The following publication Ho, C. P., Fan, J., Newton, E., & Au, R. (2017). Development and trial of athletic T-shirt using spacer blocks to enhance ventilation. International Journal of Clothing Science and Technology, 29(5), pp. 706–715 is published by Emerald and is available at https://doi.org/10.1108/IJCST-11-2016-0125.

Development and trial of athletic T-shirt using spacer blocks to enhance ventilation

1. Introduction

The fabrics used for athletic apparel serve as a potential barrier against heat and moisture transfer, thus increasing thermal insulation in athletes (Gavin, 2003). For athletes, heat stress is a major factor negatively affecting their performance (Ruckman *et al.*, 2002; Williamson and Buirski, 2002). Therefore, optimising clothing design for improving ventilation is a top priority. Various athletic T-shirts with vented details are available in the market, with vents formed using cutting, the adoption of special structured fabrics, or numerous other methods.

For multiple layers of normal clothing, the air space (or gap) is entrapped between the clothing layers. For an athletic T-shirt, the air gap is formed directly between the single fabric layer and the skin surface of the wearer. The thermal conductivity of the still air in the air space is low; thus, the low thermal conductivity inhibits the exchange of body heat and moisture vapour with the external environment through the fabric layer. During exercise, the wearer experiences heat stress and sweating. The heat stress and sweating are higher when the body heat and moisture vapour are entrapped in the air space. Ventilation in athletic T-shirts can be improved using special garment constructions or different vented details. The aim of ventilation is to ensure that the hot and humid air is released through improvement in air flow from the warmer inner microclimate to the external environment.

The study of patents and testing reports revealed the general concepts of athletic apparel design for enhancing body ventilation. To solve the problem of low air ventilation between the fabric layer and the skin surface, many different types of athletic garments have been designed with open apertures or vents (achieved by opening or the use of a mesh fabric) in certain areas such as underarms, the chest, or the back. These open apertures or vents on the garment improve the release of body heat and moisture. For example, Pyc (1992) launched a ventilated T-shirt with mesh fabric panels placed along the side torso and sleeve seams. The placement of mesh panels on the garment can provide improved air circulation around the body. This type of functional design is common in the current athletic apparel available in the market.

During body motion, the air space between the garment and the skin surface also moves, and if the garment has been designed with any vented panels or is made of a porous fabric, heat and moisture on the skin surface can be effectively released because the arms or legs “pump” air through openings or fabric pores. During body movements, air moves in and out as the fabric moves towards and away from the skin surface, resulting in ventilation (Ghaddar *et al.*, 2003). This is known as the “pumping effect” (Olesen *et al.*, 1982; Vogt *et al.*, 1983). The air space between the skin surface and the inner fabric layer changes over time and is dependent on the level of activity and movement. The effect of different vented panel placement on garments and the improved heat and moisture transfer resulting from these vented panel has been previously investigated (Ho *et al*., 2008; Zhang *et al*., 2012). Openings placed along the two body sides and in the neck area are the key for releasing body heat, because of the pumping effect facilitated by arm motion and the upward movement of warm air.

