. Lastly, EDA was measured from fingers by recording changes in skin conductance brought about by cognitive stress. This use of integrated sensors on a t-shirt provides a tool for continuous and simultaneous measurement of vital signals in at-risk patients.

Keywords: e-textiles, conducting polymer, wearable electronics, health monitoring, integrated sensors
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Introduction

Non communicable diseases constitute around 73% of all global mortality.[1] Continuous health monitoring is important for patients in need of critical care. Electrocardiogram (ECG),Electromyogram (EMG) and Electrodermal activity (EDA) are some for the techniques for measurement of vital signs from the human body. While ECG measures the magnitude of cardiac vector as heart pumps blood, EMG measures electrical currents generated in muscles during their contraction and represents neuromuscular activities.[2] EDA measures the changes in electrical conductance of the skin resulting from autonomic innervation of sweat glands. Electrodermal activity (EDA) has gained interest for assessing sympathetic dynamics because sweat glands are only innervated by sympathetic nerves. Traditionally, Ag/AgCl electrodes have been used for measuring electric signals from various parts of the body. Ag/AgCl electrodes are accompanied with an electrolyte rich hydrogel and an adhesive to reduce skin contact impedance and lower motion artifacts, respectively.[3] Attempts have been made to integrate Ag/AgCl electrodes into textiles to combine the breathability of the fabric with the functionality of the electrodes, but they suffer from poor signal quality and loss in signal over long usage due to drying of hydrogel.[4]

Recently, researchers have focused on alternative materials and coating methodologies for acquiring biopotential measurements. Some of the novel materials include silicon nanomaterials[5,6], metals [7,8], carbon materials such as graphene and carbon nanotubes(CNT)[10,11], pressure sensitive adhesives[12], polymer nanofibers[13] and carbon black[14]. Nanomaterials such as graphene have been coated by chemical vapor deposition and transfer printing in a multistep fabrication process onto a tattoo and have been shown to record electromyogram from forearm.[15] Besides recording biopotential signals, functional coatings on textiles have been recently shown as strain sensors on stretchable textile substrates.[16]

Conducting polymers are polymers that are intrinsically conducting of both ions and electrons as a result of holes in the backbone of the structure. Poly(3,4-ethylenedioxy):polystyrene sulfonate (PEDOT:PSS) is one of the most successful conducting polymers sold as an aqueous dispersion. PEDOT:PSS has been reported to conductivities up to 5000 S/cm as thin film coatings on glass substrate.[17] PEDOT chains are ionically bound with negatively charged PSS ; phase separation of PEDOT chains from PSS makes it more conducting.[18] Also, sulfonic acids are present in excess in PSS making it water dispersible. This provides the unique opportunity of exploiting the chemistry of sulfonic acids with different functional groups that may be present on the substrate. Fillers such as silica are a ubiquitous part of textiles as delustering agents, which have free silanol groups present capable of performing condensation reaction with sulfonic acids of PSS.[19] PEDOT:PSS coatings when coated on textile have been shown to have very low sheet resistances and high ampacity. Furthermore, PEDOT:PSS can be made to function as different elements of a circuit with current carrying capacities approaching that of copper.[20] Similar chemistry between silanol groups of a dispersant and hydroxyl groups of cotton fiber has been used to immobilize graphene and multiwalled carbon nanotubes (MWNT) resulting in coatings stable to multiple wash cycles. [21] Since, PEDOT:PSS is capable of carrying both ionic and electronic current, it has been explored as a viable candidate for biopotential electrodes.[22–25] Some of the other applications of PEDOT based conducting textiles include resistive heaters , thermoelectric generators and strain sensors.[26,27]PEDOT:PSS has been demonstrated to function as EXG sensor (X=C,E,M) in different applications.[23–25] Textile based electrodes, therefore offer alternative to traditional electrodes in that it combines both the breathability of the fabric with functionality of sensor. More recently, reactive vapor deposition of conducting polymers on textiles have been used to fabrication of organic electronic devices.[28,29] PEDOT:PSS based organic electrochemical transistors (OECTs) have also garnered significant attention in recent years owing to its low operating voltage, high transconductance, and biocompatibility.[30]

In this paper, a pair of electrodes containing PEDOT:PSS coatings has been shown to record EMG, ECG and EDA signals from the forearm thus making the design universal and versatile in recording signals. Herein, we describe in detail the feasibility of using PEDOT:PSS electrodes as EMG electrodes followed by testing the same set of electrodes for recording ECG and EDA signals from the wrist and fingers, respectively.

