Highly Wearable Galvanic Skin Response Sensor using Flexible and Conductive Polymer Foam

Jeehoon Kim, Sungjun Kwon, Sangwon Seo, Kwangsuk Park, *Senior Member*, *IEEE*

***Abstract*—Owing to advancements in daily physiological monitoring technology, diverse healthcare applications have emerged recently. The monitoring of skin conductance responses has extensive feasibility to support healthcare applications such as detecting emotion changes. In this study, we proposed a highly wearable and reliable galvanic skin response (GSR) sensor that measures the signals from the back of the user. To enhance its wearability and usability, we employed flexible conductive foam as the sensing material and designed it to be easily attachable to (and detachable from) a wide variety of clothes. We evaluated the sensing reliability of the proposed sensor by comparing its signal with a reference GSR. The average correlation between the two signals was 0.768; this is sufficiently high to validate the feasibility of the proposed sensor for reliable GSR sensing on the back.**

I. INTRODUCTION

Owing to advancements in daily physiological monitoring technology, diverse healthcare applications have emerged recently. Skin conductance is a method used to measure the electrical conductance of the skin, and it varies depending on the moisture of the skin. The skin conductance is changed by sweating that is caused by stimulations of the autonomic nervous system (ANS). Hence, monitoring changes in the ANS is an extremely feasible solution to support pervasive healthcare applications such as emotion recognition. Therefore, many previous works have investigated technologies for developing nonintrusive daily galvanic skin response (GSR) monitoring [1-4].

The previously developed daily GSR sensing systems have limitations with respect to unobtrusive monitoring and the usability of the system. M. Poh et al.[3] and R. Fletcher et al.[5] have proposed portable GSR sensor devices that measure the signals from the fingers or the wrist. However, GSR sensing of such frequently used body parts can limit the daily activities. M. Strauss et al. [6] have used a wet-type electrode to sense GSR. Wet-type electrodes have higher reliability, but they have critical limitations in terms of the usability because the use of electrolytic gels is often uncomfortable and long-term use may cause skin irritation. In addition, their measurement performance degrades as the electrolyte dries. T. Westeyn et al.[7] have used a rigid dry electrode. The rigid electrode has the advantage of durability, but it cannot be adapted to rounded body parts such as the back; such limited adaptability can cause unreliable sensing and discomfort.

The back is a convenient body part for wearing the GSR sensor seamlessly and unobtrusively. The back is not used frequently in daily activities. Moreover, it has a low density of sensory spots. Thus, the user can be relatively free from the discomforts that are felt when the sensor is worn in other body parts. The skin conductance response from the edge of a finger is one of the standard GSR signals. The skin conductance response from the back is also as high as that from the edge of fingers. M. Dooren et al. [8] have shown that there is considerable correlation between the GSR from the finger and from the back (henceforth, back GSR and finger GSR, respectively). We conducted preliminary investigations to verify the correlation, and our results (described in section II) also showed significant correlation between the two signals.

In this study, we propose a highly wearable and reliable GSR sensor device that measures the signals from the back of the user. We first used a foam-type conductive material for the sensing electrodes in order to make the sensor adaptive to the rounded body part and to enhance its wearability. Subsequently, we designed the sensor device that can be attached to diverse inner wears or body bands such as brassieres. Our design approach enhances the usability of the proposed sensor by enabling its easy attachment and detachment.

II. GSR ON THE BACK

We first investigated whether it is as feasible to use a back GSR as a sensitive indicator in a similar manner as the finger GSR. M. Dooren et al. [8] compared diverse GSR signals measured from 16 different body locations. Their results show significant correlation (0.577) between the finger GSR and back GSR on body locations that are similar to our targeted locations.

