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Large area, stretchable, wearable, screen-printed carbon heaters for use in elite sport

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Abstract Stretchable, nanocarbon heaters were screen-printed onto a stretchable film to create a passive heat maintenance device for elite sport. The heat uniformity and the temperature performance of these lightweight, large area electrothermal heaters were evaluated over a range of applied voltages using thermal imaging. The heaters provided a uniform heat over the 15 × 4 cm area with temperatures of 39°C, 54°C, and 72°C at 10, 15, and 20 V, respectively, within 150 s of being switched on. Tensile testing was used to examine the performance of the heaters under strain. At 20% nominal strain, the heaters gave a uniform heat output and a temperature of 44°C at 15 V, making it a promising candidate for wearable applications. The heaters were capable of maintaining temperatures of 40°C over 10 cyclic strains up to 10% nominal strain. The heaters were integrated into a proof-of-concept stretchable base-layer garment, with the effect of the heaters on skin temperature measured and thermal sensation evaluated during a simulated training session in an environmental chamber at an ambient temperature 0°C. The printed heaters maintained skin temperature and thermal sensation when compared with an unheated control.

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Introduction

Elevations in muscle temperature (T_m) have a significant effect on muscle function, force, and power production.[1, 2] However, T_m drops immediately following the cessation of exercise with the rate at which T_m declines affected by environmental conditions.[1, 3] These losses in T_m have been shown to be greater closer to the surface of the skin,[2] as superficial muscle is more susceptible to environmental heat exchange.[1] It is common for elite athletes to experience periods of inactivity between physical efforts during competition and training, whether this is between the end of a warm-up and the start of competition, during an interval (e.g., half time) or between rounds of activity. During these periods, T_m can drop below an optimal level which may have a detrimental effect on subsequent performance, particularly in sports requiring powerful movements like lifting, jumping, and sprinting.[1–3] These periods of inactivity are often important as they allow for acid–base homeostasis, phosphocreatine restoration, muscle potentiation and give an opportunity for the athlete to receive tactical instruction. Therefore, a passive method of maintaining T_m would be a more prudent option rather than a further active warm-up.[3] If T_m can be maintained following a warm-up using either insulating clothing or external heating, it will yield a benefit in subsequent activities that require high levels of power.[2–4] Passive heat maintenance strategies attenuate the decline in T_m following a post-warm-up recovery period better than an athlete's standard training attire and have been shown to improve power output in sprint cycling.[1]

A combination of warm water immersion and heated blankets has been used to passively elevate

T_m with this having a beneficial effect because of increased anaerobic ATP turnover[5]; however, methods such as this are difficult to implement outside of a laboratory environment limiting their practical use.[1]

Flexible electrothermal heaters have a broad range of applications in wearable electronics, including warming garments and as flexural warmers for medical devices and vehicles.[6, 7] Wire heating elements can be sewn into fabric inserts to create a flexible heating system which can then be integrated into clothing, such as the trousers worn by the British Track Cycling team in the London 2012 Olympics.[8] These trousers combined 7.5 W electrical heating elements with insulative trousers to reduce losses in T_m. When the performance of these electrically heated and insulated pants was assessed in a 16°C environmental chamber, they attenuated T_m losses better than a pair of insulated athletic pants and led to a ~9% improvement in peak power output during a 30 s maximal sprint cycle compared to their standard training attire.[2] However, T_m still decreased at all measured muscle depths following the 30-min recovery period.[2] Cowper et al.[9] demonstrated that using an externally heated 105 W motorcycle jacket during a 25-min post-warm-up recovery period in an 8°C environment led to increases in skin temperature (T_{skin}) and T_{core} associated with improved 2000 m single scull rowing performance compared to a control consisting of a standard tracksuit.

Metal wire heaters are rigid, suffer from oxidative corrosion, and have a relatively short lifetime on account of broken wires.[6, 7, 10] Wire heaters show poor heat uniformity as the wire is the only component that generates heat and garment fabrics tend to be poor thermal conductors. Wire heaters are also susceptible to the creation of hot spots, with any local change to the resistance of the wire, through damage or strain, causing local increases in the resistance associated with increases in temperature. As a consequence, the temperature of the heaters used by Faulkner et al.[2] was limited to 40°C to avoid skin burns as even activities such as sitting on a chair caused changes to the temperature output.[4]

Coating textiles with conductive materials can add functionality.[11–14] Polymer composites containing carbon nanofillers have advantages such as light weight, chemical inertness, controllable electronic properties, and lower manufacturing costs for electric heating applications.[10, 15–18] Intrinsically flexible materials can be formulated into coatings by dispersing conductive fillers within an elastic polymer matrix and a solvent, with electrical conductivity tuned by varying the loading of the filler material.[15, 19] These intrinsically stretchable materials can be applied selectively using high-volume printing processes onto a wide range of substrates.[12, 20–22] Screen printing specifically allows for accurate patterning of thin films onto a wide variety of substrate materials.[23, 24] DuPont™ successfully printed a flexible heater, consisting of silver tracks for carrying the current with small carbon blocks as the resistors used to generate the heat.[25] However, the heated area was relatively small compared to the silver current conductor. This was incorporated into the jackets of the USA Olympic team during the opening ceremony of the 2018 Winter Olympics. Ali et al. coated carbon black dispersions onto cotton fabric, using conductive yarn as electrodes to create wearable heating textiles incorporated into a leisure jacket.[26]

Previous garments have been designed to be used during periods of relative inactivity and removed before physical effort or competition.[2, 3, 9, 25] The development of more portable, effective, and practical passive heat maintenance devices would enable their use in an applied environment.[1] To be used during intense physical efforts, such as in training, requires the garments to be lightweight, mechanically robust, durable, able to withstand folding, creasing, and stretching, be machine washable, and not impede the garment's ability to conform to body curvatures or hamper performance.[13, 15, 27] The integrated devices must be able to stretch to facilitate flexibility and to improve the conformity of electronics with the body.[12, 28] In general, textile applications about 15–20% strain occur through the life cycle of the product.[29] The devices must also be able to accommodate and recover from larger strains such as occur when dressing.

An efficient printed heater technology is described in this paper that can be attached directly onto stretchable fabrics and maintains a uniform temperature output following tensile and crease testing. The heaters were built into a proof-of-concept stretchable base-layer garment worn during a simulated sprint canoe training session at 0°C capable of maintaining a uniform and consistent heat output while flexed allowing their effective use in an applied environment.

