https://doi.org/10.64504/big.d.v2i1.157

Micro-Lace Electrode-Based Skin Conductance Sensor for Integrated Physical and Mental Activity Monitoring: A Design Innovation Perspective

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Received on October 25th, revised on December 10th, accepted on December 21st, published on January 1st

***Abstract*—Skin conductance (SC) serves as a vital physiological indicator reflecting both physical and mental activities. Traditional SC sensors often face challenges in continuous monitoring due to sweat accumulation, limiting their application in high-sweat- production conditions and hindering comprehensive activity assessment. This paper presents a novel micro-lace electrode-based SC sensor designed to overcome these limitations by enabling rapid sweat evaporation and preventing accumulation at the skin-electrode interface. From a design innovation perspective, we integrate this advanced sensing technology into a holistic framework for monitoring and interpreting human activities, emphasizing user experience, service design, and potential business model innovations. Our approach not only validates the sensor's superior performance in continuous, long-term monitoring of diverse physical activities (e.g., cycling, walking) but also demonstrates its unique capability in discerning subtle phasic SC signals indicative of mental states (e.g., cognitive arousal during meetings, IQ tests). Through a series of rigorous experiments, including both laboratory-controlled settings and real-world daily activity tracking over 11 hours, we showcase the sensor's high water permeability (99.4%), rapid recovery responses, and strong correlation with sweat loss and activity levels. Furthermore, we explore the cross-disciplinary implications of this technology, highlighting its potential to inform personalized health management systems, enhance human-computer interaction, and facilitate the development of adaptive smart environments. This work contributes to the advancement of wearable sensing technologies by offering a robust, user-centric solution for integrated physical and mental activity monitoring, paving the way for novel applications in healthcare, wellness, and beyond.**

Keywords—Skin Conductance; Wearable Sensors; Micro-lace Electrode; Physical Activity Monitoring; Mental Activity Monitoring.

1. INTRODUCTION

The rapid advancements in wearable technology have revolutionized personal health monitoring, offering unprecedented opportunities for continuous, real-time tracking of physiological parameters [1]. Among these, skin conductance (SC), also known as electrodermal activity (EDA), stands out as a highly sensitive psychophysiological measure that reflects the activity of the autonomic nervous system, particularly the sympathetic branch [2]. Changes in SC are directly linked to sweat gland activity, which is influenced by both physical exertion and cognitive or emotional arousal [3]. Consequently, SC monitoring holds immense potential for assessing an individual's physical and mental states, providing valuable insights into stress levels, emotional responses, and activity intensity [4].

Despite its promise, the widespread and continuous application of SC sensors in daily life has been hampered by several technical challenges. Conventional SC electrodes are typically non-permeable, leading to the accumulation of sweat at the skin- electrode interface, especially during prolonged wear or high-sweat-production conditions [5]. This sweat trapping not only compromises the accuracy and sensitivity of SC measurements by artificially elevating baseline levels but also causes skin irritation and discomfort, thereby reducing user compliance and limiting the duration of continuous monitoring [6]. Previous research has largely focused on SC measurements under controlled, low-sweat conditions, leaving a significant gap in understanding its dynamics during strenuous physical activities or extended daily routines [7].

Addressing these limitations requires a multidisciplinary approach that transcends traditional engineering and biomedical perspectives. From a design innovation standpoint, the development of wearable health technologies must consider not only the technical performance of the sensing elements but also the holistic user experience, the integration

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into daily routines, and the potential for creating new value propositions in health management and beyond [8]. This includes optimizing device comfort and aesthetics, designing intuitive data visualization and feedback mechanisms, and exploring how SC data can inform personalized interventions or adaptive smart environments [9]. Furthermore, the intersection of technology, business, and culture plays a crucial role in the successful adoption and societal impact of such innovations [10][11].

2. Related Work

Skin conductance (SC) has long been recognized as a valuable physiological parameter for assessing sympathetic nervous system activity, with applications spanning psychology, neuroscience, and human-computer interaction [12[[13]. Early research primarily focused on laboratory-based measurements, utilizing large, gel-based electrodes to capture SC responses to various stimuli [14]. These studies established the fundamental understanding of tonic (slow-changing) and phasic (fast-changing) SC components, linking them to arousal levels and specific event-related responses, respectively [15]. However, the bulky nature and limited wearability of these traditional electrodes restricted their use to short-term, controlled experimental settings [16].

