Physiology & Behavior 106 (2012) 298–304

Contents lists available at SciVerse ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/phb

Emotional sweating across the body: Comparing 16 different skin conductance measurement locations

Marieke van Dooren [a,*], J.J.G. (Gert-Jan) de Vries [a], Joris H. Janssen [a,b]

[a] Philips Research Europe, High Tech Campus 34, 5656 AE Eindhoven, The Netherlands
[b] Eindhoven University of Technology, Den Dolech 2, 6500 MB Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 2 September 2011
Received in revised form 19 January 2012
Accepted 30 January 2012

Keywords:
Skin conductance
Electrodermal activity
Emotional sweating
Body positions
Measurement locations

ABSTRACT

Skin conductance (SC) is one of the most commonly used measures in psychophysiological studies involving emotional arousal and is traditionally measured at the fingers or the palms (i.e., the palmar locations) of the hand. Palmar skin conductance recording positions are, however, not always preferred for ambulatory recordings in real-life situations. This study quantifies the responsiveness and similarity with the finger of 16 different recording positions of skin conductance while watching emotional film fragments. Findings indicated foot, fingers and shoulders being most responsive, whereas arm, back, armpit, and thighbone were least responsive. The measurements at the foot were most similar with those of the finger. In contrast, arm, back, and armpit traces differed most from the finger trace. Taken together, foot and shoulders are the best alternatives to the finger for ambulatory measurement of skin conductance to reflect emotional arousal. These findings can help new applications using skin conductance, like automated emotion measurements, to come to fruition.

© 2012 Elsevier Inc. All rights reserved.

1. Introduction

Over the last decades, the research fields of the affective sciences and affective computing [1–3] employed several different modalities to measure emotions, including physiological signals, speech, facial expressions and body posture [4–7]. Amongst the physiological measurements, skin conductance (SC) is frequently used to assess emotional arousal [8–12]. However, the majority of the traditional emotion research is carried out in controlled laboratory situations. Therefore, the generalizability of the findings of such research to real-life situations can be questioned [13]. To overcome this, the affective sciences need measurement platforms that are unobtrusive for users so that they don't interfere in daily activities but still capture reliable data. As skin conductance is often used to measure emotional arousal, such ambulatory measurement platforms are likely to rely (partly) on SC emotion sensing. Therefore, we set out to identify body locations that can be used to reliably but unobtrusively measure emotional skin conductance.

Skin conductance (also referred to as electrodermal activity [10]) refers to the varying electrical properties of the skin in response to sweat secretion by sweat glands [14]. There are three types of sweat glands: eccrine, apocrine and apoeccrine. Eccrine sweat glands are mostly involved in emotional responses as these sweat glands are innervated by sympathetic nerves which accompany psychological processes including emotional arousal [12,15]. Different nerve bundles go to the head/face, abdomen, arms/hands, and legs/feet. For example, the nerves that control the sweat glands of the forehead and of the foot are different from the nerves that control the sweat glands of the fingers (overview of dermatomes in [16]). There is also evidence for the lateralization of the sympathetic nervous system and skin conductance activity [17]. The magnitude of sweating depends on the density of sweat glands, their relative size, and the output of individual glands [18] which varies between individuals [19]. The highest density of eccrine sweat glands was found on the palms and soles (600 to 700 glands/cm^2) [20,21] and in fact, psychophysiological emotion research has traditionally also focused on measuring skin conductance at the volar surface of the palms [22,23]. The palms were also recommended as the preferred SC recording position in the guideline paper from The Society for Psychophysiological Research [24]. However, the eccrine sweat glands are not solely present at the palms and soles but are actually distributed across the whole body albeit in lower densities. Estimations have been made for the forehead (181 glands/cm^2), upper limbs (108 glands/cm^2 on the forearm), and finally the trunk (64 glands/cm^2 on the back) and lower limbs [20,21]. Therefore, we hypothesize that also body locations other than the traditional palmar recording location can show an emotional response in SC recordings.

Several studies already started to explore the measurement of SC at other locations than the traditional palmar locations [25–27] among which measurements at the feet [1,28], chest and neck [29], wrist [25,30], and ankle [30]. Furthermore, Wilcott [31] describes that various body parts show an increase in sweating to both arousal and thermal

* Corresponding author. Tel.: +31 402747669.
E-mail address: marieke.van.dooren@philips.com (M. van Dooren).

0031-9384/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
doi:10.1016/j.physbeh.2012.01.020

stimuli but that there are differences in the magnitude of sweating. Hence, an investigation of the commonalities and differences between different locations in emotional sweating is warranted. However, besides brief investigations of one or a few recording positions, to our knowledge, there are no studies about the SC response to emotion elicitation with simultaneous recordings at more than five body positions. At this moment, it is therefore difficult to draw conclusions about electrode positioning for SC measurements in the development of unobtrusive affect measurement systems where the recommended finger position is rather impractical.