Materials and methods

Ink manufacture

The carbon ink contained a blend of graphite nanoplatelets (GNP) and carbon black (CB) dispersed into a thermoplastic polyurethane (TPU) elastomer in a polar solvent. Thermoplastic polyurethane was selected as the binder for the stretchable inks as it offers unique properties such as excellent elongation, high impact strength, good elasticity, and biocompatibility.[30] A silver ink comprising 55 wt% of 10 μm silver flake (Sigma-Aldrich) was dispersed in the same TPU and polar solvent system to act as a busbar to minimize voltage drop across the heaters. Silver flake was selected over spherical particles to give greater particle overlap and particle contact. The electromechanical properties of the inks used to create the heaters can be found in a previous work by the authors.[31]

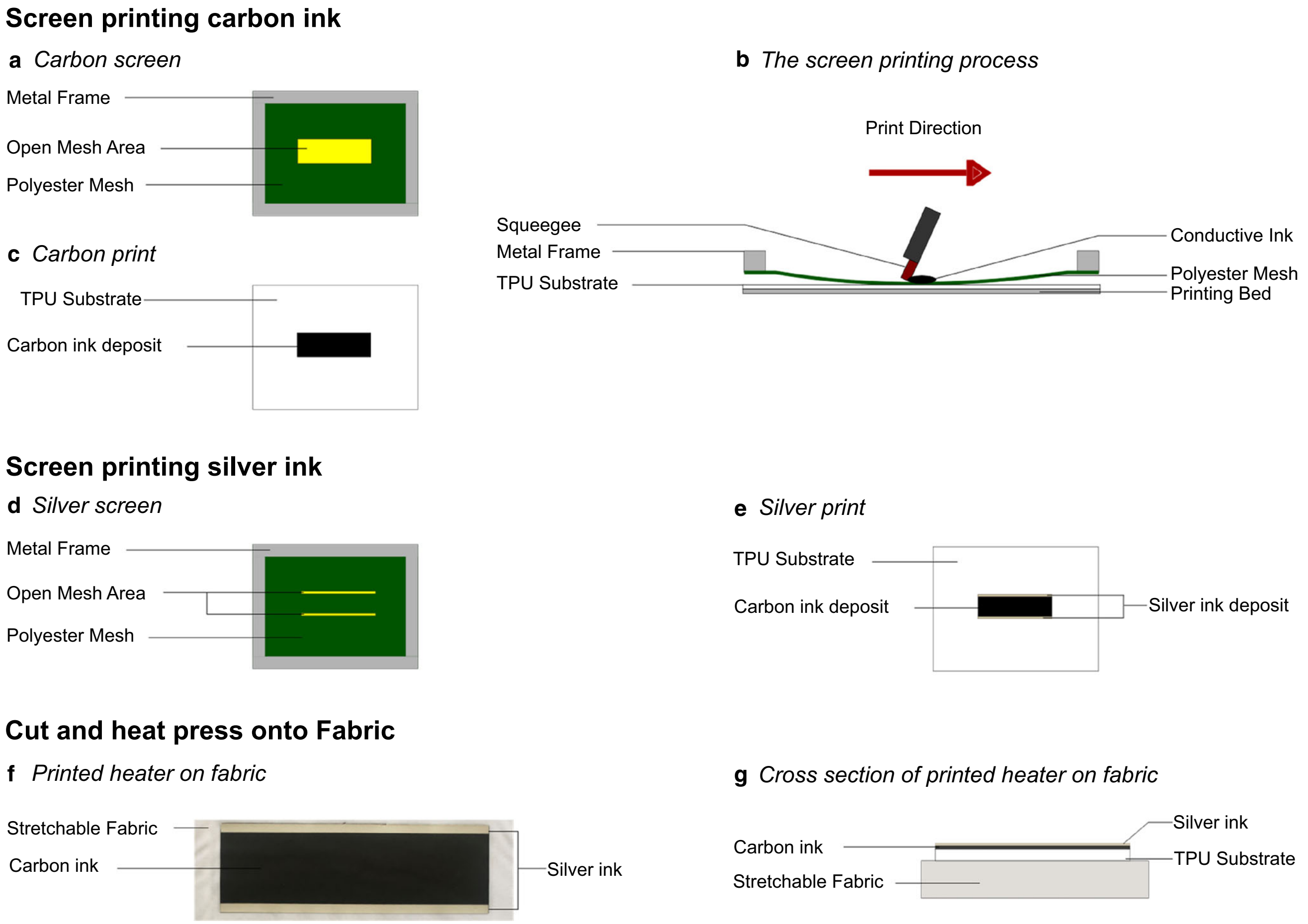

Fig. 1: The manufacture of the printed heater garments (a) plan view of the carbon screen, (b) side-view of the screen-printing process, (c) plan view of the carbon ink deposit, (d) plan view of the silver screen, (e) plan view of the silver print, (f) plan view photograph of a printed heater heat transferred onto stretchable fabric, (g) cross-sectional diagram of the printed heater structure

Heater construction for electromechanical testing

In screen-printing, ink is forced through the open-mesh area of the screen (Fig. 1a) to leave a patterned deposit onto a substrate (Fig. 1c). A squeegee is pulled across the screen, applying downwards pressure to bring the screen into contact with the substrate to leave a patterned ink deposit (Fig. 1b). To create the printed heaters for mechanical testing, two layers of the carbon conductive ink were screen-printed over a 15 × 5 cm area to create the heat generating resistive coating using a semiautomatic, flat-bed, screen press (DEK-248, DEK, ASM Assembly Systems GmbH & Co KG, Munich, Germany) using a 54-70 polyester mesh, 2.5 mm snap-off, a polyurethane diamond edge squeegee 130 mm length with a 12 kg squeegee force and print/flood speeds of 70 mm/s onto a commercially available, heat formable, and stretchable TPU substrate. Two 0.5 × 15 cm stretchable silver busbars were printed on top of the carbon to run parallel at either end of the heater, with connections at opposing corners to ensure consistent current flow through the stretchable conductive carbon coating (Figs. 1d, 1e). The inks were then dried at 70°C for 10 min in a convection dryer between subsequent printed layers and left for >24 h before subsequent testing to ensure all solvent had evaporated.

As the resistive carbon is the main area that generates heat, this gave a total heated area of 60 cm^2. The TPU substrate had a thickness of 80 ± 5 μm. The substrate was selected for its thermoformability, high abrasion resistance, and high surface energy, which gives it significantly better adhesion to the conductive material than untreated PDMS.[29] Adhesion between the ink and the substrate is important for the mechanical properties of the finished device, with good adhesion previously seen between a TPU-based silver ink and TPU substrates.[32] The heaters were then heat pressed onto a lycra-based fabric using a commercial heat press (Fusion, Hotronix, Stahls) with a pressure of 3 Bar and a temperature of 150°C (Fig. 1f, g).

