

All-in-One Wearable Hydrogel Patch for Multimodal Visualized and Quantitative Heatstroke Monitoring

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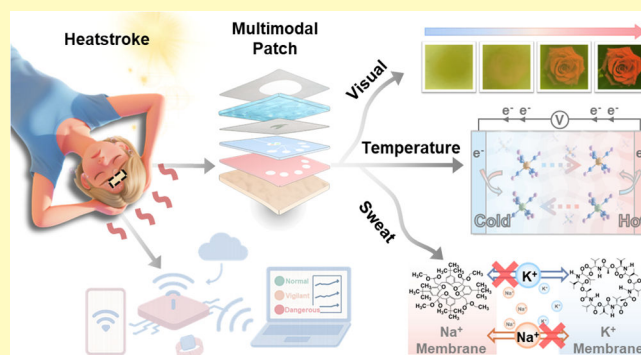
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Supporting Information

ABSTRACT: Heat-related illnesses, particularly heatstroke, pose serious risks to outdoor workers, athletes, and individuals with impaired thermoregulation. Existing monitoring strategies are limited by invasive measurements, reliance on external power sources, and lack of real-time multimodal feedback. Here, this study presents an all-in-one wearable patch that integrates a dual-functional self-powered thermogalvanic hydrogel with a selective electrochemical interface for intuitive visual feedback, dynamic temperature tracking, and durable sweat analysis. The hydrogel enables real-time thermochromic visualization and active thermoelectric sensing of body temperature, while an integrated electrochemical module allows continuous and selective detection of Na^+ and K^+ ions in sweat. The multiplexed physical–chemical health-monitoring patch provides a multimodal dual-stage evaluation of body temperature and sweat ion level toward improving metabolic status control and alerting individual to heatstroke risk, holding promise for developing personalized healthcare and a scalable route to proactive heatstroke prevention.

KEYWORDS: all-in-one patch, multimodal sensing, visual feedback, thermogalvanic hydrogel, sweat biomarkers, heatstroke monitoring



Heatstroke, characterized by rapid elevation of core temperature and systemic dysfunction, poses severe risks to outdoor workers, athletes, and vulnerable populations.^{1–3} Timely detection of hyperthermia and electrolyte imbalance is essential for effective intervention.⁴ Conventional diagnostic approaches rely on invasive temperature probes or biochemical assays of blood and saliva.^{5–7} These methods are time-consuming, costly, and unsuitable for continuous real-time monitoring of heatstroke in both daily life and dynamic environments.

Wearable technologies offer non-invasive solutions for monitoring physiological signals such as skin temperature and sweat biomarkers.^{8–10} However, their dependence on wired connections and external power sources restricts mobility, while poor conformability impedes long-term wearability.^{11–13} Zhang et al. achieved miniaturization by integrating a diminutive thermistor, a flexible embedded circuit, a miniature Bluetooth module, and a lightweight battery, enhancing mechanical flexibility and wearing comfort.¹⁴ Liu et al. designed a conformal and scalable device that integrates a flexible temperature sensor array with a hydrogel matrix for closed-loop monitoring and treatment of wound site temperature distribution.¹⁵ Chen et al. employed a triboelectric nanogenerator to power multiple modules, delivering continuous self-powered monitoring components such as cooling films, blood oxygen sensors, acceleration and angular velocity sensors, and Bluetooth module.¹⁶ Although multimodal sensing has been demonstrated, physiological and biochemical signals are often

integrated through discrete modules rather than intrinsically coupled platforms, increasing system complexity and constraining miniaturization.^{17–21} Furthermore, many wearable devices rely on external displays for feedback, restricting their effectiveness in real-world outdoor scenarios.^{22–24} These limitations underscore the need for integrated, self-powered wearable platforms that combine multimodal sensing, including visual feedback, temperature detection, and sweat electrolyte sensing, with wireless communication and long-term conformal wearability.

This study presents an all-in-one wearable patch incorporating a dual-functional thermogalvanic hydrogel (DFH) and a selective electrochemical interface, designed for heatstroke prevention and continuous health monitoring. The multimodal patch simultaneously integrates visual feedback, body temperature detection, and sweat electrolyte sensing, achieving both intuitive feedback and quantitative health assessment. By incorporating sodium dodecyl sulfate (SDS) micelles and $[\text{Fe}(\text{CN})_6]^{3-/4-}$ redox couple, the DFH with thermochromic and thermogalvanic effects not only

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exhibits a rapid (40 s) and tunable thermochromic transition within the physiological range (35–42 °C), together with a Seebeck coefficient of 1.86 mV K⁻¹. The sweat sensing module allows real-time and selective detection of Na⁺ and K⁺ ions in sweat, with sensitivities of 61.1 and 67.4 mV dec⁻¹, respectively. Combined with a flexible wireless transmission module, the patch establishes a dual-stage evaluation strategy for heatstroke risk, offering a compact and scalable approach toward personalized and proactive thermal health management.

RESULTS AND DISCUSSION

Structural Design and Working Principle

The architecture of the all-in-one wearable patch features visual feedback, thermoelectric temperature detection, and sweat electrolyte sensing for continuous physiological single tracking, thereby improving metabolic status management and alerting individuals to heatstroke risk (Figure 1a). The multimodal patch consists of a conformal adhesive substrate layer, an electrochemical interface with microfluidic channels, and a dual-functional hydrogel layer sandwiched between two patterned electrodes. The vertically stacked configuration spatially decouples thermal sensing from sweat transport, allowing directional sweat flow toward ion-selective electrodes (ISEs) while preventing interference with the hydrogel layer.

The DFH is comprised of hydrophilic polyacrylamide (PAM), gelatin, C₁₈, SDS micelles, and the [Fe(CN)₆]^{3-/4-} redox couple. The DFH exhibits both thermochromic and thermoelectric properties, enabling its dual function in signal visualization and temperature perception. Inspired by marine organisms such as the *Japetella heathi* pelagic octopus and *Taonius borealis* glass squid, which regulate body transparency through skin architectures that modulate light transmission, absorption, and reflection, a visualization unit based on the thermochromic hydrogel is developed to achieve a reversible opaque-to-transparent transition for intuitive thermal monitoring. The visualization mechanism relies on a temperature-dependent micellar transition of SDS (Figure 1b). Below the Krafft point (*T_k*), SDS shows low solubility and forms aggregated micellar structures within the polymer matrix, inducing strong light scattering and an opaque appearance. Above *T_k*, micelles dissolve and light transmittance increases, leading to a transparent state. This reversible transition enables intuitive visual monitoring of body temperature within the physiological range.

