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Low-cost monitoring for stimulus detection in skin conductance

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ABSTRACT
Not so many consumer devices are available for minimally invasive monitoring of Skin Conductance (SC), differently from what happens for other physiological signals. In this paper, a low-cost monitoring system for SC signals is presented. For comparison purposes, the SC signals are simultaneously acquired by the low-cost monitoring system and by a ProComp Infiniti desk equipment. The paper shows that, despite the simpler design and hardware limitations exhibited by the low-cost system, the collected SC signals provide the same relevant information for stimulus detection of the SC signals acquired by a much more expensive acquisition board. Specifically, the comparison is fulfilled through the ability of the low-cost monitoring system in detecting the increase of both SC baseline and peaks after stimulation.

Section: RESEARCH PAPER

Keywords: Skin conductance; Galvanic Skin Response; stimulus detection; low-cost sensor; Active Assisted Living

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1. INTRODUCTION

Several hardware technologies have been developed to integrate different physiological quantities into wearables, enabled with wireless connectivity according to the Internet of Things (IoT) [1], [2]. Wearables are often used with the aim of acquiring those parameters that evaluate the subject physiological status, from the physical and health perspective [3]-[8] to the cognitive and emotional one [9]-[11]. Indeed, the connection of smart devices to networking systems can reduce unnecessary hospital visits and lower the burden on healthcare services, by transferring data over secure infrastructures. IoT devices allow continuous remote monitoring of physiological parameters, thus supporting long-term care at home (Active Assisted Living) [12].

While existing a rich offer of wearables embedding sensors to monitor heart-related parameters, not so many devices are available to collect Skin Conductance (SC) signals, despite several applications could benefit from them. For example, the possibility to classify different physiological conditions, such as pain or perspiration, by means of SC acquisition system allows a better management of anxiety among patients under treatments, students, workers, or people affected by health problems related to distress [13]-[16].

SC is defined in a seminal work by Boucsein [17] as the phenomenon that the skin temporarily becomes a better conductor of electricity due to a change in sweat secretion, when either external or internal stimuli occur. Thus, SC signals reflect the changes in electric conductance, which is modulated by sweat gland activity. In fact, an increase in sweating, mostly composed by water, increases the skin capability of conducting electric current. Sweat secretion from eccrine glands (spread over the body skin) cannot be consciously controlled, because it is driven by the autonomic nervous system, whose activity is modified by the events involving a subject [18]. Consequently, SC signals allow to investigate the relationship between physiological status and stimuli [19], [20]. SC variations may be elicited by the response to stimuli of different nature, such as visual, acoustic [21], [22] or physical ones [23], or by stressful conditions, such as driving [24]-[26]. The so-called Skin Conductance Level (SCL) - or tonic level - reflects the slow changes depending on skin dryness, hydration, and automatic regulation. Instead, the Skin Conductance Response (SCR) - or phasic level - represents the dynamic changes associated to stimuli [27], [28].

SC signals may be collected by endosomatic approach, meaning that no external source of electricity is used, or by exosomatic approach, in which electrodes in direct contact with the skin allow to apply a current source. In the exosomatic approach, the Ohm's law is exploited to compute the skin conductance (or resistance) by means of voltage values. Despite the device design is simpler in the endosomatic case, the exosomatic approach is more common in wearables, as it does not require to collect the voltage difference between active and inactive sites of the skin.

The availability of smart devices for stimulus detection in SC signals can enable several applications regarding human response to specific events [29]. The advantage of using smart devices to collect SC signals consists exactly in the possibility to run different types of experiments with greater flexibility, without bulky equipment, thus in real-life conditions [25]. In such a context, the current work investigates the operation of a low-cost and portable system for SC monitoring. Specifically, the current work is intended to evaluate if a low-cost system, although exhibiting simpler design and hardware limitations, can be adopted for stimulus detection. To this purpose, the SC signals acquired by the proposed low-cost system are compared to the SC signals collected by a reference instrument, the ProComp Infiniti. The comparison is then carried out before and after acoustic stimulation, by analysing the reliability of the low-cost system in detecting event-related changes.

The paper is organized as follows. Section 2 describes in detail the proposed low-cost system for SC monitoring. Section 3 presents, instead, the reference instrument for SC monitoring. The applied test procedure is depicted in Section 4. The obtained results are discussed in Section 5. Finally, Section 6 provides conclusive remarks.