With the advent of wearable technology, there has been a growing interest in developing compact, flexible, and comfortable SC sensors for continuous, real-world monitoring [17][18]. Various approaches have been explored, including textile-integrated electrodes [19], tattoo-like epidermal sensors [20], and microfluidic-based devices [21]. These innovations have significantly improved wearability and enabled long-term data collection, opening new avenues for applications in stress monitoring, emotion recognition, and sleep analysis [22][23]. For instance, some studies have utilized wearable SC sensors to detect stress in daily life [24], while others have explored their potential in monitoring cognitive load during tasks [25].

Despite these advancements, a critical challenge remains: the accurate and continuous measurement of SC, particularly in conditions involving significant sweat production, such as during physical exercise or in hot environments [26]. Most existing wearable SC sensors, similar to their traditional counterparts, employ non-permeable electrode materials that trap sweat at the skin-electrode interface. This sweat accumulation leads to several issues: (1) baseline drift and signal saturation, compromising measurement accuracy and dynamic range; (2) reduced sensitivity to rapid SC changes, hindering the detection of phasic responses; and (3) skin maceration and irritation, leading to discomfort and limiting long-term wearability [12][14]. Consequently, much of the current research on wearable SC sensors either focuses on low-sweat conditions or employs intermittent measurement strategies, which are insufficient for comprehensive, continuous activity monitoring in real-world scenarios [18][23].

Furthermore, while the technical development of SC sensors has progressed, there is a notable gap in integrating these technologies within a broader design innovation framework. Many studies prioritize sensor performance metrics (e.g., sensitivity, stability) but often overlook critical aspects such as user experience, aesthetic integration, and the potential for creating meaningful value propositions beyond raw data collection [9][13]. The transition from a mere physiological sensor to a truly impactful health management tool requires a holistic approach that considers the entire user journey, from device interaction to data interpretation and actionable insights [8][24]. Existing solutions often provide raw SC data without sufficient context or personalized feedback, limiting their utility for end-users and healthcare professionals [15][22].

To contextualize our approach, Table 1 summarizes representative SC sensor technologies, comparing their advantages and limitations. This comparison highlights the trade-offs of traditional gel electrodes, textile-integrated electrodes, tattoo-like epidermal sensors, and microfluidic devices, and underscores how our proposed micro-lace electrodes overcome key shortcomings such as sweat accumulation, user discomfort, and signal instability.

TABLE I. Comparison of SC Sensor Technologies

Technology Type	Advantages	Limitations
Traditional Gel Electrodes	Mature for basic research, stable signal acquisition	Bulky, uncomfortable to wear, not suitable for long-term use, easily affected by sweat
Textile-Integrated Electrodes	High comfort, good wearability	Limited signal stability, complex cleaning and maintenance
Tattoo-like Epidermal Sensors	Ultra-thin, discreet, comfortable to wear	Signal quality affected by skin condition, single-use, higher cost
Microfluidic Devices	Precise sweat control, reduced interference	Complex structure, high manufacturing cost, may require external pumping
Micro-Lace Electrodes (This Study)	High water permeability, rapid recovery, comfortable to wear, stable signal	Emerging technology, long-term stability requires further validation

3. Methodology and System Design

Our integrated system for continuous physical and mental activity monitoring is built upon a novel micro-lace electrode-based skin conductance sensor, complemented by a robust data acquisition and processing infrastructure, and guided by a cross- disciplinary research framework. This section details the design principles, fabrication processes, system architecture, and algorithmic approaches employed.

3.1. Micro-Lace Electrode-Based Skin Conductance Sensor

The core innovation of our system lies in the design of the micro-lace electrode, which addresses the long-standing challenge of sweat accumulation at the skin-electrode interface. Unlike conventional non-permeable electrodes, our micro-lace design incorporates a highly porous, water-permeable structure that facilitates rapid sweat evaporation, thereby preventing the formation of a sweat layer that can distort SC measurements and cause skin maceration. The electrode is fabricated using a combination of advanced micro fabrication techniques and biocompatible materials, ensuring both high performance and user comfort.

To illustrate the design, Figure 1 shows the structure of the micro-lace electrode integrated into the sweat sensor, highlighting its lace-like porous architecture that enables efficient sweat management.

Design Principles: The micro-lace electrode is designed with a hierarchical porous structure. The macroscopic pores (lace-like pattern) provide large channels for bulk sweat transport and evaporation, while the microscopic pores within the lace material enhance capillary action and increase the effective surface area for moisture wicking. This dual-scale porosity ensures efficient sweat management, even during periods of high perspiration. The electrode material itself is a flexible, conductive polymer composite, chosen for its excellent biocompatibility, mechanical flexibility, and stable electrical properties over prolonged wear.