Temperature detection is achieved through the thermogalvanic effect of the [Fe(CN)₆]^{3-/4-} redox couple (Figure 1c). Under a temperature gradient, oxidation of [Fe(CN)₆]⁴⁻ occurs at the hot electrode, while reduction of [Fe(CN)₆]³⁻ takes place at the cold electrode, generating a stable thermoelectric potential. Ion diffusion and redox cycling sustain continuous voltage output proportional to the temperature difference, enabling self-powered operation of the temperature sensing module. While additional

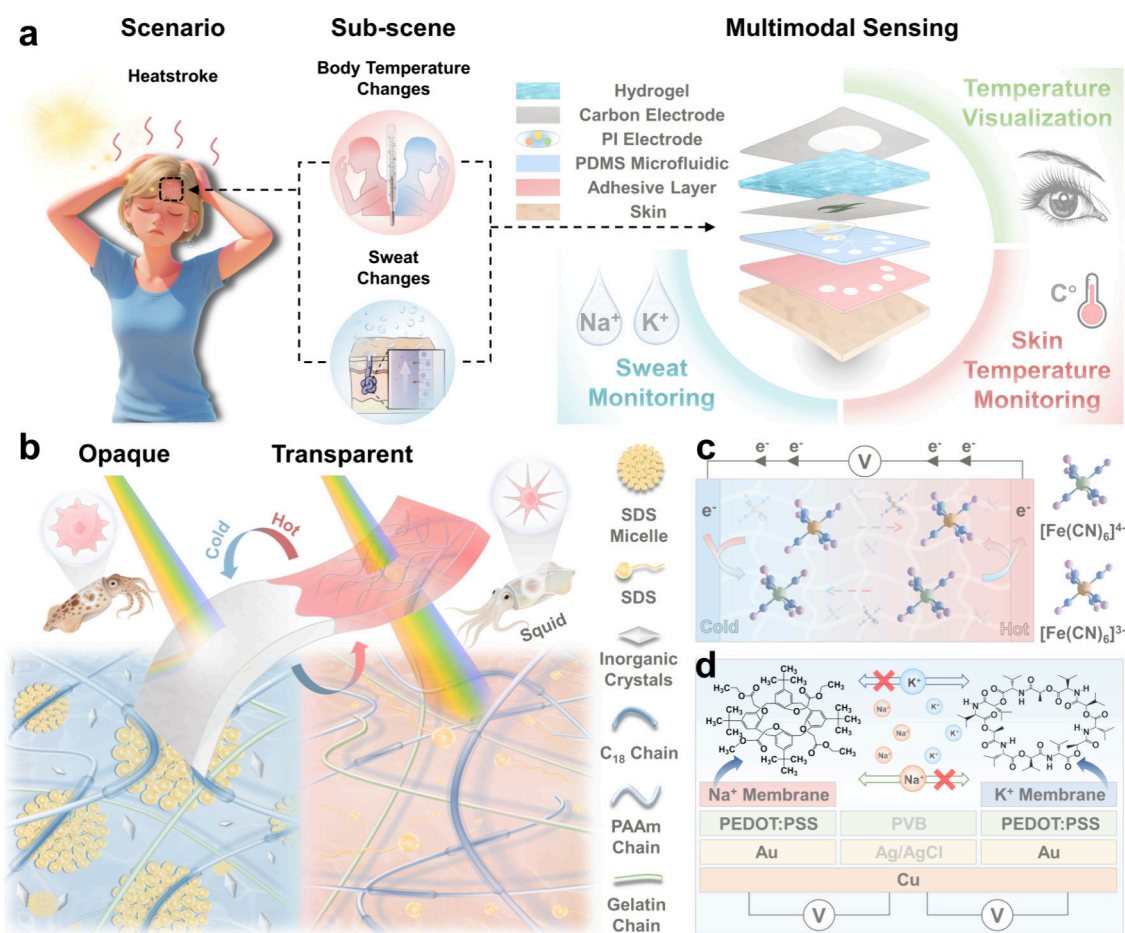


Figure 1. Schematic illustration of the all-in-one wearable patch for heatstroke diagnosis and its functional modules. (a) Potential applications for rapid and accurate diagnosis of heatstroke through synergistic detection of multiple biosignals, including color changes, skin temperature, and sweat electrolytes. (b–d) Operational mechanisms of the visualization module (b), temperature sensing module (c), and sweat sensing module (d).

power management circuits are essential for processing and filtering the signal, the initial sensing phase is autonomous and does not rely on an external energy supply, thus realizing self-powered tactile perception.

The sweat sensing mechanism is shown in Figure 1d. ISEs are fabricated by coating PEDOT: PSS and ion-selective membranes onto the metal working electrodes patterned on a flexible polyimide (PI) substrate. These layers function as the ion-specific adsorptive layer and the ion-to-electron transduction layer, respectively. The ISEs specifically bind Na^+ and K^+ ions in sweat, leading to surface potential changes that are converted into measurable electrical signals. A PVB-coated Ag/AgCl electrode serves as a reference electrode to maintain a stable potential across varying ionic strengths in sweat.²⁵ This configuration enables selective, real-time electrolyte monitoring under dynamic physiological conditions.

Thermochromic and Mechanical Properties

The thermochromic performance of the DFH was systematically evaluated in terms of response rate, optical contrast, tunability, and mechanical robustness. As shown in Figure 2a, DFH transmittance increases with temperature across 500–900 nm. DFH switches from opaque (1.2%) to transparent (61.3%) within 40 s at 40 °C, outperforming many thermochromic devices (Figure S1 and Movie S1). The thermochromic behavior originates from the temperature-dependent micellar transition of SDS within the polymer matrix. Below the T_k , self-hydrophobization promotes strong associations between the hydrophobic headgroups of SDS and the alkyl chains of C_{18} .²⁶ Consequently, SDS monomers assemble around C_{18} units, which further cluster within micelles, leading to enlarged micellar structures that impart pronounced light-scattering and result in an opaque hydrogel (Figure S2). Above the T_k , disruption of hydrogen bonding induces micellar disassembly, thereby reducing light scattering and allowing efficient light transmission through the transparent hydrogel. This optical transition is supported by the microscopic morphology of the DFH in both opaque and transparent states (Figure 2a, inset). In the opaque state, the network exhibits higher crosslinking density and smaller pores. In contrast, the transparent state of the DFH shows a looser network architecture. Zeta potential measurements (Figure 2b) show temperature-dependent variation in micelle surface charge, supporting stable dispersion behavior. The zeta potential decreases from -57.6 mV (40 °C) to -73.0 mV (20 °C), demonstrating an increase in surface charge density due to the enlarged micelle size at lower temperatures. This enhanced electrostatic repulsion among SDS micelles contributes to stable dispersion in the opaque state. The DFH maintains excellent reversibility, with negligible transmittance degradation over 100 heating–cooling cycles (Figure 2c). Over 5 days, transmittance in the transparent state decreases from 61.3 to 57%, while the opaque state remains nearly unchanged (Figure S3), confirming durability under ambient conditions.