2. LOW-COST SYSTEM FOR SC MONITORING

Monitoring for stimulus detection in SC signals is implemented in this study through a low-cost data acquisition system. The proposed low-cost system consists of the Grove-GSR Sensor v1.2 [30], with its signal conditioning circuit, and the Arduino UNO board, equipped with the ATmega328P microcontroller. Figure 1 shows the low-cost system.

The Grove-GSR Sensor collects voltage values modulated by a microcurrent, injected by means of two Nickel electrodes - worn in direct contact to the fingers through small velcro bands. Moreover, a signal conditioning circuit, including the Texas Instruments LM324 operational amplifier, is connected to the electrodes. Then, the Grove-GSR Sensor is connected by means of a 4-wire cable to the Arduino UNO board, which is useful for low power consumption.

The quantity acquired by the low-cost system is the Skin Resistance (SR), which is the inverse of SC. The voltage signal is acquired at 121 Hz and converted into 10-bit digital values, so that such values range from a minimum of 0 to a maximum of 1023. In order to remove glitches from the acquired voltage values, the code embedded into the firmware of the microcontroller computes the SR average over 5 voltage samples. Finally, data are sent via Universal Serial Bus (USB) interface from the output port of the microcontroller to a computer, where they are saved into a file.

Figure 1. The low-cost system for SC monitoring..

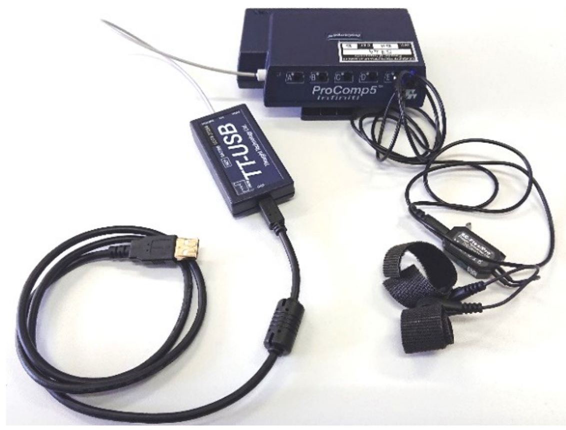

Figure 2. The ProComp Infiniti system with the TT-USB interface.

3. REFERENCE SYSTEM FOR SC MONITORING

Generally speaking, only a few devices are commercially available to acquire SC signals (see Table 1). They exhibit different operation modes and sampling frequencies. As shown in Table 1, above all, the accessibility to raw data samples can represent a critical point, causing difficulties in extracting the information of interest.

Among the available commercial devices for SC monitoring, the ProComp Infiniti by Thought Technology is desk equipment considered as a reference system to validate other devices [31],

Table 1. Comparison of commercial devices for SC monitoring.

Device	Measured value	Sampling frequency	Availability of original samples	Typology
Empatica *E4*	conductance	4 Hz	Yes	wearable
Empatica *Embrace*	conductance	4 Hz	Yes	wearable
Moodmetric	conductance	not provided	No	wearable
Shimmer3 GSR+	resistance	32 Hz	Yes	wearable
ProComp Infiniti	conductance	256 Hz	Yes	desk equipment
BioPac MP36R device	conductance	500 Hz	Yes	desk equipment

due to the accuracy of the SC sensor. It consists of a data acquisition system and five channels for monitoring of several biosignals. Specifically, the first two channels allow to acquire at a sampling frequency of 2048 Hz faster signals, such as electroencephalogram, electrocardiogram, heart rate or blood volume pulse. Instead, the remaining three channels are designated to monitor slower signals, such as respiration, temperature, and SC, at a sampling frequency of 256 Hz.

Therefore, one of the last channels is employed for SC monitoring, with a signal input range of [0, 30] μS. In particular, the electrode strap must be fastened around the finger so that the electrode surface is in contact with the pad (but not so tight to limit blood circulation). Furthermore, as shown in Figure 2, the system comprises a fiber optic cable and a TT-USB interface. The ProComp Infiniti system encodes and transmits the data via the fiber optic cable to the TT-USB interface, which is in its turn connected to the USB port of the computer. Lastly, the BioGraph Infiniti software allows to export the measured values as .csv data files.