To improve the ventilation of a garment, clothing designers can use mesh fabric panels in the shoulder, chest, and upper back areas for the release of body heat. Because of the open and porous knit structure of mesh fabrics, air exchange between the fabric layer and the external environment is higher for mesh fabrics than for non-mesh fabrics. Because of the upward movement of warm air, the mesh panels should be placed in the upper part of the garment. However, ventilation may be inhibited if the fabric clings to the wearer's skin. When properly worn, a conventional garment should hang on the shoulders, and its fabric should drape downwards, following the contours of the wearer's body. Thus, the fabric is in close contact with the shoulders, chest, and upper back. When the wearer starts to sweat, the fabric clings to these body areas, causing discomfort, loss of modesty, and embarrassment. The clinging of the fabric to the skin eliminates the air gap and leads to sweat accumulation in the air gap, leading to decreased air flow. In addition, some sweat will be absorbed by the fabric, making it less porous and thus inhibiting heat and moisture exchange through the fabric. To solve this problem, a design that prevents the wet fabric from clinging to the upper body is crucial for improving air ventilation. Previous studies have investigated how such clothing designs enhance the pumping effect for improved ventilation. Ho *et al*. (2015, 2016) designed a series of athletic T-shirts with a number of spacer loops to ensure an enlarged air gap. In the designed athletic T-shirts, the vented panels formed by the mesh fabric were placed in certain parts, including the chest, shoulders, and close to the side seams, and a fabric sweating thermal manikin was used to evaluate the total thermal insulation (R_t) and moisture vapour resistance (R_{et}) of the T-shirts. The new designs improved thermal comfort and reduced R_t and R_{et}, compared with other T-shirts without air gap enlargement. Performance was even higher when the thermal manikin simulated walking in a climate chamber with nonzero air velocity. These findings demonstrated that the pumping effect, air velocity, vented panel placement, and air space enlargement should all be considered when designing athletic clothing with optimised air ventilation.

Increasing air space in specific garment areas can improve air ventilation inside the gap. The air space can be created by cutting the garment to ensure fullness in the centre part (Ho *et al*., 2011). However, this changes the shape, style, and appearance of the T-shirt. Furthermore, strong winds may cause the upper part of the T-shirt to cling to the skin, thus eliminating the air space. In this study, an athletic T-shirt was designed with vented panels and spacer loops to enlarge the air space. To compare its effectiveness for heat and moisture transfer with that of a normal T-shirt without spacer blocks, a set of wearer trials was performed in a chamber with controlled temperature, relative humidity, and air velocity. The subjective comfort ratings of the participants were collected. Furthermore, the mean skin temperature and verbal comments of each participant were also recorded as supplementary data to thermal sensation rating during different parts of the testing.

2. T-Shirts

2.1 Design

In this study, two T-shirts, named Vented and Vented Design, were designed, and their ability to improve air ventilation was compared. The size, fabrication, and vented panel placements of the two T-shirts were exactly the same. The only difference between the two T-shirts was that the Vented Design T-shirt had spacer blocks attached to the underside of the fabric, which extended the air gap, whereas the Vented T-shirt did not have such attachment. The Vented T-shirt thus represents the design commonly used for commercially available athletic T-shirts. Figure 1 displays the two T-shirts. Vented panels were placed over the shoulders, across the front, across the back, and along the two sides near the side seams. The vented panels had a curved shape to increase their aesthetic appeal. The Vented T-shirt was used as a control garment to compare heat and moisture transfer with that of the Vented Design T-shirt. Figures 2 and 3 illustrate the construction of the spacer blocks and their position on the Vented Design T-shirt, respectively. The shaded areas on the T-shirt represent the positions of the vented detail (i.e., mesh fabric panels). The spacer block had a “W” shape, with the rounded bottoms contacting the skin surface. The average height of each spacer block was approximately 1.5 cm. Because the material used to create the spacer blocks was scratchy and might cause discomfort to the wearer, a shell fabric was used to cover the whole spacer blocks before stitching them into the Vented Design T-shirt. The spacer blocks were placed alongside the mesh panels to prevent the mesh from contacting the skin directly. In both T-shirts, an overlock stitch was used to connect the fabric panels, including rib collars, shoulders, armholes, side seams, main body joining seams, and mesh panels. A covering stitch was applied around sleeve openings and the hemline. These two finishing methods are commonly used in commercially available athletic T-shirts.

2.2 Fabrication

The main body of both garments was fabricated using 100% polyester with a pique structure, weighing 165 g/m^2. The air permeability (ISO 9237, 1995) and water vapour permeability (ASTM E96, 2013) of the fabric are listed in Table 1. The results showed that the fabric was breathable. The vented panels were made of a 100% polyester mesh fabric weighing 70 g/m^2.