FTIR spectroscopy is analyzed to elucidate the thermochromic transition mechanism in the DFH (Figure S4). The absorption peak at 1662 cm^{-1} corresponds to the $\text{C}=\text{O}$ stretching vibrations of both amide and carboxyl groups.²⁷ The peaks at 1629, 1547, and 1458 cm^{-1} can be indexed to fundamental vibrations of gelatin, including $\text{C}=\text{O}$ stretching (amide I), $\text{N}-\text{H}$ bending (amide II), and CH_2 deformation, confirming the successful synthesis of DFH.²⁸ The FTIR spectrum of the opaque DFH exhibits three distinct absorption bands at 2917, 2850, 1217 cm^{-1} , corresponding to the antisymmetric $-\text{CH}_2-$ stretching, symmetric $-\text{CH}_2-$

stretching, and $\text{S}=\text{O}$ stretching vibrations of SDS. The characteristic $\text{C}=\text{O}$ stretching vibration of C_{18} is observed at 1722 cm^{-1} , confirming the successful incorporation of both SDS and C_{18} into the hydrogel network. The FTIR spectra of DFH in its transparent and opaque states are completely identical, indicating that no chemical reactions occur within the hydrogel network during the thermochromic transition.

To adapt the hydrogel response to physiological temperature, the transition temperature (T_k) was modulated by incorporating inorganic salts. Cations interact with the $-\text{SO}_4^-$ headgroups of SDS, reducing electrostatic repulsion and promoting micellar aggregation.^{26,29} Larger cations and higher salt concentrations lead to increased micelle size, thus requiring a higher T_k for disruption. This hypothesis was supported by dynamic light scattering (DLS) measurements, where the average micelle sizes in LiCl and NaCl solutions are approximately 531 and 824 nm, respectively (Figure 2d). As shown in Figure 2e,f, the T_k can be linearly tuned within 35–42 °C. We note that $\text{K}_{3/4}[\text{Fe}(\text{CN})_6]$ was fixed at 0.06 M to ensure the thermogalvanic function, so the K^+ effect on thermochromism was not studied separately (Figure S5). Differential scanning calorimetry (DSC) analysis further confirms the adjustable phase transition behavior (Figure 2g), facilitating precise matching of the thermochromic response to human body temperature.

For wearable applications, sufficient mechanical strength and toughness are essential. The DFH adopts a double-network structure consisting of chemically cross-linked PAM and physically cross-linked gelatin (Figures 2h and S6). At 5 wt % of gelatin, the hydrogel exhibits a maximum stress of 153 kPa, a fracture strain of 411%, a Young's modulus of 77 kPa, and a toughness of 402 kJ m^{-3} (Figures 2i and S7). Due to the hydrogen bond reformation, cyclic tensile tests demonstrate good fatigue resistance (Figures S8 and S9), while compression tests confirm elastic recovery (Figure S10). The thermochromic transition also affects mechanical behavior. In the opaque state, the hydrogel shows higher fracture stress (153 kPa) and lower elongation (411%). Above T_k , fracture stress decreases to 100 kPa while elongation increases to 830% (Figures 2j,k), reflecting reduced crosslink density at elevated temperature. Considering the balance between optical transparency and mechanical reinforcement (Figure S11), the DFH containing 5 wt% gelatin was selected for subsequent experiments. The above results indicate that incorporating an appropriate proportion of gelatin into the hydrogel network improves its mechanical properties, making DFH suitable for human wearable applications.

Thermogalvanic, Antidrying, and Antifreezing Performance of the DFH

The introduction of the $[\text{Fe}(\text{CN})_6]^{3-/4-}$ redox couple equips the DFH with heat-to-electricity conversion ability based on the thermogalvanic effect (Figure 3a). Under a temperature gradient, asymmetric redox reactions at the hot and cold electrodes generate a stable thermoelectric voltage characterized by the Seebeck coefficient (S_e).³⁰ The thermoelectric performance was evaluated using a custom temperature-gradient platform (Figure S12). As shown in Figure 3b, both S_e and maximum current density initially increase and then decrease with $[\text{Fe}(\text{CN})_6]^{3-/4-}$ concentration rising. The optimal values of 1.86 mV K^{-1} and 0.72 A m^{-2} are achieved at 0.06 M $[\text{Fe}(\text{CN})_6]^{3-/4-}$. Meanwhile, electrochemical impedance spectroscopy (EIS) reveals an electrical conductivity (σ) of 25.8 mS cm^{-1} and a thermal conductivity of 0.24 W m^{-1}