To make recommendations about skin conductance sensor positioning for ambulatory emotion measurements, the present study compares 16 different SC recordings obtained from participants whilst watching emotional film clips. Film fragments were used to induce variation in emotional arousal in subjects. Emotional arousal is one of the two dimensions in the circumplex model of affect [32] where emotions are operationalized in a spatial model with emotional valence varying from positive (pleasant) to negative (unpleasant) and with emotional arousal (intensity) varying from calm to excited. Skin conductance has been found to vary systematically with emotional arousal [8–12]. During the film clips, skin conductance was synchronously recorded at 16 body positions which are graphically represented in Fig. 1 and are described in more detail below (see Section 2.4).

The quality of the 16 recording positions is investigated in two ways. First of all, we investigate the *skin conductance responsiveness* to emotional film clips with three SC features. The first feature, the mean skin conductance level (SCL), describes the overall conductivity of the skin over longer time intervals, in the order of several minutes [15]. The second feature, the number of skin conductance responses per minute (SCRs), describes the frequency of occurrence of skin conductance responses. A skin conductance response is a short fluctuation in skin conductance that lasts several seconds and usually follows a characteristic pattern of an initial, relatively steep rise, a short peak, and then a relatively slower return to baseline. Skin conductance responses reflect the higher-frequency variability of the signal that is modulated on top of the slower changes in skin conductance level [10,15]. The third feature, the sum of the skin conductance responses amplitudes per minute (S-AMPL), takes into account the strength of skin conductance responses.

Our hypothesis about the influence of recording position on SC responsiveness to emotion elicitation builds on a positive correlation between eccrine sweat gland density and electrodermal activity. Freedman et al. [22] confirmed this relation by comparing two different finger positions: higher skin conductance activity was found at the distal phalanx position which also had more active sweat glands compared to the medial phalanx position. Therefore, we expect the skin conductance responsiveness to emotional film fragments to be in line with the sweat gland densities. In that light, the fingers, feet, and forehead would be in the top three of highest SC responsiveness, according to estimations of eccrine sweat gland densities [20].

Second of all, we investigate the *similarity* of the SC traces to the traditional finger trace with the measure correlation. Correlation is an often employed statistical measure indicating linear dependency between two traces. Multiple aspects are involved in the similarity between SC traces, such as the density of sweat glands, the distribution of dermatomes, the innervations of sweat glands at different body locations, and sweat gland nerve fiber densities. We base our hypotheses on eccrine sweat gland densities and expect the highest correlations between the finger trace and the traces from the feet and the forehead.

2. Materials and methods

2.1. Participants

Seventeen subjects (12 males, 5 females) participated in this study, average age of 32 years (SD = 9 years). Subjects were recruited amongst colleagues working at an industrial campus in The Netherlands. They gave their informed consent and had normal or corrected to normal vision.

2.2. Design

For each participant, skin conductance recordings were made concurrently from 16 different positions on the body (see Fig. 1). Therefore, the measurement position was a within-subject factor in our design. *Responsiveness* of the measurement location was assessed with the mean skin conductance level (SCL), the number of skin conductance responses per minute (SCRs) and the sum of the skin conductance responses amplitudes per minute (S-AMPL). *Similarity* of the SC traces to the finger trace was assessed through the correlation between the measurements at the finger and the measurements at the other positions.

2.3. Procedure

After signing the informed consent, subjects sat down in a comfortable chair in a dimly lit laboratory room furnished to look like a living room. A female experimenter attached skin conductance electrodes at the 16 body positions (Fig. 1) and connected the electrodes to measurement equipment. For each body position, the two skin conductance electrodes were attached in such a way that the isolating outer rings around the electrodes and gel slightly touched each other in order to keep a fixed distance between electrodes for all body positions, except for the fingers that consisted of electrode measurements at two separate fingers. During the experiment, subjects wore shorts and a T-shirt to allow easy access to the body positions where the electrodes were located. Then, recordings and loggings were started. Subsequently, subjects were asked to make themselves comfortable in the experimental setting and to refrain from moving during the entire experiment to avoid artifacts in the recordings and to limit skin conductance changes due to physical activity. A rest recording was started for 3 min with subject's eyes open. After the rest recording, seven video fragments (see Materials and methods) were presented. After each film clip, subjects were asked to rate the film clip on a valence and excitement questionnaire (see Materials and methods) after which the next film clip started immediately. Ratings were provided verbally to the experimenter. After the seven film fragments had finished, a measurement of 3 min rest was made during which subjects sat quietly with eyes open. Thereafter, recordings and loggings were stopped. Physiological sensors were detached and a debriefing about the aim of the research was provided. Finally, subjects received a gift voucher for participation.

2.4. Materials

2.4.1. Skin conductance recordings

Skin conductance was recorded via a self-developed platform consisting of 16 SC Modules (hardware), 2 × 16 self-sticky Ag/AgCl gel electrodes (from Kendall) and LabVIEW software to record the measurements. A voltage of 1.2 V was put on a series circuit of the skin and a reference resistor of 3.3 MΩ. With a 16-bit A–D convertor (National Instruments), the voltage drop over the reference resistor was measured. One central computer was used to collect all the skin conductance data with one central clock to determine the sampling moments (sample rate of 2 Hz). The 16 SC Modules and the electrode wires were numbered. Each number corresponded to one body position (see Fig. 1).

