Solar thermal textiles for on-body radiative energy collection inspired by polar animals

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Abstract

Humans use textiles for maintaining thermal homeostasis amidst environmental extremes but known textiles have limited thermal windows. There is evidence that polar-dwelling animals have evolved a different mechanism of thermoregulation by controlling radiative energy exchange with the environment using a combination of light-absorbing and heat-retaining materials. Here we design a textile to mimic these adaptations to optimize direct radiative collection on the body. Two ultralightweight fabrics with complementary optical functions, a nylon “absorber” coated with a strongly-colored conjugated polymer and a nonwoven polypropylene “transparent insulator,” perform the same putative function as polar bear skin and hair, respectively. While retaining familiar textile qualities, these layers suppress radiative dissipation of body heat and maximize radiative absorption of visible light. Exposed to a radiance of 650 W/m$^2$, representative of wintertime sunlight at high latitudes, the textile supports thermal homeostasis as low as -28°C. With increasing pressures to adapt to a rapidly changing climate, our work leverages conjugated polymers to evolve one of the oldest and most basic commodities — textiles.

One-sentence Summary

Inspired by natural adaptations of polar animals, we redesign the textile with optical polymer materials to support thermoregulation with on-body solar thermal collection.

Main Text

Wearable technology is advancing rapidly to bring a host of novel functionalities – health and environmental monitoring, motion tracking, sleep evaluation – into everyday items. With a few exceptions, it is ironic that the first wearable – the textile – has not evolved in how it performs its original function: thermoregulation. After thousands of years, textiles are still woven from fibers into thick structures that manage heat transfer by inhibiting thermal conduction and convection from the body to the environment while maintaining breathability. With increasing environmental and economic pressures to find more sustainable ways of living in a rapidly changing climate, it is necessary to leverage novel materials and revisit the design of one of the oldest and most basic technologies.

In nature, organisms have met environmental challenges by manipulating light with optical materials for thermoregulation. Managing heat in a fundamentally different way than traditional textiles, specialized surfaces that selectively reflect, absorb, or transmit radiation across the visible and infrared (IR) spectrum allow certain animals to survive in extreme conditions. This strategy is used, for example, by reflective silver ants in the Sahara,(1) and polar bears(2) and moths(3) in the arctic circle. One commonly used material is melanin, an optically dense biopolymer comprised of light-interacting conjugated units with a high refractive index and broadband light absorption.(4, 5) Besides melanin’s role in the dynamic camouflage of cephalopods, it is also used in the thermoregulation of species of moths, butterflies, and birds that have evolved melanin-enriched wing coatings in cold and sunny climates.(3, 6, 7) Such surfaces may exhibit selective function over the visible and near-infrared (vis-NIR) spectrum, where
phothothermal heating takes place, and over the infrared (IR), where objects spontaneously radiate heat according to Planck’s law. There is also convincing evidence that, under the extremely high solar insolation of the polar environment (8), certain cold-adapted animals use low optical density (lightly colored) insulating features to achieve a biological, on-body greenhouse effect.(9–11) Compared to darkly colored surface features, for example, the light-colored surfaces of the polar bear and harp seal transmit significantly more radiation toward melanized skin, trapping heat with solar utilization factors ranging from 10-50%.(9, 10) Such solar harvesting supports thermal homeostasis by accessing a huge potential energy source with magnitudes exceeding 1000 W/m², i.e. up to 10 times the basal metabolic heat production of common endotherms.(11)

Garment coatings comprised of optically-active materials like MXenes, carbon nanotubes, and silver nanowires have been pursued to approximate the thermoregulation strategies found in nature.(12–16) One commercialized technology – Omni-Heat by Columbia – uses aluminum dots to reflect body heat to small effect, heating slightly better than a typical cotton fabric.(17) A crucial deficit in reported approaches is the lack of a transmitting insulator component that inhibits heat loss to the environment and, therefore, significantly amplifies the solar utilization factor. Another practical challenge is robustly coating nanomaterials onto textiles, which must stand up to laundering and wear over a garment lifetime. Certain nanomaterials are also known to be toxic and biopersistent, with safety concerns given their historical lack of regulatory oversight.(18) Such concerns are particularly worth addressing, considering that melanin and other polymers, such as silk, chitin and cellulose, that are used for thermoregulation by animals can perform these functions while being environmentally benign.(5, 19, 20) Conjugated polymers are an alternative class of soft materials with favorable properties for wearable thermoregulation. Robust, skin-compatible coatings of such polymers on complex surfaces characteristic of textiles are achievable with oxidative chemical vapor deposition.(21) Similar to melanin, polymers like poly(3,4-ethylenedioxythiophene) (PEDOT) exhibit high optical density with electromagnetic properties arising from pi-pi stacked conjugated units.(22) While being lightweight and flexible, conjugated polymers are also often water-swellable and possess chemical structures that bear resemblance to those of the optically-active biopolymer melanin described above.(23)

