ESD wrist strap-based EDA sensor cum ESD strap integrity monitor

Ashish Joglekar
Robert Bosch Center for Cyber Physical Systems
Indian Institute of Science
Bangalore, India
ashishj@iisc.ac.in

Gaurav Bhandari
RBCCPS
Indian Institute of Science
Bangalore, India
gauravbhandari11@gmail.com

Rajesh Sundaresan
Electrical Comm. Engg. and RBCCPS
Indian Institute of Science
Bangalore, India
rajeshs@iisc.ac.in

IECON 2021 - 47th Annual Conference of the IEEE Industrial Electronics Society | 978-1-6654-3554-3/21/$31.00 ©2021 IEEE | DOI: 10.1109/IECON48115.2021.9589358

***Abstract*—Workers on Electronic Manufacturing Service (EMS) assembly lines are exposed to a high degree of occupational stress and fatigue. There is a need for assistive technologies to limit worker stress/fatigue. Electro Dermal Activity (EDA) (Skin Conductance) is a known indicator of a worker's stress/fatigue level. We propose a novel Electrostatic Discharge (ESD) wrist strap-based EDA sensor. Our sensor seamlessly integrates with the dual-wire grounded ESD wrist strap that EMS operators are mandated to wear. Our approach for EDA measurement is non-intrusive, considering that the operators are accustomed to continuous usage of ESD wrist straps. Besides EDA measurement, our front-end circuit also monitors the integrity of the ESD wrist strap and alerts the wearer in the event of an intermittent or open ground. We present the circuit design and stress-test-based experimental results.**

***Index Terms*—Electrodermal Response, Fatigue, Occupational Stress, Static Charge, Wearable Electronic Devices**

I. Introduction

Workers engaged in Electronics Manufacturing Services (EMS) are at risk of exposure to occupational stress due to long working hours, strict deadlines and sleep deprivation [1]. Stress and fatigue lead to operational errors, reworking, and occupational injury. To ensure healthy working conditions, workers on assembly lines and manual soldering workstations should take timely breaks to avoid stress or fatigue. However, workers may not realize that they are stressed or fatigued. Automated alerts and interventions that help workers manage stress are therefore needed.

Work related fatigue affects a number of human physiological and psychological factors [2], [3]. An indicator of stress/fatigue is Electrodermal Activity (EDA), a physiological signal that is used in stress and fatigue research [4], [5], [6]. EDA is categorized into EDL (Electrodermal Level, also called tonic phenomenon) and EDR (Electrodermal Response, also called phasic phenomenon) [4], [7]. Electrodermal Level is the baseline level of skin conductance in the absence of a stimulus. Electrodermal Response is often attributed to stress stimuli that produce phasic responses. For example, a stress stimulus resulting in $> 0.03\mu S$ increase in skin conductance is flagged as an EDR [8]. Electrodermal Activity signals have

This work was supported by MHRD, SERB IRRD of DST, and TCS under UAY grant number IISc001

Fig. 1. EDA-cum-ESD sensor

good fidelity in a temperature- and humidity-controlled environment like an EMS facility. Wearable devices and sensors that measure EDA between two conductive surfaces in contact with the skin are available, see [9].

However, any assistive device for measuring EDA should be non-intrusive. The technique should not require the placement of additional wearable devices on the worker's body. Noting that every operator on the electronics manufacturing line is mandated to wear an electrostatic discharge (ESD) prevention wrist strap, we propose an EDA sensor that integrates seamlessly into the ESD protection device. Given that the workers are already accustomed to wearing the ESD wrist strap, our integrated EDA sensor will neither cause additional worker discomfort nor interfere with the worker's actions. See Fig. 1 for a prototype of our EDA sensor cum ESD wrist strap integrity monitor (henceforth ESD-cum-EDA sensor).