3. Measurement

3.1 Subjects

Eight male subjects voluntarily participated in the wearer trial. Their average age, height, and weight were 27 (±3) y, 1.72 (±4) cm, and 151 (± 9) lbs, respectively. All subjects were healthy and performed regular exercise. To minimise possible interference from participant fatigue, all subjects were required to have sufficient sleep on the night before the testing and were required to refrain from other exercise before the trial. They were also required to not ingest food or water from 2 hours before the trial began until the completion of the testing. To standardise the testing, subjects were provided with shorts, underwear, and socks made of 100% cotton and with the same size. The testing requirements and procedures, including the running speed, temperature, relative humidity, and survey questions, were explained before the trial.

3.2 Experimental procedure

The testing was conducted in a controlled climate chamber maintained at a temperature of 20.0 ± 0.50 °C, relative humidity of 65.0% ± 2%, and air velocity of 2 m/s. The T-shirts were placed in the controlled climate chamber for at least 2 h before the testing. The subjects were required to run on a motorised treadmill for 30 min at a running speed of 5.0 km/h. For preconditioning before the testing, the subjects sat in the climate chamber for 30 min. During the testing, all subjects provided their perceptions on the comfort levels of the two T-shirts before running and after 10, 20, and 30 min of running. After 30 min of running, the subjects rested in the chamber for 10 min. A questionnaire using a Likert 11-point comfort scale was administered to the subjects to rate the comfort level of the T-shirts, 10 being the highest rating and 0 being the lowest. The questionnaire evaluated three comfort items—body coolness, skin dryness, and overall comfort. During the completion of the questionnaire, the participants were encouraged to provide verbal comments on the overall comfort of the T-shirts. The researchers helped participants to drop down the points in the form.

The procedures were providing in writing, and all subjects agreed to follow them. The questionnaire used in this study is shown in Figure 4. To support the questionnaire findings on subjective comfort levels, the thermoregulatory responses of the participants were directly evaluated through skin temperature (T_{sk}) measurement. Temperature sensors (RS, Platinum Sensing Resistor-Pt100, UK) were attached to the face, chest, back, abdomen, upper legs, lower legs, upper arms, and lower arms. The final mean skin temperature was calculated using the following equation:

$T_{sk} = 0.21\ T_{face} + 0.21\ T_{chest\ \&\ back} + 0.17\ T_{abdomen} + 0.15\ T_{upper\ legs} + 0.08\ T_{lower\ legs} + 0.12\ T_{upper\ arms} + 0.06\ T_{lower\ arms}$ (Nadel *et al.*, 1973)

4. Results and Discussion

The results of the comfort level survey are listed in Table 2, and the mean skin temperatures of all subjects are listed in Table 3. The changes in the mean skin temperature during the testing period are plotted in Figure 5. An independent t-test was performed to determine whether the ventilation performance of the Vented Design T-shirt is higher than that of the Vented T-shirt, as perceived by the wearers. The perceived comfort levels were tested at different time points: before running; after 10, 20, and 30 min of running; and 10 min after resting.

To determine the difference in the mean skin temperature of the wearers of the two T-shirts, an independent t-test was also performed for every minute of the whole test. All statistical analyses were performed at a significance level of 95%.

Before running, no statistical difference was observed in the ratings of body coolness and skin dryness for the two T-shirts ($P > 0.05$). The subjects commented that they thought that both T-shirts would keep them cool and dry before running.

However, a significant difference was observed in the overall comfort ($P = 0.00$) of the two T-shirts. The subjects commented that the Vented Design T-shirt was slightly unnatural to wear because the spacer blocks placed slight pressure on their skin, akin to someone lightly pressing their skin using their fingers. This is reflected in the average comfort ratings of 7.5 for the Vented Design T-shirt and 8.75 for the Vented T-shirt. Adding spacer blocks also inevitably increased the weight of the Vented Design T-shirt. The subjects stated that they preferred a more lightweight T-shirt for exercise. The combination of these two factors led to the relatively lower "overall comfort" rating for the Vented Design T-shirt before running.

