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REVIEW

Stay healthy under global warming: A review of wearable technology for thermoregulation

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Abstract

Global warming has been affecting human health, including direct mortality and morbidity from extreme heat, storms, drought, and indirect infectious diseases. It is not only "global" but extremely "personal"—it is a matter of life and death for many of us. In this perspective, we propose the use of wearable technologies for localized personal thermoregulation as an innovative method to reduce the impact on health and enable wider adaptability to extreme thermal environments. The state-of-the-art thermoregulation methods and wearable sensing technologies are summarized. In addition, the feasibility of thermoregulation technology in preventive medicine for promoting health under climate change is comprehensively discussed. Further, we provide an outlook on health-oriented closed loop that can be achieved based on parallel thermoregulation and multiple data inputs from the physiological, environmental, and psychological cues, which could promote individuals and the public to better adapt to global warming.

KEYWORDS

climate change, heat-related illness, personalized thermoregulation technologies, wearable sensors

1 | INTRODUCTION

Average global temperatures have increased by ~0.85°C since the last century[1] (Figure 1A). It is likely to reach 1.5°C around mid-century, according to a report from Intergovernmental Panel on Climate Change (IPCC).[2] While these numbers may seem abstract and distant from our everyday life, global warming, and climate change are impacting our lives in an immediate and profound way.[3] Evidence is mounting that such variations in the large-scale climate system have been affecting human health, including direct mortality and morbidity from extreme heat, storms, drought, and indirect infectious diseases.[4–7] Heat gain in the human body is attributed to the integration of external heat from the environment and internal heat from metabolic processes.[8] Rapid increases in heat gain resulting from exposure to hotter-than-average environments can limit the thermal homeostasis of the human body and lead to various direct illnesses such as cardiovascular mortality, respiratory illnesses, neurological disorders, and injuries.[5,9,10] (Figure 1B). In other words, global warming is not only "global" but extremely "personal"—it is a matter of life and death for many of us.

Direct heat-related diseases are likely to happen during heatwaves or extremely hot or humid weather that can last for several days.[11] The World Health