For the selection of body positions, four aspects were taken into account. First, the finger location (body position 1) was included because it is used in most literature and recommended as the reference location for SC measurements [24]. Second, locations with the opportunity to comfortably integrate into a product application were included. For instance, body positions 2–4 can be used in a watch. The

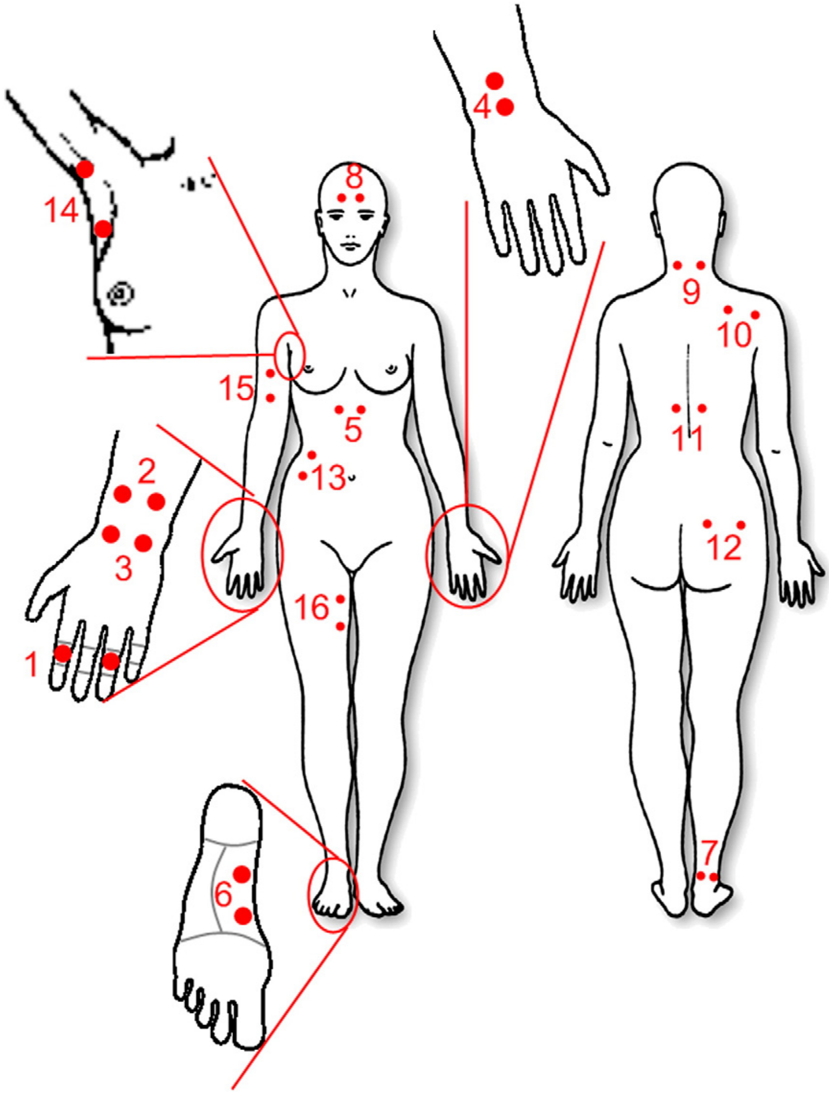

Fig. 1. Skin conductance measurement locations: 1) fingers, 2) distal wrist, 3) central wrist, 4) vertical wrist, 5) chest, 6) foot (instep), 7) calf, 8) forehead, 9) neck, 10) shoulders, 11) back, 12) buttock, 13) abdomen, 14) armpit, 15) upper arm, and 16) thighbone.

two wrist positions number 2 and 3 were attached with a distance of 3 cm in between. There might have been an influence of crosstalk because these were close together. However, the remaining body locations were more than 5 cm away from each other, which makes the possibility of crosstalk for these body positions very unlikely. Positions 5 and 11 can be used in a chest band, positions 6 and 7 can be used in a sock or sock border, position 8 can be used for a head band, position 9 can be used in a bracelet. Third, locations were selected to cover as many different areas on the body (remaining body positions 10, 12, 13–16). Finally, the non-central positions were chosen, as much as possible, to be on the right side of the body in order to reduce variation due to potential lateralization influences. From the 16 body positions, 11 positions were on the right side of the body, 4 positions were in the middle of the body and 1 position was on the left side of the body (see Fig. 1). A representative example of the 16 skin conductance recordings from one individual subject is illustrated in Fig. 2.

2.4.2. Film clips

We aimed to induce different emotional states (anger, fear, amusement, relaxation, sadness, neutral emotion, and sexual arousal) using seven video fragments (duration anger fragment: 2.21 min, duration fear fragment: 1.20 min, duration amusement fragment: 2.12 min, duration relaxation fragment: 2.16 min, duration sadness fragment: 2.33 min, duration neutral fragment: 2.00 min, duration sexual arousal fragment: 5.00 min) which were successfully used for this in previous research [33]. They were presented to the participant on a 42 inch Philips LCD-television at a distance of 2 m. It was not our goal to compare the skin conductance for different emotions. Instead, the video fragments were only used to generate variation in the skin conductance signal due to emotions. Therefore, the order of the videos was kept constant keeping cross-over effects between conditions fixed.

