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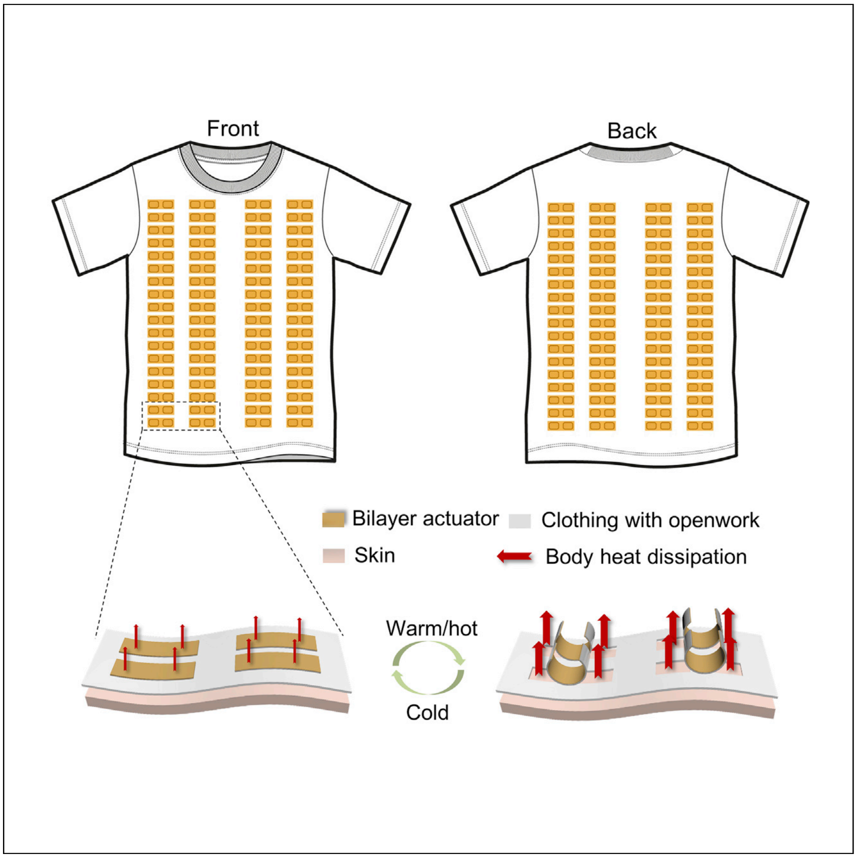

Chai et al. fabricate temperature-adaptive clothing, adopting metalized polyethylene film as actuator. The clothing can automatically adapt to ambient temperature change with multimodal body-heat regulation for improved thermal comfort and building energy savings.

Jiale Chai, Zhanxiao Kang, Yishu Yan, Lun Lou, Yiying Zhou, Jintu Fan

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Highlights

A temperature-adaptive actuator is mechanically and infrared-optically tailored

The actuator is integrated into clothing for multimodal body-heat regulation

Thermal manikin tests and thermo-physiological modeling are conducted

Thermal comfort zone is expanded by more than 2°C on both cold and hot sides

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Thermoregulatory clothing with temperature-adaptive multimodal body heat regulation

Jiale Chai,[1] Zhanxiao Kang,[1] Yishu Yan,[1] Lun Lou,[1] Yiying Zhou,[1] and Jintu Fan[1,2,*]

SUMMARY

Thermoregulatory clothing plays an indispensable role in maintaining body thermal comfort and achieving building energy savings in response to fluctuating ambient. Existing temperature-adaptive clothing without external energy input has very limited thermoregulatory power because of the lack of simultaneous regulation of multiple heat-dissipation pathways. Here, we report thermoregulatory clothing with temperature-adaptive multimodal body-heat regulation (viz. convection, radiation, and sweat evaporation), which can automatically adapt to temperature change (15°C–35°C) within seconds by incorporating mechanically and infrared optically tailored metalized polyethylene actuators into textiles. Based on thermal manikin tests and thermo-physiological modeling, it demonstrates that the designed clothing can expand comfort zone by more than 2°C on both cold and hot sides, corresponding to about 30% building energy savings when used in indoor environment. The smart clothing can also significantly improve the comfort and performance of wearers when exposed to fluctuating or extreme environmental conditions.

INTRODUCTION

Acting as the interface between human body and ambient, clothing plays an indispensable role in regulating the body heat for maintaining thermal comfort in our daily life. One of the most common scenarios is that the ambient temperature fluctuates and sometimes even changes suddenly (e.g., walking from a cool indoor [e.g., 20°C] to a hot outdoor environment [e.g., 30°C]). Failing to adapt to the fluctuating temperature, people could suffer from thermal discomfort or even sickness.[1,2] Thermoregulatory clothing is not only essential to personal thermal comfort but also highly desirable for indoor building energy savings.[3,4] The heating, ventilation, and air-conditioning (HVAC) system of a building accounts for over 50% of total building energy use.[5,6] Thermoregulatory clothing that can decrease the heating set point (e.g., 21.5°C) by 2°C or increase the cooling set point (e.g., 24.5°C) by 2°C would lead to about 12.5% heating or 17.5% cooling building energy savings, respectively.[7–9] Therefore, much work has been directed to develop thermoregulatory clothing with both heating and cooling capability.[3,4,10,11]

Generally speaking, thermoregulatory clothing can be classified into active and passive types.[3,12] The former ones provide active control on thermal regulation but require external energy inputs. The latter ones are sometimes preferred, as they require no external power or action (e.g., flipping the clothing) in adapting to the ambient variations. Among the passive types of thermoregulatory clothing with

