The design and development of a temperature sensing vest for the monitoring of on-body skin temperature

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***Abstract*— This work presents a temperature sensing vest that was created using electronic yarn (E-yarn) technology that is capable of measuring skin temperature at two sights on the chest and scapula. Temperature sensing E-yarns were engineered by soldering small-scale thermistors onto Litz wires, encapsulating them within polymer micro-pods, along with supporting yarns, and covering these in a textile braid. The temperature sensing E-yarns in this work also incorporated a resistor to complete the voltage divider circuit required to record temperature using a microcontroller. The E-yarns were calibrated against skin mountable thermistors, which are the gold standard for on-body temperature sensing. The E-yarns were subsequently incorporated into the tight-knitted vest, creating close contact between the wearer and E-yarns. This work presents an initial human trial, where a participant conducted some simple activities where skin temperature was recorded with both E-yarns and skin-mounted thermistors. As reasonably good correlation between the two sensing modalities was observed.**

Keywords*— *Electronic textiles, E-textiles, Smart textiles, temperature sensing, wearables, electronic yarn

I. Introduction

The ability to monitor human physiological parameters accurately and efficiently has become increasingly important for a wide range of applications, from healthcare and wellness monitoring to sports performance analysis, and human-computer interaction. One particularly useful parameter to monitor is temperature, which can provide valuable insights into an individual's health and physical state [1][2].

Traditionally, skin temperature has been measured using rigid thermometers, such as mercury-based or digital thermometers, which can be uncomfortable and difficult to use, especially when monitoring temperature over extended periods or on uneven body surfaces [3]. Much research into taking on-body skin temperature measurements make use of skin mountable thermistors, for example in the study shown in [4]. These are small, rigid, devices which may cause discomfort in certain locations. The devices are normally taped to the body, and the adhesion can be lost under certain conditions (such as when the wearer sweats excessively). These thermistors also do not stream data live and require the data to be downloaded off of the device, which is limiting in some scenarios.

To address the limitations of existing devices, researchers have explored the development of flexible, wearable temperature sensors that can be easily integrated with the human body [5]. As evidenced in a recent review article [6], researchers have proposed a number of potential temperature sensing technologies, including wearables created through the integration of temperature sensing into textiles.

This study presents a temperature sensor in the form of thermistor-embedded electronic yarn (E-yarn) that is integrated seamlessly within a textile with minimal obstruction to the wearer and allows for the precise positioning of the sensing element on the body. This integration method allows for the creation of highly deformable textiles with key textile properties such as breathability, moisture transfer, and heat transfer characteristics [7]. There has been a wealth of previous work on temperature sensing E-yarns [8][9], and a previous study was conducted using a cycling suit instrumented with temperature sensing E-yarns [9]. In this earlier work, experiments with human participants highlighted some limitations with using the temperature sensing E-yarns, showing the need for further trials with humans following the re-engineering of the E-yarn design.

This investigation seeks to use seamlessly integrated temperature sensing E-yarns incorporated into a knitted vest to measure skin temperature at the chest and scapula during different activities. The goal was to understand if changes in skin temperature could be correctly identified, to quantify the accuracy of the achievable absolute temperature measurements, and to identify any further limitations with the technology.

II. Methodology

A. *Creation of temperature sensing electronic yarns*

The base technology used to create the temperature sensing E-yarn used in this study is similar to that described in the literature [9].

To construct the E-yarn, the three Litz wires (Part No: BXL2001, Type 1 Litz 36AWG, MW79-C, single nylon serve to 0.010” OD: OSCO Ltd, Milton Keynes, UK) were cleaned (enamel and nylon removed) using a soldering iron at the locations where the components were to be soldered, and a small amount of solder (RS PRO Wire, 0.25mm Lead Free Solder, 228 °C Melting Point; RS Components Ltd, Northants, UK) was placed on these specific locations. The thermistor (10kΩ negative temperature coefficient thermistor, ±0.5% resistance tolerance: NTCG103JX103DT1S, NTC Thermistor 10k 0402;TDK Corporation, Tokyo, Japan) and the resistor CRCW04021K20FKED, 1.2 kOhms ±1% 0.063W, 1/16W Chip Resistor 0402 Automotive AEC-Q200 Thick Film, Vishay Dale, Malvern, USA) were electrically connected to the wires using contact soldering. The thermistor and the resistor were connected in this manner shown in Fig. 1 to create a voltage divider to allow for the easy reading of the changes in the resistance over the thermistor by a microcontroller. One Litz wire was connected to a single terminal on each of the components (a single terminal on the thermistor and a single terminal on the resistor – indicated by the blue Litz wire in Fig. 1). The remaining terminals of the two components were connected to two separate Litz wires (red and black on the diagram). The red wire was connected to power (3 V output from the microcontroller) and the black wire was connected to ground. The divided voltage value was obtained from the blue wire.