While the recommended sites for exosomatic EDA measurement are fingers, palms or inner side of foot [4], EDA can also

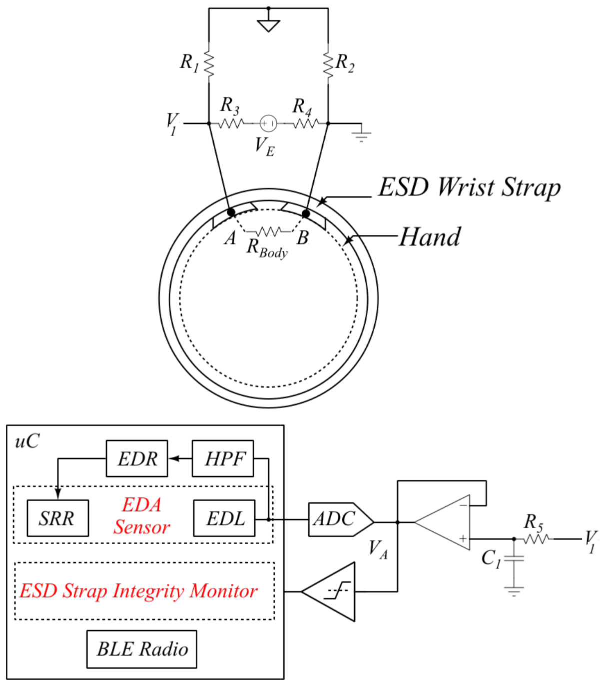

Fig. 2. Schematic of proposed EDA-cum-ESD sensor

be picked up on the wrist's volar surface [4]. Indeed, as per [9], EDA measurement on the wrist provided a cleaner phasic response than those at the fingers. This justifies our integration of EDA measurement with ESD wrist straps.

Electrostatic Discharge Standard [10] recommends the use of continuous wrist strap integrity testers. Single- and dual-wire ESD wrist strap integrity testers are available in the market. Dual-wire ESD wrist strap integrity testers may use DC voltage or AC voltage or constant current excitation [11], [12]. Electrodermal Activity measurements also require an excitation source [13]. We have adopted a common DC voltage excitation source for both ESD integrity testing and EDA measurement.

Our design alerts the wearer not only when there is an intermittent or open ground but also when the worker is stressed. The integrated device can also house additional sensors to monitor skin temperature, heart rate, etc., to become a System-on-Wrist.

The paper is organized as follows. We first describe our EDA-cum-ESD sensor hardware. We then present signatures corresponding to ESD integrity testing. Next, we describe the signal processing steps to extract the EDR from the EDL for stress level assessment. Finally, we present an experimental setup for design validation and discuss the outcomes.

II. Hardware Design

Fig. 2 shows the circuit diagram of our dual-wire EDA-cum-ESD sensor. Dual-wire ESD wrist strap makes a two-point contact with the body (A and B). The skin resistance R_{body} is a measure of EDA. $1M\Omega$ impedances R_1 and R_2 connect the ESD wrist strap to earth. V_E is a 3V DC excitation that is used for a) exosomatic measurement of EDA and b) monitoring the wrist strap's connection integrity to ground. Voltage V_1 is filtered using the R_5, C_1 low-pass filter. After buffering, we get the voltage V_A which is a measure of the voltage across the parallel combination of skin resistance R_{body} and strap resistances $R_1 + R_2$. The voltage is then digitized by an analog-to-digital converter (ADC). The ADC has a 12-bit resolution and samples V_A at the rate $2.5Hz$. (A notch filter to remove line frequency noise may also be introduced in the signal path.) The EDA-cum-ESD sensor connects to a data acquisition system using a Bluetooth Low Energy (BLE) protocol. The voltage V_A is given by

