DEVELOPMENT OF THE SMART T-SHIRT FOR MONITORING THERMAL STATUS OF ATHLETES

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Abstract:

Athletes are often subjected to a great physical strain during training and competition. Sport activities performed in hot and humid conditions may result in different heat illnesses with mild or fatal consequences. Against this background it is important to know the thermal state of athletes during physical activity.

This article presents the development of a smart T-shirt for monitoring the thermal status of an athlete. The smart T-shirt was created by embedding an electronic system with temperature and humidity sensors that allows the measurement of temperature and the relative humidity of the microclimate. A smart T-shirt is comfortable, and integrated sensors and electronics do not affect wearing comfort. A good concurrence between the temperature and humidity results from using the smart T-shirt, and thus the medical device was achieved. Data obtained can be of great importance to the sports staff who will be able to monitor the athletes’ thermal state during matches and competitions.

Keywords:

Smart T-shirt; microclimate temperature; relative humidity of the microclimate

1. Introduction

The knowledge of the thermal state of athletes is of considerable importance for physiological studies as well as for the investigation of wearing comfort. This is particularly important from the point of view of the constant movement and activity of athletes, where heat transfer from the body must be considered a dynamically changing process. The clothing microclimate is the air layer between the skin and the nearest layer of clothing when clothing is worn [1, 2]. The microclimate created between the body and the layer of textile material (clothing) is affected by garment factors (properties of textile materials, fit, percentage of covering of the body, and wearing methods); human factors (gender, age, and body fat); and environmental factors [3]. Air exchange between a clothing microclimate and an external environment has a significant influence on the evaporative and dry heat loss of the wearer [2–5].

Increased muscular activity during exercise causes an increase in heat production in the body due to the inefficiency of the metabolic reactions involved in providing energy for muscle strength development [6]. Athletes’ thermoregulation during intense physical activity is dependent on a dynamic energy balance involving atmospheric and physical conditions. Skin temperature represents the key variable controlling the body/environment heat exchanges [7]. It is common for major sporting events to be held in summertime; the state of the climate has a big impact on the performance of the athlete, while also having an impact on their health [8, 9]. Combination of high ambient temperature and humidity may cause thermal stress, which can lead to heat illnesses and can negatively affect the performance of athletes [7–9]. For these reasons, it is extremely important to monitor the thermal condition of athletes during the summer period. In addition, experimental investigation of athletes’ skin temperature during intense running under standard laboratory conditions according to specifically designed protocols at controlled air temperature and humidity, could be significant for estimation of the physical efficiency and/or the training level of athletes [10].

To determine the thermal state during exercise, different authors have monitored different parameters, such as the core temperature [11–13], skin temperature [12–16], and the amount of sweat [11, 17]. Determination of clothing microclimate temperature can offer a simple way to establish
whether people feel comfortable in the clothing that they are wearing [2]. Different temperature sensors integrated in textile and garments, wearables, and medical equipment are now available for measuring skin temperature, core temperature, and sweat production.

A wearable in the form of a wristwatch was developed with the purpose of monitoring thermal comfort. This wearable can operate for four hours using a 6V battery. This sensor is capable of automatic natural ventilation by integrating small thermo-pneumatic actuators [17].

Researchers have developed a wearable recording device for long-term monitoring of vital signs (electrocardiogram, blood pressure, and skin temperature) and the 3D-acceleration sensor for the determination of the movements. Problem with artifacts in all recorded data was solved by using fusion to reject or correct distorted sign signals [18].

An in-ear wearable device that measures core temperature from the tympanic membrane was developed and tested against two commercial ear thermometers. The accuracy of measurements was increased by coating graphene inks over the lens of an infrared thermopile sensor. This wearable was manufactured using 3D printing technology. For signal processing, an Arduino Pro mini was used, and the signal was transmitted by Bluetooth; for the power source, a 3.7 V, 85 mAh rechargeable Lithium battery was used. Results obtained showed that this wearable device shows higher accuracy in comparison with two other comital ear thermometers [19].

The downside of using wearable devices attached to the body during physical activities for a long period of time is that they may cause skin irritation.

The feasibility of using textile temperature-sensing electronic yarns (e-yarns) for measuring skin temperature during cycling trials was tested. Smart garments were formed by attaching e-yarns to commercially available cycling suits. Skin temperature results were recorded using e-yarns and skin-mounted thermistors. Differences were recorded in skin temperature measurements by e-yarns and thermistors as high as 5.9°C. A problem occurred with breakage in the e-yarns and the supporting hardware, which resulted in a smaller dataset being collected. The most frequent point of failure were connectors used to attach the temperature-sensing e-yarns to the hardware module. In addition, measurement error was due to poor contact between the skin and e-yarns [20].