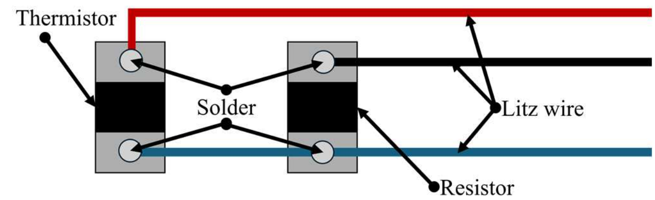

Fig. 1. A schematic diagram of the voltage divider circuit within the temperature sensing electronic yarn.

The soldered components were encapsulated within UV-curable resin. During encapsulation, four strands of polyester yarns (48 f/167 Dtex polyester yarns: J. H. Ashworth and Son Ltd, Hyde, UK) were placed alongside the Litz wires to enhance the tensile strength of the final E-yarn (see Fig. 2 for polyester yarn placement). The soldered components, Litz wires, and the polyester yarns were inserted into a translucent silicon tube with 1 mm inner diameter which acted as a mould to create an approximately 1 mm wide, 8 mm long cylindrical polymer resin pod. The yarn design included two such polymer pods, as indicated in Fig. 2.

Once the soldered areas and electronic components were protected by the polymer micro-pod, the entire assembly was passed through a Horn gear-type braider machine (Herzog RU 1/24-80; Oldenburg, Germany) where 24 polyester yarns (1 ply, 167 Dtex, 48 filaments; J. H. Ashworth & Son Ltd, Hyde, UK) were used to form a tight braided structure. The final E-yarns had a diameter of 1.84 mm at their thickest point.

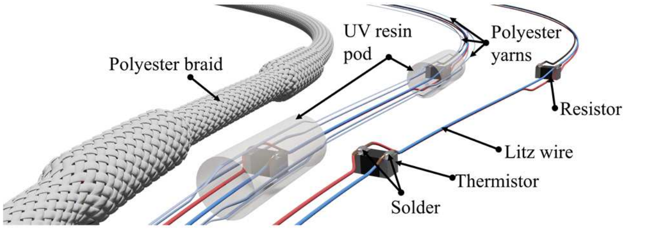

Fig. 2. Schematic showing the key stages in the E-yarn production process.

After the braiding stage, the temperature-sensing E-yarns were complete. A total of seven temperature sensing E-yarns were produced for this study, however results for only four (identified as being the most consistent) have been presented.

B. Construction of the temperature sensing vest

The temperature sensing vest was designed to measure temperature at four sites: right chest, left chest, right scapular and left scapular. Fig. 3 shows the vest and the locations of the sensing elements.

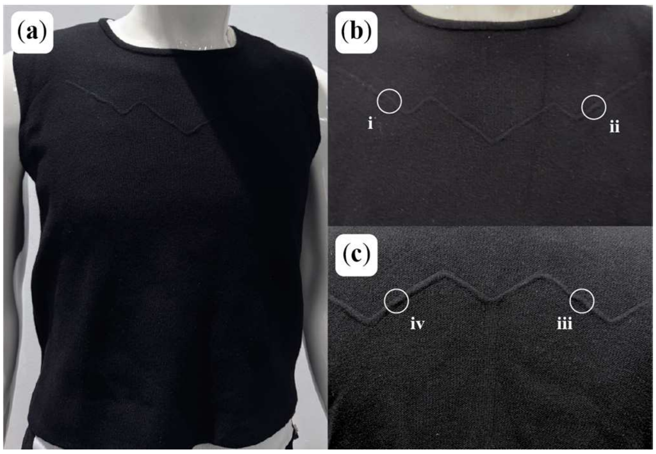

Fig. 3. Temperature sensing vest including four temperature sensing yarns positioned on the chest (i, ii) and the scapular (iii, iv).

The vest in Fig. 3 was knit using a flatbed knitting machine (Stoll ADF-3 B, 18 gauge; Karl Mayer Stoll GmbH, Oberhausen, Germany) and a mixed synthetic yarn (Fluid 1PLY 2% Elastane, 7% Nylon, 91% Viscose: Yeoman Yarns, Leicester, United Kingdom). The vest was designed with knitted channels to incorporate E-yarns positioned on the two chest locations and the two scapular locations. The knitted channels were designed to guide the yarns to a pocket positioned on the bottom left of the vest for the insertion of supporting hardware (for data management, transmission, and the power supply). This module included a micro-controller at its core (Adafruit ItsyBitsy nRF52840 Express - Bluetooth LE by Adafruit, Adafruit, New York, USA) which allowed for wireless data transmission via Bluetooth.