Experimental Section

Materials

PEDOT:PSS-Clevios PH1000 was obtained in a colloidal form (with a solid content of 1.25 wt %) from Heraeus. Dimethyl Sulfoxide (DMSO) was obtained from Sigma Aldrich and used without any further purification. Ag/AgCl snap buttons for biopotential measurements were obtained from commercial sources, and nonwoven polyethylene terephthalate was obtained from Nike Fabrics. Ag/AgCl chloride was obtained from Vermed Corporation, U.S.A. A Speedball™ screen printing setup was obtained from Jo-Ann Fabrics. Spandex compression sleeve and t-shirt was obtained from a local store.

Screen Printing of PEDOT:PSS:

A formulation containing 95% Clevious PH 1000, 5% DMSO concentrated to 40% of its original weight by evaporating water at 60 °C for 6 hours. The solid content of the formulation was measured using thermogravimetric analysis (TGA). Screen printing was carried out using a Speedball™ screen with a nylon mesh of mesh count 110, and the squeegee was held at 45° using a custom-made holder. The printing speed was approximately 50 mm/sec.

Electrical characterization:

The sheet resistance of the PEDOT:PSS coated textile sample was measured using a 4-line setup consisting of a Keithley 224 programmable source (I_{max}=101 X10^{-3} A), a Keithley 2700 multimeter, and a custom-made four-line probe cell. The sheet resistance was calculated using the equation: $R_s = R\frac{w}{l}$, where *R* is the resistance obtained from slope of the I-V curve, *w* is the width of the sample, and *l* is the distance between the electrodes. Skin contact impedance was measured using a Hioki IM3570 (Hioki E.E. Corp, Nagano, Japan) with electrodes placed on the arm. The impedance spectra of completely soaked PEDOT:PSS fabric was recorded using a Gamry Potentiostat in the frequency range of 100 mHz–1 MHz, starting with the highest frequency.

Fabrication of electrodes:

The screen printed formulation obtainedfrom evaportation of PEDOT:PSS was used to make EMG electrodes. The concentrated formulation was printed onto 2.2 cm x 3.8 cm fabrics swatches, allowed to dry in air for 30 mins and then annealed in an oven at 110 °C for one hour. The annealed fabrics were then connected to Ag/AgCl snap buttons for input to EMG amplifier. To demonstrate practical usage during exercise, the EMG electrodes were printed onto a commercially available compression sleeve with 84% polyester content. The fabrics were first allowed to dry in air for 30 mins at 25 °C and then annealed in an oven at 110 °C for one hour. The same electrodes were used for recording EDA and ECG. Scotchgard Fabric & Upholstery Protector (3M) was sprayed on both sides of the electrode from a distance of 15 cm and the samples were dried at room temperature for 12 h before washing and underwater experiments. A similar process was used to make electrodes on an arm sleeve and t-shirt.

Protocol for EMG measurement:

N=4 subjects were enrolled to take part in this test and oral consent was obtained from them. The experiments were carried out in a quiet, comfortable room (ambient temperature 26-27 °C, relative humidity between 30-50%). To ensure accurate comparison between the electrodes, simultaneous measurements were recorded. To do this, PEDOT:PSS printed electrodes and Ag/AgCl electrodes were placed side-by-side. Surface EMG (sEMG) measurements are largely dependent on location since proximity to the muscle has a great effect on signal strength. Hence, to eliminate any benefit from being on either side, the printed electrodes and the Ag/AgCl electrodes were assigned a lateral position that alternated from subject to subject. Details of the protocol and signal processing have been discussed in Supporting Information S3.

Protocol for EDA measurements:

For procuring a fair comparison, skin properties were kept as constant as possible by measurements being performed on a single subject. To evaluate the signal performance a cognitive stress in the form of Stroop test was performed. Five minutes of baseline measurements were also recorded before the start of the Stroop test. The experiments were carried out in a quiet, dimly lit room (ambient temperature 26–27 °C), to avoid other stimuli. A tablet-PC version was used for the Stroop task. A widely used standardized stimulus that induces cognitive stress on humans was used to assess the responsiveness of text EDA electrodes, because it is proven to excite the subjects' sympathetic system. For the test, subjects were asked to say loud the color of a word which named a color, to induce cognitive stress. The words and colors were "blue," "yellow," "green," "red," "purple," and "black." The background also changed randomly. The details of EDA instrumentation and signal processing have been provided in Supplementary Information S4.

Protocol for ECG measurement:

One healthy male subject was recruited for this study. Oral consent was obtained from the subject. An ECG monitoring device was fabricated for measuring single lead ECG signals. Each ECG circuit obtained a Lead I signal from the wrist via two electrodes with a virtual right-leg driven circuit. The details of ECG instrumentation and signal processing have been provided in Supplementary Information S5.