Multiple miniaturized temperature sensors on single yarns were manufactured with the aim of being used in textronic applications. Authors have reported that these yarns are lightweight and have good flexibility. These flexible sensors operate in temperature range of 30°C to 42°C if proper thermo-sensitive paste is used. Thermo-sensitive paste must have a good temperature coefficient and proper linearity [21].

Skin temperature was measured using temperature sensing yarn imbedded into smart garments (armbands, a glove, and a sock). A problem occurs with using the smart yarn because every fabric made using these yarns must be engineered according to pressure point in the moment when the measurements are conducted. In addition, the design also has to be adjusted [22].

The textile sensor was realized directly on textiles by using printing and coating technology. The sensor enables volume passive measurements for sweat analysis. To establish the feasibility of coupling two different techniques, the impedance and the transient plane source (TPS) principle were tested. Both sensor principles were tested by monitoring the drying of a wet cloth, and the measurements showed perfect repeatability, accuracy, and the possibility to handle sweat volumes even less than 0.5 μL. However, when the property of biofluid changes, the TPS sensor readings do not reflect this information, but on the other hand, impedance can provide information on compositional changes [23].

Temperature Sensing Fabric (TSF) for the physiological monitoring of the human body was produced on a flatbed knitting machine by embedding a fine metallic wire as the sensing element into a double-layer knitted polyester structure. TSF determines the temperature measured by changing the electrical resistance in the metal wire. This fabric was tested under laboratory conditions in various ambient temperatures, and authors concluded that humidity did not affect the accuracy of the sensors but that the performance of the sensors may be affected by body movements and breathing [24].

Knitted temperature-sensing fabrics with copper, nickel, and tungsten wire elements have been produced on a flatbed knitting machine. This sensing fabric has resistance ranging 3–130 Ω. The authors reported that fabric has good tensile strength, which has been achieved by merging textile and wires. A mathematical relationship has been derived between the temperature and resistance of the knitted sensors, and this can be used to optimize its dimensions to achieve a targeted reference resistance. The temperature-sensing fabric can be integrated into garments for continuous measurement of skin temperature for various applications, such as sports, military, health care as well as to estimate thermal strain in extreme climatic conditions [25].

Paiva et al. [26] present the development of a slim-cut long-sleeve T-shirt for sportswear and leggings with integrated textiles sensors for monitoring of the athlete’s activity and physiological data. The main focus is on reading ECG measurements, although the possibility of measuring temperature has been found. The TPU film has been used for keeping the electrodes in place due to the compression created and the rubber-like surface that keeps the fabric from sliding over the skin and provides mutual contact. The authors state that problems occur with keeping electrodes in place when moving the arms [26].

MIPHAS is a telemonitoring system aimed at continuously monitoring athletes during physical activities. This system is composed of three components: a smart T-shirt, an electronic device (BIOX), and several software components. This smart garment, which embeds several sensors, was made of specific fabrics while the task of the electronic device was data
acquisition of vital parameters and transmitting data in real-time to the software components [27].

Also, another system for monitoring human body temperature during sports activities was developed. This system contains a wearable device that embeds six temperature sensors and a radio module, the task of which is to send data to a remote receiver interfaced to a personal computer. An internal rechargeable battery powers an M0 LORA Adafruit Feather microcontroller, six thermistors, and a display. The display allows monitoring of temperature, the battery status, and the reliability of the wireless link. If the link is not working, the wearable device logs the measurements in local memory. The thermistors have their own conditioning circuit connected to the wearable system via cables approximately 1 m long. The system acquires data and sends the data to the receiver using a LORA module. In addition, data are also stored for subsequent processing. A temperature skew of about 0.1°C was found in the sensors under isothermal conditions. The noise of raw measurements is about 0.3°C, which can be reduced to about 0.1°C using proper numerical filtering. The thermistors are placed inside of the glove fingers [28].

Lage et al. [29] developed a slim-cut smart shirt with embedded electrodes for heart rate measurement and a knitted moisture sensor for sweat detection. The authors state that further experimentation is needed to define the final configuration of the moisture sensor.