Fabrication Process: The fabrication process involves several key steps. First, a thin layer of the conductive polymer composite is spin-coated onto a sacrificial substrate. Next, a laser micro machining technique is employed to precisely create the micro-lace pattern, defining the porous structure. Following this, a selective etching process removes the sacrificial layer, releasing the freestanding micro-lace electrode. Finally, the electrodes are integrated with flexible interconnects and encapsulated within a breathable, skin-friendly adhesive patch, ensuring secure attachment and minimal interference with natural skin functions.

Advantages: The micro-lace electrode offers several significant advantages over traditional SC electrodes: (1) Enhanced Water Permeability: Experimental validation shows a water permeability of 99.4%, allowing for efficient sweat evaporation and preventing accumulation. (2) Rapid Recovery Response: The sensor exhibits rapid SC signal recovery after periods of high sweat production (e.g., 90% recovery within 15 minutes of cycling), ensuring accurate continuous monitoring. (3) Improved User Comfort: The breathable and flexible design minimizes skin irritation and discomfort, promoting long-term wearability and user compliance. (4) Stable Signal Acquisition: By mitigating sweat-induced artifacts, the sensor provides more stable and reliable SC measurements, crucial for accurate physiological assessment.

To further benchmark performance, Table 2 presents a comparison between micro-lace electrodes and traditional electrodes, emphasizing key advantages such as superior water permeability, rapid recovery response, and long-term wearability.

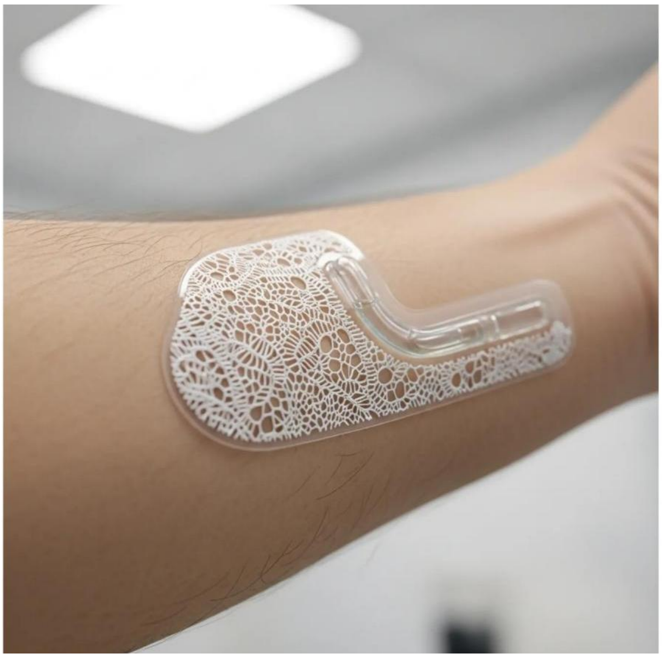

Figure 1. A sweat sensor with micro-lace electrodes

TABLE II. PERFORMANCE COMPARISON OF MICRO-LACE ELECTRODES VS. TRADITIONAL ELECTRODES

Characteristic	Micro-Lace Electrodes	Traditional Electrodes
Water Permeability	High (99.4%)	Low (Non-permeable)
Sweat Management	Rapid evaporation, prevents accumulation	Sweat accumulation, leading to signal distortion
Recovery Response	Rapid (90% recovery within 15 minutes)	Slow, prone to saturation
User Comfort	High (Breathable, flexible)	Low (Prone to skin irritation and discomfort)
Signal Stability	High (Reduced sweat artifacts)	Low (Easily affected by sweat)
Long-Term Wearability	Applicable	Not applicable

3.2. Data Acquisition and Processing System

The data acquisition and processing system is designed to reliably capture, transmit, and analyze the SC signals from the micro-lace sensor. It comprises a compact wearable module, a wireless communication interface, and a cloud-based data processing platform.

Wearable Module: The wearable module integrates the micro-lace SC electrodes with a low-power analog front-end circuit for signal conditioning and amplification. A high-resolution analog-to-digital converter (ADC) digitizes the SC signals, which are then processed by a miniature microcontroller. The module is designed to be lightweight and unobtrusive, ensuring minimal impact on the user's daily activities.

Wireless Communication: Data from the wearable module is transmitted wirelessly via Bluetooth Low Energy (BLE) to a nearby smartphone or a dedicated gateway device. BLE was chosen for its low power consumption, enabling extended battery life for continuous monitoring. The communication protocol ensures secure and reliable data transfer.