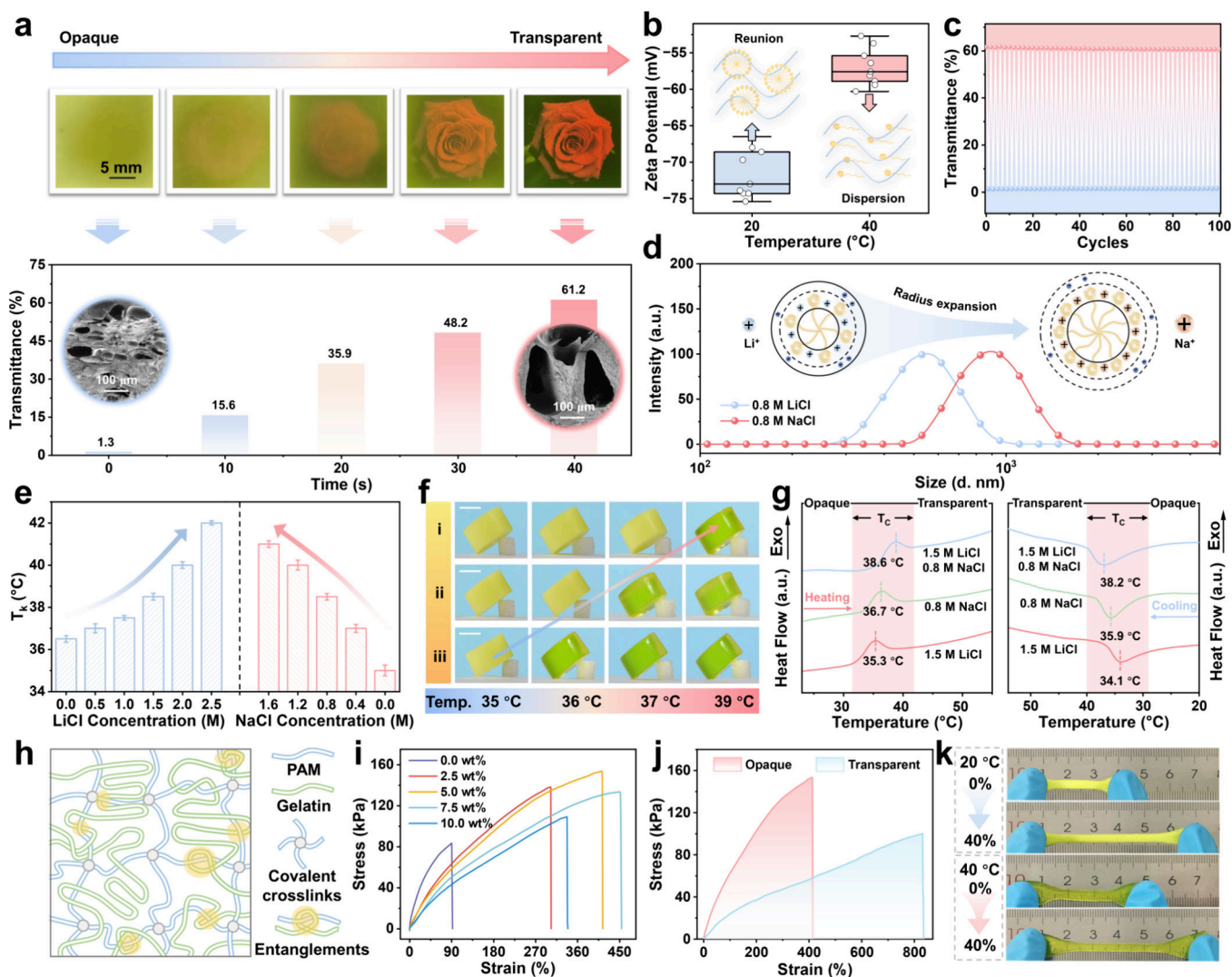


Figure 2. Thermochromic and mechanical properties of the DFH systematically characterized. (a) Photographs and transmittance of the DFH during the opaque-to-transparent transition. Inset: SEM images of the opaque (left) and transparent (right) states. (b) Zeta potential of the DFH at 20 and 40 °C. (c) Transmittance of the DFH at 600 nm over 100 cycles between 20 and 40 °C. (d) DLS results showing average micelle sizes of 0.8 M LiCl and 0.8 M NaCl precursor solutions at 20 °C with corresponding micelle structures. (e) T_k of the DFH with varying types and concentrations of inorganic salts. (f) Photographs of DFH samples at various temperatures. (g) DSC analysis of hydrogels with varying LiCl and NaCl content, showing the effect on thermal properties and T_k . (h) Schematic illustration of the double-network entangled hydrogel structure. (i) Stress-strain curves of DFH samples with different gelatin contents. (j) Stress-strain curves of DFH in opaque and transparent states. (k) Photographs of DFH under stretching in opaque and transparent states.

K^{-1} (Figures 3c and S13). Similarly, changing the LiCl or NaCl concentration shows similar trends in thermoelectric current/voltage output and ionic conductivity (Figure S14). Additionally, the power factor reaches the maximum values at 0.06 M $[\text{Fe}(\text{CN})_6]^{3-/4-}$ (Figure S15). The output voltage and current of the DFH have an excellent linear dependence on the temperature differences (Figures 3d and S16). After 60 cycles of heating/cooling, the hydrogel demonstrates excellent cyclic stability (Figure S17). Furthermore, the voltage generation and temperature gradients in the DFH were validated by COMSOL Multiphysics simulations, which show good agreement with the experimental measurements (Figure S18). The output power density increases with ΔT , reaching 28.39 mW m^{-2} , with a normalized power density of $31.54 \mu\text{W m}^{-2} \text{ K}^{-2}$ (Figure 3e,f). As shown in Figure 3g, the DFH shows a gradual increase in conductivity with increasing temperature. Cyclic voltammetry

curves exhibit symmetric redox peaks with minimal polarization (Figures 3h and S19), indicating good electrochemical reversibility within the DFH. Additionally, a thin PDMS encapsulation layer is employed to minimize airflow-induced thermal perturbations by buffering convective heat exchange (Figure S20). As physiological temperature changes occur on a much slower time scale than wind-induced fluctuations, the thermogalvanic signal can be robustly interpreted using temporal filtering in uncontrolled outdoor environments.

Continuous water evaporation can undermine hydrogel performance, leading to complete loss of function.³¹ The hydration structure of $\text{Li}^+(\text{H}_2\text{O})_n$ formed by lithium ions (Li^+) and water molecules (H_2O) serves to reduce the vapor pressure of the DFH, thereby maintaining its original state at ambient conditions (Figures 3i,j). After 5 days at 20 °C, the DFH retained $\sim 70\%$ of its initial weight, whereas the control sample without LiCl