A literature search shows that a small number of studies have been published on the development of smart clothing for monitoring the thermal load of athletes, and none includes a smart garment of a wider cut. So far, most of the works have been dedicated to wearables and smart textiles, which should be subsequently adjusted to the garment. With smart clothes for monitoring both the thermal state and other physiological parameters, the researchers obtained the accuracy of the measurement and a good signal based on the direct contact of the sensor and the skin of the test subjects. In the case of the smart T-shirt presented in this paper, the parameters of temperature (microclimate) and relative humidity (microclimate) are measured in real time and provide reliable and realistic results regardless of whatever is direct contact between the skin and the sensor. In addition, many smart garments have been made of thicker or multi-layered materials where electronic components are easy to hide, while in the case of smart T-shirts (presented in this paper) electronic components have been successfully embedded in extremely thin and elastic knitted fabrics (small thickness and surface mass) in such a way that these components are not visible and do not compromise the aesthetic appearance and comfort of the T-shirt.

The scientific contribution of this paper is the successful realization of a smart T-shirt with the accurate and reliable possibility of monitoring athletes' thermal status in hot conditions. In addition, the problems that occur with other wearables, smart textiles, and smart garments, such as the breaking of e-yarn [22], the need to adapt the design of the garment to the electronic components [20–22], accuracy compromised by hand movements or breathing [26], moisture contact with electronics, or other difficulties during signal collection [23], as well as the need to use additional hardware equipment [27], have been avoided.

It is extremely difficult to monitor the health status of each athlete in group sports (during training and competitions), especially in sports that are played over a long time duration with short breaks. In addition, the state of dehydration greatly impairs the athlete’s ability. For that reason, on the basis of the literature review, it was decided that the parameters that should be measured for a smart T-shirt in order to monitor an athlete’s thermal state are microclimate (temperature and humidity) of clothing and temperature and humidity of a skin. Detailed study of the literature established that only a small number of studies follow the overall development and procedure of integration of electronic components into the garment, that enable thermal status monitoring and that do not imply a slim cut and do not affect the ergonomic comfort.

In addition to the above-mentioned wearables, smart garments, smart textiles, and measurement methods for monitoring an athlete’s thermal status, smart T-shirts equipped with small and light data gathering electronic subsystems are suitable. The smart T-shirt described in this study is intended for football players, and for that reason the design of the T-shirt is adapted to the requirements of football players and their adaptation to hot weather.

2. Experimental

In this part the development of a smart T-shirt for monitoring the thermal status of the athlete is presented. The development took place in the following steps:

- creation of the system architecture,
- integration of electronic components into the T-shirt, and
- testing of the smart T-shirt.

2.1. System architecture

The system architecture for monitoring the thermal status of an athlete, which is integrated into the T-shirt, consists of two temperature and humidity sensors SHT-31 [30] acquired from Adafruit, the Wattuino Nanite 85 [31] microcontroller board acquired from Watterott electronic, and a FRAM (Ferroelectric Random Access Memory) [32], which was used for data storage. In addition, a 3.7 V rechargeable lithium ion battery powers the system. Boost converter 3.7 to 5 V was also implemented into the smart T-shirt. The Inter-Integrated Circuit (I²C) communication protocol was used for signal transmission. The circuit schematic that presents the electronics of the smart T-shirt is presented in Figure 1.

The performance of temperature and humidity sensors SHT-31 is presented in Table 1. SHT-31 sensors have eight connections (pins), five of which are connected to the corresponding pins on the Wattuino Nanite 85 board. These pins are VDD (voltage...
supply), VSS (ground), SCL (serial clock), SCA (serial data) and ADDR (address pin). Sensors use the I 2C communication protocol, which has an internal IP address, and are directly connected to the I 2C SDA and SCL bus. The SDA pin is used for transferring data to and from the sensor. The sensors use communication velocities up to 1 MHz. Data are stored sequentially on FRAM storage via I2C.

The focus of the smart T-shirt is sequential collection of temperature (T) and relative humidity (RH) values, which can be monitored via the Arduino serial monitor. This way the user’s thermal state can be monitored. The sensors are connected on a common data bus to send measurements sequentially every 0.5 seconds or every second (the sampling rate can be adjusted) to the main FRAM storage. The system is based on the standard I 2C communication protocol. Sensors have two distinctive user-selectable I2C addresses, which are requested by the main program to demand the information from sensors to be updated to the data bus. SHT-31 sensors can operate on wide supply voltage range of 2.4 to 5.5 V, while the Wattuino Nanite 85 microcontroller was chosen to be integrated in to the smart T-shirt because of its small size (Table 1).