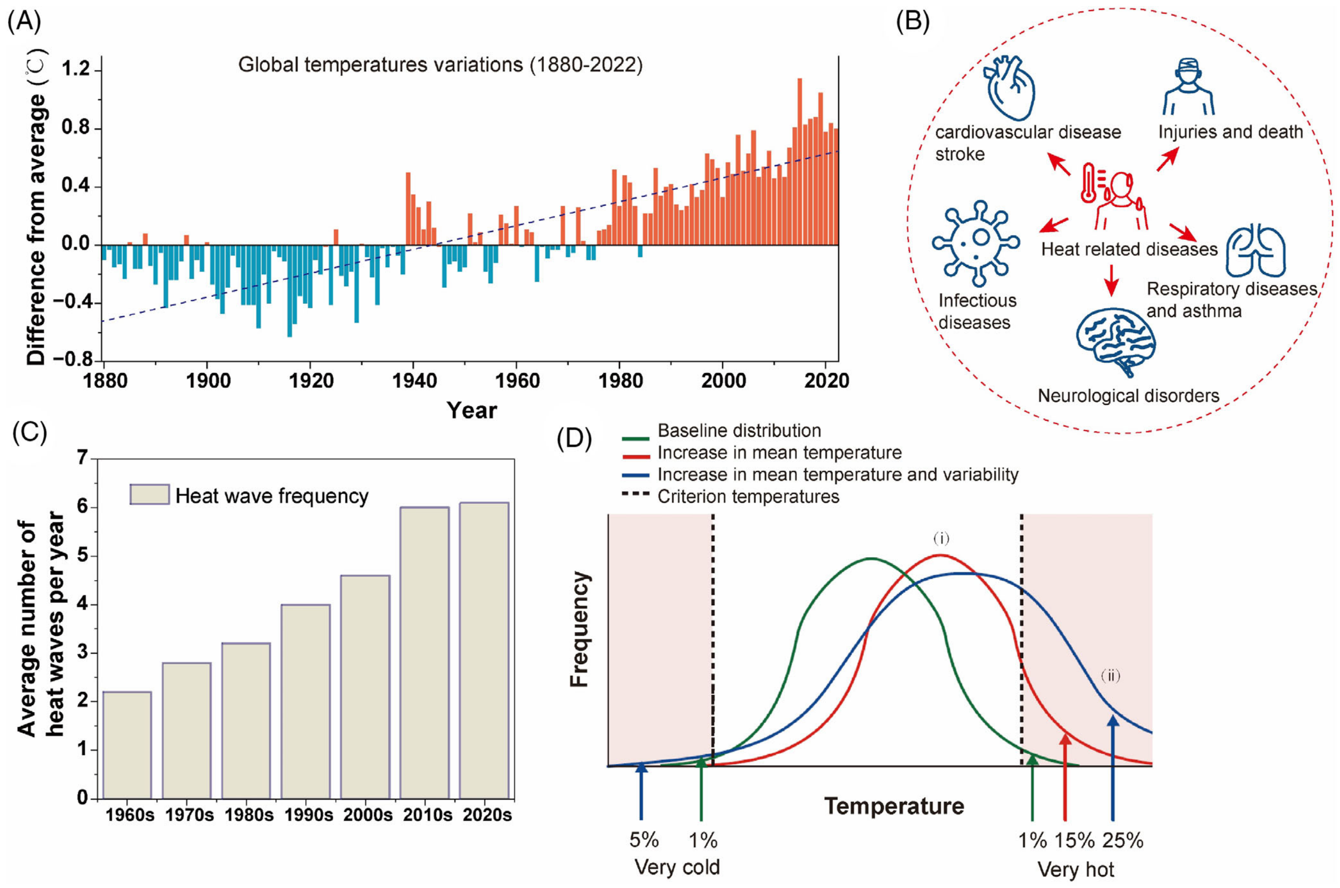


FIGURE 1 Global warming and its effect on human health. (A) Global temperature variations since 1880, show an obvious increasing trend. The anomalies are with respect to the average temperature from 1901 to 2000.[1] (B) Examples of heat-related diseases.[9] (C) Increasing average number of heat waves in the United States by decades, 1961–2021.[11] (D) The impact of increases in (i) average temperature, and (ii) average temperature and variability, on the frequency of extreme weathers. Arrows indicate the area-under-the-curve beyond the threshold temperatures for very cold and very hot conditions. Reproduced with permission: Copyright 2006, Elsevier B.V.[13]

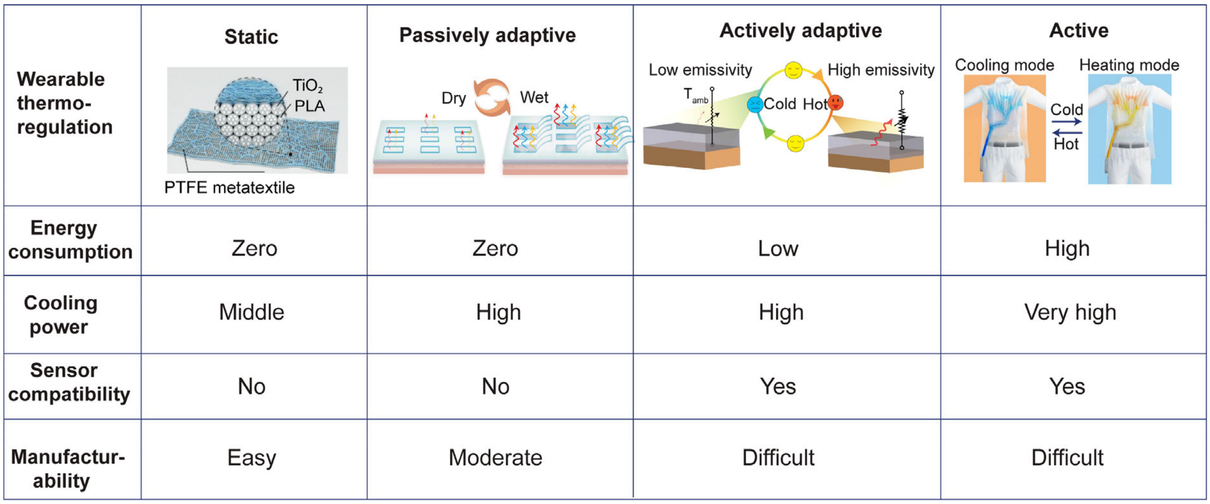
Organization estimates that the heatwave due to anthropogenic climate change has claimed over 166 000 lives since 1998.[12] As the Earth's climate warms, heat waves occur more frequently and intensely in major cities across the United States. Their average frequency per year has increased steadily from two during the 1960s to six during the 2010s and 2020s[11] (Figure 1C). In recent years, the average heat waves in major U.S. urban areas are about 4 days long, which is about 1 day longer than the average heat wave in the 1960s. The more frequent and fierce heatwave is expected to result in more heat-related diseases and deaths.[11]