Heater characterization

Following heat pressing, the sheet resistance of the prints was measured using a 4-point probe (SDKR-13, NAGY Messsysteme GmbH, Gäufelden, Germany) with a 1.3 mm gap with a digital source-meter (Keithley, Tektronix, Beaverton, OR, US). The sheet resistance of the carbon ink was taken from five measurements along the center of eight of the block carbon prints, using a correction factor of 4.5129 as proposed by Smits.[33] The sheet resistance of the silver ink was taken from five measurements from six prints along the center of the 0.5 × 15 cm prints, using a correction factor of 3.2248, as recommended by Smits.[33]

The temperature of the heaters was then measured from the carbon area at the center of the heaters using a thermal imaging camera (Optris PI precision line, Optris GmbH, Berlin, Germany) in a temperature-controlled laboratory (18±1°C) using a figure of 0.98 for the emissivity of the carbon print.[34] The temperature response of the heaters was measured at voltages between 10-20 V heating for 180 s before also studying the temperature during cool-down for 60 s. Voltages between 10-20 V were selected to examine the temperature–time response of the printed heaters at low voltages most applicable for wearable heating applications. The mean of three repeats of each condition was used with the standard deviation shown as error bars in the graphs.

Procedures compliant with British Standards were used for the determination of tensile properties of plastics, BS EN ISO 527-1:2012, and films and sheets, BS EN ISO 527-3:1996, were used to guide the measurement of the tensile properties of the coatings.[35, 36] Tensile testing was performed using a Tensile Tester (Hounsfield, Tinius Olsen TMC, Horsham, PA, US) with a 10 kN load cell, gripped to give a test section length of 10 cm and an extension speed of 50 mm/min. The samples were tested in a controlled laboratory environment (18±1°C, 50±10% relative humidity). The nominal strain used for testing was calculated from the measured displacement of the grips. The heating performance of the samples was tested by measuring the temperature output of the 15 × 5 cm heaters while being extended to 10, 20, 40, 60, and 80% nominal tensile strain, then through to failure of the heaters. Three samples were cycled to 10% nominal strain to examine the effect of small repetitive strains on the performance of the heaters. The effect of creasing on the temperature uniformity of the heaters was studied using a 20 N compressive force. Creasing can provide very high local strains upon the heater, with these strains likely to exceed any bending strains experienced by the heater in practical use and was selected to examine the robustness of the heaters under very high bending strains. The samples were compressed with the ink on the outside radius initiating large tensile strains, to simulate the inks being creased during use. Standard deviation across three samples was used to indicate variance.

Cold chamber testing of proof of concept garment

Cold chamber testing consisted of a current sprint canoe athlete (previously Olympic gold medalist) performing two simulation sprint training sessions on an indoor ergonomic rower in a 0°C environmental chamber, one session wearing the garment with the heaters switched off and the other session wearing the garment with the heaters switched on. The athlete wore a base-layer garment on top of the heated garment as extra insulation. The session was determined by the athlete's performance staff to mimic a typical sprint interval training session and consisted of a 15-min warm-up with a 15-min rest period followed by three sets of sprint intervals. Due to the applied nature of the testing, skin temperature was measured as it has been shown to follow a similar course to T_m.[4] Skin temperature was measured using Skin Thermistors at 12 points across the body, namely the head and neck, chest, upper back, upper arms, lower arms, hands, torso, lower back, buttocks, upper legs, lower legs, and feet. The thermal sensation was accessed by the athlete on a scale of − 4 to 4.

Results

Heater performance

A heater was fabricated using the stretchable conductive inks for use as a wearable heating device. The printed heaters consist of a 15 × 4 cm resistive, heat-generating carbon coating with silver busbars running parallel at either end of the heaters to ensure consistent current flow through the heaters (Fig 2a). The printed heaters had a total coating thickness of 21.29 ± 0.39 μm (s.d) and a total heater thickness of ~101 μm including the 80 μm substrate.

The sheet resistance of a single layer print of the carbon and silver inks was 230 ± 12 and 0.078 ± 0.001 Ω/□ (s.d), respectively, at thicknesses of 8.0 ± 0.8 and 8.7 ± 0.5 μm (s.d), respectively. Printing a second carbon layer nearly doubled the thickness to 15 ± 1.0 μm (s.d) and more than halved the sheet resistance to 99 ± 6.8 Ω/□ (s.d). When normalized to 25.4 μm to allow for comparison with other available inks, the sheet resistance of the carbon ink was 72 Ω/□/25.4 μm.

The printed heaters generate heat through electrical Joule Heating (Eq. 1);

$$P = \frac{V^2}{R} \tag{1}$$

where P = Heating Power (Watts), V= Voltage (Volts), R = Resistance (Ohms).

The electrical resistance of the coating and the applied voltage will dictate the heater's power and output temperature. The two-point resistance between opposing corners of the printed heaters was 26.2±1.59 Ω. As the resistance of the heaters is a function of the ink's material properties and the print quality, once printed, the power of the heaters is dependent on the applied voltage (Fig. 2c).

In agreement with Joule's law, increasing the voltage of the power supply to the heaters increased the maximum temperature achieved as well as the rate of heating (Fig 2c). The temperature of the heaters rapidly increased from a starting temperature of 22.6 ± 1.2°C (s.d) to 35.5 ± 2.0°C (s.d), 48.5 ± 2.1°C (s.d), and 65.2 ± 3.3°C (s.d) within 30 s of the power being turned on at 10, 15 and 20 V, respectively. The heaters reached approximately equilibrium temperatures within 90 s, with the heater temperature at 150 s of 38.6 ± 1.4°C (s.d), 54.2 ± 2.1°C (s.d), and 72.3 ± 1.7°C (s.d) at 10, 15, and 20 V, respectively (Fig. 2c). This plateau is associated as the point where the power input into the heater is in equilibrium with the heat loss to the environment through conduction and convection. Once the power is switched off after 180 s, the heaters return to <30.9°C within 30 s.

At 0% nominal strain, the heaters showed excellent heat uniformity with the current flowing evenly through the conductive carbon coating to give uniform heating of >50°C at 15 V across the whole 15 × 4 cm heated area (Fig. 2b). As the conductive silver coating is approximately three orders of magnitude more conductive than the carbon, this minimized the potential drop to ensure a near-constant voltage across the heater. Here, 15 V was selected as the voltage for all further testing as it was the lowest voltage capable of achieving in excess of 40°C (Fig 2c).