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both heating and cooling capability reported so far, many are moisture and sweat responsive (viz. activated after sweating),[13–17] which function after the wearers have already experienced wet discomfort (e.g., under a very hot environment or intensive exercise). The thermoregulatory function of clothing and wearables induced by temperature changes has wider applications without wet discomfort. Existing temperature-responsive clothing with both heating and cooling capability using phase-change materials, thermo-responsive hydrogels, or shape-memory polymers and alloys shows very limited performance, as few have simultaneously regulated multiple modes of heat dissipation pathways (e.g., conduction, convection, radiation, and sweat evaporation).[18–20] Phase change material (PCM) regulates the body heat by absorbing or releasing latent heat when it undergoes temperature change, but its effect is transient (i.e., no more thermoregulatory function after all PCM is phase changed). Thermo-responsive hydrogels shrink at a higher temperature, thereby opening the pores of the fabric coated by the material with only sweat evaporation regulated. Shape-memory polymers (SMPs) or shape-memory alloys (SMAs) work by changing their shape or dimension when exposed to temperature change. However, their effect is very much limited. The thermal conductivity of a developed SMA-containing fabric only changed from 0.0237 to 0.0250 W/(mK) (viz. only 5.5%) as the temperature increased from 15°C to 35°C.[21]

Another category of thermoregulatory clothing is radiative cooling textile,[22–24] which transmits infrared thermal radiation from the human body and/or reflects the solar radiation into outer space. However, such effect diminishes when the ambient temperature is close to or higher than the skin temperature[25] and the ambient environment is sheltered or cloudy. Besides, the radiative cooling textile cannot keep the body warm under cold ambient, as it would accelerate the body-heat loss. As body infrared radiation accounts for around 50% of total body-heat dissipation in typical indoor conditions,[3] it is crucial to regulate the body heat in this dissipation route in response to fluctuating ambient. Up to now, designing clothing that can automatically adapt to ambient temperature change with effective body thermal regulation remains a challenge.

Here, we propose temperature-adaptive clothing with both heating and cooling capability using metalized polyethylene as actuator for multimodal body thermal regulation via radiation, convection, and sweat evaporation. The metal layer not only contributes to the temperature-responsive actuation (i.e., bending) but also induces the radiative heating of the clothing. The thermal performance of the temperature-adaptive clothing is evaluated via thermal manikin tests and thermo-physiological modeling. It indicates that, under the same comfort level (or heat dissipation), the proposed clothing can decrease the heating set point by 2.3°C on the cold side but increase the cooling set point by 2.0°C on the hot side in comparison with conventional cotton and polyester clothing, corresponding to more than 30% of building cooling and heating energy savings. In addition, the clothing is scalable, as it uses a small quality of copper for fabricating the metalized actuator, which is significantly less expensive than silver used in the previously reported moisture-responsive clothing.[17]

RESULTS

Working principle

The clothing with rectangular openwork in its front and back sides is knitted using traditional yarns, and the openwork is covered by the actuators (Figure 1A). In hot ambient, the actuator would bend towards the ambient with enhanced body heat

