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Effects of athletic T-shirt designs on natural ventilation

ABSTRACT

Maintaining air circulation between the wearer and garment layer is crucial for activating heat and moisture transfer from the body. If such an air gap is trapped, air circulation may become ineffective and the ventilation of the garment is thus hindered. To maintain and extend the air gap, this study proposes a design method that involves placing spacer blocks underneath the garment to prevent the fabric from clinging directly to the skin. To study the application of this design method, a series of T-shirts was produced and tested using a thermal manikin in standing and walking postures. All the T-shirts were made of fabric ostensibly manufactured to have high air permeability. Porous mesh fabric was used to construct the vented panels on the T-shirts. The test was conducted in a chamber with controlled temperature, relative humidity, and wind velocity. Total thermal insulation (R_t) and moisture vapour resistance (R_{et}) were measured. The test results showed that extension of the air gap between wearer and fabric provided higher ventilation to the wearer if the vented panels were also present on the T-shirts. Different placements of the vented panels on the T-shirts also affected the heat and moisture transfer from the thermal manikin.

1. Introduction

Fabrics used for athletic apparel can be a barrier to heat and moisture transfer on the wearer (Gavin, 2003). If moisture vapour cannot pass through the garment layers to the ambient environment, the garment may absorb the liquid and cause discomfort to the wearer. In extreme cases, the inability to release body heat and moisture can place the wearer at risk. For athletes, heat stress can negatively affect performance (Ruckman et al., 2002; Williamson & Buirski, 2002). Therefore, optimisation of clothing design is crucial (Ruckman et al., 1999).

For a clothed person, an air space (or gap) becomes entrapped between the clothing layers, or between the skin and fabric layer when a garment is worn with only a single layer of fabric. Because the thermal conductivity of still air space is low, it hinders the heat and moisture transfer through the fabric layer to the outside environment. Under this condition, the wearer becomes overheated and damp, especially when exercising. This warm and wet air can be released by improving the exchange between the air inside the clothing (i.e., the inner, warmer microclimate) and the ambient air (i.e., the outside environment); this is known as air ventilation. Body temperature is easily affected by the exchange of warm air between the fabric layer and skin surface. Such air exchange is affected by the material used for the garment. Air permeability and water vapour permeability are the two key indicators of the ability of the material to facilitate heat and moisture transfer. If these two fabric properties are low, then the heat and moisture transfer is not effective. Fabric thickness, construction, and bulk density (the mass of fibres in a given volume) are the key elements (Slater 1986) that affect these two properties. Fabric with a higher ability to absorb sweat from the wearer demonstrates evaporation that is more efficient; thus, the wearer feels cooler and drier. Quick-drying fabric has been widely applied in sports clothing, high-value casual wear, and uniforms. Because water vapour can convey heat away from the body by evaporating, the absorption of sweat and the transport through the fabric layer is crucial for wearer comfort (Hu et al., 2005). Nyoni (2003) concluded that the mechanism of fabric moisture management could be divided into five states: 1) uptake of moisture from the skin surface, 2) removal of moisture from the skin and transport through the fabric surface, 3) spread of moisture within the fabric structure, 4) absorption of moisture within suitable fibres (‘dynamic’ fabrics typically contain an ‘outer layer’ of hydrophilic fibres to absorb and store sweat away from the skin surface), and 5) evaporation of moisture from the fabric surface. Coolmax® by INVISTA, Dri-FIT by Nike, and ClimaCool® are examples of this type of quick-drying material.

Apart from adopting special material to enhance body coolness, many types of athletic jerseys have been designed with open apertures or vents in the underarms, chest, or back to provide increased ventilation to wearers. These open apertures or garment vents, also known as ventilative panels, can help wearers release body heat and moisture more efficiently. The ventilative panels can be achieved by design details (such as cut holes on the garment) or open-knit structure fabrics (such as mesh) which allow air to enter the microclimate between the skin and clothing to create more air circulation. Because of the open and porous knit structure of mesh fabric, air exchange is induced between the inside and outside of the garment. Because warm air rises, the mesh panels should be placed in the upper part of the garment so that the warm air in the gap can circulate and be released through the open structure of the mesh fabric. When people move, the air within the microclimate of the garment can be forced to ambient temperature through the garment openings or fabric pores (Bouskill et al., 2002; Havenith et al., 1990; Nielsen et al., 1985; Vokac et al., 1973). The gap between the skin and inner fabric layer changes over time, depending on the level of activity and movement. During body movement, air enters and leaves as the fabric moves inwards and outwards towards the skin surface, thus causing the effects of ventilation (Ghaddar et al., 2003). This ventilation of the clothing microclimate is known as the ‘pumping effect’ (Olesen et al., 1982; Vogt et al., 1983). However, this effect may be inhibited if the fabric layer clings to the skin surface, which blocks ventilation. When a conventional garment is properly worn, the garment should hang on the shoulders as the fabric drapes downwards, following body contours. This means that the fabric is in close contact with the shoulders, chest, and upper back. Consequently, when the wearer starts to sweat, the fabric clings to these body areas, which may cause discomfort, loss of modesty, and embarrassment.