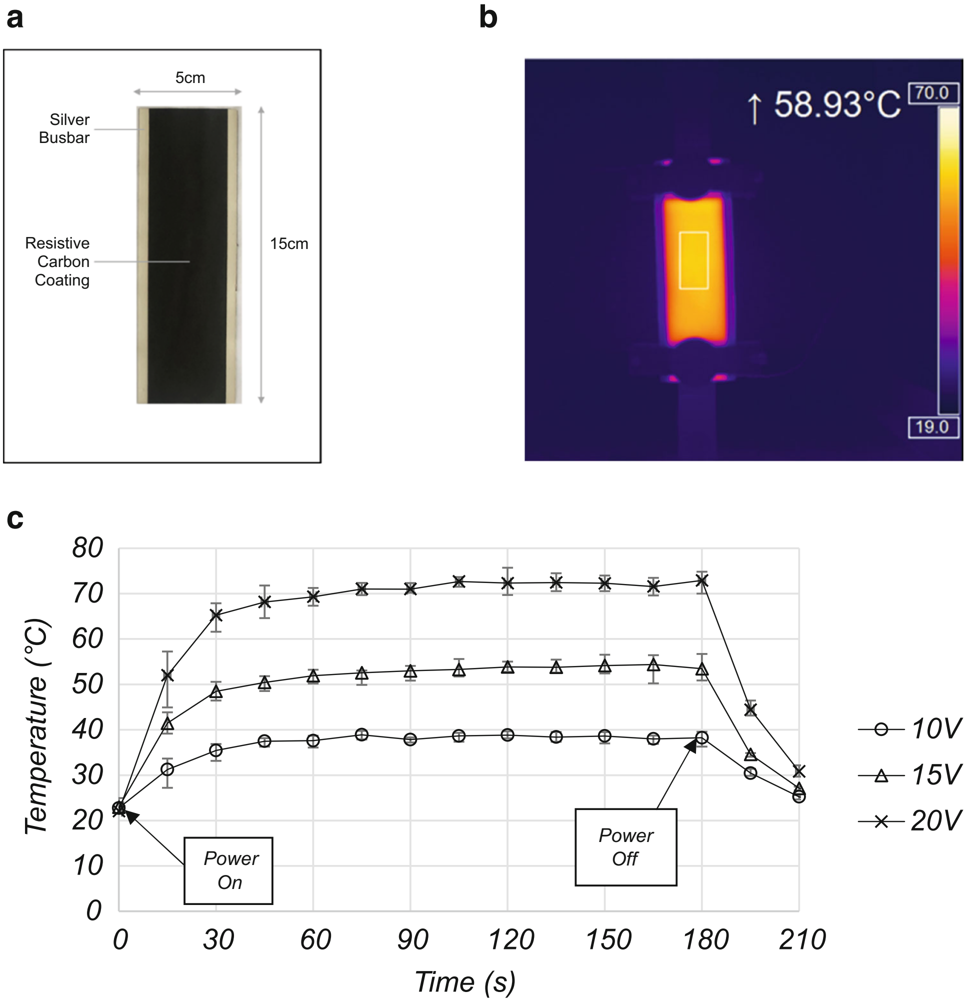

Fig. 2: (a) Annotated photograph of the printed carbon heater (b) thermal image of the heaters at 15 V at 0% nominal strain clamped in the Hounsfield tensile tester (c) the effect of applied voltage on the heat response of the printed carbon heaters from n=3 samples where the error bars represent the range of values

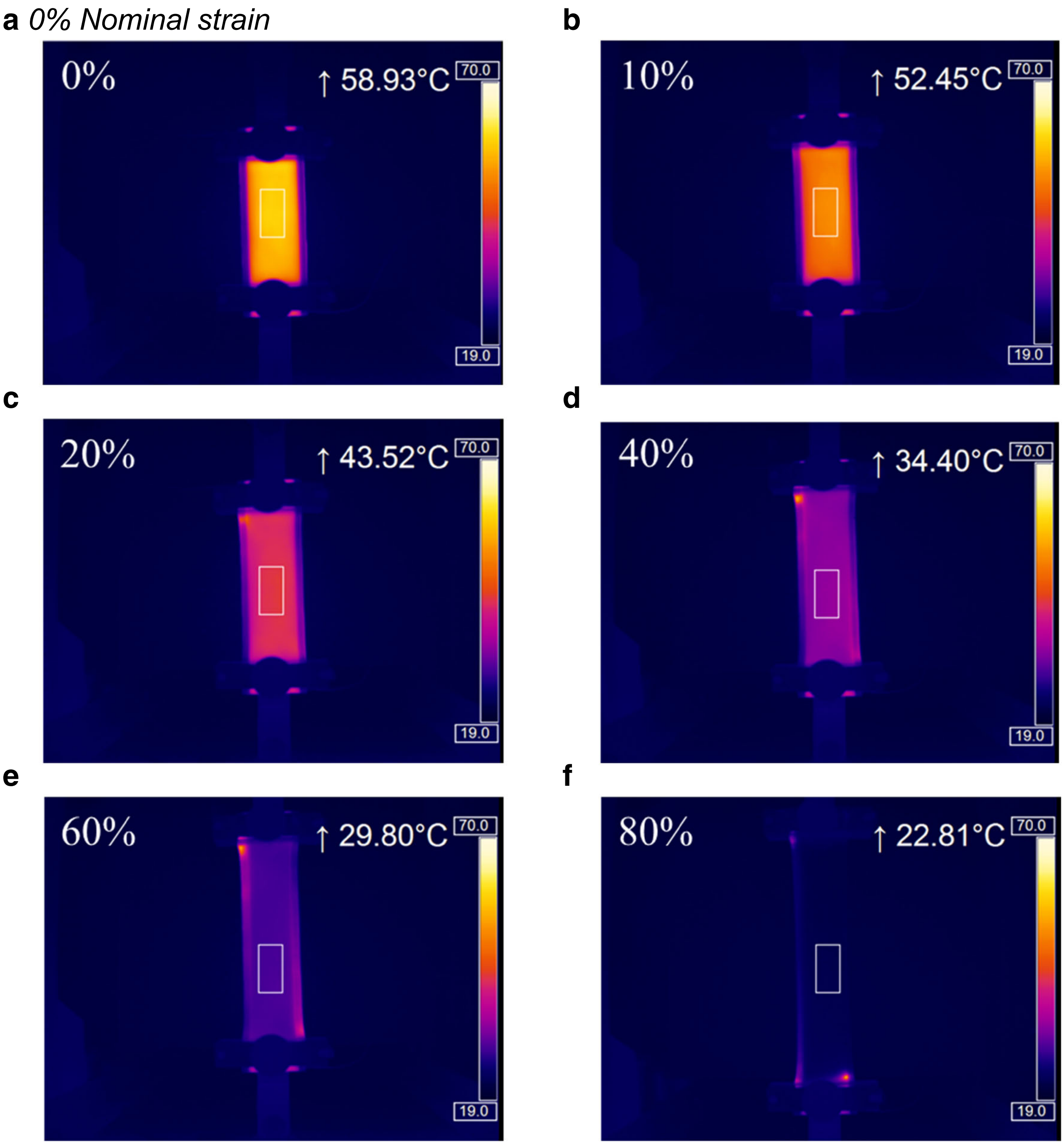

Fig. 3: The effect of nominal strain on the temperature output of the 15 × 5 cm printed stretchable carbon heaters at 15 V in a 19°C environment while at nominal strains; (a) 0% nominal strain, (b) 10% nominal strain, (c) 20% nominal strain, (d) 40% nominal strain, (e) 60% nominal strain, (f) 80% nominal strain

At 0% nominal strain, the heat output is uniform across the carbon coating and the heaters reach an average temperature of 58.9°C (Fig. 3a). Upon the application of 10% nominal strain, the temperature of the heaters decreased by 6.4°C to 52.5°C (Fig. 3b). However, the heaters continued to show good heat uniformity through the carbon heating layer. Increasing the strain further to 20% produced a further decrease in the temperature to 43.5°C as the resistance of the coating increased further. Even at 20% strain, there was still uniform heat distribution across the carbon coating with the heaters still capable of producing temperature outputs >40°C (Fig. 3c). The effect of tensile strain on the inks used to create the heaters has been studied in a previous work by the authors,[31] where it was found that increasing tensile strain increased the resistance of the inks. This would be expected to increase the electrical resistance of the heaters, reducing the Joule heating power. This effect combining with the increase in heater area because of the tensile extension is a decrease in the temperature output of the heaters.