The E-yarns were inserted into the channels through the opening in the pocket and guided through towards their end locations using a modified knitting needle to manoeuvre the E-yarn within the channels. The opposite end of the E-yarns were terminated at the pocket location at a pin connector (CONN HEADER R/A 10POS 1.27MM, Amphenol ICC: Wallingford, USA). The 3V conducting Litz wires (red) were soldered on to a single pin and similarly the 0V (ground, black) was soldered on to a second pin. The blue Litz wires from the four sensors were connected to separate pins on the connector. The female version of the connector (CONN RCPT 10POS 0.05 GOLD PCB, Amphenol ICC) was integrated into the supporting electronic module which allowed for the easy disconnection of the supporting electronics to facilitate charging of the module and the washing of the vest. A bespoke program was written using to transmit the data via Bluetooth to a laptop which logged the data.

C. Temperature sensing E-yarn calibration

Calibration experiments were conducted inside of a climate chamber (Memmert ICH110; Memmert GmbH, Schwabach, Germany). The chamber controlled and maintained temperature to an accuracy of ±0.1 °C. During all experiments readings were collected from both the E-yarns and four skin-mounted thermistors (iButton, DS1922L Thermochron Data Logger (-40 To +85°C); Measurement Systems Ltd, Newbury, UK), which would be used during the human trails. Two methods were used to calibrate the yarns. One method directly calibrated the E-yarns against the temperature of a climate controllable chamber (Calibration 2). The second method used insight from earlier work that suggested that the external temperature that the temperature sensing E-yarn were exposed to would influence their ability to accurately measure the object of interest [8][9] (for this study, the body): This calibration therefore used a temperature controllable plate to replicate the body, while the external temperate was fixed at standard laboratory conditions (Calibration 1).

1) Calibration 1 – Calibration against temperature controlled plate

A preliminary set of calibration experiments were conducted to understand which produced E-yarns were most consistent (in terms of providing similar resistance values), using a similar calibration process to that described below: Following this, the best four E-yarns were selected for further measurements.

To calibrate the E-yarns, the climate chamber was initially set to 25 °C and 35% humidity (replicating standard laboratory conditions), with E-yarns and skin mountable thermistors placed inside. The E-yarns were wired to a microcontroller (Adafruit ItsyBitsy nRF52840 Express) which was used to collect data from the yarns; this microcontroller was intended to form the basis of the final data-capture system to use with the E-yarns.

The E-yarn embedded thermistors and resistor elements were embedded in a knitted textile panel that replicated the structure of the final vest. The fabric panel was taped to a programmable temperature variable plate (Ecotherm, chilling/heating dry bath; Torrey Pines Scientific, Carlsbad, USA) which was used to replicate the heat produced by the body. Four skin mountable thermistors were placed on the plate alongside the fabric, with the top of the thermistors covered by the fabric (closely replicating the planned human trial). The temperate of the plate was changed and measurements were taken at 20, 25, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 and 45 °C. The temperature was allowed to stabilise in each case, with the temperature monitored until it had plateaued, after which recordings would begin (typically this took 3 minutes). A total of 30 readings were taken with a delay of 10 seconds between readings.

2) Calibration 2 - Calibration of the temperature sensing vest in the climate controllable chamber

The E-yarns were integrated into the vest as described in Section 2B. The completed vest and four skin mountable thermistors were placed within the climate controllable chamber. The temperature climate controllable chamber was changed to 20, 25, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 and 45 °C keeping all other variables constant, with measurements taken at each temperature. The rest of the procedure was identical to the other calibration.

D. Human trials

Trails were conducted with one human participant. Ethical approval was obtained to conduct these human trials from the Nottingham Trent University School of Art and Design, Architecture, Design, and Humanities Research Ethics Committee (Application ID 1845051, date of approval 30th 2024). Informed consent was obtained before the study.

For the human trial, one participant (cisgender male) that fit the vest well was selected. The selected participant was a healthy 5'2'' male with normal skin type and in the 18-45 age range. The participant was asked to wear the temperature sensing vest alongside commercially available skin-mounted thermistors to validate the readings recorded using the temperature sensing E-yarns. The skin-mounted thermistors were taped onto the skin directly using fabric tape (Stretch Fabric Strapping, 2.5cm × 4.5m stretched; Boots Pharmaceuticals, Nottingham, UK).

The activities conducted during the human trials were walking, sitting, high-low, and jumping. Each activity was conducted for 10 minutes to provide a wealth of data and allow for skin temperature changes to occur in some cases. Sitting and walking were carried out continuously for the 10 minutes. For the jumping experiments, a jump commenced every 5 seconds for 10 minutes. The high-to-low experiment was conducted in a similar way to the jumping experiment, with the participant reaching high, and then low, every five seconds. The average laboratory temperature during these human trials was 22.54 ± 1.39 °C (measurement before sitting = 23°C; walking = 24.6 °C; high to low = 21.06 °C; Jumping = 21.5 °C).