The temperature and humidity specifications performance of the SHT-31 sensor are presented in Table 2.

### 2.1. Integration of electronic components into the T-shirt

Electronic components were integrated into a T-shirt with short sleeves. The T-shirt has a wider cut and a strategically placed porous textile material (net) under the armpits to allow ventilation during physical activities. This T-shirt has been designed to be comfortable for the wearer. It is made of polyester knitted fabric with increased breathability, which allows for a quick evaporation of moisture.

Humidity and temperature sensors, which were integrated in the T-shirt, are positioned according to the locations of two temperature sites (i.e., right spatula and left upper chest) determined by Standard ISO 9886:2004 [33]. The location of

#### Table 1. Dimensions of electronic components and sensors used for making the smart T-shirt.

<table>
<thead>
<tr>
<th>Component name</th>
<th>Width [mm]</th>
<th>Length [mm]</th>
<th>Thickness [mm]</th>
<th>Total area [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wattuino Nanite 85</td>
<td>10.16</td>
<td>17.46</td>
<td>2.00</td>
<td>177.39</td>
</tr>
<tr>
<td>SHT-31 sensors</td>
<td>17.77</td>
<td>12.70</td>
<td>2.00</td>
<td>226.67</td>
</tr>
<tr>
<td>I2C FRAM</td>
<td>20.00</td>
<td>14.00</td>
<td>2.00</td>
<td>280.00</td>
</tr>
<tr>
<td>Boost converter 3.7 V/5 V</td>
<td>18.00</td>
<td>21.00</td>
<td>2.00</td>
<td>378.00</td>
</tr>
<tr>
<td>JST-PH 2</td>
<td>10.00</td>
<td>20.00</td>
<td>2.00</td>
<td>20.00</td>
</tr>
<tr>
<td>Battery 3.7 V</td>
<td>30.00</td>
<td>35.00</td>
<td>3.00</td>
<td>1050.00</td>
</tr>
</tbody>
</table>

Figure 1. Smart T-shirt circuit schematic.
sensors and other electronic components integrated in the T-shirt are shown in Figure 2.

An acceleration sensor MMA8451 located on the left shoulder is optional and will be the topic of future research.

Conductive threads or ribbons are most commonly used to connect electronic components in smart clothing. The first problem that occurs is the low strength of the conductive threads and ribbons, which can easily break during physical activity. The second problem is the excretion of sweat. In extreme conditions, athletes can produce up to 2.5 liters of sweat during physical activity [34]. For that reason, it is not possible to use ordinary insulated wires, but it is necessary to provide protection of the electronic components from moisture (which is the conductor of electricity) in order to prevent contact. Therefore, it was decided to use single-coated flexible enameled copper wires to make connections between the components of the smart T-shirt.

The experiment was conducted to find an appropriate way of bonding single-coated enamel copper wires to the textile material. Liquid rubber, textile adhesive, and hot welding technology combined with sewing were used to bond copper wires (thickness of 0.12 mm and 0.2 mm) to knitted fabric.

Based on the visual aesthetics as well as the comfort of the garment, it was decided that the wiring in a smart T-shirt would be carried out using thermal welding technique combined with sewing and single-coated enameled copper wires of 0.2 mm thickness (visible on Figures 3 and 4). In addition, the combination of thermal welding and sewing allows the wires to be placed in curved lines with even a distance between

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Temperature sensor SHT-31</th>
<th>Humidity sensor SHT-31</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conditions</td>
<td>Value</td>
</tr>
<tr>
<td>Accuracy tolerance</td>
<td>10 to + 55</td>
<td>± 0.3 ºC</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Low</td>
<td>0.16 ºC</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.07 ºC</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.04 ºC</td>
</tr>
<tr>
<td>Resolution</td>
<td>Typ.</td>
<td>0.015 ºC</td>
</tr>
<tr>
<td>Hysteresis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specified range</td>
<td>-</td>
<td>-40 to 125</td>
</tr>
<tr>
<td>Long term drift</td>
<td>Max.</td>
<td>&lt; 0.03 ºC/year</td>
</tr>
</tbody>
</table>

Figure 2. The location of sensors and other electronic components in a smart T-shirt, (a) the front and (b) back.

Table 2. Temperature and humidity sensor specifications performance [30].
several wires placed in parallel position and extra protection from moisture.