The effect of climate change on human health is not limited to just shifting the average temperature up, as shown in Line (a) in Figure 1D. Other factors, such as the increasing trend of urbanization, the aging of populations, and extreme weather events can greatly increase the population's exposure rate to extreme heat, as illustrated in Line (b) in Figure 1D.[13] For example, with increasing urbanization in all countries (projected to increase from 57% in 2022 to 85% by 2100),[14] more people will be exposed to the heat island effect in urban areas.[15,16] Heat island effect is formed due to urban structures, such as buildings, roads, and other infrastructures, which absorb more solar radiation compared to natural landscapes like forests and water bodies. The heat island effect in urban areas can exacerbate the impact of naturally occurring heat waves.[17] Another factor is the aging population in high-income countries, which is predicted to undergo substantial growth over the coming decades (the proportion aged over 65 years increasing from 10% in 2022 to 16% by 2050).[18] Since aged people are more susceptible to heat-related illnesses, it is predictable that a greater proportion of people in all countries will be at risk from heat extremes in future. Taking steps to adapt to climate change and stay healthy is acute and significant for human beings.

2 | WEARABLE TECHNOLOGY FOR PERSONAL COOLING

One innovative method to reduce the impact on health and enable people's wider adaptability to extreme thermal environments is using wearable technologies for localized personal thermoregulation. Personal thermoregulation can be divided into four levels, static, passively adaptive, actively adaptive, and active (Figure 2). Static thermoregulation has a single working mode. It is the most straightforward, facile in manufacturing, sustainable, and cost-effective,[19,20] but its lack of responsiveness to the changing surroundings limits its efficiency and restricts its use to certain scenarios. Passive-dynamic thermoregulation that can adapt to external environment have dual- or multi-working modes.[21–23] It improves the overall thermoregulation effect and expands the application scenarios without additional energy consumption. However, it cannot be controlled on demand, which restricts its capabilities in personalized thermoregulation. Instead, active-dynamic that integrates wearable sensors and dynamic tunable thermoregulation devices is the most promising method to enable personalized health-oriented thermoregulation.[24,25] It allows individuals to maintain customized thermal comfort under varying metabolic and environmental conditions in an autonomous manner. Active cooling thermoregulation systems that rely on external work to enhance heat transfer, such as thermoelectric device (TED),[26–28] liquid cooling circulation,[29] and air ventilation,[30,31] can successfully deliver a higher cooling power. However, these systems consume a high amount of energy. They can work as first-aid equipment for extreme weather conditions or health-threatening emergencies with strong demand for cooling.