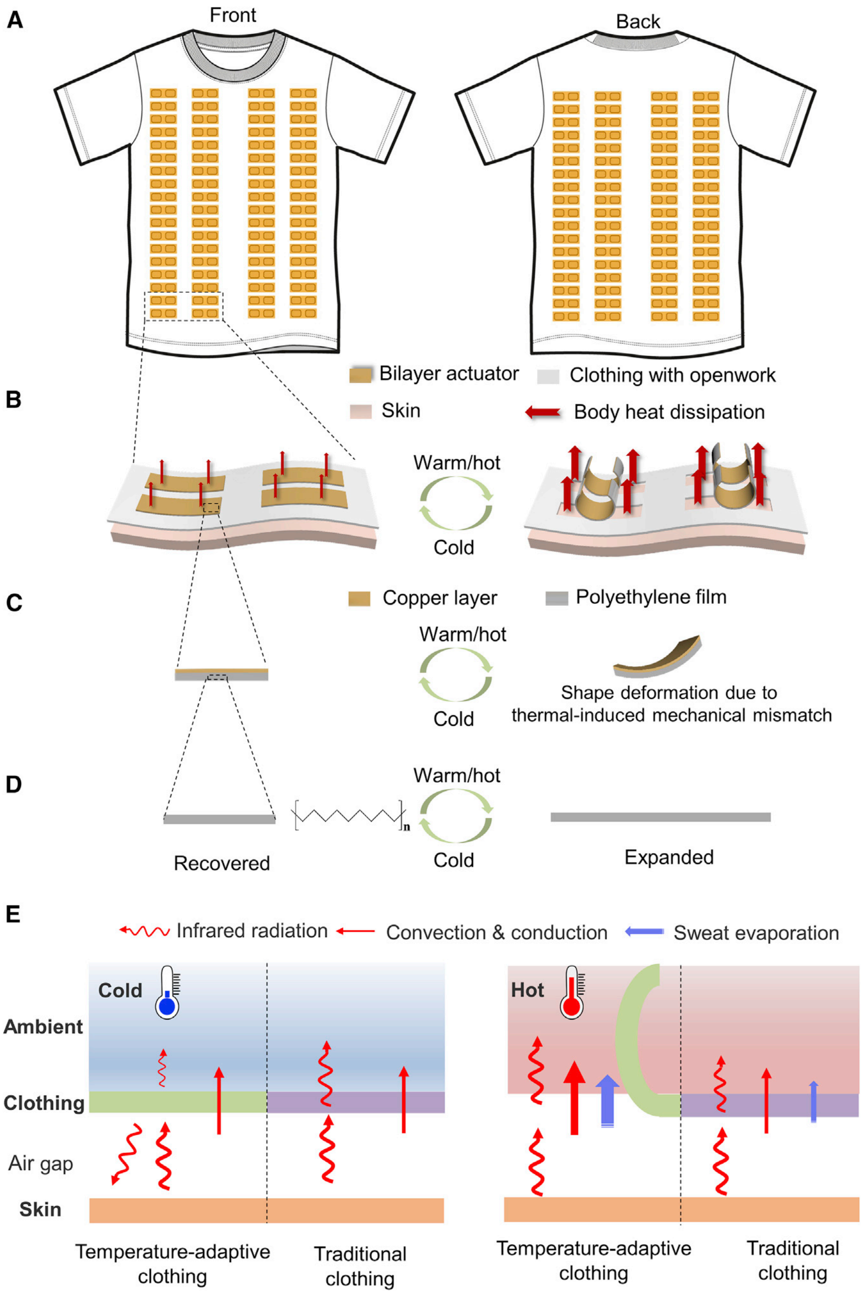

Figure 1. Conceptual illustration of the temperature-adaptive clothing using metalized polyethylene as an actuator for multimodal personal thermal regulation

(A) Schematics of the temperature-adaptive clothing on both front and back sides.

(B) Temperature-induced actuation of the designed clothing in cold and warm/hot ambient.

(C) Analysis of temperature-induced actuation of the bilayer structure.

(D) Schematic of the pure polyethylene film in response to temperature change (not scaled to the real expansion ratio).

(E) Comparisons between the temperature-adaptive and traditional clothing for personal thermal regulation.

dissipation, while in cold ambient, the actuator would recover to its original flat shape to suppress the body heat dissipation (Figure 1B). The fundamental mechanism of the proposed clothing for body thermal regulation is expounded as follows.

Generally, thermal expansion and contraction is one intrinsic property of commonly used materials. This phenomenon cannot be observed by our eyes, as the thermal expansion ratio is very small (~10^{-5}–10^{-3}). Polyethylene (PE), with simple and long C–C bonds along its main chain (Figure 1D), presents a much higher linear thermal expansion ratio than typical textile materials (e.g., nylon and polyester) (Figure S1). We hypothesize the PE film can be used as a temperature-responsive actuator. To amplify the thermal expansion property of the PE film, we design a bilayer structure by depositing a metal layer (i.e., copper-Cu in this work) onto the PE film (Figure S2). In this structure, the copper layer is regarded as the temperature-inert material, as its thermal expansion ratio (~10^{-4})[26] is much smaller than that of the PE film (~10^{-3}). In hot ambient, the PE film in the lower layer would expand, but the metal layer in the upper layer would expand little. Due to the thermal-induced mechanical mismatch, the heterogeneous bilayer actuator would bend towards the ambient (Figure 1C and Video S1). In this process, the textile with the actuators can directly transmit the infrared body radiation into the ambient and simultaneously enhances the air convection and sweat evaporation, thereby enhancing the body-heat dissipation for cooling effects (Figure 1E). In comparison, the traditional textile (e.g., cotton) would hinder the transmission of body radiation due to its mid-infrared absorption. In the cold ambient, the metalized PE film actuator would recover its original flat shape. In this state, the actuator can reflect the infrared body radiation back to the skin and simultaneously suppress the infrared radiation of the outer surface (copper layer) caused by its low infrared emissivity. Consequently, it helps suppress the body-heat dissipation and keeps the body warm (Figure 1E). In comparison, the traditional textile would largely emit the body radiation into the ambient due to its high infrared emissivity of the outer surface. A detailed explanation of the bending mechanism of the bilayer actuator can be found in Note S1 and Figure S7.

Bending property of the actuator

The bending property of the heterogeneous bilayer actuator was crucial for achieving multimodal personal thermal regulation. We measured the bending angles of the actuator with varied PE-film and copper-layer thicknesses under different ambient temperatures using a hotplate enclosed within a small environmental chamber (Figure S4). The hotplate at the bottom surface of the chamber can simulate the skin temperature (35°C), while the chamber can maintain different ambient temperatures by the supplied heating or cooling air. First, with copper layer thickness of 40 nm, the impacts of different PE film thicknesses (i.e., 0.04, 0.06, 0.08, and 0.1 mm) on the bending property were carried out under the ambient temperature of 15°C–35°C (Figure S5). It indicated that the actuator with PE film thickness of 0.04 mm achieved the maximum bending angle among the four samples at 35°C. Thus, we chose the film thickness of 0.04 mm for further investigation. Second, the impacts of different copper-layer thicknesses (i.e., 40, 100, 800, and 4,000 nm) on the bending properties of the actuators were investigated, and the samples were marked as Cu40, Cu100, Cu800, and Cu4000 (Figure 2A). For each sample, the bending angle was almost zero under the relatively low temperatures (i.e., 15°C and 20°C), while these samples gradually bent up with the further increase of the temperature. Under the relatively high temperatures (from 25°C to 35°C), the bending angle showed a nonmonotonic trend with the increase of the copper-layer thickness (Figure 2B). Among the four samples, Cu800 achieved the maximum bending angle of 310° at 35°C.