Although sports clothes that have vented panels are popular, there is a lack of understanding on how these vented panels quantitatively affect heat and moisture transfer and the resultant thermal comfort; even less is known about the effect of the placement and size of these vents and openings on thermal comfort. Ho et al. (2008) conducted an experiment to investigate this relationship by using a sweating fabric manikin. They demonstrated through experiments that openings or vents placed on two vertical side panels along the side seams of a T-shirt provide the most favourable ventilation to the wearer under conditions without wind. This is because arm motions can induce movement of the side panels of the shirt and thus generate an exchange of cool and/or dry air in an ambient environment, with warm and/or moist air inside the garment. Placing vent panels across the chest, upper back, or underarms—which has been the inclination of many designers—does not significantly enhance ventilative cooling; these panels do not create ventilation channels for air movement and exchange. However, if a space between the upper body and garment can be maintained, the effect of the vent panels on the upper part of the garment may be different. Zhang et al. (2012) conducted an experiment to study the effects of neck and hem openings on heat and moisture transfer. Eight subjects ran on a treadmill in a chamber with controlled temperature (25 ± 2 °C), relative humidity (RH; 50% ± 5%), and wind speed (0.2 $m \cdot s^{-1}$). The results showed that the neck opening could be the key aspect that affects heat transfer, especially during the recovery period. They concluded that a T-shirt with a loose neck and moderate hem openings released the most heat from the body.

Morretti (2002) proposed a method for achieving higher ventilation for the wearer. The ventilative garment was designed with spacer objects placed underneath the shoulder areas. In addition, the shoulders of the garment included vented panels for the accumulated warm air to be released through the vented panels easily. However, the inventor did not provide data proving the effectiveness of this design concept. Ho et al. (2015) further developed a set of T-shirts designed to extend the air gap between the garment and skin surface by inserting piles of spacer blocks underneath the shoulders. Different vented panels were placed on the T-shirts. All T-shirts were placed on a thermal manikin to test the functionality of the ventilation. The test results showed that the expansion of the air gap between the skin surface and garment layer could contribute to a certain degree of heat and moisture transfer. However, other factors, such as the positions of the ventilative panels, the postures of the thermal manikin (standing or walking), and the availability of wind, were the key factors affecting the result. All the T-shirts were made of 100% cotton fabric without specification of the air and water vapour permeability. This study did not investigate how this design method (i.e., increasing the air gap between the garment and body, and incorporating ventilative panels to improve air circulation) can benefit garments made of fabric with higher air permeability. Thus, this study aimed to further develop this concept in T-shirt design by improving the construction of the spacer blocks. Fabric with higher air and water vapour permeability was used to determine whether this design method is applicable to higher performance on heat and moisture transfer.

2. Materials and methods

2.1 T-shirt design

The placement of vented panels on a garment has been shown to affect the body ventilation of the wearer. In this test, 10 T-shirts were made and divided into two groups: A and B. The T-shirts in Group A were made without placing spacer blocks underneath the fabric. For Group B, spacer blocks were placed underneath the T-shirt to enlarge the distance between the garment and body skin. Except for the presence or absence of the spacer blocks, the T-shirt styles were the same for both groups. Figure 1 presents the T-shirts and their codes: NM (no mesh), MS (mesh on shoulders), MSC (mesh on shoulders and chest), MSS (mesh on shoulders and two front sides), and MO (mesh all opened). The codes represent the various positions of the mesh panels on the garment. The shaded areas on the T-shirts indicate the positions of the vented panels (Fig. 1). The NM T-shirts (basic T-shirts without vented panels or spacer blocks) of Group A were used as control pieces to compare the performance of heat and moisture transfer with that of the other T-shirts.