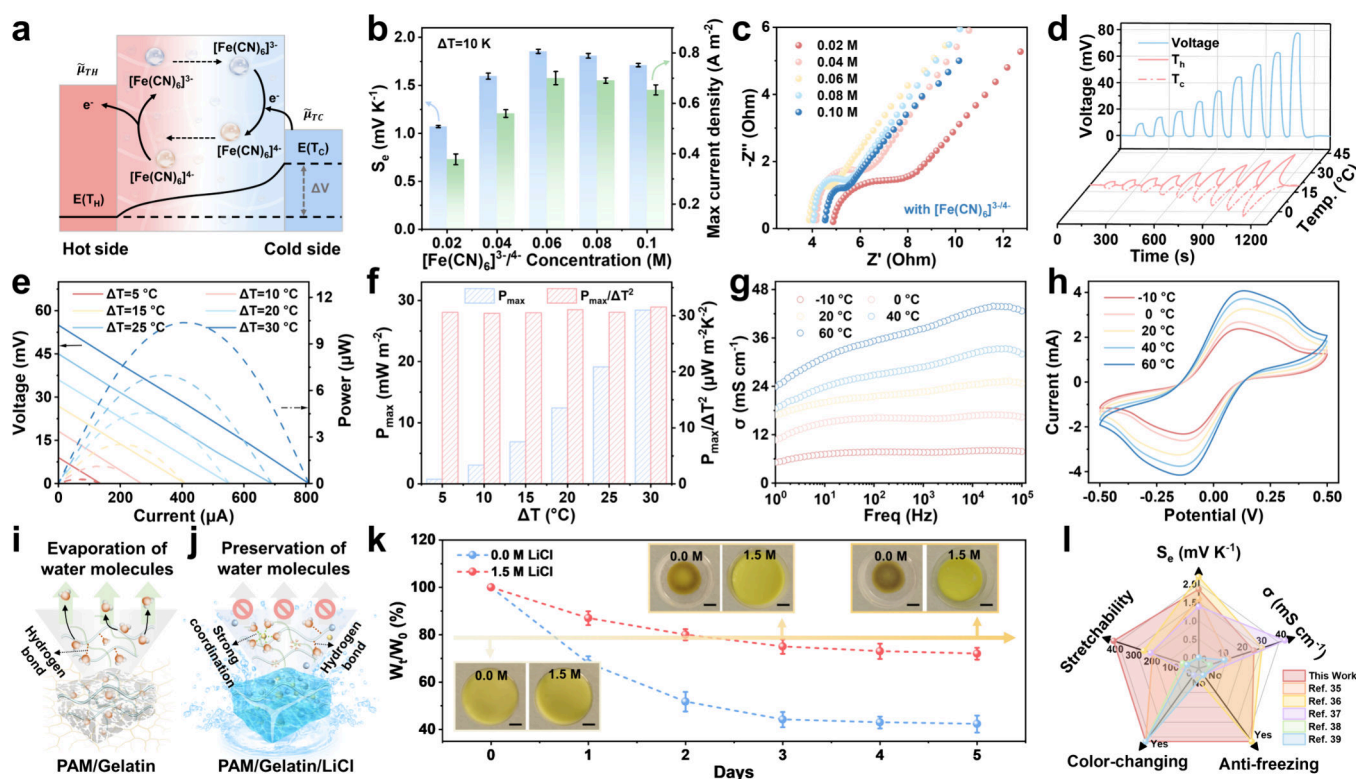


Figure 3. Thermogalvanic, nondrying, and antifreezing performance of the DFH. (a) Schematic of the thermoelectric effect as a temperature sensing mechanism and the electrochemical potential diagram. (b) S_e , maximum short-circuit current and (c) corresponding EIS diagram with $[\text{Fe}(\text{CN})_6]^{3-/4-}$ concentrations ranging from 0.02 to 0.1 M. (d) Open-circuit voltage curve of the DFH at different temperatures. (e) Output voltage–current–power curves under different ΔT with the temperature of the cold side (T_c) fixed at 20 °C and (f) corresponding maximum $P_{\text{max}}/\Delta T^2$. (g) Frequency-dependent conductance of the DFH with different temperatures. (h) Cyclic voltammetry curves the DFH at different temperatures. (i,j) Water retention capability of (i) PAM/Gelatin and (j) PAM/Gelatin/LiCl hydrogels. (k) Comparison of the DFH with LiCl and without LiCl after storage for 5 days at 293 K (scale bar 1 cm). (l) Comprehensive comparison between the DFH and the previously reported thermogalvanic hydrogels in terms of the comprehensive properties of S_e , σ , antifreezing, color-changing, and stretchability. The references and details are summarized in Table S1.^{35–39}

retained only $\sim 40\%$ and exhibited severe deformation (Figures 3k and S21). Thermogravimetric analysis further reveals the degradation peaks of the DFH are attenuated and shifted to higher temperatures with the addition of LiCl, indicating enhanced thermal stability (Figure S22). Additionally, S_e decreased slightly from 1.84 to 1.62 mV K^{-1} and conductivity from 25.0 to 22.3 mS cm^{-1} , demonstrating sustained functionality over extended periods (Figure S23). To further validate the sensor's stability in low-humidity environments, we conducted a 12 h test at 18% relative humidity. Figure S24 shows that the DFH's weight and voltage response remained stable, indicating excellent resistance to drying and long-term stability under low humidity conditions.

LiCl, as an effective antifreeze salt, disrupts hydrogen bond networks between water molecules, endowing the DFH with anti-freezing capability. After 6 h of storage at -10 °C, the DFH retained stretchability, whereas the control hydrogel became rigid due to ice crystallization (Figures S25 and S26). Differential Scanning Calorimetry (DSC) was performed to quantitatively verify the anti-freezing property, which shows that the addition of LiCl substantially depresses the freezing point of the hydrogels (Figure S27). A comprehensive comparison of the DFH with other representative hydrogels reported in previous studies is summarized in Table S1 and Figure 3l, including S_e , σ , anti-freezing ability, color-changing property, and stretchability, which clearly illustrates that the strategy developed in this study exhibits an

exceptional comprehensive performance. In addition, the cytocompatibility of the hydrogel was assessed using a live/dead staining assay. As shown in Figure S28, cells cultured with the hydrogel extract exhibited high viability over 5 days, indicating good in vitro cytocompatibility.

Design and Characterization of the Sweat Sensing Module

Sweat contains abundant physiological information that can reflect the current human health conditions.^{32,33} To achieve high sensitivity and multi-parameter detection in sweat analysis while maintaining flexibility and ease of integration, we designed and manufactured a non-invasive wearable sweat biosensor for potassium and sodium sensing. The overall architecture and the fabricated sensor patch with clearly identified electrodes are shown in Figures 4a,b and S29. The biosensor consists of four layers arranged sequentially: cover layer, sensing layer, microfluidic channel layer, and adhesive layer. Cu electrodes were patterned on a polyimide (PI) substrate with an optimized S-shaped configuration, yielding an ultra-thin (~ 40 μm) and mechanically compliant device capable of stable operation under bending (Figure S30). Because sweat secretion per unit area is limited, a polydimethylsiloxane (PDMS) microfluidic channel was incorporated to guide sweat toward a collection reservoir (Figures 4c and S31). After hydrophilic treatment, the PDMS surface exhibited a static water contact angle of 39.6° (Figure S32), facilitating