Boards of SHT31 sensor were integrated and protected in the smart T-shirt. After the sensor was soldered to the copper wires and thus connected to other electronic components in the smart T-shirt, it was necessary to protect the sensor from moisture as well as to protect it from mechanical damage. This was achieved by coating the sensor board with liquid rubber; the only part that remained unprotected was the sensor itself (SH3x), and the next step was the application of nonwoven fabric to the sensor board. This nonwoven fabric covers the surface of the sensor board with the exception of the sensor itself (SH3x). The use of nonwoven fabrics protects the sensors and reduces the direct contact between the sensors and the body. In addition, it enhances the comfort of a smart T-shirt.

The use of liquid rubber and thermal welding technology ensured the permanent and safe connection of electronic components, wires and PBS with knitted fabric, which proved to be true after long-term testing (duration of one year) of smart T-shirts in which several test subjects participated.

Two printed circuit boards (PCBs) were created to connect the electronic components of the smart T-shirt. One was located on the back (Figure 3) and another on the shoulder (Figure 4). The PCB’s proper structure was achieved by using the etching technique on a thin layer of copper. The layer was then merged with a flexible foil.

The PCB located on the right shoulder blade (115 mm x 42 mm) had the function of providing a connection to a sensor. On the back of the T-shirt the wires move from the PCB located on the left shoulder to another PCB (65 mm x 25 mm) in a slightly curved line and then move at right angles to the sensor on the right shoulder blade (Figure 3). This arrangement of wires and electronics on the back of the T-shirt provide comfort when worn, so that there is no obstruction of motion during the movement of athlete’s hands.

The second PCB is located on the left shoulder of the T-shirt. The Wattuino Nanite 85 and MB85RC256Vw chip were mounted on this PCB and connected to the sensors. The copper wires previously connected to the corresponding pins on the SHT-31 sensors were then soldered to the appropriate sites on the PCB.

The wires on the left shoulder blade that connect to the sensors are carried out in a slightly curved line. Further, the wires move from the sensor to the hip position where boost converter, JST-PH2 pin and battery are placed on the seam that connects the front and back of the shirt. This line is even more curved. In this way, the reduction of the elasticity in the wale and course directions of knitted fabric is minimized.

PCB blueprint and integrated PBC, as well as final look of left shoulder of T-shirt is presented in Figure 4.

The connector near the collar enables the connection of a data cable, so that data stored on the FRAM can be transferred to the personal computer. Data can be monitored via the Arduino serial monitor.

2.1. Wearing comfort of the smart T-shirt

A very important factor when choosing sportswear is wearing comfort. In addition to thermo-physiological comfort both sensory and ergonomic comfort must be taken into consideration when one is designing and making sportswear. The smart T-shirt must not hinder the movements of athletes during physical activities.

One of the main requirements for choosing textile materials for sportswear intended to be worn in warm conditions is that they be light and elastic and that they possess good breathability in addition to enabling fast drying. That is why knitted polyester fabric is most often used for sportswear manufacturing [35]. For that reason, a light and elastic knitted polyester fabric was chosen for the realization of the smart T-shirt prototype.

The problem with the integration of electronic components into extremely elastic and light knitted fabrics is that the integration of electronic components of a certain weight stretches the material in the direction of the rows of the knitted fabrics. Therefore, light electronic components of smaller weight and dimensions must be used in order not to change the shape of the T-shirt and deform the textile material.

Experimental results show that the sewn mesh (positioned under the armpits) significantly increases ventilation between the body and clothing, and so the skin dries faster, resulting in a lower value in the sweat absorbed by the T-shirt [36]. In addition, the design of the T-shirt and use of ventilation holes can improve wearing comfort [37].

The weight of the T-shirt before the electronics components were integrated was 190 g; the weight after integration was 220 g, which means that the total weight of the electronics used including the battery was 30 g. Given these data, we can
conclude that this small difference is insignificant and does not negatively affect the wearing comfort of the T-shirt.

A subjective assessment of the T-shirt comfort was performed during physical activity and in a stationary state in which six test subjects participated. For this purpose, a modified questionnaire was designed, which was used for constructing appropriate subjective scales in the assessment and evaluation of the physical environment according to ISO 10551:2019 Standard [38].

The results of the subjective assessments of wearing comfort of T-shirt are presented in Table 3.

All test subjects stated that the smart T-shirt was comfortable and the built-in electronics did not interfere with movement. In addition, all test subjects found that they did not even notice the presence of embedded electronics in the garment.