We conducted a preliminarily experiment to validate the correlation between the two signals. Four participants were recruited for the test. Two GSR signals were acquired for 5 min from each participant after the sensors were placed on his/her back and fingers (Figure 1). BIOPAC BN-PPGED module [9] with Ag-AgCl electrodes was used for the back GSR sensing and BIOPAC TEL100M module [10] with

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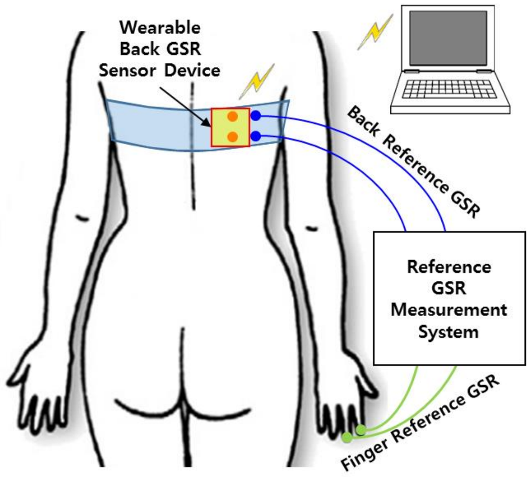

Figure 1. Experimental setup for preliminarily experiment and evaluation of sensor reliability

electrode gel was used for the finger GSR sensing. The participants heard soothing music for 5 min using headphones in a quiet environment. The music included three auditory stimuli (screaming, glass breaking, and gun blasting) lasting <1 s to surprise the participant. The stimuli were triggered at 2, 3, and 4 min from the beginning of the experiment. None of the subjects had any knowledge of the timing of the auditory stimuli.

The results show that there was a very high correlation between the two GSR signals. The correlations ranged from 0.704 to 0.932 and its average was 0.795 (SD: 0.098). Figure 2 shows an example of the comparisons between the GSRs from the back and finger. Both the signals show the skin conductance response caused by the three auditory stimuli, and the back GSR clearly shows skin conductance responses as sensitively as the finger GSR.

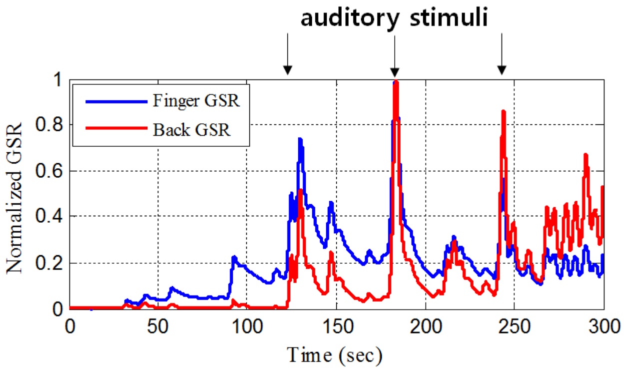

Figure 2. The example of the measured signal by the finger GSR and the back GSR

III. SENSOR DESIGN

We propose a reliable sensor device that can monitor daily GSR from the back. This device was designed to achieve a high degree of wearability. Our sensor consists of two major components: (1) flexible sensor substrate and (2) signal processing module (Figure 3).

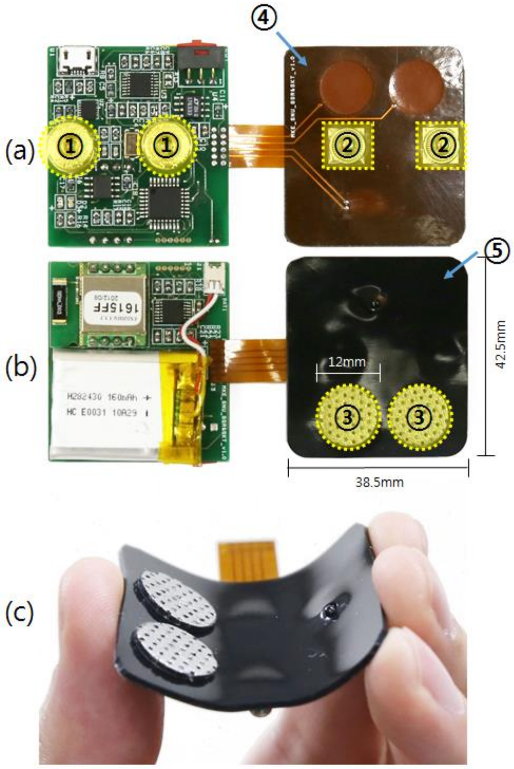

Figure 3. Wearable GSR sensor device and its size and dimensions. (a)–(b) The top and bottom views of the sensing plate and signal processing module: ①-② is the snap button for easy attachment-detachment; ③ is the conductive foam electrode for GSR sensing; ④ is the flexible printed circuit board (PCB); and ⑤ is the silicone pad. (c) Flexibility of the sensor substrate

