Wearables

https://doi.org/10.1038/s41928-025-01373-7

Monitoring physical and mental activities with skin conductance

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A skin conductance sensor with a water-permeable, micro-lace electrode can be used to continuously monitor daily activities.

Skin conductance is a physiological measure that reflects hydration. It is influenced by factors such as sweat gland density and sweat rate. Sweat gland density varies across different anatomical sites, from those with a high density of sites (such as fingertips) to those with a low density of sites (such as the wrist, forearm and upper arm). Sweat rate, on the other hand, is closely associated with both the type and intensity of activities[1]. Specifically, physical activities induce thermoregulatory responses, which occur as a gradual and accumulative process, giving rise to tonic signals. Conversely, mental activities are controlled by transient bursts of sympathetic nervous system activation in response to cognitive arousal, producing phasic skin conductance signals superimposed on the underlying tonic activity. Continuous skin conductance monitoring thus has the potential to provide a comprehensive assessment of both physical and mental activities, offering valuable insights into physiological regulation and psychological responses[2–4].

Controlling sweat evaporation, however, presents a challenge. Conventional electrodes used for skin conductance recording are non-permeable, leading to trapping of sweat at the skin–electrode interface[5], especially during high-sweat-production conditions. This trap results in persistently elevated skin conductance levels, reducing the sensitivity and accuracy of skin conductance measurements in response to sweat rate changes. Additionally, prolonged wearing of such electrodes can lead to skin swelling due to excessive sweat retention at the interface, potentially impairing sweat gland functions. As a result, previous work has primarily focused on skin conductance measurements during low-sweat-production conditions[6,7].

Writing in *Nature Electronics*, Ali Javey and colleagues now report a skin conductance sensor with a micro-lace electrode[8] (Fig. 1a). The innovative electrode achieves 99.4% water permeability, enabling rapid sweat evaporation and effectively preventing sweat accumulation at the skin–electrode interface (Fig. 1b). With this design, continuous skin