To fully understand the bending property of the metalized PE film, the maximum bending angles under different copper-layer thicknesses were calculated using

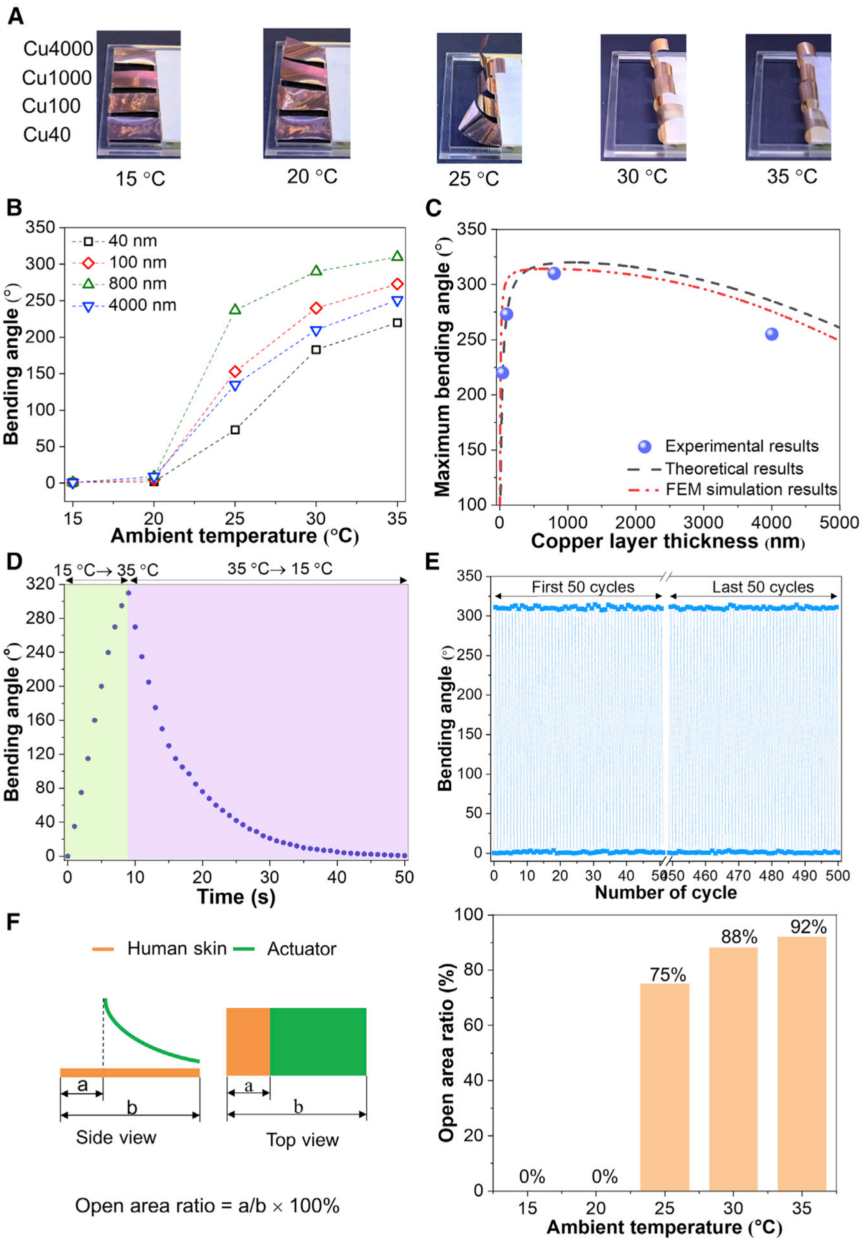

Figure 2. Bending properties of the metalized PE film as the temperature-responsive actuator

(A) Optical images of the temperature-responsive actuators under different copper-layer thicknesses with the PE thickness of 0.4 mm in response to the ambient temperature variations (15°C–35°C).

(B) Bending angles of the actuators with different copper-layer thicknesses under different ambient temperatures.

(C) Experimental, theoretical, and FEM simulation results of maximum bending angle of the actuators with different copper-layer thicknesses.

(D) Bending-angle variations of the optimal actuator (Cu800) versus time in a temperature rise and drop cycle.

(E) Cycled bending performance of the optimal actuator (Cu800).

(F) Open area ratio of the optimal actuator (Cu800) under different ambient temperatures.

theoretical formula (Note S2 and Figure S8) derived from Hooke's law[27] and numerically simulated using the finite-element model (FEM) in ABAQUS software (Note S1). With the increase of copper-layer thickness, both analytical and numerical results showed that the maximum bending angle increased sharply in the beginning but gradually decreased afterward (Figure 2C), which agreed well with the experimental results. The nonmonotonic trend of the bending angle variations was briefly explained as follows. As the temperature raised, the pure PE film would expand, but it cannot bend. In this case, we can consider that the bending angle was zero. Nevertheless, when the PE film was coated with the copper layer, the expansion of the PE film would be restricted, while the copper layer would be driven to expand due to the different thermal-expansion ratios of the two layers, resulting in bending deformation. Other than the different expansion ratios, Young's modulus of the copper (115 GPa) was much larger than that of the PE film (0.2 GPa). A larger Young's modulus indicated a higher capability to prevent shape deformation. Consequently, the expansion of the PE film would be significantly restricted by the copper layer, and it led to a sharp increase of the bending angles in the beginning. With further increase of the copper-layer thickness, the stiffness effect of the metal layer outperformed the effect of the thermal expansion ratio differences, resulting in decreased bending angles. The discrepancies between the analytical and experimental results may attribute to the deviations of physical properties (e.g., Young's modulus and layer thickness), the neglected effect of shear force between the different layers, etc.[14,17]