The flexible sensor substrate is designed using a thin printed circuit board (thickness: 0.1 mm) to reliably contact with the rounded body shape, i.e., the back. The substrate is covered with a silicon layer to enhance its durability and to maintain stable contact with the body surface. Two dry electrodes for GSR sensing are embedded in the substrate (Figure 3 (c)). The electrodes are made of a reusable, soft, and conductive material—dry polymer foam [11]—so that the sensor has high usability and wearability. Dry polymer foam is highly resilient like a sponge and highly flexible, and hence,

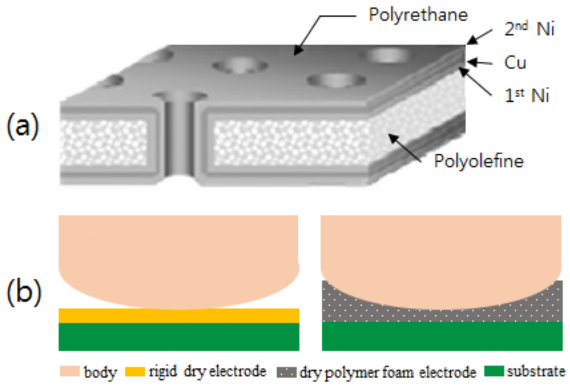

Figure 4. Structure of the conductive foam and its advantages as the electrode that contacts a rounded body. (a) Structure of the conductive foam (b) Comparison between the contacts of two dry electrodes—rigid type and polymer foam type—with the rounded body.

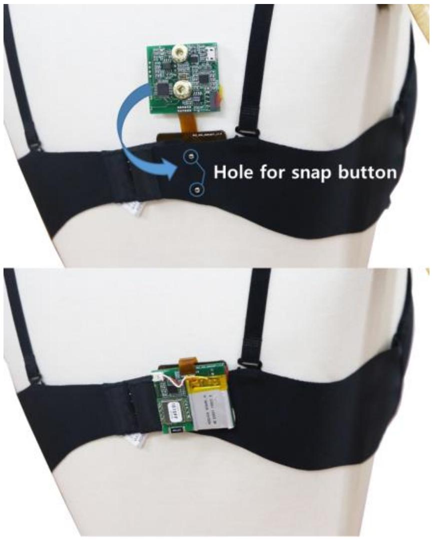

Figure 5. Example of our sensor device worn with a brassiere

the electrodes provide more reliable contact with the rounded surface (Figure 4).

Rigid electrodes cannot be easily adapted to curvatures and can cause unreliable sensing and discomfort. The foam electrode is plated with a conductive material (Ni/Cu) to establish the electrical conductivity (0.08 Ohm/sq) that is sufficient to measure the skin conductance response. The top and bottom layers are electrically connected so that it can be easily connected with the sensor substrate.

The proposed sensor device can be applied to a wide variety of clothes such as brassieres or chest belts. Snap-type connectors are equipped with each component of the sensor device. The connectors enable the sensor device to be easily attached to and detached from the clothes since they act like hooks. Figure 5 shows an example of the application of the proposed sensor device; the device is reliably attached to the brassiere band because the snap-type connectors are connected together through the two tiny holes on the band.

The signal processing module is primarily composed of an analog signal processing part and a digital data processing part. The frontend of the analog signal is designed to measure skin conductance levels from 0 to 50 µS. A 3 Hz low pass filter is included in the analog signal processing part. The filtered analog signal is followed by analog-to-digital conversion in a microcontroller (MCU). A digitized signal of 10-bit resolution is wirelessly transmitted through a Bluetooth interface.

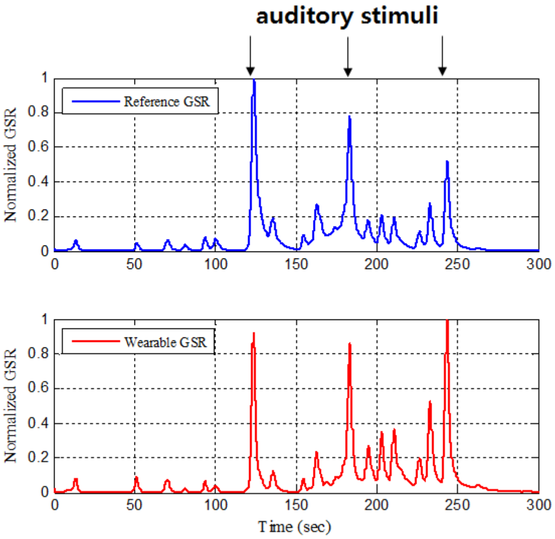

Figure 6. Comparison of the measured signal by the proposed wearable device and the reference signal