One can imagine that wearing specially engineered textiles that can better cool the human body down may reduce the possibility of getting heat-related diseases or death. Another essential point linking cooling textiles with global warming is that cooler textiles will decrease human reliance on air conditioning, which is considerable in global warming because it not only accounts for 10% of U.S. electricity consumption, but that refrigerants are also a source of high global warming potential gasses.[33] Hence, in the last decade, cooling textiles have attracted great attention in both science and industry communities. There are four different pathways for heat transfer between the human body and the environment, that is, conduction, convection, radiation, and evaporation[8] (Figure 3), which work together to maintain the core body temperature stabilized at 35–37.5°C.[8,34] Under extremely hot and humid weather, body cooling system failing to maintain the core temperature within this range will result in heat-related diseases.[34,35] Cooler textiles that could facilitate the four pathways either in better blocking heat from the



Wearable thermo-regulation	Static	Passively adaptive	Actively adaptive	Active
Energy consumption	Zero	Zero	Low	High
Cooling power	Middle	High	High	Very high
Sensor compatibility	No	No	Yes	Yes
Manufactur-ability	Easy	Moderate	Difficult	Difficult

FIGURE 2 Comparison of four levels of personalized thermoregulation, including static, passively adaptive, actively adaptive, and active. Static thermoregulation has a single working mode, while passively adaptive thermoregulation has dual- or multi-working modes. Static figure: Reproduced under terms of the CC-BY license.[32] Copyright 2023, Oxford Academic. Passively adaptive figure: Reproduced under terms of the CC-BY-NC 4.0 license.[21] Copyright 2021, AAAS. Actively adaptive, which integrates wearable sensors and dynamic thermoregulation devices into a feedback loop, is considered the most promising method for personalized health-oriented thermoregulation, as it allows individuals to maintain their thermal comfort in different metabolic and environmental conditions autonomously.[24] Active thermoregulation that normally delivers a higher cooling power can work as first-aid equipment for extreme weather conditions or health-threatening emergencies with a strong demand for cooling. Reproduced with permission.[27] Copyright 2020, Elsevier B.V.