At 40% nominal strain, the temperature of the heated carbon area dropped to 34.4°C, while a hot spot occurred on the silver busbar caused by a local increase in resistance due to strain-induced damage to the silver

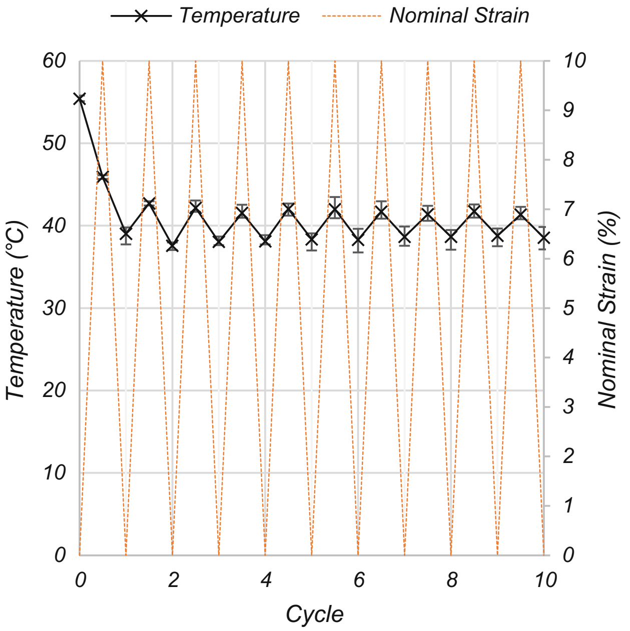

Fig. 4: The effect of cyclic straining to 10% nominal strain on heater performance for n=3 samples, where the error bars represent the range of values

busbar (Fig. 3d). Beyond this point, the increasing resistance with tensile strain combined with the local heating damage to the busbar until at 80% nominal strain, the growth in electrical resistance was enough that the current could no longer pass through the silver busbar and the heater returned to room temperature (Fig. 3f).

In wearable applications, the heaters are likely to experience cyclic strains during repeated movements or while dressing. To examine the resistance of the heaters to cyclic strains, the temperature output of the heaters was measured as the heaters were strained and held at 10% for 120 s before returning to 0% nominal strain for 10 cycles.

Following the first cycle to 10% nominal strain, the temperature of the heater decreases because of an increase in the heater's resistance (Fig. 4). After this initial deformation, the heaters show consistent temperature response to applied strain and can maintain a temperature of 40.09 ± 1.73 °C (s.d) irrespective of strains up to 10%.

The heaters showed excellent heat uniformity even while creased. Before the compressive force was applied, the heater showed good uniformity even around the bent edge (Fig. 5a). When the force was applied, the heater continued to show good uniformity while also transferring heat to the compressive loading plate (Fig. 5b). Once the force was released, the heater still showed good temperature output uniformity (Fig. 5c) and continued to do so while being flexed by hand (Fig. 5d).

Development and testing of proof-of-concept heated garment for sprint canoeist

During training, sprint canoe athletes often experience periods of inactivity on the water between sprint efforts, where body temperature can decrease and negatively affect performance, especially during winter training in the UK where temperatures can drop below freezing. The garment was designed to be used during training, with the heaters attached to a close-fitting base-layer garment to improve heat transfer between the heaters and the athlete. This heated base-layer had to be lightweight and stretchable to minimize the impact on the athlete. The garment also had to last the duration of a 2-h training session running from a suitably sized power supply. The design of the heaters was optimized with regard to the number of printed layers to deliver enough heater power and battery life from a power supply that was deemed by performance staff to be lightweight enough to not impede athletic effort.

To achieve the required heater power from a lower voltage power supply, the printed structure of the heaters was optimized from the heater characterization experiments. The new heater structure for the pilot testing garments consisted of three layers of the carbon ink with two layers of silver ink used as the busbars. The extra layer of the carbon ink was printed to decrease the resistance of the heaters, allowing the heaters to achieve a higher power from a lower voltage power supply. The extra silver layer was printed to further reduce losses across the heaters. These heater panels were then heat pressed directly onto a stretchable base-layer fabric in the pattern consisting of six 20 × 5 cm panels to cover the back and shoulders and six 10 × 5 cm panels to cover the biceps, triceps, and pectorals (Fig. 6b).

Conventional wiring was then attached to the silver busbars of each heater using flexible printed circuit connectors (Fig. 6a). Temperature sensors were used to limit the heaters to a set temperature of 40°C by regulating the power to the heaters. The garment was split into two sides, left and right, with the heaters connected in parallel and with each side powered by an 11.1 V lithium-ion battery (mass = 145 g). The electrical resistance of each side of the garment was 5.6 Ω; therefore, by applying the Joule heating law (Eq. 1), each side of the garment produced 22.2 W to give a total garment heating power of 44.4 W, nearly three times greater than the electrically heated and insulated trousers (15 W) used by Faulkner et al.[2]

The effect of the printed heaters on the change in T_{skin} following the recovery period can be seen in Fig. 7a. Turning the printed heater panels on reduced losses in the T_{skin} during the 15-min rest period for all the measured skin temperatures with the benefits greatest in the triceps, latissimus dorsi, and abdominal areas where the use of the printed heaters reduced losses in skin temperature by >1°C (Fig. 7a). The relative change in T_{skin} following the 15-min recovery