The second assessment was conducted after 10 min of running on the treadmill. The body coolness and skin dryness ratings for the Vented Design T-shirt were slightly higher than those for the Vented T-shirt, but no significant difference ($P > 0.05$) was observed between the two T-shirts. By contrast, the overall comfort rating for the Vented Design T-shirt (6.75) was slightly higher than that for the Vented T-shirt (6.25), although the difference was not significant ($P = 0.116$). The subjects commented that the unnatural feeling caused by the spacer blocks was less than that experienced before running. This finding may be because the sweat on the skin surface reduced the friction caused by the spacer blocks. Alternatively, they had started to sweat after running for a few minutes, and heat stress had become more significant; therefore, their perception of "comfort" was more focused on the degree of coolness and dryness provided by the T-shirt. This explains their higher overall comfort rating for the Vented Design T-shirt than that for the Vented T-shirt, in contrast to their ratings before running. This finding was also supported by the mean skin temperature measurements. No significant difference was observed in the mean skin temperature of the wearers of the two T-shirts ($P > 0.05$) after 10 min of running

($P = 0.015$). Because the subjects were rated their comfort level after 10 min of running, it is understandable that they did not report much difference in body coolness and skin dryness between the two T-shirts.

Significant differences were observed in their comfort ratings after 20 min of running, after 30 min of running, and 10 min after resting (all $P < 0.05$). The Vented Design T-shirt was rated as being more cool, dry, and comfortable than the Vented T-shirt after 10 min of running (i.e., the second assessment). The mean scores of all three comfort items were higher for the Vented Design T-shirt. From the mean scores listed in Table 2, the ratings of body coolness and skin dryness decreased rapidly for the Vented T-shirt. A decrease was also found for the Vented Design T-shirt, but the reduction was comparatively smaller, implying that this T-shirt's performance was more consistent. This was also supported by the mean skin temperature of all subjects. A significant difference was observed for every minute from 10 min of running until the end of the test (10 min after resting), with all P values less than 0.05. Although the shell fabric used to make the Vented T-shirt had high air and moisture vapour permeability, the data revealed that the Vented Design T-shirt had improved air ventilation. The subjects commented that the cooling effect of the mesh panels on the Vented T-shirt was limited to specific body areas, in contrast to the overall air ventilation of the Vented Design T-shirt. Furthermore, the fabric contacted the skin during running, which limited the air gap between the fabric and skin surface.

Over the whole testing period, the mean skin temperature of subjects wearing the Vented Design T-shirt was on average lower than that of subjects wearing the Vented T-shirt. In the 10–30 min running period, the average mean skin temperature of the subjects wearing the Vented T-shirt was 31.6 °C, whereas the average mean skin temperature of those wearing the Vented Design T-shirt was 30.63 °C. This finding implies that the air gap between the fabric and the skin surface was increased or maintained by the spacer block design, which reduced the skin temperature. However, this difference was not significant during the first 10 min of running. Therefore, for short periods of exercise (10 min or less in this wearer trial), no significant difference was observed between the cooling and drying effects of the two T-shirts. In addition, the spacer blocks and their additional weight negatively influenced the overall comfort level of the wearer.

5. Conclusions and Suggestions for Future Research

Moisture management and high-air permeability fabrics are widely used for athletic clothing. These special materials are designed to wick away sweat, keeping the body dry and cool. However, these fabrics themselves cannot guarantee ventilation in the air gap between the fabric and the skin surface. This study proposed a T-shirt design to increase the air gap by attaching spacer blocks along the vented panels and demonstrated that this design improved the ventilation of the T-shirt during exercise. Heat and moisture transfer was more effective in the T-shirt with spacer blocks than in that with only flat vented panels. The T-shirt with flat vented panels did not enhance the pumping effect, because the mesh fabric clung to the skin, blocking air circulation between fabric and the skin surface. Therefore, the Vented T-shirt did not result in cooling after the subjects had started sweating. The participants were not accustomed to the feeling of spacer blocks on the underside of the T-shirt. Therefore, a different assembly method using softer and lighter spacer material and different spacer block constructions, should be explored in additional studies. The current prototype was not ready for commercialisation at the end of the study. In the future, more design variations should be tested using both subjective and objective measurement techniques.

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