4. TEST PROCEDURE

The stimulus detection in SC is evaluated on a population of ten subjects, six women and four men, aged between 23 and 49 years (the details are given in Table 2). All the involved subjects declared to be in good health and signed an informed consent before participating in the experimental acquisitions.

SC signals were simultaneously acquired by the low-cost system and the ProComp Infiniti. Acquisitions were performed inside a laboratory, with subjects comfortably sitting on a chair. In order to simultaneously acquire the SC signals by both the systems on index and middle fingers of the dominant hand, as suggested in [32], the electrodes of the Grove-GSR Sensor were placed on the fingertips, while the electrodes of the ProComp Infiniti were placed on the medial phalanx of the fingers, as shown in Figure 3. Specifically, the electrodes of the low-cost system are located on the fingertips, as suggested in the literature [32], to favor the best possible contact between electrodes and skin, while the electrodes of the ProComp Infiniti were applied on the medial phalanx of the same fingers. This choice aims to compensate for the smaller amplitude of the signal obtained by the low-cost system, which includes components with lower amplification gain with respect to the ProComp Infiniti. In any case, as detailed in Section 5, the comparison between the two considered systems is carried out by normalizing the amplitudes of the acquired signals. Moreover, the subjects were asked to keep their arm in a relaxed position, with the palm of the hand resting on a desk to minimize involuntary movements and favor the contact of the finger skin with the electrodes.

Table 2. Dataset population details.

Subject	F/M	Age (years)
S1	F	47
S2	M	34
S3	F	33
S4	M	48
S5	F	29
S6	F	40
S7	M	32
S8	F	31
S9	M	49
S10	F	23

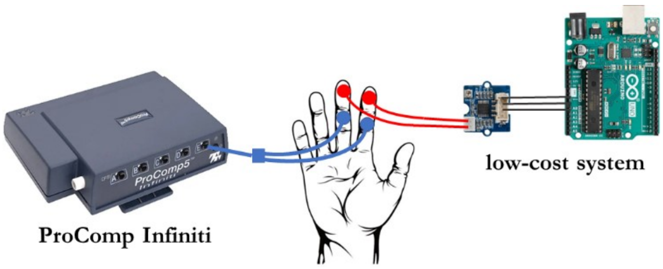

Figure 3. Test setup for simultaneous acquisition of SC signals by the low-cost system and the ProComp Infiniti.

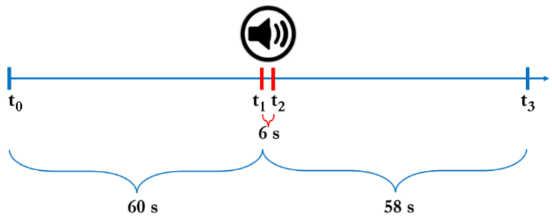

Figure 4. Time sequence of the SC acquisition protocol.

The aim of the paper is verifying if the stimulation can be identified in the SC signals collected by both the low-cost system and the ProComp Infiniti. For such a reason, only a single audio stimulus was considered. In detail, each acquisition session lasted less than 2 minutes (see Figure 4). The SC baseline of each subject was firstly acquired for 60 s, in relaxed conditions and in the absence of any external stimulus. Then, an audio clip of 6 seconds was played through computer loudspeakers, while the SC acquisition went on for 58 s. Thus, the acquisition duration was 1 minute and 58 s overall. The audio clip was chosen with a short duration to elicit a reaction in the listening subject, without generating the so-called "habituation effect" [33]. The audio clip of 6 seconds was extracted from the International Affective Digitized Sounds (IADS) database [34]. The IADS database is a set of 167 audio clips for experimental investigations on emotion and attention, where at least 100 listeners, equally divided in males and females, rated each sound in the dataset. Specifically, the sound clip *RockNRoll* - 815 was used in our experiments, since it exhibits the highest average value of the *pleasure* score (8.13/9.00) over the whole dataset, as reported in the documentation available together with the dataset.