2.4.3. Questionnaire

A short questionnaire was used to check whether a variety of different emotions was induced. The experimenter asked subjects to indicate the strength of their negative feelings, positive feelings and level of excitement on a 7-point Likert scale ranging from *very weak* to *very strong*. As such, the questionnaire data were positioned in the circumplex model (Russell) [32] which consists of these two dimensions, emotional valence and arousal.

2.5. Data analysis

For the questionnaire data, the ratings of negative feelings were reverse coded and averaged with the ratings for the positive feelings

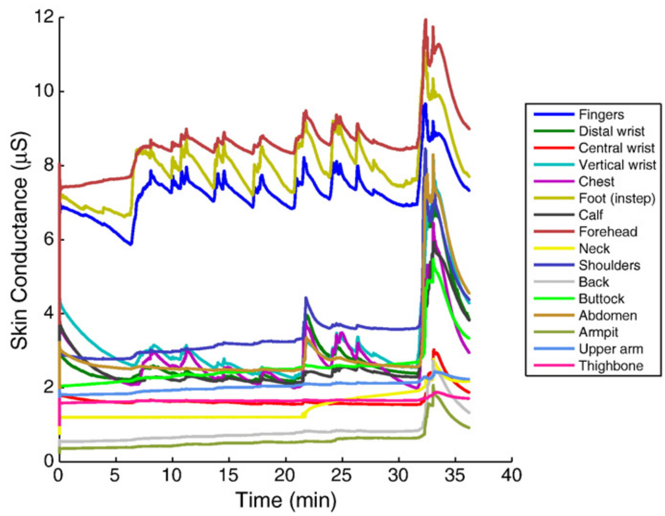

Fig. 2. An example of the SC traces at all 16 body positions for one individual participant.

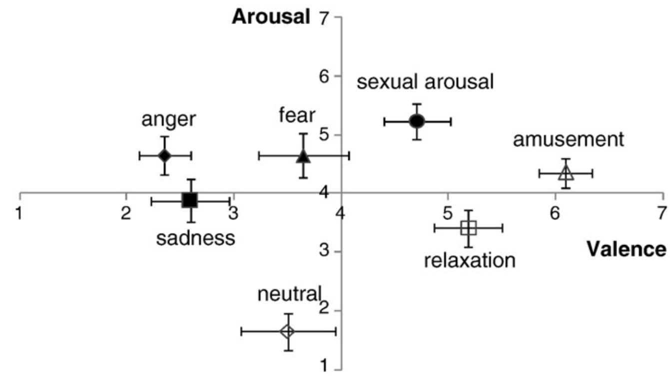

Fig. 3. Mean ratings of film clips eliciting anger (black diamond), sadness (black square), fear (black triangle), sexual arousal (black circle), neutral (white diamond), relaxation (white square), and amusement (white triangle). Error bars depict +/−1 SE.

(Cronbachs alpha = .81 which indicates high consistency). These will be further referred to as the self-reported *valence* ratings. These ratings were used to check if the films' clips elicited different emotions.

Subsequently, the 16 skin conductance recording positions were compared with four measures. For this, full skin conductance traces were used so as not to introduce artificial discontinuities. Full traces include the total recording session consisting of the seven video fragments, two rest periods and intermediate questionnaire rating periods (see Procedure). Out of the 272 (17 × 16) measured SC signals, six (i.e., 2.2%) had to be discarded due to detachment of the electrodes during the experiment.

To analyze the responsiveness of the different measurement locations, we calculated mean skin conductance level (SCL), the number of skin conductance responses per minute (SCRs) and the sum of the skin conductance responses amplitudes per minute (S-AMPL). An automated detection algorithm called SCRGauge [34] was applied for detecting all individual skin conductance responses and their amplitudes, using a threshold-amplitude of 0.02 μS as the criterion for counting the number of skin conductance responses. In the literature, threshold-amplitudes range between 0.015 μS and 0.3 μS [35]. Our threshold-amplitude is relatively small because we expected to find low basal skin conductance levels at several body locations and this is correlated with the amplitude of skin conductance responses [31]. These three measures of responsiveness were submitted to a repeated measures ANOVA with measurement position as within-subject factor. Deviations of sphericity were corrected using Huyn–Feldt corrections. All tests were two-tailed with alpha levels of .05. Next to this, an explicit decomposition into tonic and phasic components of skin conductance was made according to continuous decomposition analysis (Benedek & Kaernbach [36]) to obtain correlations with the three responsiveness measures.

To analyze the similarity between the finger and the other measurement location, we calculated the correlation between the finger and the other measurement locations per participant. This measure of similarity was submitted to a repeated measures ANOVA with measurement position as within-subject factor. Again, deviations of sphericity were corrected using Huyn–Feldt corrections. Tests were two-tailed with alpha levels of .05.