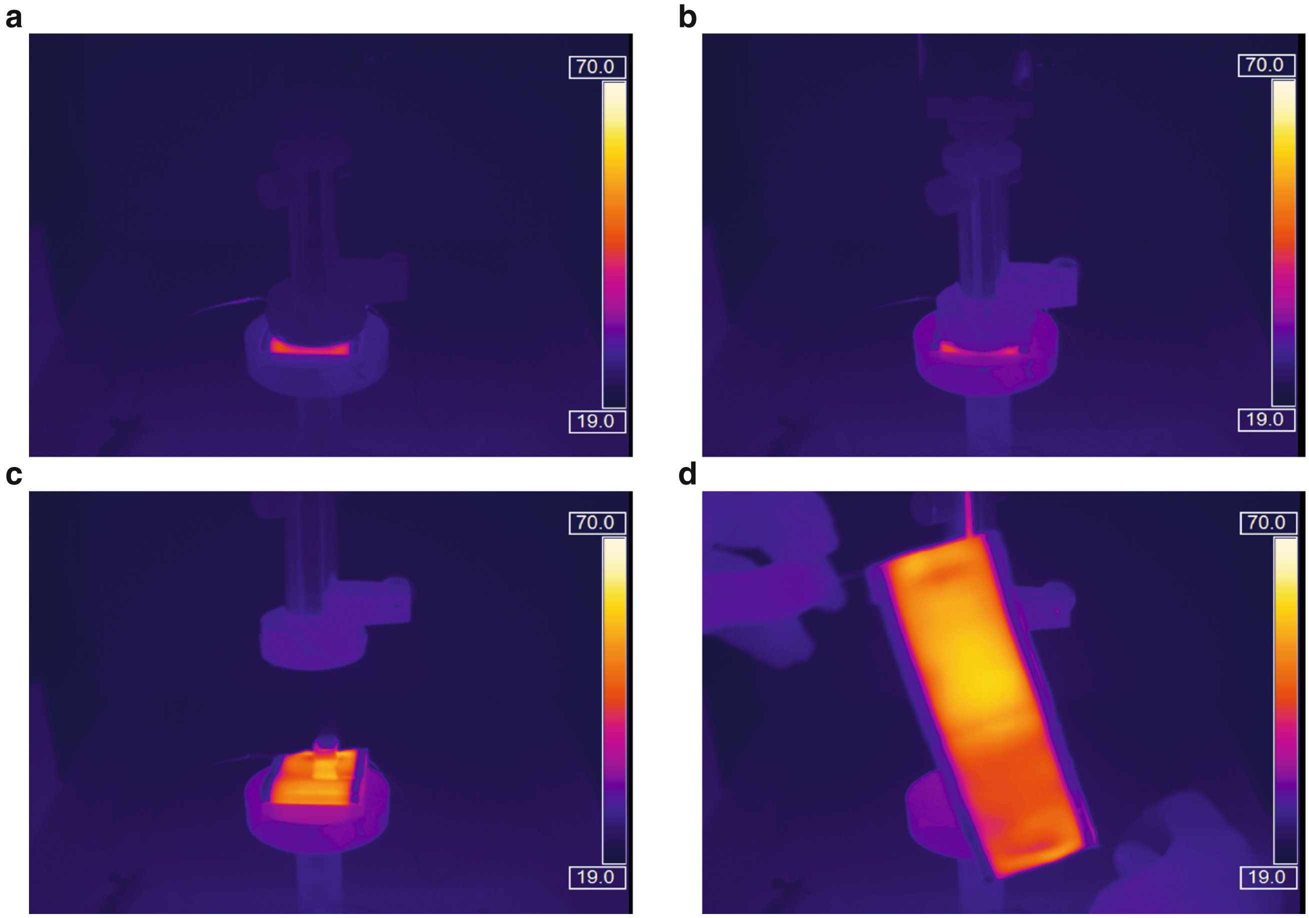

Fig. 5: The performance of the printed heater under a 20 N compressive force. (a) Before the compressive force is applied, (b) under 20 N compressive force, (c) 20 N compressive force released, and (d) opening the heater back out to demonstrate the heat uniformity following the compressive test

in the 0°C environmental chamber with the heater switched off was − 1.3, − 3.2, − 2.4, − 1.1, and − 2.5°C for the pectorals, triceps, latissimus dorsi, upper back, and abdominals, respectively. In contrast, the relative change in T_{skin} with the heaters switched on following the 15-min recovery period was relatively lower at − 0.5, − 0.8, − 1.4, − 1.0, and − 1.1°C for the pectorals, triceps, latissimus dorsi, upper back, and abdominals, respectively, (Fig. 7a). This gave a relative change in T_{skin} following the 15-min recovery period across the five measured areas of − 2.1 ± 0.9°C (s.d) and − 1.0 ± 0.3°C (s.d) for the unheated and heated conditions, respectively.

The athlete's perception of warmth was also evaluated throughout the trial on a scale of − 4 to 4, with − 4 indicating the athlete is feeling cold and 4 indicating the athlete is feeling warm (Fig. 7c). In line with the skin temperature measurements, the athlete felt warmer following the warm-up when the heaters were switched on, again with this greatest during the 15-min period of inactivity during the warm-up (Fig. 7c). Noticeably, the athlete did not feel a decrease in their perception of warmth during the 15-min period of inactivity being in a 0°C environmental chamber.

Discussion

Thin, flexible, stretchable printed heaters have been developed for use as an in-training, and competition, passive heat maintenance device for elite sport. The low thickness of the printed heater, <101 μm, ensures the heaters can be unobtrusive and have minimal effect on the athletic performance. The sheet resistance of the carbon ink, 72 Ω/□/25.4 μm, is considerably lower than the <500 Ω/□/25.4 μm found for other commercially available stretchable conductive carbon inks used in wearable heating applications.[25]

The fast temperature response of the heaters to applied voltage enables better temperature control of the heaters, which is important in a wearable device, especially at higher temperatures, where skin burns could occur. For this, 40°C was selected as the target temperature of the heaters to maintain elevated T_m gained during a warm-up, while being below the 45°C