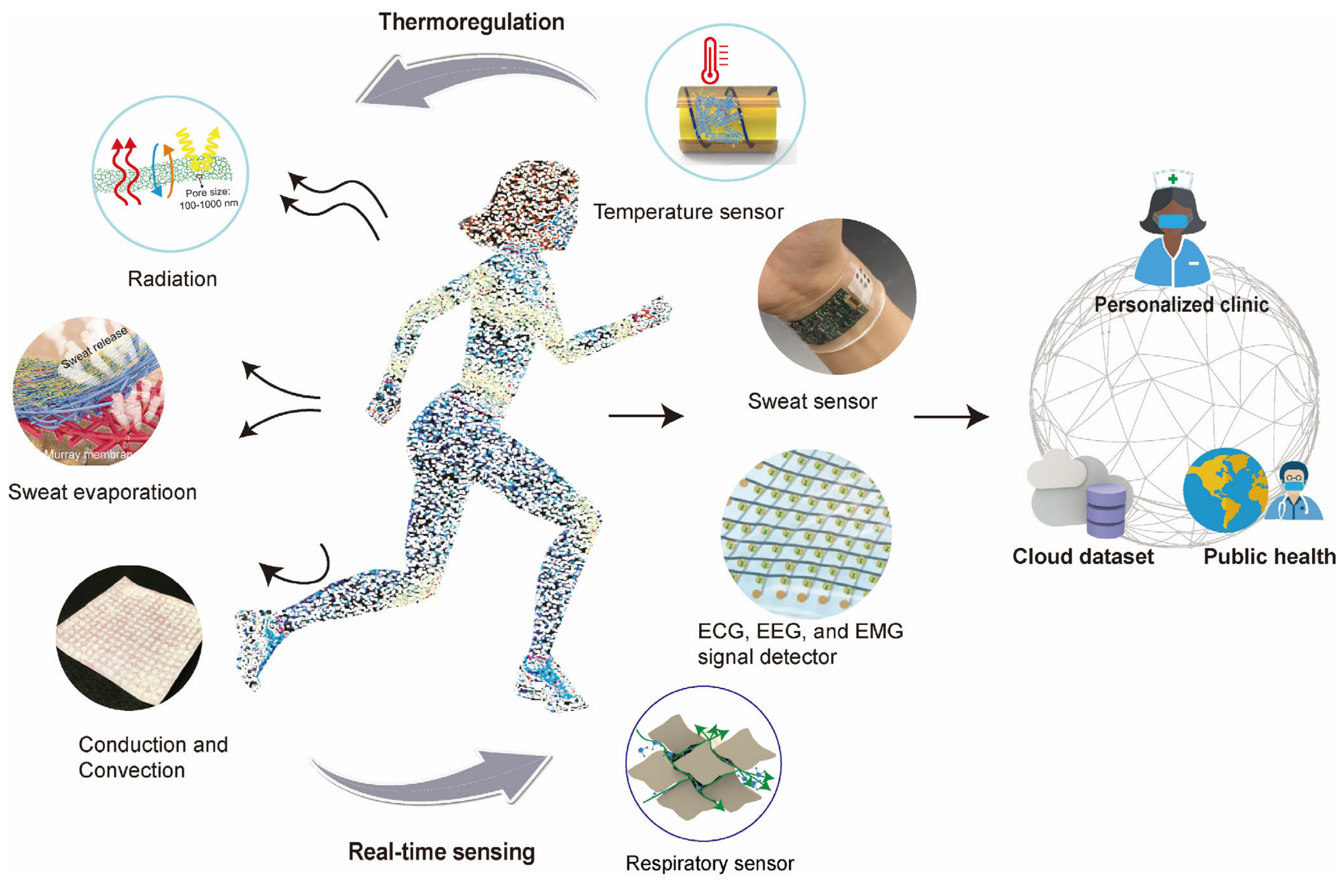


FIGURE 3 Closed loop enabled by parallel thermoregulation and real-time sensing for wearable personalized healthcare. Autonomous thermoregulation device maintains the human body in a safe temperature zone by regulating the heat dissipation pathways, that is, radiation, evaporation, conduction, and convection, while wearable sensors detect human pyretic state (temperature sensor), metabolites, and biomarkers (sweat sensor), bioelectric signals (ECG, EEG, and EMG signal detector), and respiratory states. The detected signals are transferred to the cloud dataset for big data analysis, promoting individual and public healthcare. Person: Reproduced with permission.[68] Copyright 2020, Elsevier B.V. Radiation: Reproduced with permission.[33] Copyright 2016, AAAS. Sweat evaporation: Reproduced with permission.[60] Copyright 2016, American Chemical Society. Conduction: Reproduced under terms of the CC-BY 4.0 license.[54] Copyright 2021, Springer Nature. Temperature sensor: Reproduced with permission.[69] Copyright 2019, Wiley-VCH. Sweat sensor: Reproduced with permission.[70] Copyright 2019, Springer Nature. EMG signal detector: Reproduced under terms of the CC-BY 4.0 license.[71] Copyright 2016, Springer Nature. Respiratory sensor: Reproduced with permission.[72] Copyright 2019, Wiley-VCH. Cloud dataset: Reproduced under terms of the CC-BY 4.0 license.[73] Copyright 2022, Springer Nature.

atmosphere or dissipating metabolic heat will reduce the impact of extreme weather on human beings.