Results and Discussion

Electromyography using PEDOT:PSS electrodes

An EMG sensor, with 0.85 mg/sq cm of PEDOT:PSS coating and a sheet resistance of *ca.* 5 ohm/sq using 4-line technique, was fabricated on a commercially finished textile using a screen-printing process. A formulation containing 95% PH 1000 and 5 % DMSO was prepared and reduced to 40% of the original weight for printing. (Figure 1(a)-(b)) The solids of the formulation being estimated using thermogravimetric analysis. (Figure S1, Supporting Information S1) To test the viability of the design, one subject was recruited during exercise. EMG signals were chosen to record from biceps on the right arm with Ag/AgCl, placed adjacent to the PEDOT:PSS printed electrodes, serving as control electrodes. (Figure 1(c)-(d)) Figure 1(e) shows the response of the printed electrodes on sleeve and as the muscle contracts there is an increase in amplitude of the filtered signal. As the muscle is brought back to rest, there is a decrease in the signal from the electrodes indicating inactivity of the muscle cells. No gel was used with PEDOT:PSS printed electrodes and the amplitude of recorded signal was approximately twice when compared to Ag/AgCl electrodes.

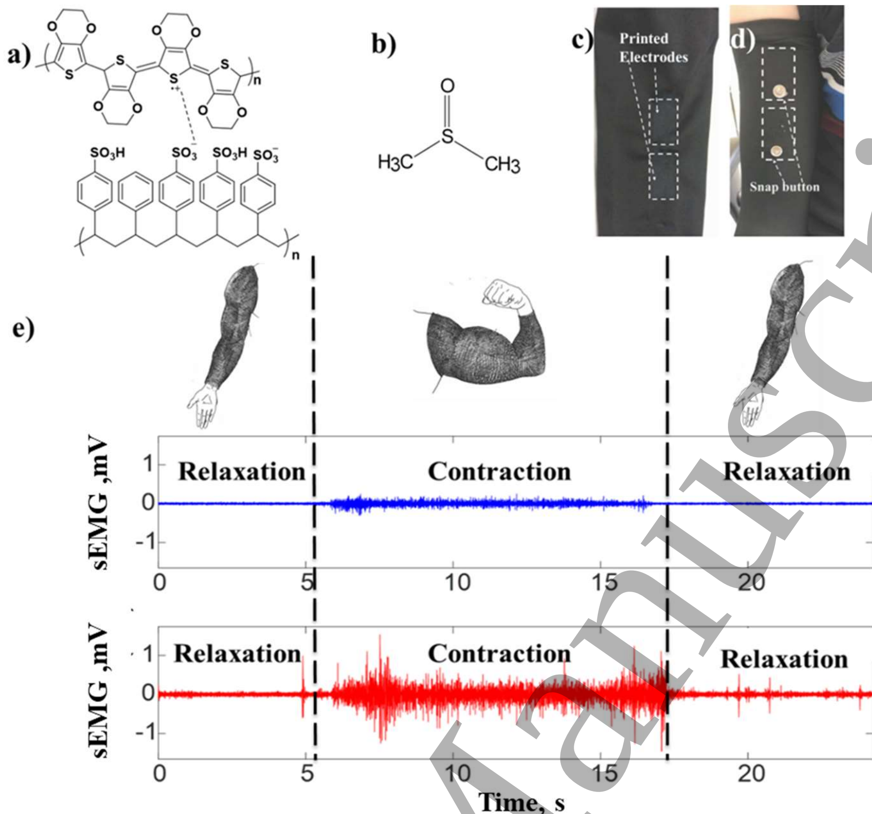

Figure 1: a) Structure of PEDOT:PSS ; b) Structure of DMSO ; c) Printed electrodes on Sleeve; d) Sleeve when placed on biceps; e)EMG signal recorded from Ag/AgCl electrode(blue) and PEDOT:PSS electrode (red).

Conventional EMG uses needle electrodes inserted into the muscle in which the bare tip of the needle electrode is used as a detection surface. Surface electrodes, on the other hand, provide a non-invasive technique for measurement and detection of the EMG signal. These electrodes form a chemical equilibrium between the detecting surface and the skin of the body through electrolytic conduction, so that current can flow into the electrode. Papaiordanidou and coworkers used PEDOT:PSS printed electrodes for recording EMG signal and stimulating muscles using the same electrodes.[19] The electrodes consisted of PEDOT:PSS doped with ethylene glycol coated on a knitted polyester substrate. The electrodes were shown to record EMG signal from tibialis and was able to stimulate tibial nerve to get neuromuscular responses. Both the ECG and EMG electrodes comprised of an ionic liquid gel in a crosslinked polyacrylate matrix and therefore can be considered as wet electrodes. The results from the current study clearly suggest that PEDOT:PSS even in its dry state acts like an ion-electron transducer most likely as a result of hydrophilicity of PSS which helps in transport of ionic current from the body to the electrode.[31]