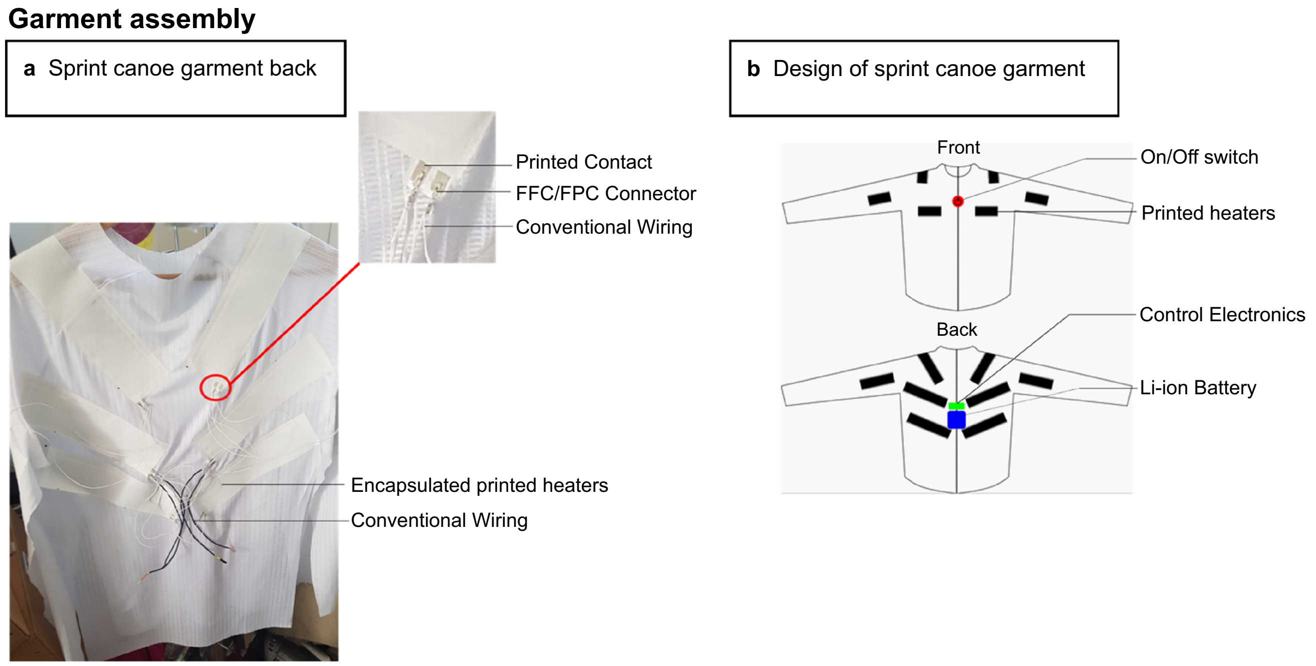

Fig 6: (a) Photograph of the back of the sprint canoe garment used in the cold chamber test, (b) diagram representing the design and component locations of the sprint canoe garment for cold chamber testing

to reduce the risk of skin burns.[4] The heaters were capable of heating such a large area to temperatures in excess of 38°C from a 10 V power supply making them a promising candidate for wearable heating applications. The consistency of the maximum temperature achieved by the three separate heaters without any control electronics indicates repeatability and scalability of the screen-printed heaters.

As a consequence of the good electrical properties of the flexible carbon ink, at 15 × 4 cm, the heated area is far greater than for other coated flexible heaters in the literature. The significantly lower bulk resistivity of the GNP/CB/TPU carbon ink allows the heaters to uniformly heat a large 15 × 4 cm area to >50°C at 15 V. The ability to uniformly produce high temperatures over a large area from low voltages makes the printed heaters a promising candidate for wearable technology. The heaters are capable of achieving temperatures >50°C from a 15 V power supply, and as a result of the fast temperature response to applied voltages, by using temperature sensors and an intelligent feedback loop, this temperature output can be carefully controlled and maintained at 40°C during exercise.

The performance of printed heaters for wearable applications has been measured under flexing and bending strains[6, 7, 37]; however, the temperature output of these heaters under strain is often not studied and characterized. The printed heaters demonstrated in this paper can accommodate strain to allow them to conform to the body to give tight fit and efficient heat transfer, while still maintaining uniform temperatures above 40°C while strained. The heaters maintained good heat uniformity at >40°C across the carbon coating up to 20% nominal strain. In textile applications about 15–20%, repetitive strain occurs through the life cycle of the product,[29] so the ability of the heater to maintain uniform heat at >40°C across the carbon resistive heating element is promising for wearable heating applications.

The temperature output of the heaters decreased with increasing nominal strain. The authors previous work demonstrated that the resistance of the carbon and silver ink used increases with nominal strain.[31] This increase in resistance of both the carbon and silver inks would decrease the joule heating power and therefore the temperature output. At nominal strains greater than 40%, the temperature output of the heaters dropped to 34.4°C. The large decreases in temperature at high strain show the importance of the silver busbar in delivering a constant voltage across the heater panel. Once the pathway along the silver busbar has broken down, the current must travel through the resistive carbon coating, reducing the current flow through the heater and the subsequent temperature output.

After initial deformation during the first cycle to 10% nominal strain, likely a consequence of an increase in the electrical resistance of the heaters with nominal strain, the heaters showed good stability against cycles to 10% nominal strain at temperatures of 40.09±1.73°C irrespective of strains up to 10%. This consistency in output temperature with repeated cycles is important to ensure safety of the heaters while in use and over the whole lifetime of the device. Prestraining the heaters to account for this initial change in resistance could allow them to maintain a constant