III. RESULTS AND DISCUSSION

A. Calibration

The graphs generated using the two different E-yarn calibration methods are shown in Fig. 4 (Calibration 1 - Calibration against temperature controlled plate) and Fig. 5 (Calibration 2 - Calibration of the temperature sensing vest in the climate controllable chamber).

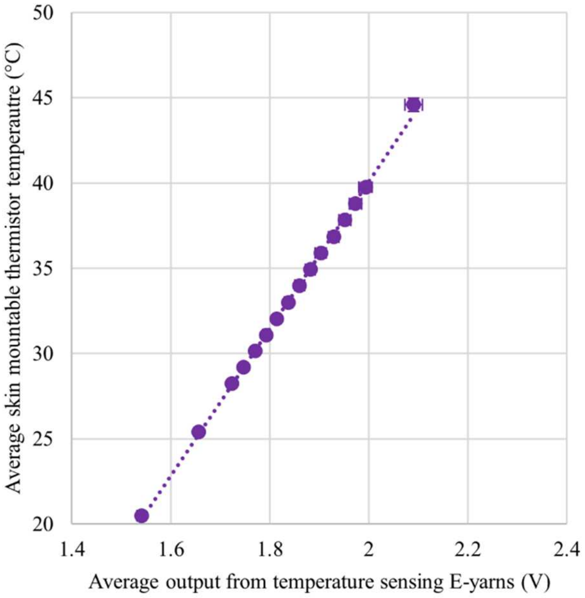

Fig. 4. Calibration 1 - Calibration against temperature controlled plate. Average skin mountable thermistor temperature is shown against the average output from the temperature sensing E-yarns. The fitting equation is shown in Eq. 1, and had an $r^2 = 0.9989$. This calibration sort to best replicate the scenario of a person wearing the vest, with the temperature controlled plate repliacating the heat radiated from the body.

$$y= 43.089x - 46.088 \tag{1}$$

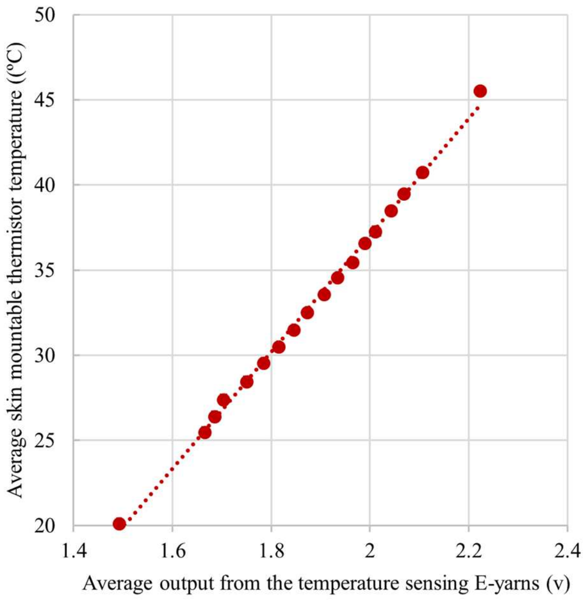

Fig. 5. Calibration 2 - Calibration of the temperature sensing vest in the climate controllable chamber. Average skin mountable thermistor temperature is shown against the average output from the temperature sensing E-yarns. The fitting equation is shown in Eq. 2 and had an $r^2 = 0.9976$.

$$y = 34.253x – 31.444 \tag{2}$$

It was observed that the different calibration methods yielded different results, with Calibration 1 showing a steeper gradient when compared to Calibration 2. It was understood that for Calibration 1, the skin mounted temperature sensors read a direct temperature from the plate while the temperature sensing E-yarns experienced a greater influence from the external chamber temperature. As most readings were taken above 25 °C, this meant that the temperature being recorded by the E-yarns was less than the surface temperature of the plate.

B. Sitting

Fig. 6 shows the temperature recorded using skin mounted thermistors and the E-yarns when the participant sat. The E-yarn temperature values were calculated using Calibration 2 in Fig. 6a and Calibration 1 in Fig. 6b.