$$V_A = V_E \frac{R_p}{(R_p + R_3 + R_4)} \tag{1}$$

where

$$R_p = \frac{R_{body}(R_1 + R_2)}{R_{body} + R_1 + R_2} \tag{2}$$

If $R_1 = R_2 = R_3 = R_4 = 1M\Omega$ and $V_E = 3V$, then

$$V_A = \frac{3R_{body}}{2R_{body} + (2 \times 10^6)} \tag{3}$$

The impedance R_{body} is an indicator of the wearer's stress level; R_{body} decreases as stress level increases because the induced stress causes sweating that increases the conductivity between the pads A and B. Thus, as per (3), V_A decreases as the stress level increases. The voltage V_A also indicates the state of the ESD wrist strap. If the wrist strap is not in use (i.e., $R_{body} = \infty$) and the connection to ground is intact, then $V_A = 1.5V$. If the wrist strap is not in use ($R_{body} = \infty$) but the connection to the ground is compromised, then $V_A = 3V$. When the wrist strap is in use, with the connection to the ground intact, V_A is given by (3). In the event when an in-use wrist strap disconnects from ground ($R_p = R_{body}$), the measured voltage V_A will instantly step up to $V_A = 3R_{body}/(R_{body} + (2 \times 10^6))$; this will be flagged as an ESD wrist strap ground-open event, and the wearer will be alerted. The comparator shown in Fig. 2 detects the ESD integrity failure event by comparing the voltage V_A with a predefined threshold.

The ESD-cum-EDA sensor hardware, the excitation components, the low-pass filter, the ADC, and the BLE radio were all integrated on a custom PCB and packaged inside the white 3D printed housing shown in Fig. 1.

Fig. 3 shows a family of curves for the voltage V_1 across electrodes A and B over a typical range of skin conductance values. Each curve in Fig. 3 corresponds to a specific value of $R_3 + R_4$. Fig. 4 shows a similar set of curves for the current flow across the skin over a typical range of skin conductance values. An appropriate value of resistance $R_3 + R_4$ is chosen to keep current density in the skin below $10\mu A/cm^2$ as recommended in [14] to avoid damage to sweat glands. Thus, the value of $R_3 + R_4$ depends on the surface area of contacts A and B. For our prototype device, $R_3 + R_4$ was chosen

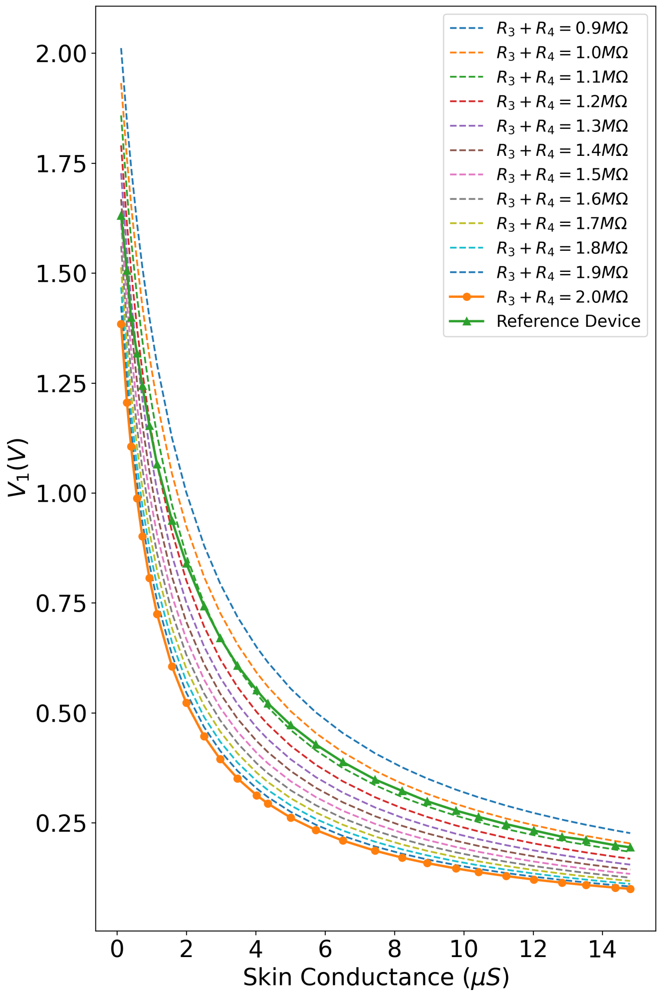

Fig. 3. Comparison of voltage across skin vs skin conductance for different values of $R_3 + R_4$. Also shown is the voltage profile for reference device [14].