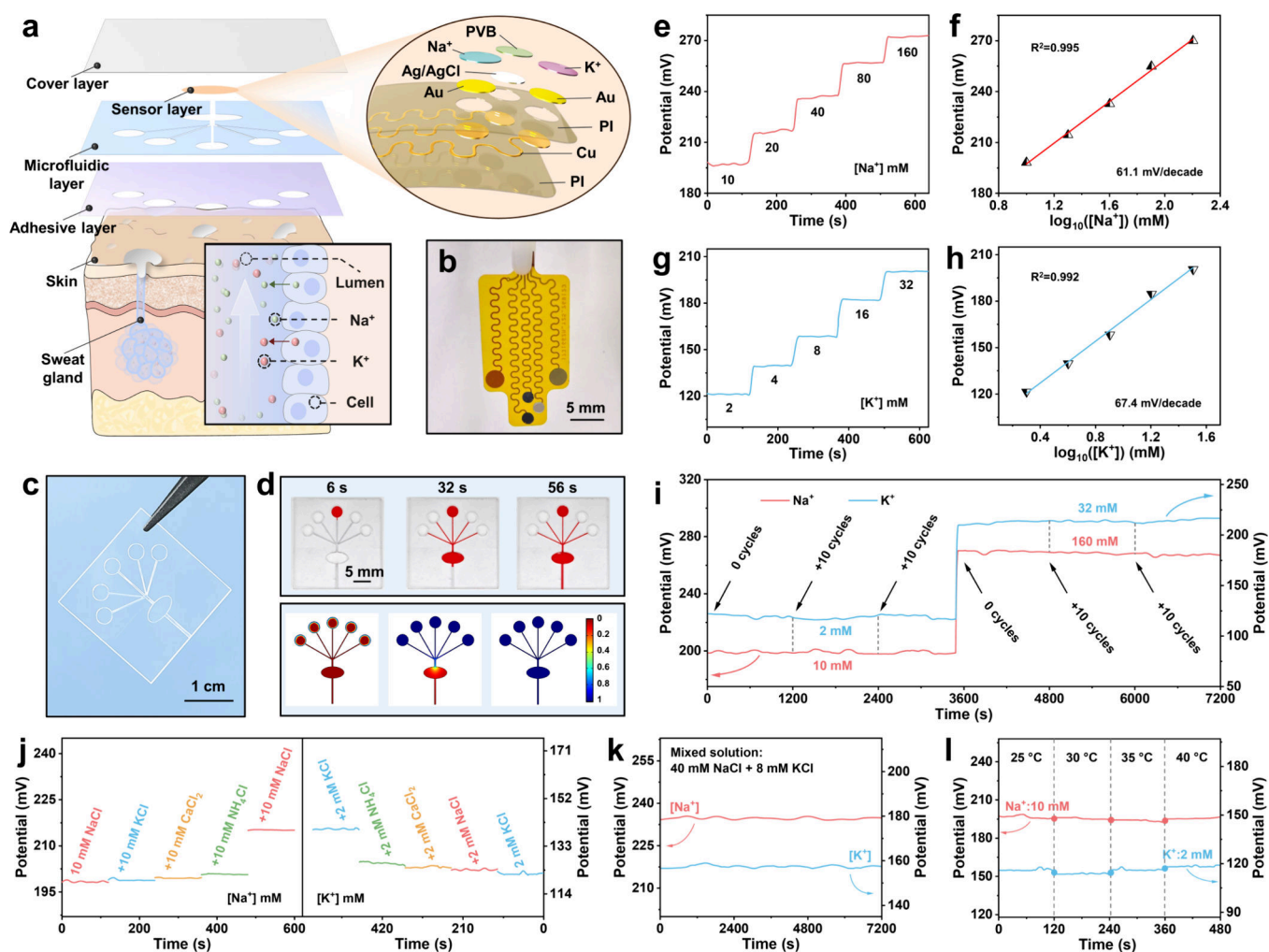


Figure 4. Design and characterization of the noninvasive wearable sweat biosensor for sodium and potassium detection. (a) Schematic diagram of a noninvasive, wearable sodium and potassium sweat biosensor. (b) Photographs of the electrode. (c) Photographs of the microfluidic channels. (d) Experimental visualization of the microfluidic filling process using dyed water and simulated filling dynamics in the microfluidic module. The colormap shows a normalized tracer field c (dimensionless), where $c = 0$ indicates air-filled regions (red) and $c = 1$ indicates water-filled regions (blue). Water progressively fills the channels and the reservoir while air is displaced and exits through the pressure outlet boundary. (e) OCP responses of the Na^+ sensor at different concentrations. (f) Calibration curve of the Na^+ sensor ($n = 5$). (g) OCP responses of the K^+ sensor at different concentrations. (h) Calibration curve of the K^+ sensor ($n = 5$). (i) Repeatability evaluation of Na^+ and K^+ sensors. (j) Selectivity evaluation of Na^+ and K^+ sensors. (k) Stability of Na^+ and K^+ sensors in mixed electrolyte solutions. (l) Effect of temperature on Na^+ and K^+ sensors.

wetting-assisted transport during filling. Finite element simulations and experimental visualization confirm that the reservoir can be fully filled within ~ 60 s (Figure 4d and Movie S2). This well-constructed microfluidic module can effectively collect sweat from the skin and store it for subsequent analysis. Additionally, Figures S33 and S34 demonstrate the patch's reliable skin adhesion capability during perspiration and mechanical deformation.

To verify the performance of the sweat biosensor, we functionalized the electrodes to detect Na^+ and K^+ ions and calibrated each electrode using standard solutions.³⁴ The open-circuit potential (OCP) responses increase with ion concentration and exhibit excellent linearity (Figures 4e–h), with correlation coefficients of 0.995 for Na^+ and 0.992 for K^+ . The sensitivities are 61.1 and 67.4 mV dec^{-1} , respectively. As shown in Figure S35, the calibration sensitivities remain nearly unchanged across the tested flow-rate range, indicating that variations in sweat flow rate have

a negligible effect on sensor sensitivity. The sensors exhibit good reproducibility (Figures 4i and S36) and strong selectivity against interfering ions (Figure 4j). As plotted in Figure 4k, the sensors maintain a stable potential response during 2 h of testing in a mixed solution containing 40 mM Na^+ ion and 40 mM K^+ ion. Even after 5 days of exposure to ambient conditions, the sensitivities of both sensors show negligible variation, demonstrating good stability (Figure S37). Importantly, the potential responses remain insensitive to physiological temperature variations (Figure 4l), ensuring reliable operation under thermal stress. Overall, Na^+ and K^+ sensors have good sensitivity, detection range, and long-term stability, making them promising candidates for the efficient detection of biomarkers in human body fluids.