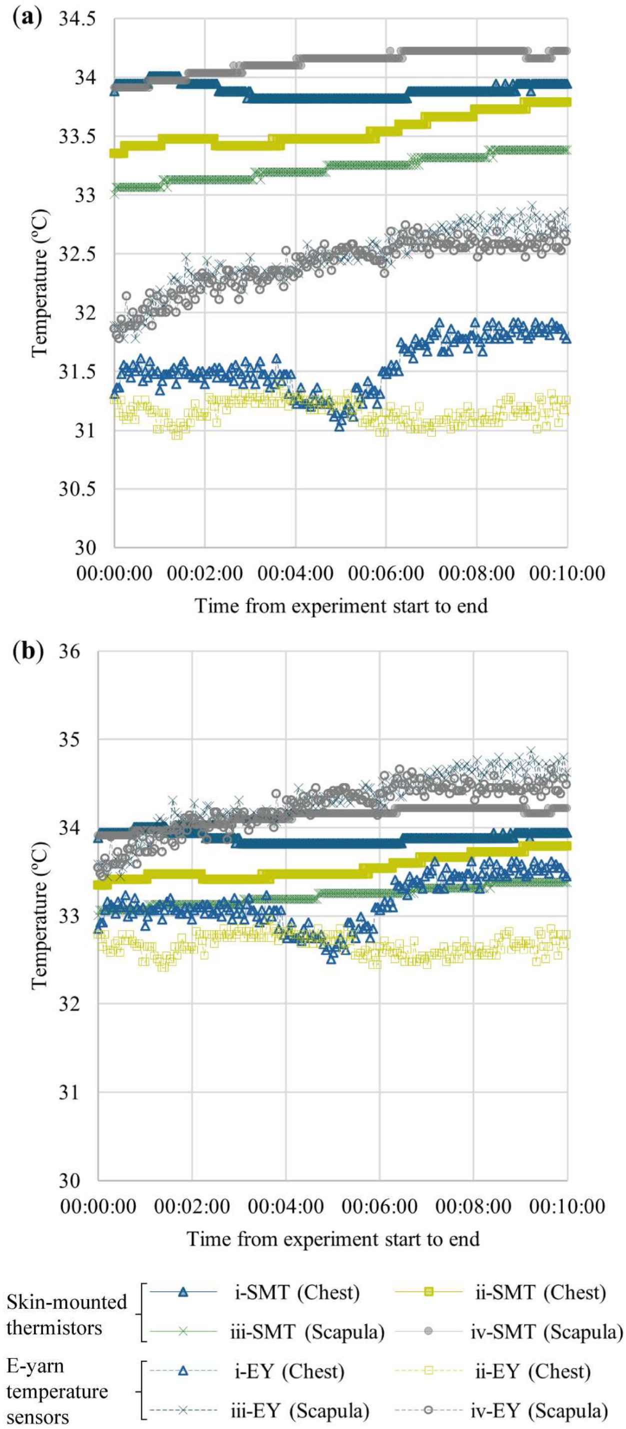

Fig. 6. Temperature readings from the temperautre sensing E-yarns and skin mounted thermistors plotted against duration while the participant was sittingi-SMT, ii-SMT, i-EY, and ii-EY are the sensors on the chest. iii-SMT, iv-SMT, iii-EY, and iv-EY are the sensors on the scapula. SMT represents

the skin mounted thermistors, while EY represents the E-yarns. The x-axis shows a timestamp where the second two digits are minutes elapsed. (**a**) Calibration 2 used. (**b**) Calibration 1 used.

Results showed that using Calibration 1 provided much closer absolute temperature readings between the two-measurement modality, where a difference of around 1.5 °C or less was observed. Importantly the observed pattern of temperature changes was similar in most cases. For example, scapula data s4 and i4 showed close agreement, and both exhibit an increase in temperature with time until plateauing.

The behavior observed for the chest sensors, s2 and i2, did not follow the same general trend. This was believed to be due to wrinkling in the vest during siting, causing the contact between the E-yarn sensor and the skin to differ with time.

C. *Walking*

Fig. 7. shows skin temperature as a function of time during experiments where the participant was asked to walk.