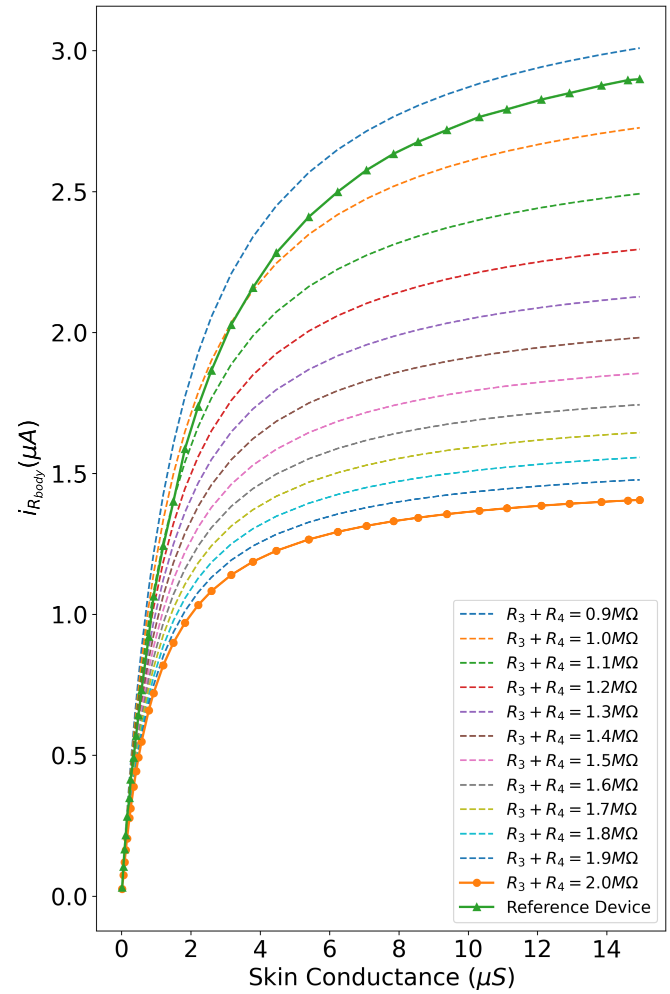

Fig. 4. Comparison of skin current vs skin conductance for different values of $R_3 + R_4$. Also shown is the current profile for reference device [14].

to be $2M\Omega$. The corresponding voltage and current curves for our prototype device are highlighted as solid lines with circular markers in Fig. 3 and Fig. 4 respectively. Also shown are the skin voltage and skin current curves of another EDA measurement device [14] for comparison. These curves are highlighted as solid lines with triangular markers. This device measures EDA using a sleeve with two conductive fabric electrodes. These electrodes make contact with the distal forearm at the wrist. It is clear from Fig. 3 and Fig. 4 that the voltage and current profiles of our device are comparable with those of the EDA measurement device in [14]. For the specific case of $R_3 + R_4 = 2M\Omega$, the magnitude of skin current for our device is lower than that for the reference device in [14]. However, once we consider the surface area of contacts, the value of the average skin current density for our device is still comparable ($< 10\mu A/cm^2$) with that of the reference device in [14].

Devices described in [15] and [16] are commercially available wrist worn wearable devices that measure EDA using two electrodes on their strap. Device in [15] samples EDA at $4Hz$. Device in [14] includes a low pass filter with a cutoff frequency at $1.6Hz$ in the signal path. Our ESD-cum-EDA device samples the EDA signal at $2.5Hz$.