All-in-One On-Body Patch with Dual-Stage Heatstroke Alerting

Heatstroke progression involves both hyperthermia and electrolyte imbalance, highlighting the need for simultaneous

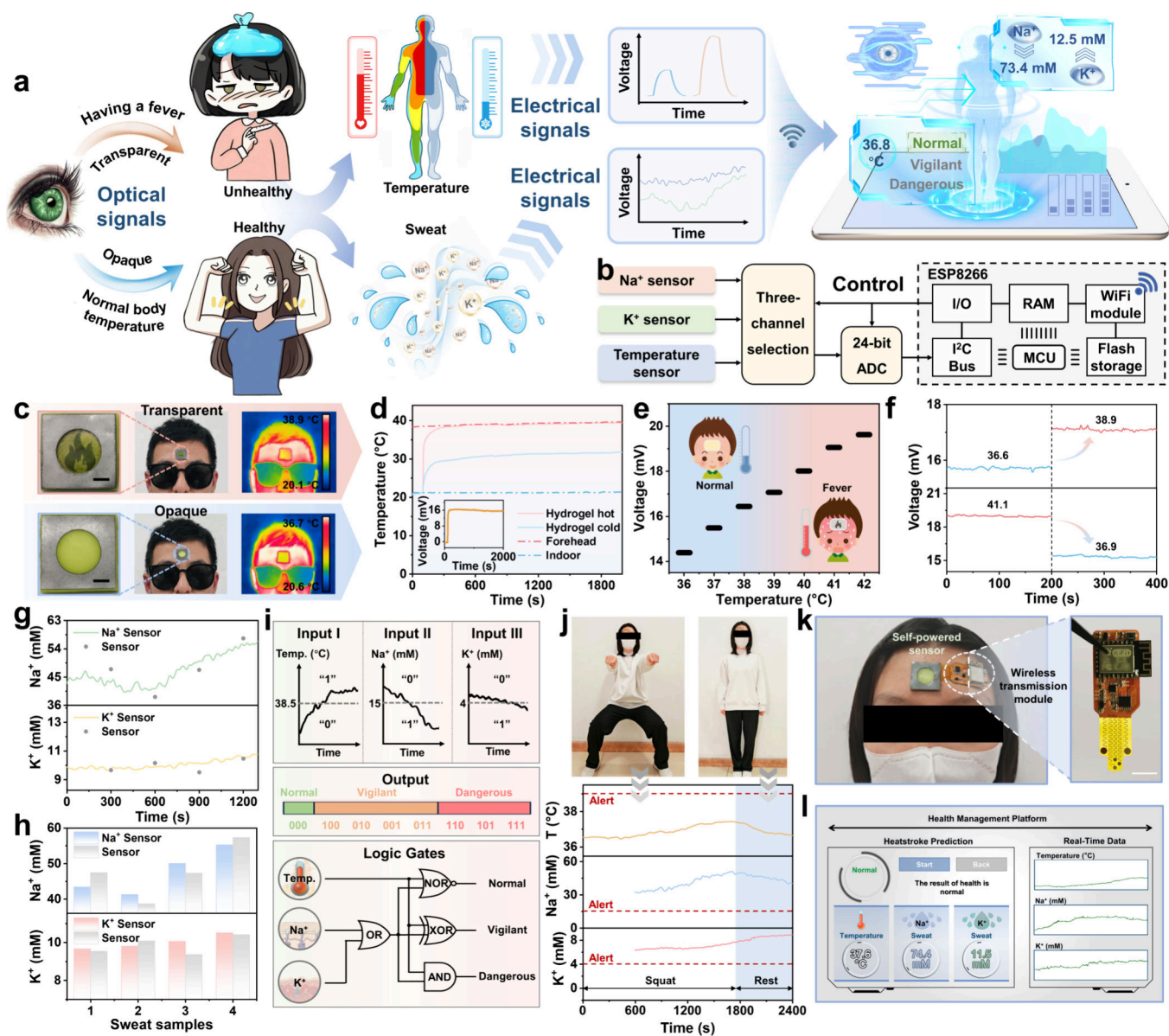


Figure 5. Wearable multimodal patch for visual thermal warnings and physiological signal monitoring in heatstroke prevention and health management. (a) Illustration and detection functions of heatstroke prevention and health monitoring using the patch with visual feedback, body temperature detection, and sweat electrolyte sensing. (b) Operational principle of the patch. The Na^+/K^+ sensors and temperature sensor are responsible for detecting physiological data, which is then processed by the ESP8266 module. The data is wirelessly transmitted for real-time monitoring. (c) Thermal imaging of human forehead temperature before and after and photos taken before and after phase change of the patch. (d) Long-term temperature variations of the patch, forehead, and indoor environment, with an inset showing the voltage changes. (e) Relationship between voltage and body temperature in two typical regions. (f) Real-time output voltage response of the patch for temperature perception before and after human fever. (g) Real-time monitoring of sweat Na^+ and K^+ levels during exercise. (h) Comparison of Na^+ and K^+ concentrations from sweat analysis with the commercial sensor results. (i) Schematic illustration of the logic-gate based decision system for dual-stage heatstroke monitoring. (j) Photographs shows the patch attached to the forehead during exercise and the dynamic variations in body temperature and sweat electrolyte concentrations under thermal stress. (k) Photograph of the patch mounted on the forehead (scale bar: 1 cm). (l) User interface displaying real-time temperature and Na^+/K^+ concentration data and waveforms during exercise.

monitoring of body temperature and sweat ion levels. To address this, a multiplexed physical–chemical patch was developed for real-time health monitoring and dual-stage heatstroke prevention during prolonged heat exposure and intensive physical activity (Figure 5a). The system integrates thermochromic visualization, thermogalvanic temperature sensing, and sweat electrolyte detection with a wireless transmission module (Figures 5b and S38), enabling both intuitive feedback and

quantitative assessment. Through this innovative approach, a safer and more informed environment can be established for outdoor workers, athletes, and individuals with impaired thermoregulation, ensuring timely alerts to potential health risks and continuous access to physiological information.