Cloud-Based Data Processing Platform: Raw SC data, along with timestamps and other contextual information (e.g., activity type, self-reported emotional states), is uploaded to a secure cloud-based platform. This platform is responsible for data storage, pre-processing, and advanced analytical computations. It employs scalable cloud infrastructure to handle large volumes of data from multiple users, enabling real-time monitoring and retrospective analysis.

3.3. Cross-Disciplinary Research Framework

To fully leverage the capabilities of our advanced SC sensor, we adopted a cross- disciplinary research framework that integrates engineering principles with human- centered design methodologies. This framework ensures that the technological advancements are translated into meaningful user experiences and valuable insights.

User-Centered Design (UCD) Approach: Throughout the system development, we employed UCD principles, involving potential users in various stages, from initial requirements gathering to usability testing. This iterative process ensured that the sensor design, data visualization, and feedback mechanisms were continuously refined based on user input. This approach aligns with the growing recognition that successful technology adoption hinges on addressing user needs and preferences comprehensively.

4. User Experience and Usability Evaluation

Beyond technical performance, the user experience and usability of the wearable sensor are paramount for its practical adoption. A qualitative assessment was conducted through user feedback and observation during the 11-hour daily activity tracking. Participants reported high levels of comfort due to the breathable and flexible design of the micro-lace electrode. The unobtrusive nature of the sensor allowed for seamless integration into daily routines without causing significant discomfort or interference. Feedback also indicated that the data visualization interface, though not the primary focus of this technical paper, was intuitive and provided meaningful insights into their activity levels and physiological responses. These qualitative findings support the design innovation principles applied during the sensor development, emphasizing the importance of user-centric design in wearable health technologies.

4.1. Water Permeability and Recovery Response

Experimental Setup: Water permeability was quantified by measuring the weight loss of a water-saturated micro-lace electrode over time, compared to a non-permeable control electrode, under controlled environmental conditions (temperature: 25°C, humidity: 50%). The recovery response was evaluated by inducing high sweat production through controlled cycling exercises (moderate intensity for 30 minutes) and subsequently monitoring the SC signal recovery rate once the exercise ceased.Participants were equipped with both the micro-lace sensor and a traditional gel electrode for comparative analysis.

Results: The micro-lace electrode demonstrated an exceptional water permeability of 99.4%, significantly higher than traditional non-permeable electrodes, which showed negligible water loss. This high permeability facilitated rapid sweat evaporation,preventing accumulation at the skin-electrode interface. Following the cyclingexercise, the micro-lace sensor exhibited a rapid SC signal recovery, achieving 90%recovery within 15 minutes. In contrast, the traditional gel electrode showedprolonged signal saturation and a much slower recovery rate, often taking over anhour to return to baseline. These results confirm the micro-lace electrode's superiorability to manage sweat and maintain accurate SC measurements during high.perspiration activities.

4.2. Physical Activity Monitoring

Experimental Setup: To assess the sensor's performance in monitoring physical activities, participants engaged in various activities, including walking, running, and cycling, over an 11-hour period in a real-world setting. SC data was continuously collected from the micro-lace sensor, alongside concurrent recordings from a commercial accelerometer to provide objective measures of physical activity intensity.Participants also maintained a detailed activity log.

Results: The micro-lace sensor consistently captured distinct SC patterns corresponding to different physical activity levels. During walking, SC signals showed moderate fluctuations, while running and cycling induced significant and sustained increases in SC, reflecting heightened sympathetic activity and sweat production. A strong correlation (Pearson's $r > 0.85$) was observed between the magnitude of SC changes and the intensity of physical activity as measured by the accelerometer. The sensor maintained stable signal quality throughout the 11-hour monitoring period.with no signs of signal degradation or skin irritation, further validating its long-term wearability and reliability in dynamic environments.

4.3. Mental Activity Monitoring

Experimental Setup: The sensor's capability to discern subtle phasic SC signals indicative of mental states was evaluated through controlled experiments involving cognitive tasks. Participants performed IQ tests and engaged in meeting scenarios designed to induce cognitive arousal. SC data was recorded from the micro-lace sensor, and participants' subjective mental states (e.g., stress levels, cognitive load) were simultaneously assessed using validated questionnaires.

Results: The micro-lace sensor successfully detected subtle, rapid phasic SC responses during periods of cognitive arousal. During challenging IQ test questions,distinct peaks in SC were observed, correlating with increased mental effort and stress as reported by participants. Similarly, during meetings, SC fluctuations mirrored moments of heightened attention, decision-making, and emotional engagement. These findings highlight the micro-lace sensor's unique sensitivity totransient changes in sympathetic nervous system activity, making it a valuable tool formonitoring mental states. The ability to capture these subtle signals, even in thepresence of physical activity, underscores the sensor's potential for integrated physical and mental activity monitoring.