TABLE 1. CORRELATION BETWEEN MEASUREMENTS FROM TWO GSRS

	Correlation	R-Low	R-Up	P-value
P1	0.431	0.428	0.434	<0.0001
P2	0.918	0.918	0.919	
P3	0.901	0.901	0.902	
P4	0.822	0.821	0.824	
Mean **SD**	0.768 ±0.229	0.767 ±0.230	0.770 ±0.228	<0.0001

*, ** : lower and upper limit of correlation of 95% confidence interval

IV. EVALUATION AND RESULTS

We evaluated the sensing reliability of the proposed sensor by comparing the signals obtained from the back with signals measured by the reference GSR measurement system.

A. Experiment setup and analysis

Four participants were recruited for the evaluation. Each participant wore the proposed GSR sensor device using an elastic chest belt. The measurement spot of the GSR was slightly to the right side (approximately 3–4 cm) from the center of the back. The reference sensor was attached next to our sensor (Figure 1). The remaining experimental protocol and analysis were identical to the preliminary experiment described in section 2.

B. Result

The evaluation results show the feasibility of the proposed GSR sensor device for reliable GSR sensing on the back. Table 1 shows that the correlations ranged from 0.431 to 0.918, and its average was 0.768 (SD: 0.098); the p-value of the correlations was less than 0.0001 for all the subjects. Three participants showed high correlations greater than 0.82 (S1, S2, S3). Only one participant, S4, showed relatively low correlation than the others, and it was lower than the average.

Figure 6 shows an example of a comparison between two normalized GSR waveforms on the back, which were measured by the proposed sensor and the reference measurement system. The waveform shows that the proposed GSR sensor device can detect skin conductance changes as sensitively as the reference system. The highest correlation value was 0.918. Both the waveforms clearly show three dominant skin conductance changes caused by the auditory stimuli (2 min, 3 min, and 4 min). Furthermore, other relatively small responses shown in the reference signal are clearly observed in the device signal as well.

V. DISCUSSION

The experimental results demonstrated high feasibility of the proposed wearable sensor device for reliable GSR sensing. Most of the proposed sensor GSR signals showed high correlation with those of the reference system. However, participant 4 showed relatively low correlation (0.431). In general, the skin conductance level rapidly increases immediately after a stimulus, and subsequently, it has a recovery stage with a gradual decrease to a similar level before the stimulus. However, in the case of the second stimulus of participant 4, immediately after the rapid increase, the conductance level of the reference signal dramatically decreased to a lower level than the level before the stimulus. Thus, the device signal recovered its level after the increase but the reference sensor signal decreased. Therefore, the two signals were negatively correlated after the second stimulus. If this period is excluded, the correlation of participant 4 increases up to 0.673.

Although the signal of participant 4 is relatively less correlated with the reference signal, it shows changes in the skin conductance as sensitively as the reference signal. To estimate the sensitivity of the proposed device for the skin conductance response, we manually detected the skin conductance response in the two signals and compared the number of responses. Nineteen responses were detected in the reference signal and most of them (18 responses, 94.7%) were clearly observed in the signals of the proposed sensor. This clearly demonstrates that the proposed sensor can sensitively measure the variations in the skin conductance.

VI. CONCLUSION

In this study, we have proposed a highly wearable and reliable GSR sensor device that measures GSR signals from the back of the user. To enhance the wearability and usability of the sensor, we utilized conductive foam as the GSR sensor material; further, our design makes it easy to attached the sensor to, or detach it from, a wide variety of clothes by using button connectors.

We conducted experiments to evaluate the sensing reliability of the proposed sensor by comparing the GSR signals from the backs of participants with similar signals measured by a reference GSR measurement system. The average correlation between the two signals was 0.768; it is sufficiently high to support the feasibility of the proposed sensor for reliable GSR sensing on the back. In this manner, our GSR sensor enables reliable and convenient daily physiological monitoring, and it can be expected to assist the development of diverse healthcare applications.

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