In this paper, we create a lightweight textile platform for on-body light and heat management by taking inspiration from materials and structures found in nature. Our approach is to (1) adapt PEDOT as a spectrally-selective coating on textiles to mimic the thermoregulating role that melanin plays in many organisms and (2) adopt a semi-transparent upper textile layer to mimic polar bear fur and minimize heat dissipation while transmitting light to the bottom photothermal layer. A key advantage to this approach is that, unlike other thermoregulation strategies which rely on metallic or inorganic materials, the structure proposed here can be realized with all-polymer materials. Photothermal harvesting of ambient light – indoors or outdoors – allows high-power, wireless delivery of heat directly to the body without the need for bulky and low-power wearable energy storers-harvesters like photovoltaics, triboelectrics, lithium-ion batteries, etc. A climate-controlled chamber with a skin and solar simulator is used to evaluate the heating performance relative to common garments. Exposed to a moderate light intensity of 130
W/m² (ca. 0.1 sun), this thermal textile has a temperature rating that extends 9.9°C lower than a typical cotton fabric (4.2°C/~40°F versus 14.1°C/~60°F) while weighing 30% less. A steady-state heat transfer model that considers solar absorbance and infrared emissivity is developed to understand the performance limits of a spectrally optimized absorber layer.

Results

Biomimetic system design and material selection. Traditionally, textiles have been made from a limited material set. Natural or synthetic fibers are spun and woven into thick fabrics that inhibit heat diffusion between the body and the environment. Perhaps due to the lack of suitable materials, traditional textile design has largely overlooked the management of radiative heat (i.e. energy carried by light). Recently, this has begun to change with, for example, the development of radiative heating textiles enabled by reflective metallic coatings(17) and radiative cooling textiles enabled by IR transparent polyethylene fibers(24). A performance gap still exists for more efficient personal heating in a comfortable, familiar textile format. One way forward is to not only limit dissipation of radiant body heat outward, but to also optimize absorption of ambient radiant energy inward. The power density of sunlight, for example, is sufficient (100–1000 W/m²) to augment typical metabolic heat production (~70–120 W/m²). It is therefore unsurprising to see both directions of radiative energy management in adaptations of polar animals.