3. Results

3.1. Manipulation check

The questionnaire ratings were used to check if the films' clips elicited different emotions. Means and SEs are depicted in Fig. 3. Standard error was calculated by dividing the SD by the square root of N. Fig. 3 confirms that the film clips induced a wide range of emotions in this sample of subjects, containing emotions in the four quadrants of the valence-arousal model for emotions [32].

3.2. Skin conductance responsiveness to emotional film clips

Position showed a significant main effect on mean skin conductance level ($F(10, 154) = 16.10$; $p < .001$; partial $\eta^2 = .50$), the number of skin conductance responses per minute ($F(9, 148) = 9.15$; $p < .001$; partial $\eta^2 = .36$) and the sum of the skin conductance responses amplitudes per minute ($F(6, 90) = 5.84$; $p < .001$; partial $\eta^2 = .27$). Means and standard errors of SCL, SCRs and S-AMPL are depicted in Table 1. Standard error was calculated by dividing the SD by the square root of N. The mean skin conductance traces, averaged across participants, are depicted in Fig. 4.

The main effect of Position was also significant for the tonic component ($F(10, 157) = 17.6$; $p < .001$; partial $\eta^2 = .52$) and the phasic component ($F(6, 98) = 7.63$; $p < .001$; partial $\eta^2 = .32$) of the skin conductance decomposition. Tonic activity showed significant, very high correlations with SCL ($r = .99$, $p < .001$) and phasic activity with S-AMPL ($r = .97$, $p < .001$). Because of this large dependency between measures, the rest of the results focus on the three responsiveness measures SCL, SCRs and S-AMPL (see Table 1).

Table 1
Means and SEs for the three responsiveness measures, the mean skin conductance level (SCL), the number of skin conductance responses per minute (SCRs) and the sum of skin conductance response amplitudes per minute (S-AMPL), for each of the 16 positions. The positions are sorted on the mean SCL.

Position	SCL [μS]		SCRs [1/min]		S-AMPL [μS/min]	
	M	SE	M	SE	M	SE
Forehead	8.72	0.72	2.97	0.54	0.32	0.07
Foot (instep)	8.50	0.88	4.88	0.76	0.92	0.18
Finger	6.50	0.53	3.80	0.64	0.53	0.13
Shoulders	5.96	0.94	2.41	0.69	0.43	0.12
Neck	5.38	0.84	1.57	0.42	0.19	0.07
Abdomen	5.15	0.91	1.26	0.63	0.29	0.14
Calf (sock)	4.70	0.95	1.63	0.47	0.28	0.09
Wrist (vertical)	4.65	0.73	2.10	0.62	0.44	0.15
Buttock	4.33	0.59	0.98	0.35	0.19	0.07
Wrist (distal)	4.23	0.89	1.43	0.42	0.31	0.11
Chest	4.20	0.69	1.57	0.50	0.35	0.10
Wrist (central)	4.18	0.72	1.77	0.57	0.44	0.14
Thighbone	3.72	0.58	0.90	0.33	0.18	0.07
Arm	3.04	0.52	0.62	0.23	0.13	0.05
Back	2.18	0.60	1.21	0.43	0.26	0.09
Armpit	1.61	0.34	0.71	0.27	0.10	0.05

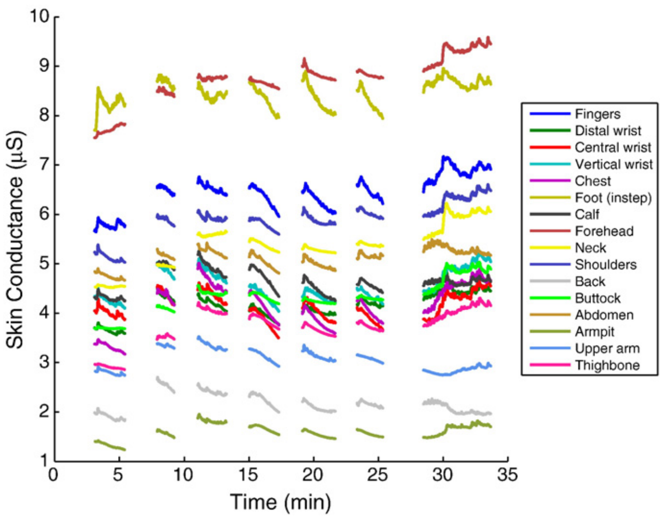

Fig. 4. Mean skin conductance for the sixteen different measurement locations over time. The vertical axis depicts the skin conductance and the horizontal axis depicts time. Parts not involving movie watching are left out as they are not the same duration for each participant.

SCL and SCRs were highest for forehead, foot, finger and shoulders. The lowest SCL was found for armpit, back, arm, and thighbone. The lowest SCR was found for arm, armpit, thighbone, buttock, back and abdomen. The other measurement locations were in between these two groups. Hence, except for the abdomen and the buttock, the results of the SCL and SCR scores were very much in line with each other. For the S-AMPL, foot gave highest scores, followed by finger, wrist positions and shoulders. Forehead was not in the top 3 for S-AMPL. Armpit, arm, thighbone and buttock had the lowest S-AMPL. The results for S-AMPL and SCRs were thus also much in line with each other, except for the forehead.