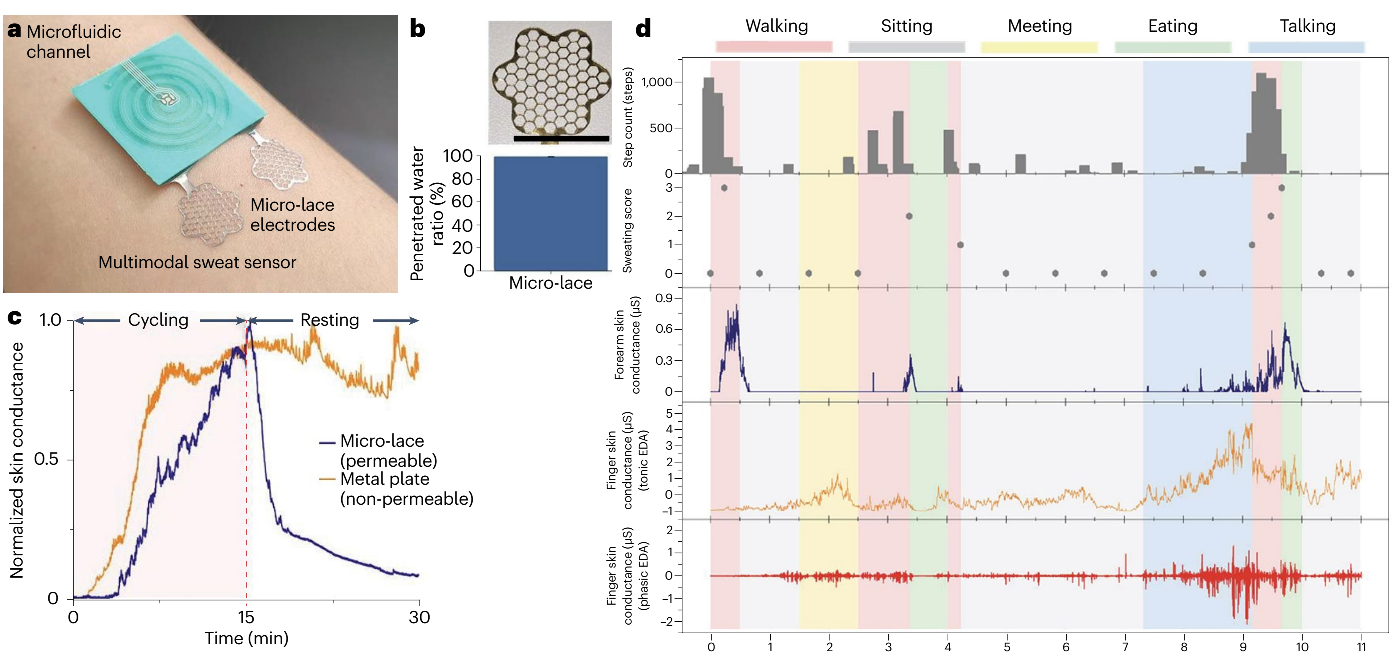

Fig. 1 | A sweat sensor with micro-lace electrodes. a, Photograph showing skin conductance sensor with micro-lace electrodes integrated with the microfluidic channel for multimodal sweat sensing on a participant's forearm. **b**, Photograph (top) and water permeability data (bottom) of micro-lace electrodes. Scale bar, 1 cm. **c**, Skin conductance recovery responses on the upper arm for permeable micro-lace electrodes and non-permeable metal plate electrodes after 15 minutes of cycling on a stationary bike. **d**, A participant wore two skin conductance sensors on the forearm and fingers and an activity tracker on the wrist during 11 hours of daily activities (walking, sitting, attending meetings, eating and talking). The participant also qualitatively scored their sweat rate on a scale from 0 to 3. EDA, electrodermal activity. Figure adapted from ref. 8, Springer Nature Limited.

conductance monitoring during high-sweat-production conditions becomes feasible. The researchers — who are based at the University of California Berkeley, Lawrence Berkeley National Laboratory and VTT Technical Research Centre of Finland Ltd — show that the sensor can offer more than 90% skin conductance recovery after 15 minutes of cycling (Fig. 1c). By contrast, non-permeable electrodes exhibited no recovery because of the sweat trapping beneath the electrode. Furthermore, relative changes in the forearm skin conductance were calculated by normalizing skin conductance variation to the resting baseline, showing a strong positive correlation with local sweat loss measured by a commercial device also placed on the forearm (Pearson correlation coefficient $r = 0.89$, coefficient of determination $R^2 = 0.79$). Integrating these relative changes over time also exhibited a strong correlation with total sweat loss, as determined by the weight difference before and after exercise ($r = 0.89$, $R^2 = 0.80$).

During mental activities, sweat production is minimal and quickly evaporates in areas with low sweat gland density, making reliable detection of skin conductance challenging. However, regions with high sweat gland density exhibit greater sweat production, resulting in both phasic and tonic signals. For example, during a 25-minute IQ test, both phasic and tonic skin conductance changes were observed only at the fingertip. To decouple phasic and tonic signal components, the team applied high-pass and low-pass filtering techniques. During physical activities, however, sweat production is high, resulting in accumulative tonic signals across all body sites[9]. For example, during a stationary cycling task, tonic skin conductance changes were observed in all measured body areas.

An 11-hour recording of skin conductance illustrates the capabilities of the system to capture various activities, including walking, sitting, attending meetings, eating and talking (Fig. 1d). Forearm tonic skin conductance correlated well with both step count and qualitative sweating scores (self-assessed by the individual on a scale from 0 to 3) during walking, while mental tasks (such as attending meetings) were reflected only in finger skin conductance. Additionally, finger skin conductance measurements during sleep suggest a potential correlation between the frequency of phasic spikes and sleep states.

The technology developed by Javey and colleagues offers several avenues for further exploration. First, while the study provides a comprehensive discussion on the measurement of direct current skin conductance, additional parameters — such as skin admittance, skin capacitance and overall alternating-current skin impedance — are also believed to be closely correlated to skin hydration[10]. Future research could integrate these multiple parameters to enhance monitoring accuracy and reliability. Second, the distinction between phasic and tonic responses at the fingertip primarily relies on frequency differences. However, variations in signal frequency across different intensities of mental and physical activities, as well as inter-individual differences, remain unclear. Further investigations are needed to ensure the generalizability of this technology. Third, the study suggests that only skin conductance signals from the fingertip respond to mental activities. However, it remains uncertain whether skin conductance measurements from other body sites are responsive to mental activities, especially under intense mental activities (such as grant writing before a deadline). Fourth, the current skin conductance measurements are primarily qualitative or semi-quantitative. To maximize the impact of this technology, a fully quantitative framework with rigorous validation of skin conductance responses during both physical and mental activities would be beneficial. Finally, simultaneous mental and physical activities are common in real-world scenarios. Developing methods to separate — and ideally quantify — their individual effects would enhance the practical utility of the technology. Expanding on these points could provide deeper insights into the robustness and real-world applicability of the technology.

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Published online: 14 April 2025

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Competing interests

The authors declare no competing interests.