Two natural structures inspire the design of our solar thermal textile. The first is a type of structural coloration in some species of cold-adapted moths and butterflies that enables selective absorption of visible-NIR light and suppression of thermal (IR) emission (Fig. 1a). In this case, melanin is the optically active material. With an electron-dense pi-pi stacked structure, melanin behaves as a disordered organic semiconductor and has a significantly higher refractive index than most biopolymers.(4, 5) A variety of donor-acceptor units enable broadband light absorption, while a high optical density enables light interference effects (IR reflection) in melanin-enriched wing coatings. The second source of inspiration is the pelt of the polar bear which, key to the animal’s survival in the extreme cold, simultaneously provides high thermal resistance (R) and high solar utilization (Fig. 1b). The dual function arises from a specific material set and optical structure. Lacking melanin pigment, hollow hair fibers have a low optical density and efficiently forward-scatter light, permitting photothermal capture at the melanized skin while inhibiting heat loss to the environment.(2, 9, 11, 25, 26) The essential optical structure of the pelt - a transmitter-insulator (transparent hair) stacked above an absorber (darkened skin) - efficiently harvests solar thermal energy to support thermoregulation in the extreme cold. While several groups have reported personal heating materials nominally mimicking polar bear fur, none have demonstrated this crucial optical structure nor a transmitting insulator fabric.(27–29) More accurate polar bear inspired textiles and structures have been reported for building-level solar collectors,(25, 30, 31) but here we analyze the energetic significance of direct radiative capture at the body-environment interface and show the high thermoregulation efficiency of a wearable solar thermal textile.
To mimic such adaptations, we engineered a bilayer textile using optical polymer materials (Fig. 1c). The bottom layer is a nylon fabric robustly vapor coated with the conjugated polymer PEDOT, enabling selective absorption of visible light and suppression of IR emission. In structure and function, the soft material PEDOT bears resemblance to melanin. This pi-pi stacked electronic polymer interacts strongly with light due to high free-electron density associated with long conjugated chains. While PEDOT is an organic conductor, it shares the same broadband vis-NIR light absorption of melanin due to plasmon (surface electron) resonance near 1000 nm with a high optical density \( \kappa \). At longer wavelengths into the IR, PEDOT is a reflector (a weak emitter). Like the melanin-enriched microstructure of moth wings, a PEDOT coating can therefore be used to efficiently manage radiative heat transfer between the body and the environment. Photothermal heat generated at the PEDOT-nylon absorber is further trapped by the top layer, a semi-transparent fabric mimicking the light colored fur of polar animals. This lightweight fabric (Agribon AG-19) is made of low optical density polypropylene bers that forward-scatter visible light with about 85% transmission and more weakly transmit IR light with about 60% transmission (Figure S1). By confining solar thermal heat as both a diffusion and IR radiation barrier, AG-19 essentially acts like a breathable greenhouse material. Indeed, it is used in the agricultural industry for this purpose. Individual bers are visualized in an optical transmission micrograph in Fig. 1e. Fiber diameter is in the range of 9–10 microns, comparable to IR wavelengths and thus capable of Mie scattering to trap IR radiation. As with polyethylene and other polyolefins, polypropylene is an attractive material for textiles for its potential sustainability, durability, and ultra-light weight. Along with the spectrally selective PEDOT-nylon fabric, the fabric transmitter layer operates differently than traditional textiles and has the potential to provide highly efficient thermoregulation.

**Optical and thermoregulation characterization.** A one-micron thick coating of PEDOT onto nylon fabric dramatically changes the surface optical properties due to the high optical density of PEDOT. Figure 2a visualizes this change in photographs and thermal images. Under a commercial lightbulb, the coated fabric absorbs more photothermal energy relative to the reflective uncoated nylon. Over an IR source (human body), the coated fabric emits less thermal energy (appears colder) than the high emissivity surface of the uncoated nylon. These effects are quantified in Fig. 2b, where emissivity of the coated fabric (blue) and uncoated (black) is plotted against wavelength. The uncoated nylon fabric shows a behavior typical of traditional textiles: low emissivity (absorbance) in the visible and high emissivity in the IR. With a PEDOT coating, this optical behavior is reversed, and the fabric behaves more like an ideal photothermal absorber.

With the ability to control the optical properties of the fabric, we next evaluate the thermoregulating performance of a set of traditional and unconventional fabrics. A simple way to conceptualize this task is by considering the lowest temperature rating for which a certain textile can maintain the wearer’s thermal comfort. Warmer textiles are needed for colder environments (Fig. 3a). More specifically, a textile should limit the loss of body heat (\(~ 75 \text{ W/m}^2\) for an average adult at rest) to the environment so that a comfortable skin temperature (33°C) is maintained at steady state. Excluding factors like wind chill and humidity, this situation is simulated in a chamber depicted in Fig. 3b. For a given textile sample, the
temperature of a skin heater with a constant output is monitored by a controller that lowers the environmental temperature until thermal comfort ($T_{\text{skin}} = 33^{\circ}\text{C}$) is reached at steady state. A similar chamber design was previously used to evaluate passive heating solutions,(17) except here a window allows for environmental light (radiative energy) input to the textile-skin system.

Uncoated and PEDOT-coated nylon were tested, as well as a range of traditional and non-traditional textile comparators of varying weights, as shown in Fig. 3c. A cotton jersey sample represents typical T-shirt material, while cotton terry is typical of heavier, warmer garments like a sweatshirt. The other optically-active textiles include commercial Omni-Heat and spun-bonded polypropylene (AG-19). The Omni-Heat fabric is tested with the reflective face up (R up) and down (R down). The AG-19 is held by a 5 mm thick plastic frame for consistency across measurements. The low temperature ratings of the textiles were measured in the environmental chamber and results for dark conditions are shown in Fig. 3d. The low emissivity fabrics – PEDOT-nylon and Omni-Heat (R up) – perform similarly to the cotton jersey fabric as has been previously demonstrated.(17) The thicker cotton terry and AG-19 fabrics offer more insulation and have lower environmental temperature ratings in the range of 18$^{\circ}$C.