Apart from the bending angle, the actuator's response time and stability were also crucial in application. Regarding the optimal sample (Cu800), the bending angle changed from zero to the maximum value in response to the fluctuating temperature from 15°C to 35°C within 9 s, while it returned to zero in less than 40 s (Figure 2D). It indicated the actuator can fast respond to the temperature change for adaptive body thermal regulation. The actuator also showed high stability, as the maximum bending angle changed little after 500 cycles from low ambient (15°C) to high ambient (35°C) (Figure 2E). Last, the open-area ratio of the optimal sample (Cu800) was measured from the optical images, which represented the percentage of human skin uncovered by the actuator (Figure 2F, left). A larger ratio indicated more body infrared radiation would directly transmit into the ambient, more air would blow around the skin, and more sweat would evaporate into the ambient for enhanced body cooling. In the relatively cold ambient (15°C–20°C) the ratio was almost zero, which indicated the body-heat loss would be largely suppressed. In warm and hot ambient (25°C–35°C), the area ratio sharply increased and eventually exceeded 90%, indicating enhanced body-heat dissipation.

Infrared optical property of the actuator

Body infrared radiation, which accounted for a large proportion (around 40%) of body-heat dissipation and drew a lot of attention in recent years,[11,24,28] was also regulated by this textile. Under the open and closed states of the actuators, the temperature-adaptive clothing achieved corresponding radiative cooling and heating effects, respectively. As the actuator opened at the higher temperature, the body radiation would directly transmit into the ambient with radiative cooling achieved. As the actuator closed at the lower temperature, radiative heating was achieved, owing to the mid-infrared optical properties of both PE film and the metal layer. PE had only C–H and C–C bonds, and it showed narrow infrared absorption peaks at the wavelengths of 3.5, 6.8, 7.3, and 13.7 μm,[29] which were all far away from the peak (i.e., 9.5 μm) of the body infrared radiation.[24] It was thus considered as an infrared transparent material (Figure 3A). The copper layer showed high mid-infrared reflectance but low mid-infrared emissivity. From the view of the heat-transfer route, the mid-infrared optical property of the textile's inner surface affected the radiative heat transfer between the skin and the textile, while that of the textile's outer surface

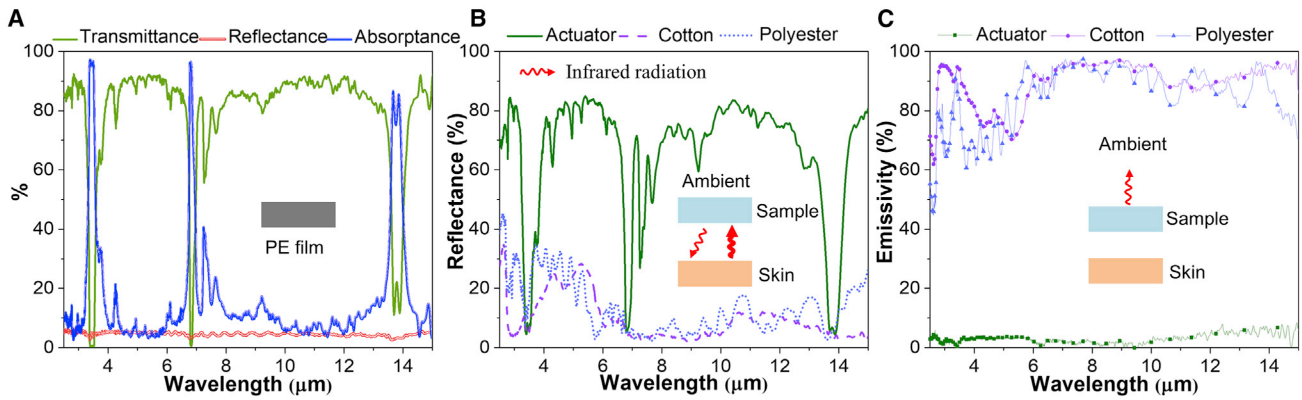

Figure 3. Mid-infrared optical properties of the metalized PE film

(A) Optical properties of the pure polyethylene film.

(B) Mid-infrared reflectance of the actuator, cotton, and polyester.

(C) Mid-infrared emissivity of the actuator, cotton, and polyester.

affected the radiative heat transfer between the textile and the ambient. On one hand, due to the high infrared transparency of PE film, the body radiation would be largely reflected back to the human skin by the actuator's inner surface. On average, the mid-infrared reflectance of the actuator was around eight times higher than conventional fabrics (i.e., cotton and polyester) (Figure 3B), indicating excellent thermal insulation. Note that the mid-infrared transmittance of the three textiles was almost zero (Figure S6). On the other hand, the thermal radiation emitted from the textile's outer surface to the ambient can be largely suppressed by the copper layer. It showed that the associated mid-infrared emissivity was almost 10 times smaller than the conventional fabrics (i.e., cotton and polyester) (Figure 3C), indicating excellent suppression of heat dissipation from the textile to the ambient. Owing to the synergic effects of the high infrared reflection of the inner surface and low infrared emission of the outer surface, the proposed temperature-adaptive clothing showed promising radiative heating effects.

Thermal performance evaluation of the temperature-adaptive clothing

A textile fabric with rectangular openwork was knitted using polyester yarns (Note S3). The actuators in rectangular shape were then integrated onto the textile to cover the openwork using hook and loop fastener (Figure 4A), which was a commonly used tool to combine two different materials in textile design.[30,31] T-shirts made of conventional cotton and polyester fabrics as well as the textile fabric attached with temperature-responsive actuators were tested on a perspiring thermal manikin[32,33] to measure the thermal and moisture resistances under different ambient temperatures, which were then used in a validated thermo-physiological model[34] to estimate the heat dissipation of an average person. From these tests, the thermal and moisture resistances of the bare skin (i.e., bare top with pants) and T-shirts made of conventional cotton, conventional polyester, and the temperature-adaptive textiles were quantified under the ambient temperatures of 15°C, 20°C, 25°C, 30°C, and 35°C, respectively. As an example, Figure 4B showed the optical images of the perspiring thermal manikin wearing the temperature-adaptive clothing in the cold (15°C) and hot (30°C) ambient during the test.