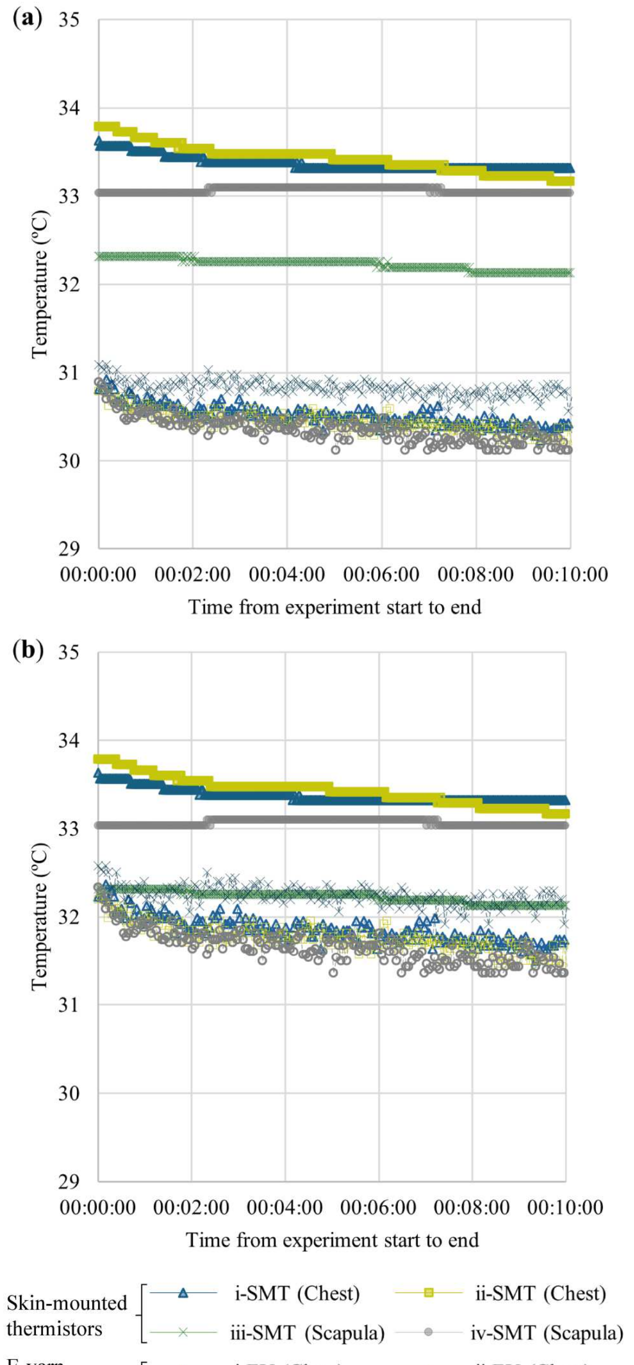

Fig. 7. Temperature readings from the temperautre sensing E-yarns and skin mounted thermistors plotted against duration while the participant was walking. i-SMT, ii-SMT, i-EY, and ii-EY are the sensors on the chest. iii-SMT, iv-SMT, iii-EY, and iv-EY are the sensors on the scapula. SMT represents the skin mounted thermistors, while EY represents the E-yarns. The x-axis shows a timestamp where the second two digits are minutes elapsed. (**a**) Calibration 2 used. (**b**) Calibration 1 used.

The general trend observed was the skin temperature dropping slightly over the duration of the experiment. This was recorded for all sensors, except for the skin mounted thermistor on the scapula in one case (i4). The reason for this is unknown.

D. High to low

Fig. 8 shows temperature readings against time while the participant conducted the high-to-low activity.