3.3. Similarity with the skin conductance trace of the fingers

The repeated measures ANOVA showed a significant effect of position on correlation ($F(7, 95) = 2.15$; $p < .05$; partial $\eta^2 = .14$). Means and standard errors are depicted in Table 2. Standard error was calculated by dividing the SD by the square root of N.

The correlation was highest for the foot ($r = .68$). The foot was followed by the thighbone, shoulders, forehead, and wrist locations, which all had correlations between .55 and .59. Neck, chest, and calf had slightly lower correlations between .45 and .53. The lowest correlations were found for arm, armpit, back, and abdomen (all correlations between .29 and .41). Fig. 5 shows an example of the skin conductance traces from one participant measured at the fingers, foot and abdomen. SC traces from fingers and foot show higher similarity whereas SC traces from fingers and abdomen show smaller similarity.

Table 2
Means and SEs of the correlation assessing similarity with the finger. The positions are sorted from highest to lowest correlation.

Position	Correlation	
	M	SE
Foot (instep)	.680	.071
Thighbone	.588	.077
Shoulders	.577	.074
Wrist (central)	.574	.066
Forehead	.566	.083
Wrist (vertical)	.563	.081
Wrist (distal)	.546	.069
Neck	.528	.083
Chest	.502	.088
Calf (sock)	.496	.092
Buttock	.449	.094
Arm	.411	.097
Armpit	.382	.099
Back	.342	.129
Abdomen	.294	.081

4. Discussion

The aim of this study was to explore the emotional responsiveness of different body locations. Simultaneous skin conductance recordings were performed at 16 body locations. Emotions were induced by means of film clips. Subjective self-ratings of participants confirmed that we succeeded in inducing different emotions.

We hypothesized that body locations other than the traditional palmar recording location [24] can also show an emotional response in SC recordings because they have eccrine sweat glands which respond to emotional arousal [15]. To test this hypothesis, we investigated the quality of 16 recording positions in two ways. For the skin conductance *responsiveness* to emotional film clips, we hypothesized that the fingers, feet and forehead are in the top three of most responsive body locations because they have the highest densities of eccrine sweat glands [20]. This was confirmed albeit partially because forehead is not in the top three for S-AMPL. Thus, the relation between sweat gland density and electrodermal activity [22] depends on the measures being used to quantify the skin conductance responsiveness. Furthermore, we found lowest skin conductance responsiveness for armpit, back, arm and thighbone. Wrist positions, shoulders, calf and chest show intermediate skin conductance responsiveness to emotional film clips. For the *similarity* with the skin conductance trace of the fingers, we hypothesized to find highest correlations between the finger trace and the traces from the foot and forehead. The foot indeed showed the highest correlation and the forehead is also highly correlated with the trace of the fingers. We found lowest correlations for the abdomen, back, arm and armpit and intermediate correlations for the shoulders, wrist positions, neck, chest and calf.

The results of this study can be used for recommending recording positions for measuring skin conductance in emotion sensing platforms. The traditional finger position [24] can work very well for skin conductance measurements in laboratory situations but becomes problematic in ambulatory situations because many everyday tasks require the use of the hands. The feet are less obtrusive as measurement position because sensors can for example be integrated into a sock. In line with this, skin conductance at the foot has already been used for long-term monitoring of skin conductance in daily life [1,28]. These studies have for example integrated skin conductance sensors in the arch of the shoe. The forehead position is also in the top three of most responsive body positions for SCL and SCRs and might be used with skin conductance sensors integrated in a headband or headphones. Besides the fingers, feet, and forehead, we also found more different body positions that show high skin conductance

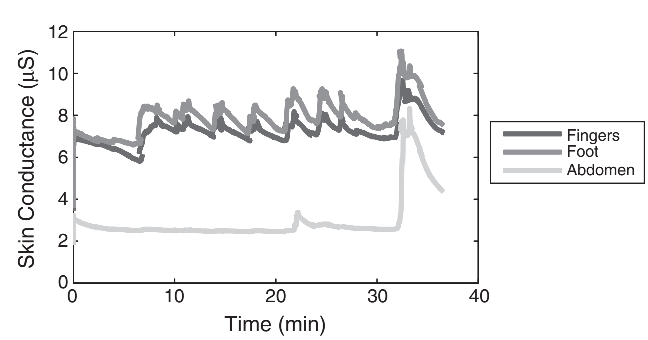

Fig. 5. Skin conductance in microSiemens at the fingers, foot and abdomen of one participant.

responsiveness to emotional film clips and similarity to the fingers. The shoulders and neck [29] are positions which can be used in a necklace, the calf can be used in a sock border, wrist positions [25,26,30] can be used in a watch, and the chest position can be used in a chest band. These measurement positions are also more convenient in ambulatory monitoring than the fingers.