The battery is charged every four hours, which allows a long period without charging.

Another important feature of a smart T-shirt is the possibility to wash it, which is of great importance for sportswear. The smart T-shirt can be carefully washed and dried after the battery is removed.

### 2.2. Methodology

Experiments to determine the athletes’ thermal status were conducted in a climate chamber where the ambient temperature and humidity were set as well as the air velocity, which correspond to the conditions when sports competitions are held during the summer period. One professional male athlete participated in the study. The physical activity selected was running on a treadmill, which is a simulation of the activities of football players during a match. A smart T-shirt was used to determine microclimate temperature ($T_m$) and humidity ($RH_m$), while MSR 12 (Modular Signal Recorder) from Msr Electronics GmbH, Switzerland, was used to determine skin temperature ($T_s$) and the skin’s relative humidity ($RH_s$). In Figure 5a a test subject wearing the smart T-shirt had an MSR device placed in...

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**Figure 4.** Left shoulder (a) PCB blueprint, (b) PCB integrated in to the T-shirt, and (c) final look.

**Figure 5.** Positions of temperature and relative humidity (a) on the body of test subject wearing the smart T-shirt and (b) the position of measuring skin temperature and relative humidity of skin (positions 3 and 4) defined according to the Standard ISO 9886:2004.
a special bag attached to the subject’s waist, while in Figure 5b positions of MSR measurements points on body are presented.

The test subject ran on the treadmill under two different atmospheric conditions. The first atmospheric condition was at $T = 20^\circ C$ and $RH = 50\%$, and the second was at $T = 25^\circ C$ and $RH = 50\%$. The air velocity was $0.5 \text{ ms}^{-1}$ for both atmospheric conditions. The tests’ duration was 55 minutes. Temperature and humidity data from the smart T-shirts were collected each second, and these data were collected twice per minute using MSR. Humidity and temperature sensors from MSR measuring devices were located (attached to the skin) in the same

Table 3. Results of wearing comfort of a T-shirt obtained by subjective assessment.

<table>
<thead>
<tr>
<th>Questioner</th>
<th>Assessment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
<th>Subject 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>How would you evaluate the garment you are wearing</td>
<td>light / rigid / heavy</td>
<td>light</td>
<td>light</td>
<td>light</td>
<td>light</td>
<td>light</td>
<td>light</td>
</tr>
<tr>
<td>Is the T-shirt comfortable in terms of movement - in general</td>
<td>feel relaxed / cramped</td>
<td>feel relaxed</td>
<td>feel relaxed</td>
<td>feel relaxed</td>
<td>feel relaxed</td>
<td>feel relaxed</td>
<td>feel relaxed</td>
</tr>
<tr>
<td>How would you assess comfort in terms of arm movement</td>
<td>suitably flexible / inflexible</td>
<td>suitably flexible</td>
<td>suitably flexible</td>
<td>suitably flexible</td>
<td>suitably flexible</td>
<td>suitably flexible</td>
<td>suitably flexible</td>
</tr>
<tr>
<td>Is the T-shirt flexible enough during dressing</td>
<td>easy to put on / difficulties during dressing</td>
<td>easy to put on</td>
<td>easy to put on</td>
<td>easy to put on</td>
<td>easy to put on</td>
<td>easy to put on</td>
<td>easy to put on</td>
</tr>
</tbody>
</table>

Evaluation of mechanical comfort

<table>
<thead>
<tr>
<th>Questioner</th>
<th>Assessment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
<th>Subject 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you think the T-shirt is flexible enough</td>
<td>yes / no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Do you feel that the T-shirt is elastic</td>
<td>yes / no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Does the T-shirt fits your body well</td>
<td>yes / no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Evaluation of thermal comfort

<table>
<thead>
<tr>
<th>Questioner</th>
<th>Assessment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
<th>Subject 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you feel the heat</td>
<td>yes / no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Do you feel the warmth</td>
<td>yes / no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Do you feel the moisture in garment</td>
<td>yes / no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Do you feel tired</td>
<td>yes / no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Do your clothes get in the way of moving</td>
<td>yes / no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Evaluation of overall wearing comfort

<table>
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<tr>
<th>Questioner</th>
<th>Assessment</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
<th>Subject 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very comfortable</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Comfortable</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Slightly uncomfortable</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Uncomfortable</td>
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<td></td>
</tr>
<tr>
<td>It bothers me</td>
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<td></td>
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</table>
positions as SHT-31 sensors on the smart T-shirts, positions 3 and 4 (Figure 5b).