Devices [15] and [16] use a proprietary EDA measurement

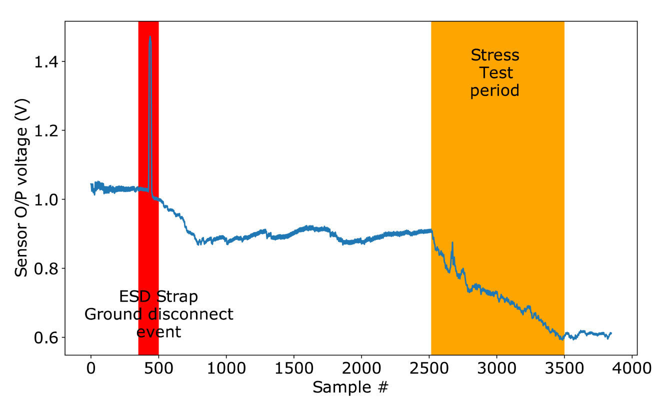

Fig. 5. Detection of ESD strap disconnect from safety earth

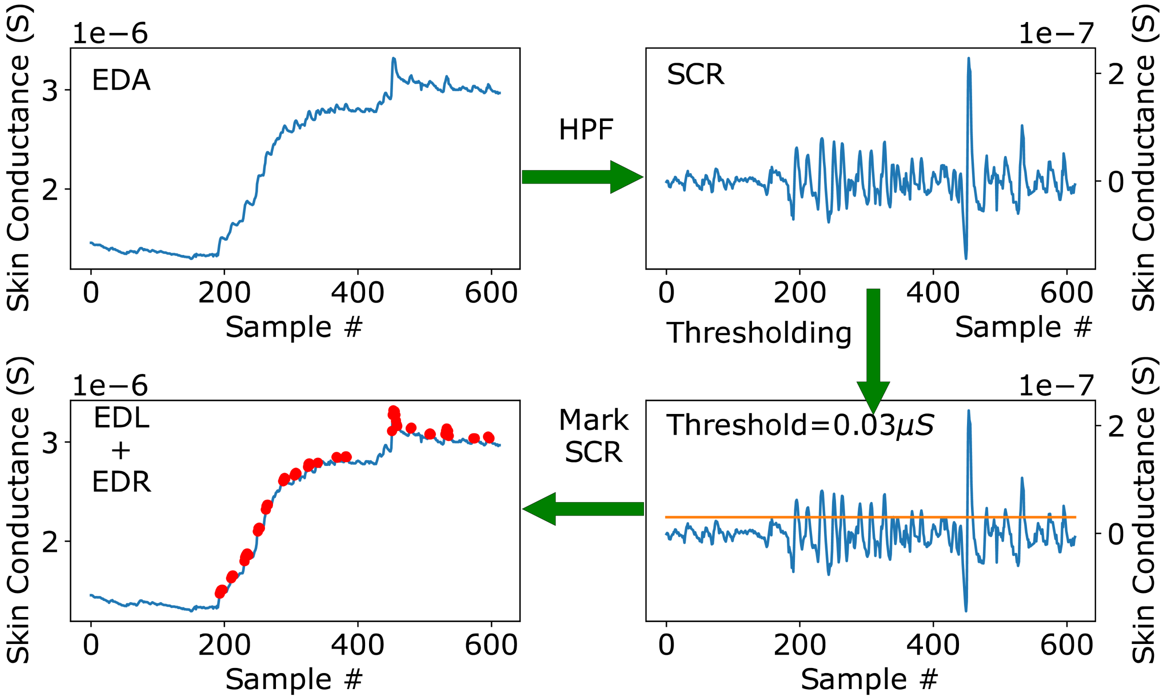

Fig. 6. Algorithm for Extraction of EDR from EDL

frontend [17] with a means to desaturate the output voltage using a compensation current source. Device [14] uses an automatic bias control circuit to improve the resolution in the measurement of Skin Conductance Response (SCR).

III. Continuous ESD integrity tester

The ESD standard [10] recommends the use of continuous wrist strap integrity testers. Fig. 5 shows the voltage signature in the event the wrist strap momentarily disconnects from safety earth. Fig. 5 highlights this event in red around sample 500. The user will be alerted if the voltage V_A crosses a set threshold. Fig. 5 also highlights the start of a stress test in yellow around the samples $2500-3500$. As Fig. 5 is a plot of voltage, the voltage across the two skin contacts falls as the skin conductance increases during the stress test.