2.2 Fabrication

To test the applicability of this new design concept, 100% polyester fabric with a pique structure weighing 165 g/m^2 was used for all T-shirts. The fabric was ostensibly manufactured to have higher breathability than a normal 100% cotton jersey fabric, and therefore might be suitable for making sports apparel for improved body ventilation. The air permeability (ISO 9237:1995) and water vapour permeability (ASTM E96:2013) of this fabric are listed in Table 1. Air permeability is a test for measuring the permeability of fabrics to air. Higher values indicate a higher velocity of air flow passing perpendicularly through the specimen (i.e., more permeable to air). The water vapour permeability test is conducted to reflect the rate of water vapour transmission of materials. The vented panels were made of 100% polyester mesh fabric weighing 70 g/m^2.

2.3 Construction and placement of spacer blocks

According to the designs of Moretti (2002) and Ho et al (2015), spacer material was placed underneath the garment to prevent contact between the fabric layer and skin. After trial and experimentation, the spacer blocks were designed in a 'W' shape (Figure 2). The cross section of the spacer blocks is depicted in Figure 3. Two holes (i.e., 'W' shape) of each spacer block were left to prevent trapping excessive air inside the spacer block. Apart from

the chest area, spacer blocks were also placed underneath the neckline to prevent the T-shirt fabric layer from touching the neck. The larger aperture was assumed to help release body heat and moisture vapour when the pumping or chimney effects were activated. Spacer blocks were also placed along the hemline of the T-shirt to create apertures that allow more ambient air for cooling. Figure 4 shows the allocation of spacer blocks placed underneath the T-shirt. The black rectangles indicate the locations of the spacer blocks. Each spacer block was approximately 1.5 cm high.

3. Measurement

To objectively evaluate the effects of various T-shirt designs on heat and moisture transfer and the resultant thermal comfort, the T-shirts were tested using a sweating fabric manikin under no-wind and windy conditions. The manikin was connected to a heat controller and sensors for measuring skin temperature. Because the manikin was covered with a waterproof but moisture-permeable fabric, it could simulate the sweating condition of a human body. It was filled with water to create a soft body similar to that of a human. Using a thermal manikin is an internationally standardised means of thermal evaluation in a controlled environment. In the same environmental setting, thermal manikins measure heat loss relevantly, reliably, and accurately (Qian & Fan, 2006). The tests were conducted in a climatic chamber at 20.0 ºC ± 0.5 ºC and 65.0% ± 2% RH with an air velocity of <0.3 m/s (no-wind condition) and 2 m/s ± 0.3 m/s (windy conditions). Under the no-wind condition, all built-in fans were switched off, but weak air velocity was recorded because the ventilation system in the chamber was essential for air exchange to maintain the consistency of temperature and relative humidity. To generate wind velocity under the windy condition, nine built-in fans in the chamber were switched on. To measure the air velocity, anemometers were placed near the thermal manikin. During the tests, the manikin remained in standing and walking postures. The walking posture was applied to test the heat and moisture transfer under the pumping effect. In the walking mode, the arms and legs of the manikin were moved to simulate the walking motion of a human being. The walking speed was set at 1.24 km/h. For all the tests, the core temperature of the manikin was set at a normal human body temperature of 37 ºC. Throughout the testing, a pair of short trousers (made of 100% cotton) was worn by the manikin. To prevent the effects of dirt and grime, which could affect the test results, the T-shirts were washed once before undergoing testing.

Clothing thermal insulation (R_t) and moisture vapour resistance (R_{et}) were the two major parameters for this study. Using a sweating fabric manikin enables determining these two parameters effectively (Fan & Chen, 2002). According to the specifications of the sweating thermal manikin, the total thermal insulation, including the insulation of the clothing and surface air layer, is calculated as follows:

$$R_t = \frac{A_s(\overline{T}_s - T_a)}{H_s + H_p - H_e}, \quad (1),$$

where A_s is the total surface area of the manikin (A_s = 1.79m^2), T_s is the mean skin temperature, T_a is the mean temperature of the environment, H_s is the heat supplied to the manikin or the heat generated by the heaters, H_p is the heat generated by the pump, and H_e is the evaporative heat loss from water evaporation. The evaporative heat loss can be calculated using

$$H_e = \lambda Q \quad (2),$$

where λ is the heat of the evaporation of water at the skin temperature, and Q is the perspiration rate or water loss per unit time, which can be measured by measuring the water supply.