The raw data acquired by the low-cost system are firstly converted into SR values according to (1) [30]:

$$SR = (2^{10} + 2 \cdot x) \cdot R \,/\, (2^{9} - x), \qquad (1)$$

where x is the serial port reading, i.e., the digitized value displayed on the serial port, ranging from 0 to 1023 (10-bits digital values), while R=10^4 Ω is the resistance value of the resistor in the voltage divider circuit used to read the variable resistance of the sensor. Thus, the SR data acquired by the low-cost system were saved as local .txt files on the computer, and then processed through MATLAB environment. In particular, the SC values are calculated as inverse of the SR values.

Instead, the SC signals acquired by the ProComp Infiniti are directly provided in Siemens and do not need to be pre-processed to be comparable to the SC signals obtained by the low-cost system. The SC data acquired by the ProComp Infiniti were saved by the BioGraph Infiniti Software-SA7900 of Thought Technology as .csv files and processed through MATLAB environment.

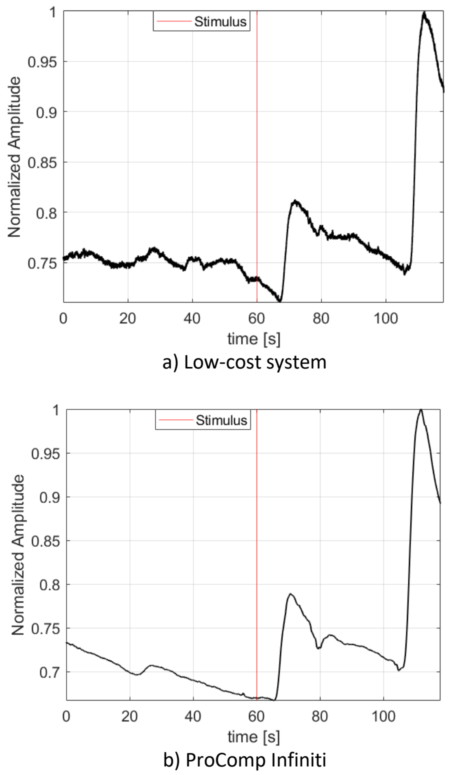

Figure 5. SC signals with normalized amplitude of subject S4 (male) acquired by a) low-cost system, and b) ProComp Infiniti.

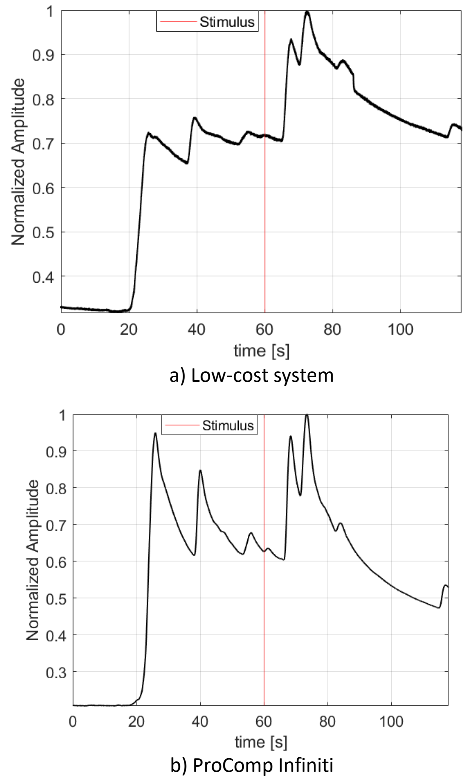

Figure 6. Normalized amplitude SC signals of subject S10 (female) acquired by a) low-cost system, and b) ProComp Infiniti

5. RESULTS AND DISCUSSION

Figure 5 and Figure 6 show, for instance, the SC signals of the subjects S4 (male) and S10 (female), acquired by means of both the low-cost system and the ProComp Infiniti. In order to take into account the different electrode location for the two systems, as well as their different amplification components, the signals are shown with normalized amplitudes, allowing a fair comparison between them. It should be underlined that, looking at the signals in Figure 5 and Figure 6, clear peaks follow the stimulus event for both the subjects. In fact, as reported in [34], event-related peaks usually happen within 2.5 to 7.0 seconds after the stimulus.

Stimulus detection by the data acquisition systems is carried out by analyzing the SC signals of the ten subjects, before and after the acoustic stimulation, in terms of variation of SCL average and SCR peaks. For this reason, the SC signals are filtered, obtaining the two SCL and SCR components.