There are some limitations to the results found in this study and suggestions for future research. For the emotion elicitation, we made use of film clips presented in a fixed order to keep carry-over effects between conditions fixed for all participants. This implies that we cannot directly draw conclusions about comparisons of different emotions, which was also not our main aim. Nonetheless, it might be interesting for future research to investigate skin conductance measurement locations related to specific emotions. Next to this, future research may investigate the aspect of convenience (and comfort) to be able to create unobtrusive emotion sensing. Also technical aspects of physiological sensors can be improved, like miniaturization, power consumption, etc. in order to develop more advanced platforms and further increase comfort. Furthermore, our findings in a laboratory situation should also be confirmed in field tests when making use of ambulatory skin conductance monitoring. Therefore, we need wireless skin conductance measurement technology that enables SC sensing at a multitude of positions in a synchronized way. When comparing different measurement locations, it is also important to take into account the conduction velocity of the skin conductance response. Time lags between different measurement locations can lead to an underestimation of effective correlations between locations that are further apart from each other [37]. In our study design (with relatively low sampling rate) the effect of these time lags will be negligible. Furthermore, we used a general, relatively low threshold-amplitude for counting the number of skin conductance responses obtained at the 16 different body positions. We have discussed the validity of this approach; however, future research needs to further investigate evidence whether this is an adequate criterion for measurements at non-standard recording positions. In this study, we aimed to reduce variation due to potential lateralization influences by measuring mostly on the right side of the body. Only for one position, vertical wrist, we measured on the left side of the body. As we also measured two wrist positions on the right side of the body, distal wrist and central wrist, it's interesting to make the comparison, keeping in mind that these positions are not perfectly similar (different orientation on the wrist). We find higher skin conductance responsiveness for the left wrist compared to the right wrist, although these differences are rather small. Future research should investigate the lateralization of skin conductance activity in detail by comparing similar body positions on the left and on the right side of the body.

Finally, our study relied on estimations of sweat gland densities from the literature and did not directly determine the number of active sweat glands at the 16 different body positions. A few results are not completely in line with the ranking according to estimations of sweat gland densities. For example, forehead showed a higher skin conductance level than fingers and foot although its sweat gland density is lower. As mentioned in the Introduction, in addition to the density of sweat glands, multiple aspects are involved in determining skin conductance traces, such as the distribution of dermatomes, the innervations of sweat glands at different body locations and sweat gland nerve fiber densities. Future research could investigate these different physiological aspects. Therefore, we recommend making use of the combination of multiple methods to make the relation even stronger for more different body positions.

In conclusion, although finger measurements are traditionally being employed in laboratory measurements of SC, we have shown that there are ample opportunities for unobtrusive measurement locations of SC elsewhere on the body. This is important for future research in the affective sciences, as it can enable applications for emotion sensing in ambulatory situations. This way, experiments can be designed that generalize laboratory findings to real-world situations. Furthermore, it can enable technology that automatically measures emotional responses, which may be useful for a wide variety of applications.

Acknowledgments

The authors would like to thank Mark Johnson, Estrella Mena and Joyce Westerink for their contribution in the execution of this study and Martin Ouwerkerk and Richard van der Wolf for the development of the skin conductance modules. We would also like to thank Marjolein van der Zwaag for her helpful comments and suggestions to improve this manuscript.