The thermochromic hydrogel provides immediate visual indication of physiological status. When attached to the forehead, the patch transitions from opaque to transparent once body

temperature exceeds 38.5 °C, revealing the underlying pattern as a hyperthermia warning (Figures 5c and S39). Beyond providing visual cues for physiological status, the multimodal patch allows quantitative assessment of body temperature and electrolyte concentrations. Notably, the patch establishes a stable thermal gradient within 100 seconds, resulting in reliable, long-term thermoelectric output (Figure 5d). Impressively, the patch exhibits a temperature resolution of 0.1 °C (Figure S40), enabling recognition of subtle temperature variations on human skin. Body temperature during fever rises rapidly and remains elevated until heat dissipation restores thermal equilibrium (Figure S41). As shown in Figure 5e, the output voltage steadily increases with the rising temperatures of two representative body regions, demonstrating that the patch can reliably convert temperature variations into measurable electrical signals. Under normal conditions, a voltage of 15.7 mV corresponds to 36.6 °C, whereas during simulated fever, the voltage rises to 17.1 mV at 38.9 °C (Figure 5f), confirming reliable quantitative self-powered sensing. This outstanding temperature perception capability demonstrates significant potential in the field of heatstroke warning.

In thermally stressed environments, physiological responses involve not only body temperature variations but also dynamic fluctuations in sweat electrolyte composition. By integrating the sweat sensing module into the all-in-one wearable patch, we achieved continuous, on-body tracking of sweat electrolytes during thermoregulation. In a proof of concept, two healthy volunteers wore the patch on their foreheads while exercising for 30 minutes under controlled indoor conditions. The sweat Na⁺ levels increased significantly, whereas K⁺ levels remained relatively stable, consistent with previous non-invasive studies (Figures 5g and S42). The decoded Na⁺/K⁺ concentrations extracted with the patch were further validated by commercial electrolyte assay kits. In general, the perspiration fluctuation tendency from the patch is consistent with those from commercial electrolyte assay kits (Figures 5h and S43), indicating remarkable reliability and great potential of the patch for non-invasive human health monitoring.

Beyond independent monitoring of body temperature and sweat electrolytes, the all-in-one wearable patch further implements a dual-stage heatstroke detection mechanism by integrating these physiological indicators. To enable rapid assessment of heatstroke risk, a logic-based decision architecture was implemented (Figure 5i). Body temperature (threshold 38.5 °C), Na⁺ (15 mM), and K⁺ (4 mM) were encoded as binary inputs and processed through NOR, XOR, and AND logic gates to generate three output states: Normal, Vigilant, and Dangerous (Figure S44). Notably, these thresholds are personalizable to align with user baselines and requirements and adjustable in response to changes in physiological status. Rather than relying on thermogalvanic output as a sole diagnostic parameter, our system adopts a multimodal decision framework, in which thermal, electrochemical, and visual signals are synergistically evaluated. Sweat electrolyte imbalance and thermochromic phase transition provide ΔT -independent indicators of physiological stress, enabling reliable heatstroke risk assessment even when the thermogalvanic voltage is diminished. Dynamic on-body testing demonstrates synchronized variation of temperature and sweat electrolytes under thermal stress (Figure 5j). Real-time wireless transmission of temperature and Na⁺/K⁺ data during running further confirms practical applicability (Figure 5k,l and Movie S3). The integrated multimodal patch thus enables non-invasive, accurate, and real-time heatstroke prediction in wearable healthcare applications.

CONCLUSIONS

In this work, we developed an all-in-one wearable patch that integrates intuitive visual feedback, dynamic temperature tracking, and durable sweat analysis for continuous monitoring under heat stress. The patch utilizes a dual-functional hydrogel that couples thermogalvanic and thermochromic effects, featuring a tunable transition temperature of 35–42 °C, a rapid and reversible color change within 40 s, and a Seebeck coefficient of 1.86 mV K⁻¹, thereby achieving simultaneous visual and electrical signal transduction. An electrochemical sensing module is further incorporated to provide stable and selective detection of Na⁺ and K⁺ ions, with sensitivities of 61.1 and 67.4 mV dec⁻¹, respectively, which guarantees reliable operation under dynamic physiological conditions. Through the functional synergy of these sensing components, the multimodal patch establishes a dual-stage evaluation framework capable of delivering both early and emergency heatstroke alerts, offering continuous and personalized monitoring for proactive heatstroke prevention.

METHODS

A detailed experimental section can be found in the Supporting Information.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acssensors.5c04692>.

Experimental details, material characterization, fabrication processes of self-powered wearable patches, mechanical and electrochemical performance evaluations, simulation of microfluidic filling behavior, response speed and transmittance comparison of our DFH to previously reported thermochromic devices, DLS data of the DFH precursor solution at different temperatures, transmittance variations for 5 days, Fourier transform infrared spectra from bottom to top are PAM, Gelatin, opaque, and transparent DFH hydrogel, effect of different [Fe(CN)₆]^{3-/4-} concentrations, diagram of PAM cross-linking, comparison of Young's modulus and toughness values of hydrogel samples with varying gelatin content, loading-unloading tests for the DFH with different strains, dissipated energy values of the DFH during successive loading cycles at a tension strain of 100%, cyclic compressive loading-unloading curves, transmittance curves of the DFH samples, σ and thermal conductivity diagram, power factor variation, short-circuit current curve of the DFH at different temperatures, thermal charging/discharging cycles, COMSOL simulations demonstrate the thermoelectric potential of DFH under a 10K temperature difference, cyclic voltammetry curves at different scan rates, TGH output voltage versus time, TG and DTG curves of PG hydrogels with or without LiCl, variation of voltage and conductivity after being placed in the air for 5 days, weight variation and voltage curve of the sensor, tensile stress-strain curves of the DFH, DSC curves for DFH with different compositions, live/dead staining images of cells cultured, ultra-thin elastic sweat multiparameter electrochemical sensor bending tests, working principle and cross-section of the

microchannel, test for measurement of shear strength, long-term stability of Na⁺ and K⁺, schematic diagram of remote monitoring utilizing cloud technologies, different patterns engraved on carbon electrodes, voltage-time curve under a temperature difference of 0.1 K, schematic illustration of human body temperature regulation during fever, logic-based decision architecture, advancements in the thermoelectric, antifreezing, mechanical, and color-changing properties of the DFH (DOCX)

Thermochromic property of DFH (MP4)

Water filling process in the chamber (MP4)

Real-time health monitoring (MP4)

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X.Y.: investigation, methodology, writing—original draft. Y.N. and N.L.: investigation, data curation. X.C. and Z.L.: validation, review and editing. H.Z. and Z.-H.L.: conceptualization, resources, supervision.

Notes

The authors declare no competing financial interest.

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