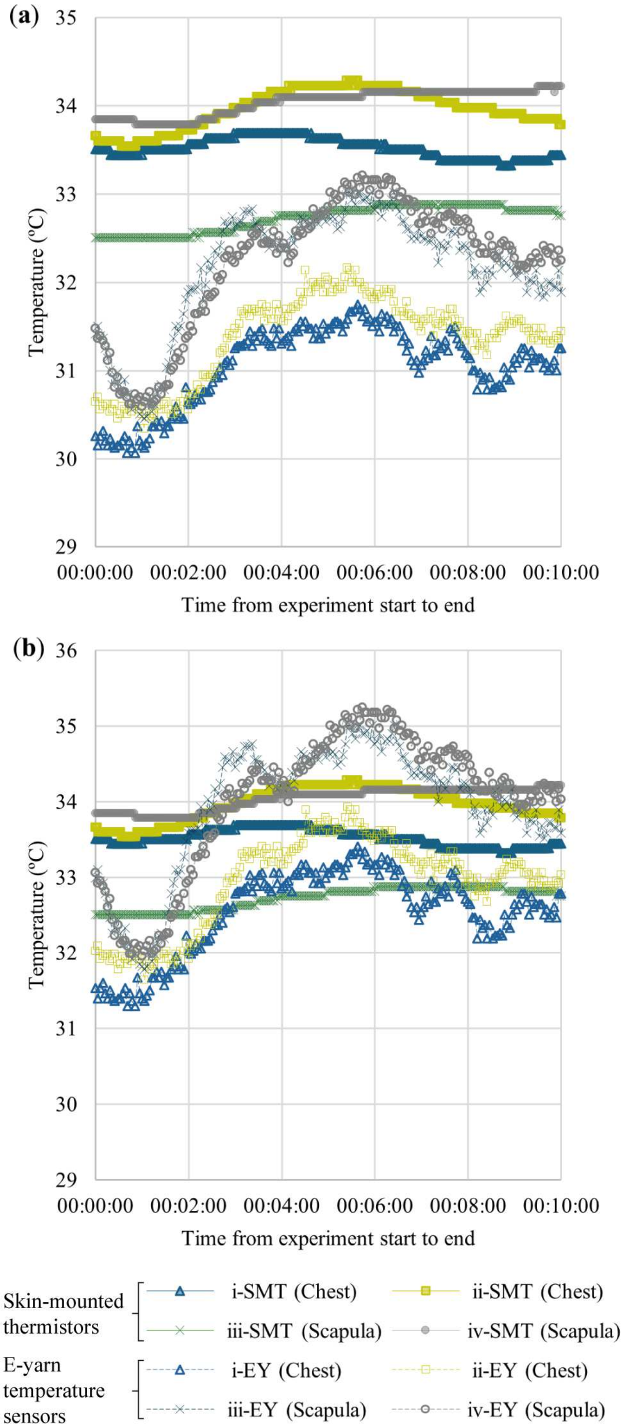

Fig. 8. Temperature readings from the temperautre sensing E-yarns and skin mounted thermistors plotted against duration while the participant was carrying out a high-to-low activity. i-SMT, ii-SMT, i-EY, and ii-EY are the sensors on the chest. iii-SMT, iv-SMT, iii-EY, and iv-EY are the sensors on the scapula. SMT represents the skin mounted thermistors, while EY represents the E-yarns. The x-axis shows a timestamp where the second two digits are minutes elapsed. (**a**) Calibration 2 used. (**b**) Calibration 1 used.

The temperature readings from the E-yarns at all locations followed a near-identical trend, showing an increase, followed by a decrease. This trend did not align with the readings from all of the skin mounted thermistors. It was thought that this might have been due to the contact between the vest and body changing slightly during the activity, however this has not been confirmed.

E. Jumping

Fig. 9 shows the skin temperature while the participant carried out the jumping activity.

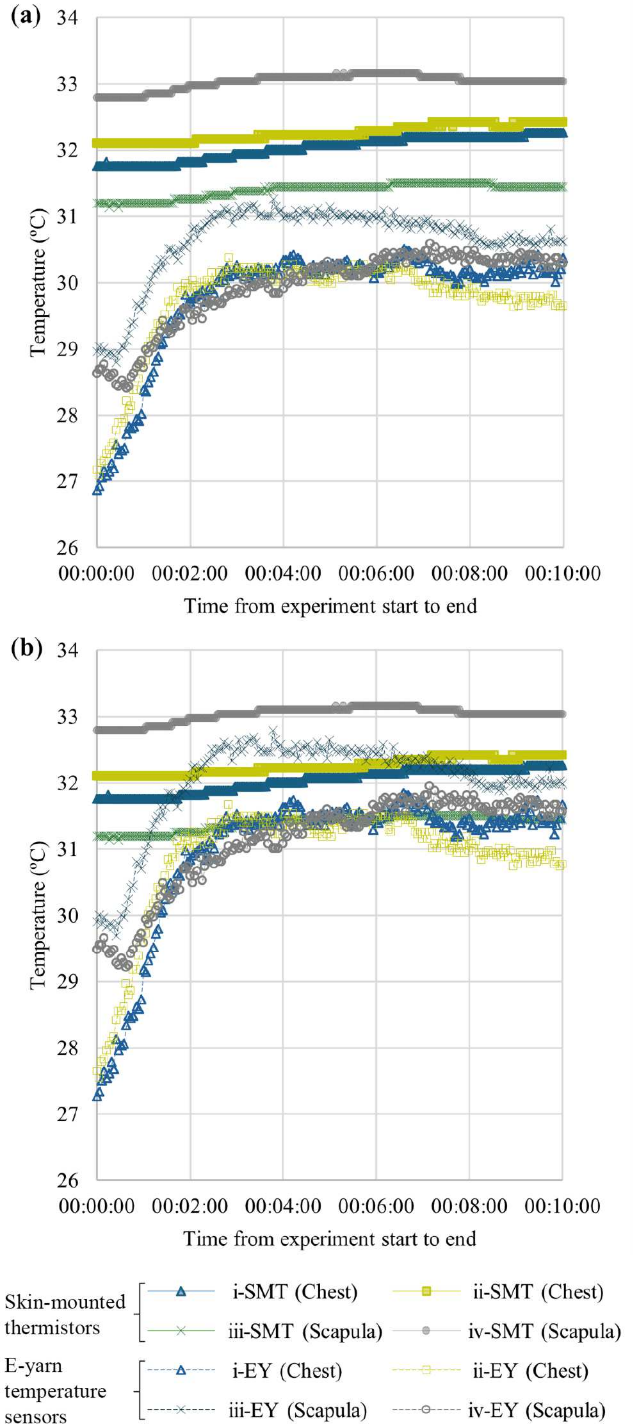

Fig. 9. Temperature readings from the temperautre sensing E-yarns and skin mounted thermistors plotted against duration while the participant was carrying out a jumping activityi-SMT, ii-SMT, i-EY, and ii-EY are the sensors on the chest. iii-SMT, iv-SMT, iii-EY, and iv-EY are the sensors on the scapula. SMT represents the skin mounted thermistors, while EY represents the E-yarns. The x-axis shows a timestamp where the second two digits are minutes elapsed. (**a**) Calibration 2 used. (**b**) Calibration 1 used.