IV. Algorithm for Extraction of Phasic Response

There are many algorithms proposed in the literature for the extraction of Phasic Response (EDR) from EDL [6], [8]. There are two primary components of EDA viz. EDL and EDR [4]. The slowly changing baseline level is called the tonic phenomenon (EDL). Skin conductance level (SCL) is a measure of EDL. The fast-changing component is called the phasic response (EDR). Skin Conductance Response (SCR) (or Skin Resistance Response (SRR)) and non-specific Skin Conductance Response are measures of EDR. Fig. 6 shows the steps involved in the extraction of SCR (Phasic response) from the EDA. The EDA signal is passed through a $0.05Hz$ cutoff high-pass filter (HPF) to remove the slowly changing SCL component. The output of the HPF reveals the EDR. The phasic response to external stimuli (SCR) is characterized by a change in EDR that crosses a certain threshold. The threshold is set to $0.03\mu S$, as suggested in [8]. The final plot of Fig. 6 shows the EDR and the EDL. We superimpose the EDR on the EDL as red circular markers.

V. Experimental Stress Test

We placed the EDA-cum-ESD sensor on the wrist of a test volunteer. The strap shown in Fig. 1 is the same type of ESD wrist strap typically worn by workers in an electronic assembly line. The volunteer took deep breaths for 90 seconds to de-stress, which revealed the volunteer's baseline EDL. The volunteer then completed a task in a controlled test setup. We chose a wire loop game for our controlled stress-test task. The setup consisted of a curved serpentine wire and a metal loop, as shown in Fig. 7. The volunteer's task was to maneuver the loop along the curved wire without making contact with