As concerns the SCL component, on the basis of the literature [36], an increase of positive fluctuations from relaxed condition to pleasant stimulation should be clearly evident in the baseline. In Table 3, the results of the SCL acquired by both the low-cost system and the ProComp Infiniti are reported before and after the acoustic stimulus. Generally, the results provided by the low-cost system confirm the literature findings, as they highlight an increase in the SCL average following the stimulus over most of the subjects (eight out of ten). Furthermore, in one case out of ten (subject S3), the signals acquired by the two systems lead to different results, to the advantage of the low-cost system. In fact, an increase following the stimulus is recorded in the SCL average by the only low-cost system.

The data provided in Table 4 refer to the analysis of the variation in the number of SCR peaks detected before and after the stimulus, for each subject and by both the acquisition systems. For six subjects out of ten, the low-cost system detects an increase in the number of SCR peaks following the acoustic stimulus, in accordance with the literature, as reported in [37], [38]. On the other hand, by analyzing the signals collected by the ProComp Infiniti, the peak increase is found only in four cases out of ten.

Therefore, the analysis on the acquired sets of signals proves that the low-cost system can contemplate the meaningful variations of the SC signals, as well as the ProComp Infiniti, taken as a reference device. These results agree with [39], confirming the possibility to implement a low-cost and portable system for SC monitoring aimed at stimulation detection. In fact, the signals collected by the prototypal system shown in this work allow to extract meaningful information in line with the results available in the literature and typically obtained by means of desk equipment, which cannot be suitable for scenarios requiring the mobility and freedom of movements for users.

6. CONCLUSIONS

Measuring SC signals by means of minimally invasive and low-cost systems can enable the out-of-lab monitoring of subjects under different types of stimulation without bulky equipment, thus in real-life conditions. In this paper, a low-cost and portable monitoring system for stimulus detection in SC has been proposed. The performance of the proposed low-cost system has been evaluated in comparison to the performance of a reference desk equipment, the ProComp Infiniti, on ten subjects. The analysis on the SC signals, acquired before and after acoustic stimulation, highlights the capability of the low-cost system to provide their relevant variations, in the slowly varying SC component (SCL), as well as in the rapidly varying one (SCR). In fact, the increase of SCL average and SCR peaks after

Table 3. Detection of average baseline increase following stimulation, for each subject and by both the systems used.

	Low-cost system			ProComp Infiniti		
Subject	SCL average in µS before stimulus	SCL average in µS after stimulus	Baseline increase	SCL average in µS before stimulus	SCL average in µS after stimulus	Baseline increase
S1	2.46	2.59	Yes	0.60	0.63	Yes
S2	4.38	4.75	Yes	1.07	1.23	Yes
S3	3.58	4.03	Yes	1.65	1.62	No
S4	2.49	2.63	Yes	1.73	1.89	Yes
S5	0.96	0.88	No	0.81	0.69	No
S6	1.53	1.75	Yes	1.57	1.67	Yes
S7	2.68	2.82	Yes	0.55	0.60	Yes
S8	3.85	3.54	No	1.13	1.05	No
S9	1.64	1.67	Yes	1.10	1.12	Yes
S10	1.89	2.70	Yes	2.10	2.59	Yes

Table 4. Detection of SCR events number increase following stimulation, for each subject and by both the systems used.

	Low-cost system			ProComp Infiniti		
Subject	SCR peaks before stimulus	SCR peaks after stimulus	Peaks increase	SCR peaks before stimulus	SCR peaks after stimulus	Peaks increase
S1	0	1	Yes	3	2	No
S2	3	5	Yes	3	6	Yes
S3	2	4	Yes	2	0	No
S4	1	2	Yes	0	2	Yes
S5	0	0	No	0	0	No
S6	1	1	No	0	2	Yes
S7	4	3	No	4	2	No
S8	0	0	No	0	0	No
S9	0	1	Yes	0	1	Yes
S10	1	2	Yes	2	2	No

stimulation is correctly monitored by the low-cost system, in accordance with the results obtained by means of the desk equipment of greater hardware capabilities.

Additional investigations aimed at generalizing the promising results obtained in this work will be performed as future work, increasing the dimension of the test population and possibly testing different types of stimulation.

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