To further understand the signal amplitude, PEDOT:PSS electrodes were used to study the electric responses of four different muscles i.e. biceps, triceps, tibialis, and quadriceps. Figure 2(b) shows the responses of different muscles in dry skin condition from a subject. An elastic strap was used to hold the PEDOT:PSS electrodes in place with same pressure on PEDOT:PSS and Ag/AgCl electrodes. With exception to biceps in contraction, the EMG responses from the dry state PEDOT:PSS electrodes were comparable to Ag/AgCl electrodes with hydrogel. The signal-to-noise ratio(SNR) of printed electrodes were lower possibly due to improper skin contact since there is no adhesive to hold the electrodes in place during muscle movement. For the SNR calculation, it was assumed that noise had a constant power density over the frequency region of interest in EMG recordings, and that no power related to muscular activity falls beyond 400 Hz. Based on this, the power was calculated for the frequency range above 400 Hz and was summed over the whole frequency range as an estimation of noise power. The SNR was calculated as the ratio of the total power to the estimated noise power. Table 1 summarizes the results obtained from two electrodes from different muscles being tested.

Table 1) EMG results Ag/AgCl electrodes and PEDOT:PSS coated textile obtained from 1 subject.

Muscle	Activity	Amplitude, mV		SNR, dB	
		Ag/AgCl	PEDOT:PSS	Ag/AgCl	PEDOT:PSS
Biceps	**Relaxation**	11.9	34.4	72	35
	Contraction	32.8	91.2		
Triceps	**Relaxation**	13.5	164	73	39
	Contraction	56.6	302		
Tibialis	**Relaxation**	10	27.6	74	33
	Contraction	57.9	38.4		
Quadriceps	**Relaxation**	9.18	11.3	74	57.5
	Contraction	30.6	39.6		

Skin contact impedance obtained from the same subject reveals approximately one order higher amplitude of PEDOT:PSS electrodes compared to Ag/AgCl electrodes with hydrogel indicating contact impedance is not significant for EMG results.(Figure S2 , Supporting Information S2) Similar results were obtained by Posada-Quintero and coworkers who found that addition of salt to carbon based electrodes resulted in decrease in skin contact impedance but did not affect the EMG signal amplitude.[32]

A closer look from the signals obtained from experiments gives different correlation factors. (Table 2) Textile based electrodes suffer from high motion because of lack of adhesive which would otherwise keep it in place. Signal-to-motion artifact ratio (SMR) is a measure of how a signal is affected by minor changes of position of electrode brought about by movement of body. The estimation of the SMR is based mainly on the assumptions that the frequency of motion-induced artifacts of the signal stays well below 20 Hz, and that the shape of the non-contaminated

EMG power spectrum is fairly linear between 0 and 20 Hz [33]. For this reason, the motion artifacts' spectral power is mixed in with the true signal dynamics at frequencies between 0 to 20 Hz. The motion artifacts' power can be fairly estimated by summing the PSD area below 20 Hz that exceeds a straight line between the origin and the highest mean power density [33]. SMR was computed as the sum of the area under the Power spectrum deformation (PSD) for all frequencies divided by motion artifact power. In this study, the SMR ratio of PEDOT:PSS electrodes is lower than that of Ag/AgCl chloride indicating the need of keeping the electrodes in place.

The drop in power (DP) ratio is an indicator of whether the spectral frequency contents of interests are adequately peaked and is sensitive to the signal's amplitude. For computing DP ratio, the mean PSD was computed by averaging a spectral window length of 12.7 Hz. The highest mean PSD was defined as the largest mean PSD value within 35 Hz to 500 Hz. The DP ratio was obtained as the quotient between the highest and lowest mean PSD values. We computed Ω ratio in terms of spectral moments, as follows [34]:

$$\Omega = (M_2/M_0)^{\frac{1}{2}}/(M_1/M_0),$$

$$\text{where } M_n = \sum_{i=0}^{i_{max}} power\ density_i \cdot frequency_i^n$$

The DP obtained is higher for printed PEDOT:PSS electrodes indicating that electrodes are more sensitive to detecting the absence of EMG activity. Power spectrum deformation (PSD,Ω ratio) is sensitive to changes in symmetry and peaking of the PSD and to additive disturbances in the high- and low-frequency regions. This index identifies all dynamics of spectral changes except those caused by pure translations along the frequency axis. In this manner it adapts to myoelectric changes due to muscle fatigue but not to additive disturbances. The power spectral density (PSD) of each EMG signal was calculated using Welch's periodogram method with 50% data overlap.

A Blackman window of 256 data points was applied to each segment and the calculated the Fast Fourier Transform for each windowed segment. The power spectra of the segments were then averaged. The PEDOT:PSS electrodes show almost double the value than that of Ag/AgCl electrodes indicating it is more likely to suffer from signal contamination during muscle fatigue. Therefore, there are significant challenges with fabric based electrodes and need to be evaluated further for fabrication of better electrodes.[35]

Table 2) Signal Parameters of EMG obtained from textile electrodes from 1 subject.