Under moderate illumination of 130 W/m$^2$, the performance of the textile samples varies more widely. While the PEDOT-nylon and Omni-Heat (R-up) fabrics perform similarly in dark conditions due to comparable thermal emissivity values, the PEDOT-nylon has a greater visible absorbance and so performs significantly better ($9.6^{\circ}$C versus $11.5^{\circ}$C) under illumination. Compared to PEDOT fabrics, other metal-coated textiles may show poor solar thermal heating due to the higher resonant frequencies (in the UV-visible range) of commonly used metals like aluminum and silver.(35) Individually, AG-19 also performs well ($8.2^{\circ}$C) but when stacked in the absorber-transmitter structure, the complementary optical functions of the PEDOT-nylon and AG-19 yield a more dramatic heating effect. The bilayer textile has a temperature rating that extends $10^{\circ}$C lower than the cotton jersey fabric ($4.2^{\circ}$C/$\sim40^{\circ}$F versus $14.1^{\circ}$C/$\sim60^{\circ}$F) while weighing 30% less. With an additional layer of AG-19, the performance improves more modestly (extending to $2.9^{\circ}$C), suggesting that the sacrifice of solar utilization (light transmission) for thermal insulation becomes less favorable to thermoregulation.

Taking the temperature rating of the cotton jersey fabric as a baseline for the other measurements allows comparison of textile performance in both light and dark conditions (Fig. 3f). While the thick, insulating cotton terry fabric shows good performance in dark conditions ($+1.6^{\circ}$C relative to cotton jersey), it has relatively weak performance in light conditions ($+1.3^{\circ}$C). This is representative of traditional textiles – thick, opaque insulation that limits heat dissipation outward also necessarily limits photothermal heat transfer inward. On the other hand, the bilayer textile excels in both dark ($+2.7^{\circ}$C) and light ($+9.9^{\circ}$C) conditions due to the insulating yet light-transmitting AG-19 layer.

Other wearable photothermal mimics comprise outward-facing darkly colored surfaces,(27–29) which may explain the reduced solar heating effect (relative to cotton T-shirt, $+5.5^{\circ}$C versus $+9.9^{\circ}$C) of one such report.(Figure S1) We confirm the importance of optical structure by reversing our absorber-
transmitter stack, i.e. facing the dark colored PEDOT surface outward, which significantly reduces relative performance (+ 7.1°C versus + 9.9°C). (Figure S2) This is in agreement with counterintuitive observations that darker colored pelt features, due to inhibited light transmission, may achieve less solar utilization than light colored pelts. (9–11)

**Modeling textile thermoregulation under illumination.** While previous work in radiative heating textiles has studied the impact of IR surface properties, here we study the combined impact of IR and visible optical properties on personal heating under moderate light intensity. As a simple case, we focus on an absorber-only system which, due to the broad IR and visible transparency of the transmitter layer (Figure S3), may also inform the bilayer textile design. (Figure S4) Our steady-state heat transfer model (Supplementary Note 1) of the skin-textile system includes incident radiation (130 W/m²) and a natural convection coefficient that varies with the skin-environment temperature difference (Fig. 4a). The results of the simulation are shown in Fig. 4b and experimental data points of uncoated and PEDOT coated nylon are overlaid. The performance of the radiative heated textile is optimized at maximum solar absorbance and minimum thermal emissivity, and we note that the PEDOT coating brings the nylon fabric closer to this target. At 130 W/m², the dependence of environmental temperature on solar absorbance is roughly comparable to that of thermal emissivity; however, at greater radiance (325 W/m²), solar absorbance becomes the dominant contributor. (Figure S5).