Among these four pathways, radiative heat exchange is extremely important under static conditions,[33,36,37] making radiative cooling textiles important in personalized thermoregulation. The fundamental principle for radiative cooling textile is that a material surface spontaneously cools down by radiating heat to the cold outer space through the atmosphere's transparent window[38–41] while suppressing all the solar heat gain.[42–44] From the photonic engineering point of view, the solar bands should be reflected as much as possible,[45] while enhancing human body radiative heat loss can be achieved by enabling the textile's mid-infrared (mid-IR) property in two ways: high transmittance or high emissivity. The former allows the broadband human body radiation to directly transmit and can be achieved by polyethylene (PE) because of its simple chemical bonds and very few resonance peaks in the mid-IR region.[46] In 2016, Hsu et al.[33] demonstrated multifunctional nanoporous PE radiative cooling fabric, featuring its visible-light opacity, breathability, and softness. After that, PE was further developed into woven and knitted fabrics,[47] colored cooling textiles,[48] and outdoor cooling textiles.[49] On the other hand, high-emissivity textiles equilibrate with the underlying human skin by both thermal radiation and conduction in the air gap and re-emit to the atmosphere at the outer side.[38,50] Their IR-opaque property inevitably results in radiation shielding effect,[51] but it is easier to perform spectrum engineering for solar reflectivity and emissivity within the atmospheric transparent window.[52] In 2021, Tao et al.[40] developed a mass-productive metafabric with high emissivity for outdoor radiative cooling textiles. The excellent mechanical properties, breathability, washability, and well-developed textile manufacturing techniques enable wide adaptability to extreme outdoor thermal environments.

When the ambient temperature and/or the metabolic heat generation is exceedingly high, evaporation dominates the human body thermoregulation. At a mild state, about 20% of heat dissipation of the dry human body relies on water vapor loss via insensible perspiration.[53,54] With a further increase of heat gain, the evaporation of liquid sweat facilitates more and more heat loss and becomes the major route for human body heat dissipation in intense scenarios such as heavy exercise and hot environments.[55,56] Compared with traditional textiles, fabrics with unidirectional sweat transportation functionality could drive the sweat through the human skin through capillary pores and then guide it to the outer surface for fast evaporation.[57,58] To realize the functionality, the construction of an asymmetric surface structure, including fiber morphology, wettability, and surface energy gradient is a standard method.[59] For example, in 2019, Wang et al.[60] developed a biomimetic fibrous membrane by combining a multibranch porous structure with multilayer micro- and nano-fibers. The smart fabric shows an outstanding water evaporation rate of $0.67\ \mathrm{g\ h^{-1}}$, which is 5.8 and 2.1 times higher than the cotton fabric and Coolmax fabric, respectively.

In some cases, the heat transfer within the textile becomes the limiting factor for the human body cooling.[54] One extreme case is that only the textile surface, instead of the human skin, can be cooled. Therefore, heat conduction for the textile should be considered. For IR-opaque textiles, conduction dominates the heat transfer at the interface between human skin and the inner surface of the textile. It is also the only way of heat transfer in the textile itself. Traditional textiles typically have a low thermal conductivity, such as $0.07\ \mathrm{W\ (m\ K)^{-1}}$ for cotton and $0.087\ \mathrm{W\ (m\ K)^{-1}}$ for silk.[61] Coating functional materials with high thermal conductivity, such as carbon nanotubes (CNT) or graphene, on fiber surfaces is a viable approach to enhance thermal conductivity. The thermal conductivity of CNT/resin-coated cotton fabric can be increased to $0.1\ \mathrm{W\ (m\ K)^{-1}}$.[62] This high conductivity promotes heat transfer from skin to the outer side of textiles, realizing a 3.9°C lower equilibrium surface temperature than the uncoated cotton fabrics.

Multiple heat pathways can be incorporated together to further improve the overall cooling effect and expand the application scenarios.[63–66] For example, by synergizing radiation and evaporation, radiative cooling can slow down water evaporation and extend the evaporative cooling period. When evaporation stops, radiative cooling can still work independently and play a long-term cooling effect.[67] Another example is the combination of heat-conductive pathways and water transport channels in fabrics.[54] Evaporative cooling mostly happens on textile outer surface. While spreading sweat to the textile's top surface, the heat conduction pathway transfers the heat generated by the human body to the location of evaporation, promoting fast evaporation. Meanwhile, it efficiently delivers the evaporative cooling effect to the human skin. As people's exposed environment and body metabolism status frequently change, these kinds of synergistic cooling methods that can utilize multiple heat transfer pathways are highly effective.