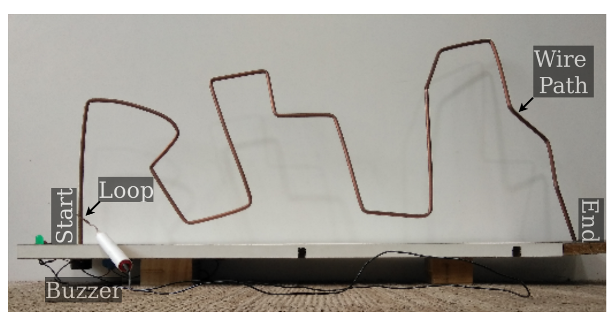

Fig. 7. Experimental stress test setup

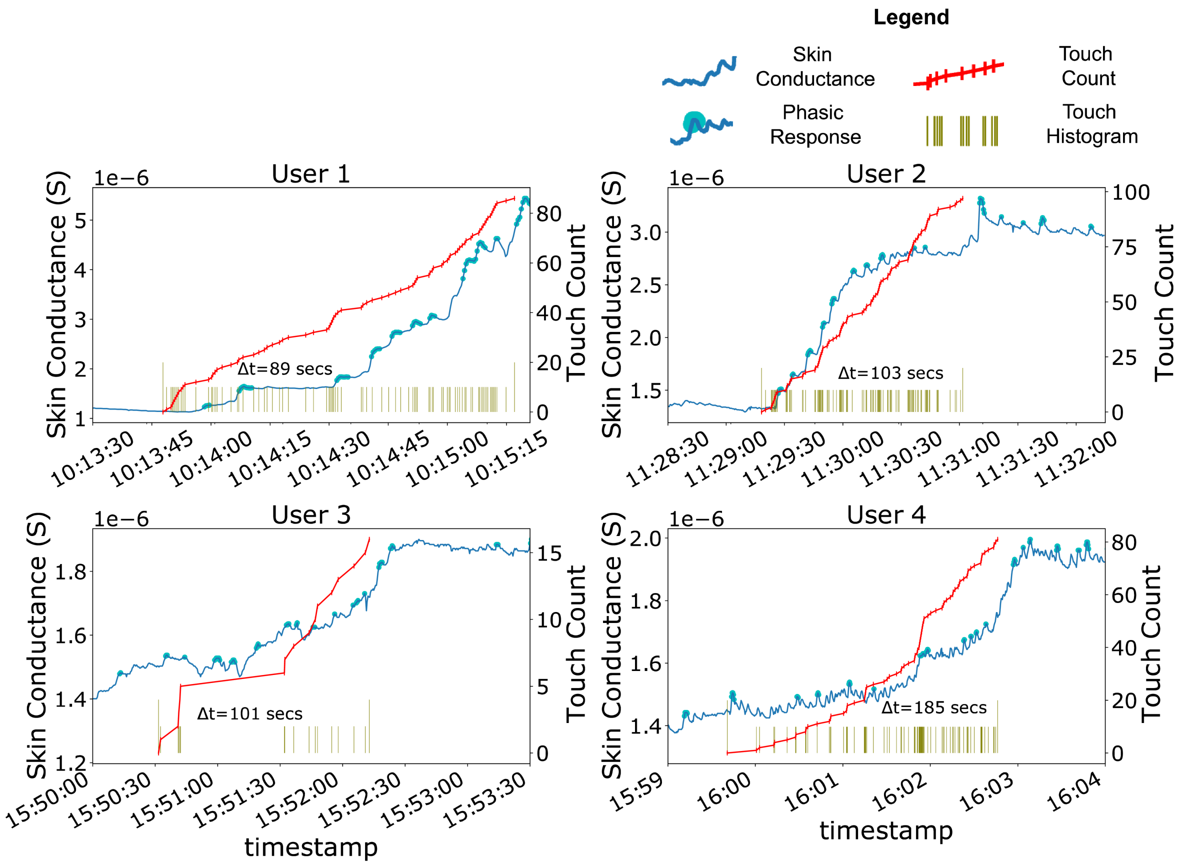

Fig. 8. EDA and performance data for four users collected during the stress test.

the wire. A computerized referee deducted points for every touch, and for the time taken to traverse the wire from start to finish. A loud buzzer would sound upon each contact of the loop with the wire. The stress test helped correlate the phasic response to external stimuli. Fig. 8 shows the test results for four users. The red curve indicates the touch-count (right Y-axis). The green bar plot marks every touch instance. The tall green bars denote the start and stop epochs of the wire loop game. The blue curve represents the skin conductance in Siemens (S) as measured by our EDA-cum-ESD sensor (left Y-axis). The plot also indicates the time taken to complete the game. We observe that the EDA rises as the user starts the wire loop game. The phasic response is extracted and superimposed on the skin conductance plot as cyan-colored markers. The SCR correlates with external stress stimuli viz. a) when the user makes multiple successive touches, b) when the user tries to maneuver the loop around tight corners that require intense hand-eye coordination and c) when the user is apprehensive about the game score at the end of the game. We also observe that the EDA flattens at the end of the stress-test. Table I summarizes the results of the experiment. The value of Pearson's correlation coefficient indicates a statistically significant correlation between measured voltage VA and the touch count.

TABLE I
RESULTS OF EXPERIMENTAL STRESS TEST VALIDATING OPERATION OF EDA-CUM-ESD SENSOR

User #	**Stress Test completed in (secs)**	**Touch Count**	**Correlation Coefficient (V_A and touch count)**	**Change in skin conductance (μS)**
User 1	89	86	-0.98174	4.31
User 2	103	97	-0.90841	2
User 3	101	16	-0.95597	5.56
User 4	185	81	-0.95262	2.77

VI. CONCLUSION

In this paper, we presented a non-intrusive device for EDA-based monitoring of stress/fatigue levels of EMS workers. We integrated EDA sensing into the ESD wrist strap that workers are mandated to wear. The device can assist workers to better manage their stress/fatigue by enabling automated triggers upon indications of stress/fatigue. The circuit also acts as an ESD wrist strap continuous integrity tester and warns the user in the event of an intermittent or open ground. Results from an experimental stress test reveal the components of EDA and their good correlation with external stress stimuli. We also presented an algorithm for the extraction of EDR from EDL.

Acknowledgment

Authors thank Sampad Mohanty and Raghunath D. for their help in setting up the stress test experiment.