Parameter	Biceps	Triceps	Tibialis	Quadriceps
SM ratio (Ag/AgCl)	0.008	0.017	0.015	0.007
SM ratio (PEDOT:PSS)	0.041	0.049	0.038	0.007
DP ratio (Ag/AgCl)	37	27	43	37
DP ratio (PEDOT:PSS)	66	79	63	54
Ω ratio (Ag/AgCl)	4.1	4.7	4.2	4
Ω ratio (PEDOT:PSS)	7.7	4.3	7	7.1

Washability of PEDOT:PSS electrodes

Washability is an important factor in commercially sold wearable electronic device. PEDOT:PSS based coatings have been shown to be hydrophobic with coating of fluorochemicals either by spraying commercially sold fabric protectors or through modification of substrates.[20,28] The fluorinated side groups migrate to the surface resulting in increase in water contact angle and resistance to chemicals.[36] One of the most successful coatings is Scotchgard^{TM} coating and has been used as a protective layer for textile surfaces.[37] EMG signal was first acquired using

PEDOT:PSS coated electrodes which showed similar amplitudes from the four different muscles. The skin contact impedance was found to be slightly higher than PEDOT:PSS electrodes with no hydrophobic coating On further examining the electrode impedance using impedance spectroscopy, it was found that hydrophobic coating does not affect the electrode impedance significantly although an increase in electrode impedance was seen.(Figure S2 , Supporting Information S2) . The hydrophobic coating used in this study is composed to perfluorinated compounds and comprises of many the carbon-fluorine bond which is polarizable and has been found to be responsive to electric field. As an example, PVDF has been reported as a piezoelectric sensor for cardiorespiratory applications.[38] Therefore, it is safe to assume that the fluorinated coating will not affect the electrode characteristics of PEDOT:PSS printed electrodes.

Besides, providing a protective coating for the printed electrodes, scotchgard also provides hydrophobicity to the electrodes. Guo and coworkers tested the washability of PEDOT:PSS wires printed on PET and found that wires coated with this hydrophobic coating have loss of resistance of *ca.* 6% after 3 cycles of wash and dry.[20] Ryan and coworkers coated silk fibers with PEDOT:PSS using exhaustive dyeing and found it stable to 4 wash cycles. The electrostatic interaction of silk with PEDOT:PSS was attributed to its excellent wash and wear resistance.[39] In a similar way, the PEDOT:PSS electrodes were coated with Scotchgard and washed to different extent. Figure 2(d) shows the change in signal amplitude obtained from biceps with both scotchgard and normal electrodes after 10 washes with commercially available detergent. A slight increase in amplitude of PEDOT:PSS electrodes is seen after 1 wash most likely due to residual salts from the detergent. The signal amplitude plateaus after 4 washes for both the control and scotchgard coated electrodes and decreases after 10 washes for control electrodes. The scotchgard coated electrodes continued to plateau after 10 washes indicating excellent wash stability, though abrasion in coatings was seen after 10 washes (Figure 2(e)). The results pave way for designing hydrophobic coatings for extended usage without loss in signal quality.