To understand realistic sunlight utilization, the human body is approximated as a vertical cylinder (36) and normal incident radiance per total surface area (typically 1.8 m² for adults) is calculated across the year assuming half of the body is illuminated. For solar-powered personal heating, a convenient coincidence is that the coldest season may correspond with the maximum solar radiance on a vertical body due to the reduced solar elevation. In Boston, MA, for example, the calculated on-body radiance of direct sunlight increases from about 108 W/m² at the summer solstice to about 325 W/m² at the winter solstice. The presence of snow fields can also dramatically increase overall solar insolation values, as is the case in polar environments, which may further double the incident solar contribution. (8) With a combined body-surface irradiance of 650 W/m², the available wintertime solar thermal power at high latitudes may therefore be up to 10 times larger than the body heat generated by a moderately active adult (70–120 W/m²). (37) The bulky, opaque nature of winter outerwear assures low utilization of this power source, as the weak solar heating of the thick cotton terry fabric demonstrated above suggests. On the other hand, the bilayer textile described here harnesses sunlight to provide remarkable heating for its weight. Exposed to the calculated wintertime radiance of 650 W/m², the textile supports thermal homeostasis as low as -28°C (Figure S6), approaching the temperature extremes of the polar environment. Indoors, a light capturing textile can support the development of passive solar architectures (38) as personal heating and design elements, as well as be powered by existing indoor light fixtures capable of the lower radiance levels modeled here. (39)

**Wearability characterization.** Everyday clothing is expected to be comfortable, breathable, and washable. The optically-active textiles presented herein were also evaluated for these functions. Despite being
nonwoven, the AG-19 transmitter fabric has many familiar textile qualities that make it suitable for garments and apparel, upholstery, and décor. The nonwoven material has a similar drape to traditional woven textiles (Fig. 5a) and may be sewn and ironed without damage. Advancing from the frame-supported textile presented earlier, we next demonstrate the use of such materials in a self-supported garment made by sewing two layers of AG-19 and ironing pleats to form insulating baffles. PEDOT-nylon is then sewn to the bottom to complete the solar thermal textile (Fig. 5b). This textile performs similarly to the previously characterized bilayer structure and, importantly, is stable after three washing cycles using common laundry detergent and after two total hours of light exposure (130 W/m²)(Fig. 5c). Optical microscopy of the PEDOT coating across washings shows a small change in color and no damage to the mechanical stability of the films (Figure S7). A water vapor transmission test across an AG-19/PEDOT-nylon stack reveals that this bilayer is as breathable as other common fabrics used in the study (Fig. 5d). This is unsurprising given the diffuse open mesh of the AG-19 fabric, designed to be breathable, and the hydrophilic nature of PEDOT.(23)

**Discussion**

Here we leverage optical polymer materials to design a radiative heating textile as a wearable mimic of the absorber-transmitter structure of the polar bear skin and fur and are the first to demonstrate the dramatic personal heating effect this structure has when worn on the body. While retaining familiar textile qualities, the bilayer design suppresses radiative dissipation of body heat and maximizes radiative absorption of visible-NIR light. Due to a faithful imitation of the light collecting structure and function of polar bear pelt, the garment achieves a significantly greater personal heating performance than other nominal mimics which either lack a transmitter or sacrifice solar utilization for thermal insulation.(27–29) Under moderate illumination of 130 W/m² (ca. 0.1 sun), this textile maintains the wearer's thermal comfort down to 4.2 °C – an additional heating effect of 10 °C relative to a typical cotton T-shirt that is 30% heavier. Under full sunlight, the garment supports thermal homeostasis in extreme conditions as low as -28 °C.

Using similar design methods, it is also possible adapt our strategy to radiative cooling and access a reflector-emitter structure like that found on the Saharan silver ant.(7) By rejecting solar heat and dissipating thermal heat through the atmospheric window, such a structure may allow adaptive living in extremely hot conditions. The material properties and vapor deposition of PEDOT can enable different kinds of optical control beyond the photothermal effect shown here. When used with specific surface geometries, the plasmon-coupled light interactions of PEDOT can also be directed to produce the high reflectivity needed for daytime radiative cooling.(40–43) The oxidative vapor deposition process used in this work is uniquely suited for such optical engineering purposes. Electronic polymer coatings of precise thickness can be conformally deposited over complex surface arrays which may, like the faceted triangular hairs that endow the silver ant with its optical thermoregulation, possess features ranging in size from sub-micron to micron.(44) The second adaption of our strategy involves designing a transparent thermal emitter layer. While the polypropylene fibers here primarily serve to transmit visible
light, Mie scattering theory informs optical tuning toward high IR emittance by adjusting fiber size and geometry to achieve dielectric resonance at IR frequencies.\(^{(45)}\)

The solar thermal textile presented here is a flexible, lightweight platform for collecting radiative energy. Indoors, this technology can enable efficient thermoregulation by local, low-power lighting (i.e. LEDs) as well as support the design of passive solar architectures. Outdoors, a lightweight solar textile will make winterwear more comfortable and enable passively heated shelters for adaptive living in harsher climates. As the energy and environmental crises progress, reinventing textiles with polymer-enabled light and heat control will prove increasingly useful.