3 | THERMOREGULATION AS A PREVENTIVE MEDICINE

Tunable wearables that can modulate the heat transfer coefficients are another approach for better adaptation to the changing environment.[74] So far, our discussion mainly focuses on single-functional static cooling. While this is the top priority in extremely hot weather, static cooling-only textiles cannot satisfy the ever-changing physiological and environmental conditions. When we consider the immense illness and death toll related to heat, wearable thermoregulation essentially becomes a type of preventive medicine. In this regard, the criteria of health-oriented thermoregulation extend beyond static cooling function towards dynamic controllability and various sensors that can complete the feedback loop and maintain thermal comfort in an autonomous and personalizable manner. In 2022, Chen et al.[24] developed a wearable variable-emittance device (WeaVE), which is a layered semi-solid electrochemical cell with electrodeposited polyaniline (PANI) on electrodes. As the carrier concentration and optoelectrical property of PANI can be varied by switching continuously and reversibly between oxidation/reduction states, WeaVE is able to realize mid-IR electrochromism, which can dynamically control the emissivity to stabilize the radiative heat loss under varying ambient temperature. The autonomous tuning system is further demonstrated by incorporating a humidity and temperature sensor and a controlling electronic component. Dynamic thermoregulation tunable devices have the potential to be integrated with other types of wearable sensors, such as yarn temperature sensors that embed carbon nanotube (CNT) and ionic liquid as temperature-sensitive materials within a twisting yarn.[69] Besides providing real-time temperature signals, wearable sensors are also crucial in monitoring human perspiration conditions, which can be indicated by the sweat sensor and humidity sensor. The detected human perspiration conditions offer feedback to the thermoregulation module and indicate whether radiation cooling or evaporation cooling should be dominant and thereby perform the tuning. Therefore, by integrating wearable sensing systems, responsive thermoregulation textiles are capable of working in various situations, such as indoor/outdoor and static/moving scenarios under hot weather.

The above-mentioned static, passively adaptive, and actively adaptive thermoregulation methods modulate thermal comfort based on heat gain and dissipation control. They require low or no energy consumption, which could provide long-term body cooling and work as preventive medicine in the context of global warming. On the other hand, in situations of extreme weather or health-threatening emergencies where a significant need for cooling exists, active thermoregulation that can achieve a higher cooling power is able to function as personalized medical rescue equipment for emergency first-aid purposes. For example, TED can deliver more than 10°C cooling effect of the device by tuning the input current.[26] These thermoregulation methods will be effective in cooling body's core temperature during hyperthermia. By in conjunction with other measures such as rehydration and rest, cooling devices may reduce the symptoms and prevent more serious complications from developing.

4 | FUTURE OUTLOOK: OPEN THE DATA COMMUNICATION, CLOSE THE FEEDBACK LOOP

To step further to the medical side of applications, wearable sensors can probe real-time human physiological signals,[75] which allows personalized clinics to give treatment or guidance when the person gets heat-related illness in the first place. Such smart diagnostic textiles have the potential to enable continuous physiological monitoring while freeing patients from cumbersome clinic visits.[71,76,77] Wearable electrodes have been researched for the detection of bioelectrical signals such as electrocardiograms (ECGs), electroencephalograms (EEGs), and electromyograms (EMGs). These electrodes can measure the activity of the heart, muscles, and brain by detecting the electric potentials on the surface of living tissue.[71,78] For example, flexible conductive artificial silk textile patches made of PEDOT were reported for continuous monitoring of EMG, with a design that allows for easy and conformable positioning on the skin.[79] These phycological signals will help diagnose heat-related diseases, such as cardiovascular diseases and neurological disorders. Moreover, a fibrous human sweat sensor that can measure the metabolites and biomarkers (e.g., glucose, lactate) and electrolytes (e.g., Na^+, K^+, and Ca^{2+} ions) from perspiration is able to monitor health status in a non-invasive manner.[70,80,81] The concentrations of Na^+ and K^+ in sweat are considered as effective biomarkers for detecting dehydration, which easily happens when the body is producing a high rate of sweat under extreme weather. Real-time detection of these biomarkers can monitor the progressive dehydration, protecting individuals from more severe health risks, such as heat exhaustion.[82] In 2018, Wang et al.[83] developed independent fiber sensors into electrochemical signal detectors by coating active materials onto CNT fibers. Different fibers are further assembled into a woven fabric and work together to realize the multiplexed sweat-sensing system. The fiber-yarn-fabric multilayer textile structure increases the wearing comfort and human body conformity of the sweat sensors. Other health-related physiological signals, such as respiratory information can be also detected using wearable devices.[84,85] Respiration rate and respiratory arrest are critical vital signs in determining heat-related diseases and death. To realize real-time monitoring, a smart mask incorporated with a yarn humidity sensor and Inductance-capacitance (LC) wireless testing system was developed.[72] Profiled fibers with a fast water molecular transportation capability were used as water transportation dielectric yarn, resulting in a fast humidity-capacitance response and recovery for the yarn sensor. These real-time health signals are further transmitted to cloud servers and accumulated for big data analysis.