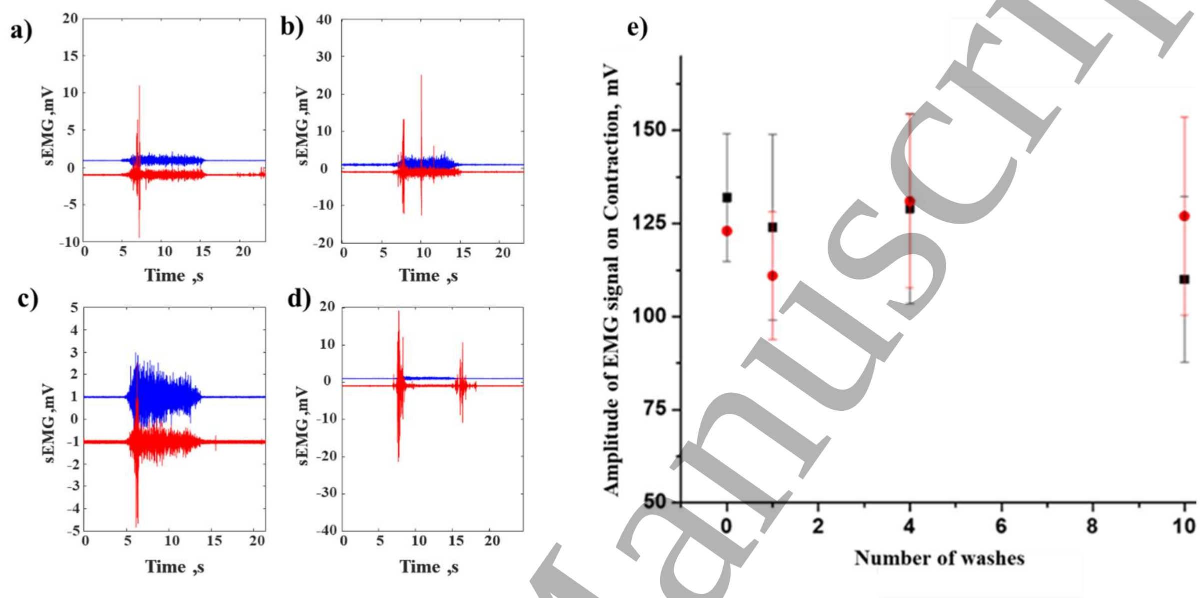

Figure 2: EMG signal recorded from Ag/AgCl electrode(blue) and PEDOT:PSS electrode (red): a) biceps, b) triceps, c) tibialis, d) quadriceps; e) Variation of EMG signal with number of washes of PEDOT:PSS electrode (black square) and scotchgard coated PEDOT:PSS electrode (red circle).

Electrodermal Activity using PEDOT:PSS electrodes

EDA data shown in Figure 3 (a) and Figure 3 (b) was collected from one subject in periods of resting and performing the Stroop task. Elevation of level of EDA as well as increased phasic shifts of the signal have been associated with higher cognitive stress faced by the subjects . Same behavior has been observed in this experiment. Figure 3(c) and Figure 3 (d) shows the ensemble average of individual skin conductance responses elicited in the study, normalized to the power of the signal collected with the reference electrodes. As shown, the electrodes with 3 layers (0.85

mg/cm^2) of coating exhibited higher average amplitude of skin conductance responses than 1 layer of coating (0.57 mg/ cm^2). This is desirable, as the phasic (i.e. higher frequency) components bear useful information for detecting concussion, fatigue, among others.[40–42]Phasic components of EDA are known to be evoked by central (hypothalamus, medulla) or peripheral (pre- and postganglionic peripheral nerve) mechanisms [43]. Indices derived from the phasic components of EDA have been found to be linked to vigilance and attention [44], whereas lower frequencies index have been linked to reactiveness [45]. Furthermore, a classic study found that phasic responses of EDA are elicited by stimulus novelty [44]. Recently, the power of EDA in the range 0.045 to 0.25 Hz was found to be highly sensitive to cognitive stress [46].

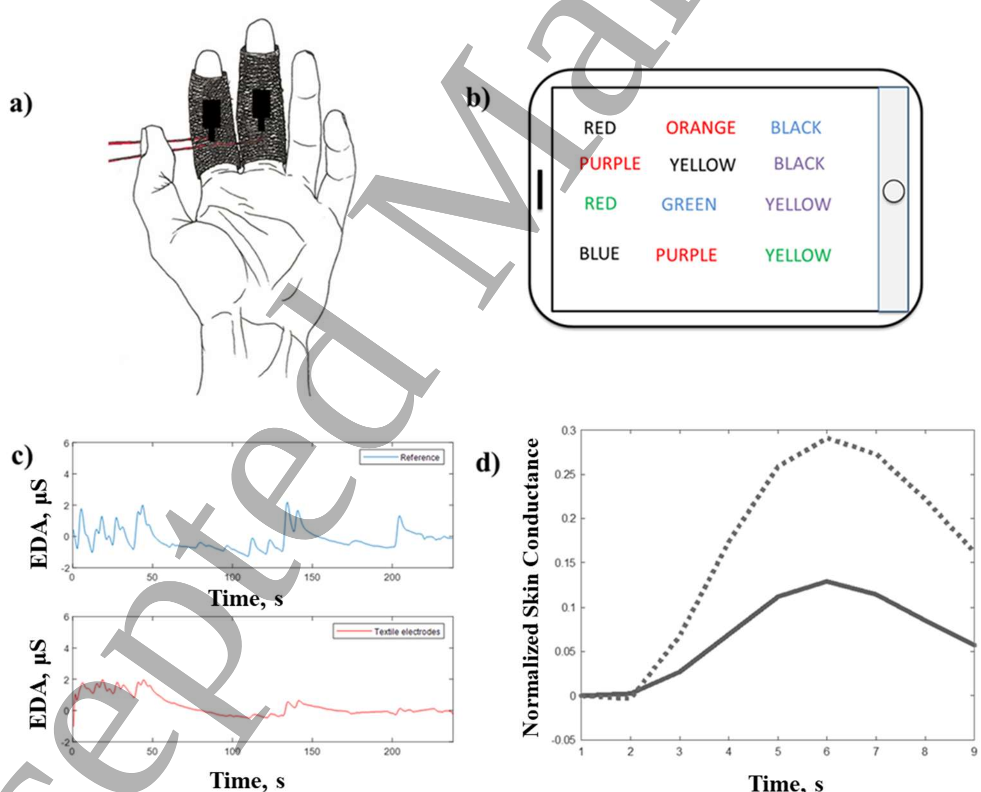

Figure 3: a) Placement of electrodes on fingers for EDA signals; b) An example of Stroop test; c)EDA responses obtained from 1 layer of PEDOT:PSS coated electrodes(red) and stainless steel reference

electrodes (blue); d) Normalized skin conductance response obtained from 1 layer(solid line) and 3 layers of coated PEDOT:PSS electrodes(dotted line).