The total moisture vapour resistance, including that of the clothing and surface air layer, can be calculated using

$$R_{et} = \frac{A_s(P*_s - RH_a P*_a)}{H_e} - R_{es} \quad (3),$$

where $P*_s$ is the saturated water vapour pressure at the skin temperature, which is the water vapour pressure of the water film inside the skin. RH_a is the relative humidity of the surrounding environment as a fraction, $P*_a$ is the saturated water vapour pressure in the surrounding environment, and R_{es} is the moisture vapour resistance of the skin.

4. Results and discussion

The results of the tests are listed in Tables 2 and 3 for the no-wind and windy conditions, respectively. The coefficients of variation of repeated tests were less than 5.0%. The T-shirts with lower R_t values are preferred, because such values indicate a greater ability to release body heat through the garment. In addition, a lower R_{et} value signifies that the T-shirt can release body moisture vapour into the ambient environment more efficiently. Tables 4 and 5 list the percentage changes of R_t and R_{et} for all T-shirts under no-wind and windy conditions, respectively. The reductions of the percentages in R_t and R_{et} of the T-shirts were calculated based on a comparison with those of the NM T-shirt in Group A.
he fabric used for making the T-shirts was recorded as having high air permeability. In general, the fabric could contribute to reducing R_t and R_{et} significantly only under the windy condition. For the NM and MO styles without spacer blocks, for example, the MO styles reduced R_t and R_{et} by 5.6% and 9.2% under a no-wind standing condition, by 2.7% and 6.3% under a no-wind walking condition, by 4.8% and 7.5% under a windy standing condition, and by 4.9% and 11.3% relative to the NM design (without spacer blocks) respectively under a windy walking condition. When spacer blocks were added to the design, the reduction was -6.4% and -13.65 under a no-wind standing condition, -4.42% and -11.5% under a no-wind walking condition, -7.9% and -14.6% under a windy standing condition, and -8.2% and -17.4%, compared with the NM (with spacer blocks) design under a windy walking condition.

Of all the designs, MO with spacer blocks achieved the lowest values for the reduction of R_t and R_{et} in both the standing and walking postures under windy conditions. When the thermal manikin was standing under a windy condition, MO with spacer blocks reduced R_t by 7.9% and R_{et} by 14.6%, compared with the NM design without spacer blocks. MO with spacer blocks even had lower R_t and R_{et} values than those of MO without spacer blocks, with the difference being 3.1% for R_t and 7.1% for R_{et}. This indicates that although the thermal manikin was standing still without moving arms, the wind was sufficiently effective for strengthening the ventilation. The combination of the spacer blocks and vented panels improved the effective release of moisture vapour.

The ventilation was even stronger under the walking condition. The MO design with spacer blocks reduced R_t by 8.2% and R_{et} by

17.4%, compared with NM without spacer blocks. Comparing these results with the same style (MO) without spacer blocks shows that the T-shirt with spacer blocks lowered R_t by 3.3% and R_{et} by 6.1% 5.347; the difference was significant for reducing the moisture vapour resistance. The data suggest that this new design concept could allow a garment made of breathable fabric to further reduce the total thermal insulation and moisture vapour resistance when the vented chest, shoulder, and two side panels are applied.

5. Conclusion

Under the no-wind condition, the vented panels added on the T-shirts improved the total thermal insulation by 0.9% to 5.6% and moisture vapour resistance by 1.2% to 9.2%. When the spacer blocks were added, improvement was recorded from 0.9% to 6.4% for total thermal insulation and from 0.7% to 13.7% in moisture vapour resistance. The improvement of the percentage was markedly higher when more vented panels were added on the garment. Under the windy condition, T-shirts with vented panels improved the total thermal insulation from 1.6% to 5% and moisture vapour resistance from 3.2% to 8.2%. A T-shirt with vented panels and spacer blocks could improve the total thermal insulation from 3.2% to 7.9% and moisture vapour resistance from 5.1% to 17.4%, except for NM in Group B, which showed no improvement. This result indicates that this design concept was more effective at reducing the moisture vapour resistance under all conditions, when vented panels were incorporated into the T-shirt design. This study reports the effect on heat and moisture transfer of the new design method applied on T-shirts with breathable fabric. Although this study proposes that placing objects underneath the garment can expand the air gap between the fabric layer and skin surface, whether this approach is functional when the garment is worn by subjects remains unclear. To strike a balance between stiffness and lightness of these supporting objects, spacer material was investigated in this study. However, the additional spacer blocks touching the skin may cause discomfort to the wearer because of the increasing weight of the garment and the rough surface texture of the spacer blocks. Thus, a trial in which people wear these clothes is essential for the next stage of product development.

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