In sum, smart textiles and wearable devices are the keys to facilitating personalized health care and public health by enhancing adaptability to climate change. First, wearable devices that accumulate individual data can broaden the database for public health.[86] At present, most phenotypic health data is collected from patients who have advanced diseases and are in a clinical setting where diagnostic procedures have been or are being conducted.[87] Comparable data from the healthy population and those in the very early stages of disease development are lacking, as well as reference data of the exposed environment temperature and humidity of the patients. With wearable sensors detecting individuals' physiological signals and environment information, representative samples and larger group sizes can be established, which results in more robust predictive models, thereby better revealing the impact of global warming on human health. Second, leveraging insights from population data can enhance personalized healthcare.[88,89] For example, if a patient displays features similar to those of a population exposed to a hot temperature, one can increase the diagnostic efficiency by considering assigning treatments already shown safety and efficacy. Third, integrating individual, population, and environmental data helps paint health trajectories and forecast future health crises caused by extreme weather, which is important for both individual and public healthcare. Comparing real-time individual and environmental information with historical datasets facilitates early disease discovery and better future prediction.[90] Based on these predictions, an instant preventive alarm can be sent to the individual who might be at risk of heat-related diseases or death. In the era of 5G and the Internet of Things (IoT),[91,92] those predictions and alerts can be quickly announced to the public or individuals by portable or wearable electronics, such as smartwatches or mobile phones, so that people can take protective measures to stay safe under extreme weathers. Therefore, a health-oriented closed loop can be achieved based on parallel thermoregulation and multiple data inputs from the physiological, environmental, and psychological cues, promoting individuals and the public to better adapt to global warming.

There are still numerous challenges to overcome in the pursuit of a health-oriented feedback loop. First, for thermoregulation devices that show potential as preventive medicines in extreme weather conditions, substantial cooling power is typically required during emergency situations. The primary concern is how to enhance cooling performance while minimizing energy consumption. One promising solution is to explore the synergistic effects of different cooling pathways in textiles, which could contribute to a significant boost in cooling power. Second, the integration of thermoregulation devices and multifunctional sensing presents a crucial and challenging task without compromising wearing safety and comfort. Many advanced sensors employ nanomaterials such as graphene or carbon nanotubes as detecting materials, which may pose safety concerns if they enter the human body. In addition, they may lack abrasion resistance, washability, and wearing comfort. Consequently, a more stringent assessment of wearable devices is essential before they can be widely applied to individuals. Third, the presence of interference between sensing networks can result in measurement errors or baseline shifts in long-term wearing. In this regard, the utilization of machine learning algorithms for data analysis can be beneficial in mitigating such interference-related issues.

AUTHOR CONTRIBUTIONS

Po-Chun Hsu and Ronghui Wu conceived the perspective. Ronghui Wu and Ting-Hsuan Chen wrote the manuscript under the supervision of Po-Chun Hsu.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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