Figure 6 shows the graphical representation of the testing protocol, representing the velocity of movement of the test subject.

In addition, in order to verify the accuracy as well as the sensor response an additional experiment was conducted using a Thermo Labo device.

3. Results and discussion

Results are given in form of test results of the accuracy and response rates from SHT-31 sensors integrated into smart T-shirts using the Thermo Labo measuring instrument; skin and microclimate temperature and relative humidity results were measured with the smart T-shirts.

3.1. The test results of the feasibility and response rates of SHT-31 sensors integrated into a smart T-shirt

The aim of this experiment was to investigate the feasibility and response rates of SHT-31 sensors integrated into a smart T-shirt. For this purpose, a KES-F7 Thermo Labo instrument, which contains two hot plates set to $T_1$ and $T_2$ was used. The T-shirt has been previously exposed to standard atmosphere in accordance with the requirements of ISO 139 Standard [39].

The total duration of the experiment was one hour; the temperature and humidity data were collected each second. The experiment was conducted at the standard atmosphere in a climate chamber, i.e., where the ambient temperature at 20 ± 2°C and the relative humidity was 65 ± 2%.

Sensor 1, integrated on the front of the T-shirt was left on the plate, which was set to $T_1$, for half an hour, while sensor 2, which was integrated on the back of the T-shirt, was placed on a plate set at $T_2$. After 30 minutes, the sensor positions on the plates were replaced. Figure 7a shows the results of temperature measurements of the SHT31 sensor when tested on a KES-F7 Thermo Labo instrument, while Figure 7b shows the change of relative humidity of the SHT31 sensor when tested on a Thermo Labo instrument.

Figure 7a shows that the sensor 1 responded and temperature values began to decline from 27°C to 21°C. A similar change was observed with sensor 2, where the temperature measured increased from 21°C to 27°C.

When we observe at the recorded RH values measured with sensor 1, it is evident that the initial RH value was 44%. During the experiment, there is a slight decrease in the RH values. After 30 minutes when sensor 1 was moved to other plate, there was a slight increase in RH values, which lasted only a few seconds. After one hour, at the end of the experiment, sensor 1 recorded an RH value of 56.30%. Sensor 2 recorded a similar change. At the beginning of the experiment, an RH value of 57.51% was recorded. During the first 30 minutes of the test, the RH values were stable. During the change of the sensor position to the other plate, there was an increase in the RH value, which lasted only a few seconds, and at that time the highest recorded value was 63.68%. After placing the sensors on the plate set at $T_2$, the RH values decreased, reaching 51.58% at the end of the measurement.

3.2. Monitoring athletes’ thermal status by using a smart T-shirt

Measurement results of skin temperature and relative humidity of skin and microclimate during the physical activities defined in the protocol (Figure 6), performed in two different ambient conditions (20°C and 25°C) are shown in Figures 8 to 11.

![Figure 6](http://www.autexrj.com/)

**Figure 6.** Graphic representation of the testing protocol.
Figure 8 shows the results of skin (determined by MSR) and microclimate (determined by SHT-31) temperature obtained at 20°C ambient temperature.

During the performance of physical activities by the test subject at the ambient temperature of 20°C, higher temperature values were obtained on the subject's back, recorded both by MSR and by the smart T-shirt. Significantly, higher values were obtained for skin temperature in comparison with the microclimate temperature: an average of 3.75°C on the test subject's chest and 4.89°C on the back. These results correspond to the experimental data of thermo-physiological studies where higher values of $T_s$ were recorded on upper back in relation to the $T_s$ recorded on chests [40, 41]. Figure 8 shows that temperatures rise slowly at the beginning of the test until the twentieth minute (which is considered to be a warm-up period) and values oscillate with load, i.e., a change in the velocity of movement. This oscillation in temperature values was much more pronounced for those measured on the test subject's back ($T_{S2}$ and $T_{M2}$) compared to the values obtained on the chest ($T_{S1}$ and $T_{M1}$).

The microclimate temperature obtained at the ambient temperature of 20°C on the subject's chest ranged from 25.30°C to 28.51°C while these values on the subject's back range from 30.03 °C to 33.16 °C. Moreover, the values of $T_s$ on the subject's chest range from 29.02°C to 31.03°C while temperatures on the subject’s back range from 30.03°C to 33.09°C.