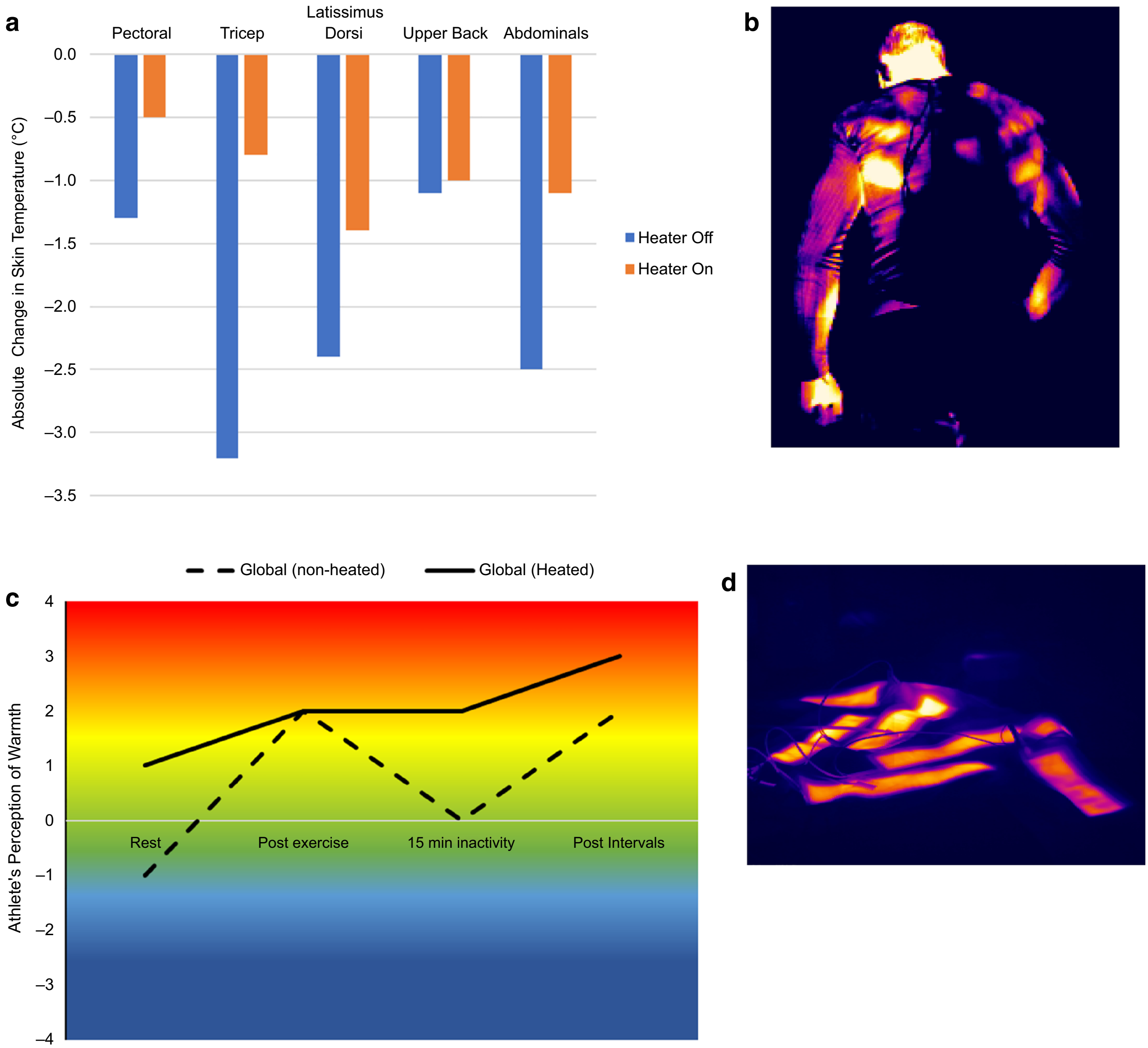

Fig. 7: (a) Absolute change in the athlete's skin temperature between the end of the warm-up and the end of the 15-min rest period in a cold chamber set to 0°C, (b) the heated base-layer in use during cold chamber testing, (c) athlete's perception of warmth during the cold chamber testing, with a value of − 4 indicating the athlete was feeling cold and a value of 4 indicating the athlete was feeling warm, and (d) the heated base-layer on the bench top

temperature over a given strain range. The heaters also showed good heat uniformity even while bent and creased, which is important in sports applications where the heaters would be expected to flex to conform to the muscles to achieve efficient conductive heat transfer through the fabric to the skin.

When developed into a garment and used for proof-of-concept testing with an elite athlete, the combination of increased skin temperature and increased athlete perception of warmth demonstrates the viability of the printed heaters as a method of maintaining skin temperature. With the printed heaters switched on, the heated base-layer better-maintained athlete skin temperature and thermal sensation than the control condition with the heaters switched off. The relative change in T_{skin} following the 15-min recovery period across the five measured areas of − 2.1 ± 0.9°C (s.d) and − 1.0 ± 0.3°C (s.d) for the unheated and heated conditions, respectively. This is in good agreement with the works of Faulkner et al.[1, 2] and Racuglia et al.,[4] who showed reduced losses in muscle temperature for an electrically heated trouser than a non-heated control, when worn during the recovery period only[1, 2, 4] and during both the warmup and recovery period.[1] For this initial testing, a temperature sensing feedback loop was used to control the heater temperature of 40°C. Water perfused trousers at 43°C[4] and an electrically heated jacket at 50°C[9] have been shown to increase superficial muscle temperature[4] and T_{skin} during a passive recovery period. Optimizing the heating temperature further could provide greater improvements in muscle and skin temperature maintenance. Care must be taken when comparing across these studies given the differences in environmental temperatures used 0°C (this study), 8°C,[9] 16.1°C,[1] 15.9°C[2] and 17.7°C,[4] and the method of body temperature measurements, whether that is muscle temperature[1, 2, 4] or T_{skin} (this study).[9]

When using the heated base-layer, the athlete's perception of warmth did not decrease during the 15-min recovery period following warm-up in a 0°C environmental chamber. This increased perception of warmth could improve athlete comfort during interval sprint training in cold environments, improving training quality.

Traditional wire heaters are typically relatively heavy, rigid, high cost, suffer from oxidative corrosion, provide nonuniform heating, have low heating efficiency, and have a relatively short lifetime on account of broken wires.[6, 7, 10] The printed heaters showed good robustness to tensile stressing and creasing, maintaining good uniformity of the temperature output during extension, creasing and cyclic loading to 10% nominal strain. The thin, lightweight nature of the printed heaters combined with the improved flexibility and robustness of the printed heaters compared to traditional wire heating elements allowed the heaters to be attached to a stretchable base-layer fabric. This stretchability allowed the heaters to closely conform to the athlete's body to give efficient heat transfer between the heaters and the skin leading to increased athlete skin temperature and perception of warmth.

The lightweight, flexible nature of the printed heaters was attached to a stretchable heated base-layer that could be worn during a training session as it did not impede the athlete's ability to perform a maximal sprint session. The printed heaters can reach temperatures in excess of 50°C over large areas from a 15 V combined with their flexible nature demonstrates the potential for the printed heaters to be used as ''in training'' heating garments. This gives them an advantage over the water-perfused trousers used by Raccuglia et. al., which have to be attached to a water bath making them impractical to be used in the field.[4]

Refinement and further characterization of the printed heaters, as well as improvement to their integration into a wearable garment, could lead to further improvements in the effectiveness of the garments and widescale uptake. This testing was done on a single elite athlete as a proof-of-concept, and further physiological study should be considered to further prove the effectiveness of these garments. Physiological testing on the effectiveness of the heaters to improve T_{skin} and T_{muscle}, and the use of the garment on athletic performance would help guide heater and garment design optimization.

Conclusions

The low sheet resistance of the intrinsically stretchable ink allowed for the creation of a low voltage, large area printed carbon heater with excellent heat uniformity. The 15 × 5 cm heater was capable of reaching up to 50°C from a 15 V power supply. The heater showed rapid response to applied voltage with the heaters reaching >50°C within 45 s of voltage being applied and cooled to <30°C within 30 s of the power being removed. This rapid response to applied voltage is critical in wearable applications where voltage can be used to control temperature to ensure device safety. The device was manufactured using screen-printing before being pressed onto a stretchable fabric. The temperature response of the heater was studied under applied nominal strains. The heater showed good heat uniformity up to 20% nominal strain and was still capable of producing a heat output of 43.5°C. At 40% nominal strain, a hot spot developed within the silver busbar as the applied strain caused large local increases in the resistance of the silver ink causing localized heating. The cyclic performance of the heater to 10% nominal strain was tested with the heater capable of maintaining temperatures of 40°C over a 10% strain range.

A stretchable, upper body base-layer garment for use during training in cold environments has been developed using printed nanocarbon heaters to output 44 W of heating power to specific muscle groups. The ability of the heaters to maintain T_m was evaluated during a simulated training session inside a 0°C environmental chamber and compared to a nonheated control. The heated garment better maintained skin temperature and gave the athlete higher perceptions of warmth than the unheated control. This increased skin temperature would be expected to be associated with increased power performance. The flexibility and stretchability of the heaters meant that they could be attached to a stretchable base-layer garment and could easily conform to the athlete's body, increasing the efficiency of heat transfer between the heaters and the skin while not impeding the athlete's ability to perform a sprint training session. Nanocarbon screen-printed wearable heaters have been shown to be a viable method of muscle heat maintenance in elite sport.

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