Electrocardiography using PEDOT:PSS electrodes

Electrocardiography is a technique used for measuring the magnitude and direction of cardiac vector and has been used for detection of abnormalities in cardiovascular activity. ECG signals have been recorded from electrodes placed on various parts of the test. Since, the heart sets up different cardiac potentials all over the body, it is possible to record ECG signals from the wrist as well. In this study, the PET coated electrodes which were used to record EMG and EDA signals were also used to ECG signals. Figure 4 (a) and figure 4(c) shows the raw signal obtained from both PEDOT:PSS electrodes and scotchgard coated PEDOT:PSS electrodes. To test the feasibility of recording ECG signals in wet conditions, the electrodes placed on wrist were exposed to running water resulting in successful gathering of ECG signals. The SNR of the measurements was *ca.* 44.8 dB for all the measurements, however the amplitude of the signal obtained during dry conditions was higher than that obtained during underwater testing. This result paves a direction for recording biopotential signals from hydrophobic conducting textiles making it possible for application in underwater monitoring.

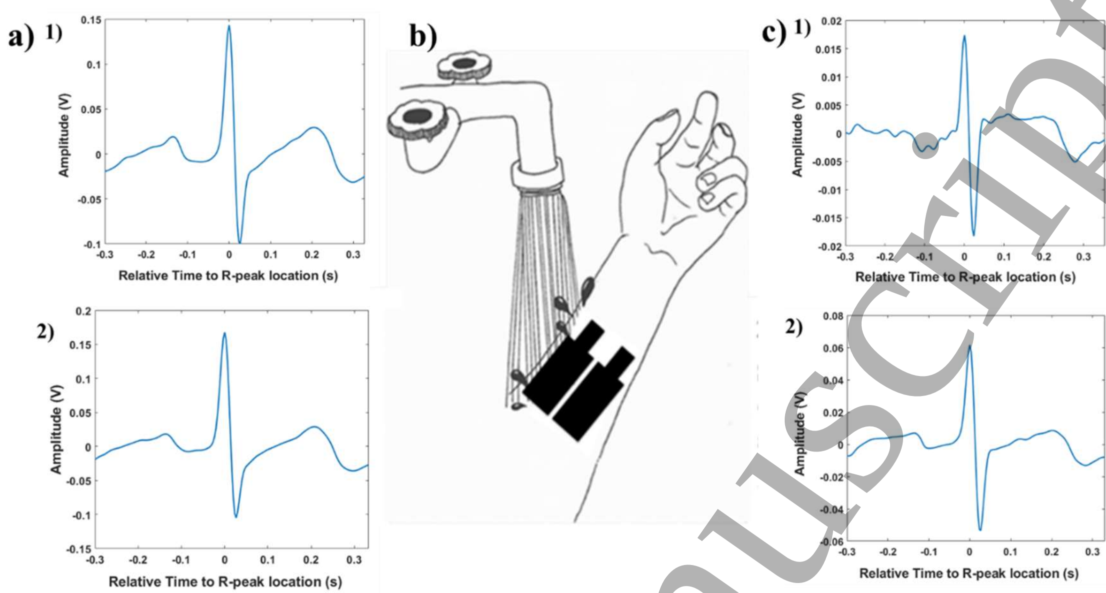

Figure 4: a) ECG signals recording from 1) PEDOT:PSS and 2)Scotchgard coated PEDOT:PSS electrodes from wrist ; b)ECG signals being recorded in underwater conditions; c) ECG signals recording from 1) PEDOT:PSS and 2)Scotchgard coated PEDOT:PSS electrodes from wrist in underwater conditions.