A rise in temperature was observed in all cases and then plateaued, however the increase observed was significantly greater for the temperature sensing E-yarns. It was speculated that this may have been due to poor contact between the body and vest initially, with a greater (fixed contact) thermal conductivity occurring once the participant started to sweat, however more research will be needed to prove this hypothesis. The temperatures recorded by the E-yarns began to drop slightly later in the experiments, which may have been due to sweat evaporating off of the vest.

This experiment required the most activity (in terms of movement and energy expenditure) and showed temperature changes that where consistent between the chest and scapular regions, whereas for the other lighter exercises, a difference in temperature between the two muscle regions was observed.

It should be noted that despite significant physical movement, there does not appear to be any notable motion artefacts in the data.

F. *Absolute temperature readings*

To understand the difference in the absolute temperature recorded using both methodologies in a quantifiable way, sections of data where the skin temperature was showing minimal changes was averaged and compared. Table 1 shows the temperature difference between the skin-mounted thermistor and the E-yarn temperature data when using the two calibration methods. Temperature differences between the sensor types was within 3 °C when either calibration was used, however Calibration 1 showed a reduced difference, with the greatest observed difference for the selected section of data being 1.70 ± 0.11°C.

Overall, the temperature differences at the scapula were seen to be smaller when compared to the sensors located on the chest when Calibration 2 was used. The E-yarn temperature showed a higher value than that of the skin-mounted thermistors on the scapula when Calibration 1 was used.

Considering the values in Table 1, Calibration 2 generally provided closer results for sensors on the scapula, while Calibration 1 provided better results for the sensors on the chest. Ultimately, further study is needed to confirm the best method of calibration for temperature sensing E-yarns for on-body skin monitoring at different locations on the human body.

TABLE I. AVERAGE TEMPERATURE DIFFERENCES BETWEEN THE SKIN-MOUNTED THERMISTOR AND TEMPERATURE SENSING E-YARNS

Activity	Temperature difference (ºC)							
	Calibration 1				***Calibration 2***			
	Chest 1	***Chest 2***	***Scapula 1***	***Scapula 2***	***Chest 1***	***Chest 2***	***Scapula 1***	***Scapula 2***
Sitting	2.09 ±0.06	2.64 ±0.08	0.59 ±0.07	1.56± 0.07	0.41 ±0.08	1.13 ±0.10	-1.33 ±0.08	-0.32±0.08
Walking	2.83 ±0.06	3.00 ±0.06	1.39 ±0.06	2.70± 0.07	1.48 ±0.07	1.67 ±0.07	-0.04 ±0.08	1.39±0.09
High-to-low	2.12 ±0.19	2.43 ±0.16	0.23 ±0.21	1.26± 0.2	0.57 ±0.24	0.79 ±0.2	-1.66 ±0.26	-0.69±0.25
Jumping	1.85 ±0.09	2.11 ±0.08	0.43 ±0.05	2.95± 0.09	0.58 ±0.11	0.87 ±0.10	-1.04 ±0.07	1.70±0.11

IV. CONCLUSION

The study found a reasonably close match between data collected using temperature sensing E-yarns and skin-mounted thermistors, and trends in skin temperature changes could be identified using the E-yarns in most cases.

The level of accuracy observed would be adequate when moderate skin temperature changes needed to be monitored, such as monitoring people in extreme environments or elderly individuals at risk of hypothermia. Closer and more consistent contact between the temperature sensing E-yarns and the skin would likely result in superior measurements, and for sports applications a more tightly fitting vest, possibly produced using an elastomeric yarn, should be produced. Generally, the skin temperature data measured during the human trials showed trends specific to each exercise performed, which confirmed the potential of using the technology to differentiate activity by collecting temperature data.

Conducting these experiments with one human participant limits the generalizability of the results, however is an important step towards understanding the operational boundary conditions for the vest. Future work must repeat experiments with further human participants to confirm the trends observed.

ACKNOWLEDGMENT

This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) grant EP/T001313/1 Production engineering research for the manufacture of novel electronically functional yarns for multifunctional smart textiles. The authors would like to thank Nottingham Trent University, (United Kingdom) for providing some funding and support towards this research.

The human trial in this study was conducted in accordance with the approval of the Nottingham Trent University Schools of Art and Design, Arts and Humanities and Architecture, Design and the Built Environment Research Ethics Committee (Application ID 1845051, date of approval 30th May 2024).

Data are contained within the article. The raw datasets collected for the analysis of this study can be found on figshare at 10.6084/m9.figshare.27382086.

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