References

[1] Y. Ji, S. Li, C. Wang, J. Wang, and X. Liu, "Occupational stress in assembly line workers in electronics manufacturing service and related influencing factors," *Chinese journal of industrial hygiene and occupational diseases*, vol. 34, no. 10, pp. 737–741, 2016.

[2] I. Völker, C. Kirchner, and O. L. Bock, "Relation between multiple markers of work-related fatigue," *Safety and Health at Work*, vol. 7, no. 2, pp. 124 – 129, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2093791115000967

[3] I. Völker, C. Kirchner, O. L. Bock, and E. Wascher, "Body sway as a possible indicator of fatigue in clerical workers," *Safety and Health at Work*, vol. 6, no. 3, pp. 206 – 210, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2093791115000335

[4] W. Boucsein, *Electrodermal Activity*. Springer Science and Business Media, 2012.

[5] J. T. Kider Jr, K. Pollock, and A. Safonova, "A data-driven appearance model for human fatigue," in *Proceedings of the 2011 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, 2011, pp. 119–128.

[6] J. Bakker, M. Pechenizkiy, and N. Sidorova, "What's your current stress level? Detection of stress patterns from GSR sensor data," in *2011 IEEE 11th International Conference on Data Mining Workshops*. IEEE, 2011, pp. 573–580.

[7] M. Benedek and C. Kaernbach, "A continuous measure of phasic electrodermal activity," *Journal of Neuroscience Methods*, vol. 190, no. 1, pp. 80–91, 2010.

[8] J. J. Braithwaite, D. G. Watson, R. Jones, and M. Rowe, "A guide for analysing Electrodermal Activity (EDA) and Skin Conductance Responses (SCRs) for psychological experiments," *Psychophysiology*, vol. 49, no. 1, pp. 1017–1034, 2013.

[9] S. Ollander, C. Godin, A. Campagne, and S. Charbonnier, "A comparison of wearable and stationary sensors for stress detection," in *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, 2016, pp. 004 362–004 366.

[10] "ESD TR1.0-01-01 Survey of constant monitors for wrist straps," ESD Association, Tech. Rep., 2001. [Online]. Available: https://www.esda.org/store/standards/product/71/esd-tr1-0-01-01

[11] J. A. Quinn, G. D. Deneault, C. H. Bridge, and J. R. Dempsey, "Continuous monitoring electrostatic discharge system," U.S. Patent 5 422 630, 1995.

[12] V. Kraz and K. A. Martin, "Device and method of monitoring grounding of personnel and equipment in ESD-sensitive areas," U.S. Patent 6 930 612, 2005.

[13] W. Boucsein, D. C. Fowles, S. Grimnes, G. Ben-Shakhar, W. T. Roth, M. E. Dawson, and D. L. Filion, "Publication recommendations for electrodermal measurements," *Psychophysiology*, vol. 49, no. 8, pp. 1017–1034, 2012.

[14] M.-Z. Poh, N. C. Swenson, and R. W. Picard, "A wearable sensor for unobtrusive, long-term assessment of electrodermal activity," *IEEE transactions on Biomedical Engineering*, vol. 57, no. 5, pp. 1243–1252, 2010.

[15] M. Garbarino, M. Lai, D. Bender, R. W. Picard, and S. Tognetti, "Empatica E3 — A wearable wireless multi-sensor device for real-time computerized biofeedback and data acquisition," in *2014 4th International Conference on Wireless Mobile Communication and Healthcare-Transforming Healthcare Through Innovations in Mobile and Wireless Technologies (MOBIHEALTH)*. IEEE, 2014, pp. 39–42.

[16] S. Cecchi, A. Piersanti, A. Poli, and S. Spinsante, "Physical stimuli and emotions: EDA features analysis from a wrist-worn measurement sensor," in *2020 IEEE 25th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*. IEEE, 2020, pp. 1–6.

[17] S. Tognetti, I. Cenci, D. Resnati, M. Garbarino, and M. Lai, "Apparatus for electrodermal activity measurement with current compensation," U.S. Patent US20 200 315 490A1, 2020.