Simultaneous Measurement of ECG, EMG and EDA

Having demonstrated that PEDOT:PSS electrodes can be used to measure different signals emanating from the body in the form of ECG, EMG and EDA, an attempt was made to record all the three signals simultaneously from the body. It has been demonstrated that screen printed PEDOT:PSS electrodes can be used to record ECG from t-shirt and sleeve in this study can be made to record EMG on biceps, an attempt was made to combine the two measurements. PEDOT:PSS electrodes were printed on the body of the t-shirt, left sleeve and right wrist as ECG , EMG and EDA electrodes The signals were recorded simultaneously from one subject which under different conditions as shown in Figure 5.The analysis of the signals can be found in Supporting Information S6. ECG was recorded when the biceps undergo contraction and relaxation as well as during a Stroop test. Simultaneous EDA and EMG testing was also performed with ECG being recorded the whole time. By using a single t-shirt to record the various biosignals emanating from body, an integrated sensor system based on PEDOT:PSS has been developed which is capable of recording both physical and cognitive stress. Since, EDA measures the activity of the autonomic nervous system and EMG and EDA measures the activity of heart and muscle, the current system could provide the activity of the autonomic nervous system under exercise stress which can lead to better guidance and interventions to improve human health and performance. Once such application is for continuous monitoring of seizures in epilepsy patients. Epilepsy is a non-communicable disease where in the patient suffers from seizures on a regular basis. Seizure detection studies have focused on detecting physiological changes that occur before and during a seizure. Such as increased cerebral oxygen levels, alteration of movements, heartrate changes, electrical activity in muscles and changes in galvanic skin resistance. It has been shown separately that tonic-clonic seizures in epilepsy patients results in increase in skin conductance (measured by EDA),contraction of muscle (measured using EMG) and changes in heart rate (measured by ECG). [47–49] Therefore, integrated sensors on textiles provides a tool for continuously monitoring the conditions of at-risk patients especially patients suffering from epilepsy.

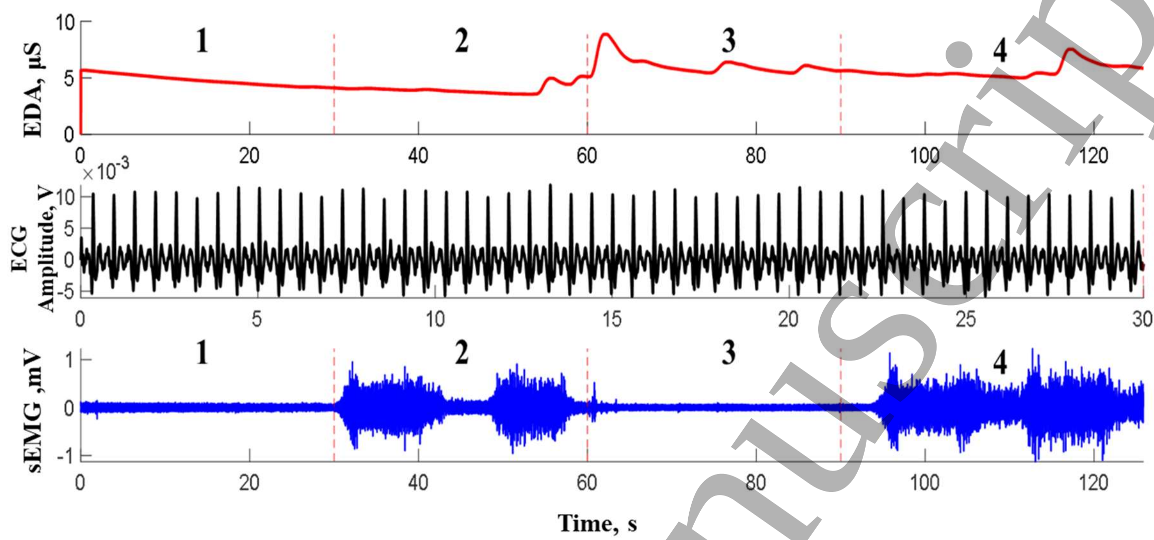

Figure 5: EDA signals (red) ,ECG signals (black) EMG from biceps (blue) from a single t-shirt under different experimental conditions. 1) At rest, 2) Muscle Contraction, 3) Stroop test, 4) Simultaneous Muscle Contraction and Stroop test.

Conclusion

Herein, PEDOT:PSS based EMG electrodes has been demonstrated in a dry state on a commercially sold spandex arm sleeve using screen printing process. A detailed study was carried out to understand the signal characteristics obtained from four different muscles in the body with PEDOT:PSS electrodes showing marginally higher signal amplitude than Ag/AgCl electrodes and lower signal-to-noise ratio. PEDOT:PSS electrodes were made hydrophobic via scotchgard coating and shown to be stable to 10 accelerated wash and dry cycles. Additionally, PEDOT:PSS electrodes have also been shown to record EDA and ECG signals from the wrist. Finally, a prototype t-shirt was fabricated which recorded ECG,EMG and EDA together under simultaneous cognitive stress and exercise. This easy-to-fabricate metal-free skin conformable electrodes could find application in continuous health monitoring as well as physiotherapy.

Conflicts of interest

There are no conflicts to declare

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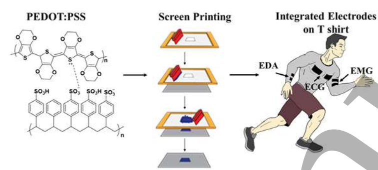

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