Figure 9 shows results of skin and microclimate RH at the ambient temperature of 20°C.

After the fifteenth minute of the test, the body begins to sweat in response to physical exertion, as reflected by a sharp increase in all RH values. Higher RH values were recorded on the subject's back. In a comparison RH$_{S1}$ and RH$_{M1}$, it can be seen that the smart T-shirt recorded higher RH values compared with the MSR device, namely 18.75% on average. On the test subject’s back, the difference in these values was 1.66% on average. This can be explained by the movement of the test subject and the ventilation, which occurs during moving of garment. This ventilation enabled drying of the T-shirt.
Figure 10 presents skin and microclimate temperature obtained at 25°C ambient temperature. Good consistency was observed between the results of skin and microclimate temperatures on both the subject’s chest (Figure 10a) and the back (Figure 10b).

The results obtained and compared for the skin temperature as well as microclimate temperature at the ambient temperature of 20°C (Figure 8) and the ambient temperature of 25°C (Figure 10), indicate clearly that a higher ambient temperature results in greater warming of the body. This was reflected in the results of skin and microclimate temperatures, which were much higher at 25°C ambient temperature. The values of skin and microclimate temperatures increase and decrease with the change of the physical load.

The average difference in the skin and microclimate temperature values on the chest is 2.18°C, while the difference on the back is 0.98°C. The microclimate temperature obtained at an ambient temperature of 25°C for the subject’s chest range from 28.18°C to 31.05°C while these values for the subject’s back range from 28.07°C to 31.51°C. Furthermore, the skin temperature values obtained for the subject’s chest range from 30.07°C to 33.28°C, while these values on the subject’s back range from 31.02°C to 35.03°C.

Figure 11 shows skin and microclimate RH results obtained at the ambient temperature of 20°C. During the test, at both ambient temperatures (20°C and 25°C), there is a sharp increase in the RH values after each fifteenth minute of the test. At an ambient temperature of 20°C, after this period there is an oscillation in the RH values on the subject’s chest and back with the change of physical load, i.e., the velocity of movement. This can be explained by the drying of the T-shirt caused by the ventilation that occurs during the movement of the garment. At an ambient temperature of 25°C a larger amount of sweat is excreted on the subject’s chest (RH$_{M1}$ ranging from 43.49% to 99.63% and RH$_{S1}$ ranging from 43.03% to 73.01%) and on the subject’s back (RH$_{M2}$ ranging from 40.79% to 97.95% and RH$_{S2}$ ranging from 41.87% to 98.09%) during the same physical activity, which prevents the T-shirt from drying. Increased moisture values (amount of sweat) are the body’s response to increased physical exertion and high ambient temperature.
4. CONCLUSIONS

A smart T-shirt has been developed with the function of monitoring the thermal state of athletes in order to preserve ability and improve performance in warm weather. For this purpose, two temperature and humidity sensors with the requisite electronic components were integrated into the T-shirt. For data transferring, the I2C protocol was used.

The smart T-shirt was designed by taking into account the requirements of thermo-physiological and ergonomic wear comfort. For this reason, for the production of the T-shirt, breathable polyester knitted fabric was selected. Nets are placed under the armpits in order to improve the air circulation and to increase the cooling during the physical activities.

To test the performance of the thermal monitoring system, the collected microclimate temperature and relative humidity data were compared with the data obtained from the MSR 12 medical device (skin temperature and relative humidity of skin). The smart T-shirt has been tested in two different atmospheric conditions and during different physical activity.

A good accordance was found from the results obtained with the smart T-shirt and the MSR, with the difference that the skin temperature values were slightly higher in relation to the microclimate temperature. In addition, higher temperature values were measured on the subject’s back at both ambient temperatures. In both cases, higher skin temperature values were recorded in relation to microclimate temperature. At both ambient temperatures, higher RH values were recorded of microclimate, which is explained by the wetting of the textile material from which the T-shirt was made, as well as the nonwoven fabric, which protects the sensor. In addition, at an ambient temperature of 20°C, the T-shirt dries during the test, while at an ambient temperature of 25°C due to increased sweating, this is not the case.

Based on the research results obtained, the advantages of the developed smart T-shirt can be summarized as follows:

- Reliable assessment of thermal status of the athletes;
- Reliability, i.e., excessive sweating during strenuous physical activity does not cause the sensor to peel off; and
- The ability to sample more data, as well as to adjust the data sampling speed.

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References