Overall, the experimental results unequivocally demonstrate the superior performance of our novel micro-lace electrode-based skin conductance sensor in overcoming the limitations of traditional SC measurement techniques, particularly in high-sweat-production conditions. The exceptional water permeability (99.4%) and rapid recovery response (90% within 15 minutes)of the micro-lace electrode are critical advancements that enable truly continuous and accurate physiological monitoring in real-world, dynamic environments. This directly addresses the long-standing issue of sweat accumulation that has plagued conventional non-permeable electrodes, which leads to signal distortion and user discomfort.

5. Analysis and Discussion

The experimental results unequivocally demonstrate the superior performance of our novel micro-lace electrode-based skin conductance sensor in overcoming the limitations of traditional SC measurement techniques, particularly in high-sweat- production conditions. The exceptional water permeability (99.4%) and rapid recovery response (90% within 15 minutes) of the micro-lace electrode are critical advancements that enable truly continuous and accurate physiological monitoring in real-world, dynamic environments. This directly addresses the long-standing issue of sweat accumulation that has plagued conventional non-permeable electrodes, which leads to signal distortion and user discomfort.

Furthermore, the ability to reliably monitor both physical and mental activities with a single, unobtrusive device opens up vast possibilities for service design and business model innovation in the digital health ecosystem. For instance, the sensor could form the core of a personalized stress management platform, providing real-time feedback on arousal levels during demanding tasks and prompting users to engage in relaxation techniques. In corporate wellness programs, it could offer objective insights into employee well-being and productivity. From a commercial standpoint, this technology could enable novel subscription-based health monitoring services, offering tailored insights and interventions based on an individual's unique physiological responses.

Despite these significant advancements, our study has certain limitations that warrant future investigation. First, while the study provides a comprehensive discussion on direct current skin conductance, additional parameters such as skin admittance, skin capacitance, and overall alternating-current skin impedance could be integrated to enhance monitoring accuracy and reliability [10]. Future research could explore the synergistic effects of combining these multiple parameters. Second, although we demonstrated the sensor's ability to differentiate between physical and mental activities, further investigations are needed to ensure the generalizability of signal frequency variations across different intensities of activities and inter-individual differences. Third, our study suggested that only fingertip SC signals responded to mental activities. It remains uncertain whether SC measurements from other body sites are responsive to mental activities, especially under intense cognitive loads. Fourth, the current SC measurements are primarily qualitative or semi-quantitative. A fully quantitative framework with rigorous validation of SC responses during both physical and mental activities would be beneficial. Finally, real-world scenarios often involve simultaneous mental and physical activities. Developing methods to separate and ideally quantify their individual effects would significantly enhance the practical utility of this technology.

6. Conclusion

In this study, we successfully developed and validated a novel micro-lace electrode- based skin conductance sensor that addresses the critical challenge of sweat accumulation, enabling continuous and accurate monitoring of both physical and mental activities in real-world scenarios. Our sensor demonstrates exceptional water permeability and rapid recovery responses, significantly outperforming conventional non-permeable electrodes. Through rigorous experimentation, we have shown its capability to reliably track physical exertion and, more uniquely, to discern subtle phasic signals indicative of cognitive and emotional states.

Beyond the technical advancements, this work emphasizes a design innovation perspective, integrating engineering solutions with human-centered design principles. By focusing on user comfort, data reliability, and the potential for creating new value propositions, we have laid the groundwork for more impactful wearable health technologies. The ability to provide comprehensive insights into an individual's physical and mental well-being opens up new avenues for personalized health management, adaptive human-computer interaction systems, and innovative service models in the digital health ecosystem.

While acknowledging certain limitations, such as the need for further exploration of multi-parameter integration and quantitative frameworks, this research represents a significant contribution to the field of wearable biosensors. Our micro-lace SC sensor offers a robust, user-centric solution that paves the way for future advancements in pervasive healthcare, mental wellness monitoring, and the broader integration of physiological data into intelligent systems. Future work will focus on refining algorithms for more precise activity and emotion recognition, exploring long-term monitoring applications, and validating the technology across diverse populations and contexts.

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ACKNOWLEDGEMENTS

None.

FUNDING

None.

AVAILABILITY OF DATA

Not applicable.

ETHICAL STATEMENT

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures were conducted in accordance with relevant ethical guidelines and regulations.

AUTHOR CONTRIBUTIONS

Zixian Wang conceived and designed the study, developed the micro-lace electrode-based SC sensor, conducted the experiments and data analysis, and wrote the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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