**Declarations**

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**References**


**Figures**
Figure 1

Designing a multilayer textile to mimic thermoregulation structures found in nature. a, b Animals that efficiently harvest solar thermal energy to reduce metabolic needs - a In the wings of certain moths and butterflies, melanin microstructures interact with light to control heat. The high optical density of melanin (representative structure shown) enables broadband light absorption and efficient light interference effects to suppress thermal emission. b The polar bear has similarly evolved melanin-enriched skin which may aid in photothermal capture. This effect may be enhanced by its unique hair – hollow and pigment-free fibers with a low optical density that forward-scatter light inward and inhibit thermal diffusion outward. C Our bilayer textile combines such light and heat control elements. D The bottom nylon fabric is vapor coated with PEDOT (structure shown), an optically dense organic conductor with high visible light absorption and low thermal emission. E The top fabric is made of spun-bonded polypropylene fibers (Agribon AG-19) and acts as a semi-transparent insulator, transmitting ~85% of visible light. A transmission optical micrograph shows the polypropylene fiber network. Scale bar 20 μm.
Figure 2

Characterizing the spectral selectivity of PEDOT-nylon fabric. **a** Photographs and infrared (IR) images comparing uncoated and coated nylon fabric interacting with a visible light source (lamp) and an IR source (human body). Scale bars 2.5 cm. **b** Emissivity (absorptivity) of PEDOT coated fabric (blue) relative to uncoated (black) compared against the blackbody spectra of the sun (5,504 °C) and human body (33 °C). Emissivity is calculated as 100% - .
Figure 3

Characterizing the thermoregulation of traditional and novel textiles. a Textiles control heat transfer between the body and environment but are not currently optimized to collect indoor or outdoor light as heat. A chamber is used to simulate such heat transfer and evaluate the low temperature ratings of textile samples in varying ambient light conditions. The skin surface is simulated by a heater with a constant output ($Q_{gen}$). To characterize a sample, a microcontroller monitors the skin temperature ($T_{skin}$) and finds the lowest environmental temperature ($T_{environment}$) that is thermally comfortable ($T_{skin}=33^\circ C$). Warmer textiles have lower environmental temperature ratings. Ambient light exposure is varied. b Textile samples characterized. Fabric weights (mg/cm$^2$) are shown. Scale bar 2.5 cm. Temperature ratings of textiles
exposed to c dark and d light (130 W/m²) conditions. e Relative heating performance. Positive values indicate an extension of the textile temperature rating relative to a typical cotton jersey (T-shirt) fabric.

Figure 4

Modeling the impact of optical properties on textile thermoregulation for a moderate light intensity of 130 W/m². a Schematic of the steady-state heat transfer model for a single-layer textile. \( T_{environment} \) is calculated as a function of textile spectral selectivity given the thermal comfort condition (\( T_{skin} = 33°C \)). b Results of the simulation. Textile thermoregulation is optimized at high solar absorbance and low thermal emissivity. Two experimental points (uncoated and PEDOT-coated nylon) are shown. c Approximation of solar radiance on a vertical body at high latitude (Boston, MA). The coldest season may correspond with the maximum radiance due to reduced solar elevation; snow cover (albedo > 90%) as much as doubles light exposure. The human body is taken as a vertical cylinder and incident radiance, illuminating half of the body area, is divided by total surface area (typically 1.8 m²).
Figure 5

Practical characteristics of the solar thermal textile. **a** The nonwoven AG-19 fabric has a similar drape to traditional woven fabrics. **b** Two layers of AG-19 are sewn together and ironed to make insulating baffles. The PEDOT-nylon layer is then sewn to the bottom. **c** Textile thermoregulation characterization across three washing cycles. **d** Breathability characterization shows similar water vapor transmission across the textiles tested.

**Supplementary Files**

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