As the bare skin, cotton, and polyester were non-responsive to the temperature change, their thermal and moisture resistances changed little under different temperatures (Figures 4C and 4D). In comparison, the proposed clothing showed

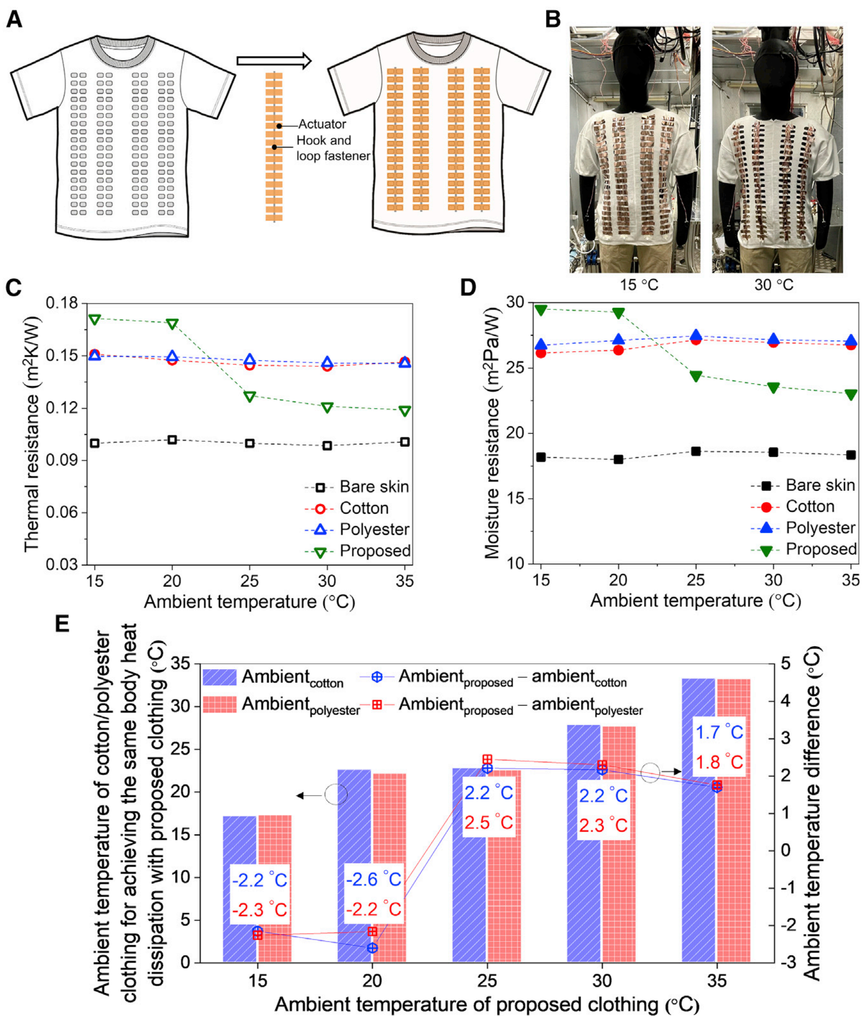

Figure 4. Thermal performance evaluation of the proposed temperature-adaptive clothing

(A) Integration of the actuators onto knitted clothing with openwork.

(B) Optical images of the thermal manikin wearing the temperature-adaptive clothing in cold (15°C) and hot (30°C) ambient.

(C and D) Thermal (C) and moisture (D) resistances of the bare skin (bare top with pants), cotton, polyester, and proposed clothing under ambient temperatures from 15°C to 35°C.

(E) Ambient temperature expansions of the proposed clothing quantified using a validated thermo-physiological model.

temperature-responsive thermal and moisture resistances. The two resistances were larger than that of the cotton and polyester under cold ambient (15°C and 20°C), indicating warming effects, while the two became smaller under warm and hot ambient (25°C, 30°C, and 35°C), indicating cooling effects. For instance, the thermal resistance of the proposed clothing was 13.6% larger than that of cotton under 15°C, while it was 16.0% smaller than that of cotton under 30°C. The variation of the two resistances can be well explained by the changes of heat dissipation induced by the temperature-responsive actuator as a result of its mechanical and optical properties (discussed in previous sections).

With the quantified thermal and moisture resistances, the heat dissipation of an average person wearing different clothing was estimated using a validated thermo-physiological model (Note S5).[34] The model can simulate the physiological reaction of the actual body in response to ambient change. For instance, at higher ambient temperature, human body would generate relatively more sweat, and thus a larger skin wettedness was assigned to the model. To figure out the building energy-saving potentials via personal thermal regulation, we calculated the ambient temperature of the cotton and polyester clothing that achieved the same body-heat dissipation (i.e., the same level of thermal comfort) as that of the temperature-adaptive clothing under the ambient of 15°C–35°C (Figure 4E). It indicated that, in comparison with the cotton and polyester clothing, the proposed one had the same heat dissipation at a 2.2°C–2.6°C (average value of 2.3°C) lower ambient temperature (i.e., ≤20°C) on the cold side and a 1.7°C–2.3°C (average value of 2.0°C) higher ambient temperature (i.e., ≥30°C) on the hot side. In particular, when the ambient temperature was close to the skin temperature (35°C), at which the latent heat dissipation via sweat evaporation was dominant, the reduction in moisture resistance by the proposed temperature-responsive clothing can still create a large amount of cooling (i.e., equivalent to 1.75°C reduction in ambient temperature) resulting from increased evaporative heat dissipation. Overall speaking, the proposed temperature-adaptive clothing can decrease the heating set point by 2.3°C on the cold side and increase the cooling set point by 2.0°C on the hot side in comparison with the conventional cotton and polyester clothing. The expansion of the comfort zone by 4.3°C (sum of 2.3°C and 2.0°C) corresponds to more than 30% of building cooling and heating energy savings.[7–9]