References

[1] Picard RW, Healey J. Affective wearables. IEEE ISWC Proc 1997;1:90–7.
[2] Petta P, Pelachaud C, Cowie R. Emotion-oriented systems: the Humaine handbook. Cognitive technologies. Berlin/Heidelberg, Germany: Springer-Verlag; 2011.
[3] Picard RW, Vyzas E, Healey J. Towards machine emotional intelligence: analysis of affective physiological state. IEEE TPAMI 2001;23:1175–91.
[4] Tsunoda T, Yoshino A, Furusawa T, Miyazaki M, Takahashi Y, Nomura S. Social anxiety predicts unconsciously provoked emotional responses to facial expression. Physiol Behav 2008;93:172–6.
[5] Zeng ZH, Pantic M, Roisman GI, Huang TS. A survey of affect recognition methods: audio, visual, and spontaneous expressions. IEEE TPAMI 2009;31:39–58.
[6] Pantic M. Machine analysis of facial behaviour: naturalistic and dynamic behaviour. Philos Trans R Soc B 2009;364:3505–13.
[7] van den Broek EL, Lisy V, Janssen JH, Westerink JHDM, Schut MH, Tuinenbreijer K. Affective man–machine interface: unveiling human emotions through biosignals. In: Fred A, Filipe J, Gamboa H, editors. Biomedical engineering systems and technologies: communications in computer and information science, 52. Berlin/Heidelberg, Germany: Springer-Verlag; 2010. p. 21–47.
[8] Lang PJ, Greenwald MK, Bradley MM, Hamm AO. Looking at pictures: affective, facial, visceral, and behavioral reactions. Psychophysiology 1993;30:261–73.
[9] Andreassi JL. Electrodermal activity and behavior. Psychophysiology: human behavior and physiological response. London: Lawrence Erlbaum Associates; 2007. p. 259–88.
[10] Boucsein W. Electrodermal activity. New York and London: Plenum Press; 1992.
[11] Bradley. Emotion and motivation. In: Cacioppo JT, Tassinary LG, Bernston GG, editors. Handbook of psychophysiology. Cambridge University Press; 2000. p. 602–43.
[12] Dawson, Schell, Filion. The electrodermal system. In: Cacioppo JT, Tassinary LG, Bernston GG, editors. Handbook of psychophysiology. Cambridge University Press; 2000. p. 200–24.
[13] Wilhelm FH, Grossman P. Emotions beyond the laboratory: theoretical fundaments, study design, and analytic strategies for advanced ambulatory assessment. Biol Psychol 2010;84:552–69.
[14] Benedek M, Kaernbach C. A continuous measure of phasic electrodermal activity. J Neurosci Methods 2010;190:80–91.
[15] Figner B and Murphy RO. Using skin conductance in judgment and decision making research. In: Schulte-Mecklenbeck M, Kuehberger A, Ranyard R, editors. A handbook of process tracing methods for decision research. New York, NY: Psychology Press; 2011.
[16] Biology of eccrine, apocrine, and apoeccrine sweat glands. In: Wolff K, Goldsmith LA, Katz SI, Gilchrest BA, Paller AS, Leffell DJ, editors. Fitzpatrick's dermatology in general medicine. McGraw-Hill; 2007.
[17] Mangina CA, Beuzeron-Mangina JH. Direct electrical stimulation of specific human brain structures and bilateral electrodermal activity. Int J Psychophysiol 1996;22:1–8.
[18] Randall WC. Quantitation and regional distribution of sweat glands in man. J Clin Invest 1946;25:761–7.
[19] Sato K, Dobson RL. Regional and individual variations in the function of the human eccrine sweat gland. J Invest Dermatol 1970;54:443–9.
[20] Saga K. Structure and function of human sweat glands studied with histochemistry and cytochemistry. Prog Histochem Cytochem 2002;37:323–86.
[21] Frewin DB, Downey JA. Sweating—physiology and pathophysiology. Aust J Dermatol 1976;17:82–6.
[22] Freedman LW, Scerbo AS, Dawson ME, Raine A, McClure WO, Venables PH. The relationship of sweat gland count to electrodermal activity. Psychophysiology 1994;31:196–200.
[23] Scerbo AS, Freedman LW, Raine A, Dawson ME, Venables PH. A major effect of recording site on measurement of electrodermal activity. Psychophysiology 1992;29:241–6.
[24] Fowles DC, Christie MJ, Edelberg R, Grings WW, Lykken DT, Venables PH. Publication recommendations for electrodermal measurements. Psychophysiology 1981;18:232–9.
[25] Westerink J, Ouwerkerk M, de Vries G-J, de Waele S, van den Eerenbeemd J, van Boven M. Emotion measurement platform for daily life situations. International conference ACII 2009, 10–12 Sept; 2009.

[26] Poh M, Swenson NC, Picard RW. A wearable sensor for unobtrusive, long-term assessment of electrodermal activity. IEEE Trans Biomed Eng 2010;57:1243–52.
[27] Tronstad C, Gjein GE, Grimnes S, Martinsen OG, Krogstad A, Fosse E. Electrical measurement of sweat activity. Physiol Meas 2008;29:S407.
[28] Kappeler-Setz C, Schumm J, Kusserow M, Arnrich B, Tröster G. Towards long term monitoring of electrodermal activity in daily life. 5th International Workshop on Ubiquitous Health and Wellness. UbiHealth 2010, 26 Sept; 2010.
[29] Brown DE, Sievert LL, Morisson LA, Reza AM, Mills PS. Do Japanese American women really have fewer hot flashes than European Americans? The Hilo women's health study. Menopause 2009;16:870–6.
[30] Fletcher RR, Dobson K, Goodwin MS, Eydgahi H, Wilder-Smith O, Fernholz D, et al. iCalm: wearable sensor and network architecture for wirelessly communicating and logging autonomic activity. IEEE Trans Inf Technol Biomed 2010;14:215–23.
[31] Wilcott RC. Arousal sweating and electrodermal phenomena. Psychol Bull 1967;67:58–72.
[32] Russell JA. A circumplex model of affect. J Pers Soc Psychol 1980;39:1161–78.
[33] Overbeek TJM, van Boxtel A, Westerink, JHD. Development of an emotion-eliciting stimulus set: results of emotional pictures and film fragments ratings. Technical Note PR-TN2007/00574 (Unpublished), Philips Research, 2007.
[34] Kohlish P. SCRGAUGE: a computer program for the detection and quantification of SCRs. In: Boucsein W, editor. Electrodermal activity. New York: Plenum; 1992. p. 432–42.
[35] Schmidt S, Walach H. Electrodermal activity: state-of-the-art measurement and techniques for parapsychological purposes. J Parapsychol 2000;64:139–63.
[36] Benedek M, Kaernbach C. Decomposition of skin conductance data by means of nonnegative deconvolution. Psychophysiology 2010;47:647–58.
[37] Lim CL, Seto-Poon M, Clouston PD, Morris JGL. Sudomotor nerve conduction velocity and central processing time of the skin conductance response. Clin Neurophysiol 2003;114:2172–80.