DISCUSSION

The advantages of the proposed temperature-adaptive clothing and its real application are discussed as follows. The proposed clothing weighs 306.2 g, which is lighter than that of conventional polyester clothing of the same style (∼350 g). Regarding the cost, the extra cost of the proposed clothing mainly comes from the temperature-responsive actuators. The cost of the PE film is minimal. The coated copper film of the actuator is around 800 nm. Thus, it only needs 2.86 g copper to prepare the actuators covering all the openwork area (∼0.4 m^2) of the clothing, which costs around $0.03. Therefore, the additional material cost is very small. Regarding the applicable temperature range, the actuator shows highly repeatable changes in bending angles as the temperature changes from 15°C to 35°C for 500 cycles (Figure 2E). Thus, it can be applied in the ambient temperature range of 15°C–35°C in practice. Regarding comfort, as the actuators are fixed on the clothing's outer surface, they do not affect skin tactile comfort. Besides, the clothing has high air breathability, owing to the pores of supporting fabric (e.g., polyester in this study).

In this work, we choose copper as the metal layer due to its low economic cost. Other cheap metals (e.g., aluminum and zinc) are also suitable to develop the metalized PE film. On one hand, these metals show similar elastic properties (e.g., Young's modulus) and linear thermal expansion ratios with the copper.[35,36] Thus, they can also achieve similar bending properties based on the previous theoretical analysis. On the other hand, these metals show high infrared reflectance but low infrared emissivity, which are essential for radiative heating.[37] Future work should focus on the aesthetic design of the clothing, especially the colors of the actuator and geometric patterns of the supporting clothing with openwork. First, the actuator should be designed to achieve diverse colors to cater to different wearers' preferences. Conventional organic dyes usually have strong absorption in mid-infrared regions due to the special chemical bonds (e.g., C–O stretching and C–N stretching).[38] These dyes are not suitable for this temperature-adaptive clothing, as they would increase the infrared emissivity of the clothing's outer surface, resulting in deteriorated radiative heating effects. Recent studies prove that inorganic materials (e.g., Prussian blue and iron oxide) are potential candidates, as they can make the textiles achieve various colors with little impact on the infrared emissivity, due to their low mid-infrared absorption.[39] Second, the sizes of all the openwork on the supporting textile may not be identical, as the temperature distribution of the human body is not exactly uniform. For instance, the temperature of the chest is usually a little higher than that of the tummy. Thus, larger openwork sizes may be required in the chest area for enhanced body thermal regulation. It seems the temperature distribution map of the human body[40] can be utilized to tailor the design of the temperature-adaptive clothing for maximizing the body-heat-regulation efficiency. In addition, the actuator can be designed in more appealing shapes (e.g., semilunar and petal shape).

Apart from the application in textile and clothing design, we foresee that the developed temperature-responsive actuator may also bring benefits in other thermal regulation fields where temperature variation is a trigger. For instance, the prevailing radiative cooling materials applied on the building envelope mainly focus on reducing building cooling energy use at high ambient temperature (e.g., in summer), while they inevitably increase building heating energy use at low ambient temperature (e.g., in winter). When covering the radiative cooling material with the developed actuator, the device would achieve radiative heating in cold ambient but radiative cooling in hot ambient, and thus it would enable all-year-round building energy savings. The details of the potential application of the temperature-responsive actuator on the building envelope can be found in Note S6.

In summary, we have developed temperature-adaptive clothing using metalized polyethylene as an actuator for multimodal body-heat regulation, which can simultaneously modulate the body-heat dissipation via radiation, convection, and sweat evaporation. The metal layer not only contributes to the temperature-responsive actuation (i.e., bending) but also induces the radiative heating of the clothing. With tailored mechanical and infrared optical properties of the actuators, we quantified the thermal and moisture resistances of the clothing via thermal manikin tests. The two resistances were further adopted to estimate the equivalent increase or reduction of ambient temperature achieved by the thermal regulation effect of the temperature-adaptive clothing. Results show that, under the same comfort level (or heat dissipation), the proposed clothing can decrease the heating set point by 2.3°C on the cold side while increasing the cooling set point by 2.0°C on the hot side in comparison with the conventional cotton and polyester clothing, corresponding to more than 30% of building cooling and heating energy savings. The proposed clothing will also largely improve the comfort of wearers when exposed to changing environments, such as moving from a cool indoor to a warm environment or vice versa. Future work will focus on the aesthetic design of the clothing, including colors of actuator and apparel patterns of the supporting clothing with openwork. In addition, we foresee that the developed temperature-responsive actuator can also help the building achieve radiative heating in cold ambient but radiative cooling in hot ambient and thus enable all-year-round building energy savings.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and procedures should be directed to the lead contact, Prof. Jintu Fan (jin-tu.fan@polyu.edu.hk).

Materials availability

This study did not generate new unique materials.

Data and code availability

All of the data supporting the findings are presented within the article and supplemental information. All other data are available from the lead contact upon reasonable request.

Materials

The low-density PE film was purchased from a company (Wangshi Packaging). The cotton textile (100% cotton) with a thickness of 0.4 mm was purchased from a local Uniqlo retail store. We made the polyester textile (100% polyester) with a thickness of 0.6 mm using yarns.

Preparation of the metalized PE film

We found that, if we directly coated a thick copper layer (e.g., 800 nm) on the PE film using the magnetron sputtering, it would accumulate much heat and cause severe thermal stress on the film, leading to deteriorated results (e.g., twisted) (Figure S3). To address this issue, the metalized PE film was prepared in two steps (Figure S2). First, a very thin copper layer (~5 nm) was deposited onto the PE film using magnetron sputtering (MAT 400). The coating thickness was controlled by tuning the input power and the sputtering time. The purpose of this step was to make the PE film electroconductive for the later electroplating. Then, the rest of the copper layer was deposited on the PE film using electroplating. The Cu plating bath contained 48 g/L $CuSO_4$ (99%, Macklin), 60 ppm chloride (98%, Sigma Aldrich), 100 mL/L sulfuric acid (99.5%, Sigma Aldrich), 5 mL/L copper gleam 2001 carrier, and 2.5 mL/L copper gleam additive (Rohm & Haas Chemicals). The layer thickness was controlled by tuning the input current and plating time. The sample was washed with deionized water and dried at last. The sample was prepared in size of 50 mm × 70 mm, and then it was cut into small rectangular shapes.

Bending angle measurement

The bending angles of the actuators were measured using a hotplate enclosed within a small environmental chamber (YG(B)606G, Wenzhou Darong Textile Instrument; Figure S4). The hotplate at the bottom surface of the chamber can simulate the skin temperature (i.e., 35°C), while the chamber can maintain different ambient temperatures by the supplied cooling and heating air. The temperature can be manually set via a control panel. A sample holder was placed on the hotplate, and then the samples were put onto the holder with one end fixed. The bending angle measurement was conducted under the ambient temperatures of 15°C, 20°C, 25°C, 30°C, and 35°C, respectively. Photos were taken using a camera when the bending angles of the actuators reached a steady state under each temperature. We recorded the bending angles of the actuators by analyzing the photos using ImageJ software.

Linear thermal expansion ratio measurements

The thermal-mechanical analyzer (Mettler Toledo TMA/SDTA1) was adopted to measure the linear thermal expansion ratio of the polyethylene, nylon, and polyester films. Each film was prepared in rectangular shape (20 mm × 4 mm at 20°C) and attached onto two hooks. During the test, a small tensile force of 0.05 N was applied on the film to ensure it kept straight along its length. The temperature scan was performed at 2°C/min. Taking the length at 20°C (l_{20}) as a reference, the linear thermal expansion ratio at each temperature T was calculated as $(l_T - l_{20})/l_{20}$, where l_T was the length of film at temperature T.

Infrared optical measurements

The infrared optical properties of the sample, including infrared transmittance (τ, unit: %) and reflectance (ρ, unit: %), were measured using a Fourier transform infrared (FTIR) spectrometer (PerkinElmer Spectrum 100, 2.5–15 μm) with a gold-integrating sphere. The infrared emissivity (ε, unit: %) of the sample was then calculated using the mathematical formula $\varepsilon = 100\% - \tau - \rho$.[41]

Fabrication of the temperature-adaptive clothing

The clothing with rectangular openwork was fabricated by a computerized flat knitting machine (Shima Seiki, Japan) using polyester yarns. Then, the temperature-responsive actuators in rectangular shapes were integrated onto the clothing to cover the openwork using hook and loop fasteners. One benefit was that the fastener can be easily removed from the clothing before washing, avoiding the damage of the actuators. Details of the clothing fabrication can be found in Note S3 and Figures S9–S11.

Thermal manikin test

The thermal manikin is a human model, and it can simulate the heat transfer between the human body and the ambient. In this work, the thermal manikin test was conducted to quantify the thermal and moisture resistances of the temperature-adaptive clothing in response to the varying ambient temperature. A standing perspiring thermal manikin developed by our group[32,33] was placed in a large environmental chamber (8 m length × 4 m width × 3.2 m height). The manikin was filled with water, which was heated by the embedded electrical heaters. A proportional-integral-derivative controller was adopted to adjust the electrical heating power for maintaining the mean skin temperature (35°C). When the manikin reached a thermal equilibrium state, the power inputs of the manikin were equal to the body heat transferred to the ambient. The manikin test was conducted under five different ambient temperatures (i.e., 15°C, 20°C, 25°C, 30°C, and 35°C) for bare skin (i.e., bare top with pants) and traditional (i.e., cotton and polyester) and temperature-adaptive clothing, respectively. The relative humidity was fixed at 50%. For each case, the associated power values at the thermal equilibrium state were recorded by a computer. These values were adopted to calculate the thermal and moisture resistances (Note S4).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2022.100958.

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AUTHOR CONTRIBUTIONS

J.F. and J.C. conceived the idea and planned the work. J.C. prepared the metalized polyethylene film, and L.L. provided assistance. Y.Y. fabricated the two polyester textiles (with and without openwork). J.C. conducted the characterizations, including the linear thermal expansion ratio and infrared optical measurements. Z.K. conducted the finite element simulation and the thermo-physiological modeling. J.C. and Y.Z. conducted the thermal manikin test. All the authors contributed to the writing of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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