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# Influence of Sportswear Fabric Properties on the Health and Performance of Athletes

## Abstract

The main goal of this work was to study the Influence of sportswear fabric properties on the physiological responses and performance of athletes. The influence of three different types of sportswear fabrics on the physiological response and performance of volunteers in sports conditions was investigated. The fabrics and garments tested were made of 100% cotton, a 65/35 polyester/cotton blend and 100% polyester fibres. Seven volunteer were selected to wear the sportswear during the physical exercise assigned and their physiological responses were tested. The results of the study show a statistically significant effect on the athletes' physiological responses and performance parameters measured for the different types of sportswear tested. The sample with 100% polyester produced the best physiological responses and performance from the athletes. This effect can be related to better moisture management, which reflects the amount of relative water vapour permeability (68%) and lower thermal conductivity. This will enhance the body's temperature regulation leading to increase athletes' cardiorespiratory fitness and performance. The results also show the high correlation between the sportswear fabrics properties and athletes' physiological responses and performance, except the relationship between the end-tidal partial pressure of oxygen (PETO<sub>2</sub>) and fabric thickness (h), air permeability (AP) and thermal resistance (r), which are not highly correlated. The other correlation values vary between ( $\pm 0.62$  and  $\pm 1$ ).

**Key words:** sportswear fabrics, comfort properties, athletes' physiological responses, performance of athletes.

## Introduction

In active and endurance sports, the performance of a sportswear is synonymous with its comfort characteristics. The wear comfort of sportswear is an important quality criterion that affects performance, efficiency and well-being. For instance, an active sportsperson that wears poor breathable sportswear will experience an increase in their heart rate and rectal temperature more rapidly than one who wears breathable sportswear [1 - 3]. Hence fabric breathability (moisture and air permeability) and thermal properties should be tailored in order to meet the requirements of sportswear. The type of fibre (natural, synthetic or blend), the fabric structure (woven or knitted) and fabric constructions (densities of yarns, fabric thickness, etc) are amongst the parameters that may affect the thermal and breathability properties of sportswear fabrics. Studying these properties of sportswear fabrics is important, but, at the same time, it is so important to connect them with the performance of an athlete when wearing this kind of clothes during the course of exercise. Generally four different aspects can define wear comfort: physiological, psychological, ergonomic and skin sensorial aspects [4, 5]. Thermal insulation, breathability and the heat and moisture transportation process are a fabric's physical properties that can affect the comfort sensation from a physiological point of view. The psy-

chological aspect can include personal preferences, fashion, ideology, etc. Ergonomic wear comfort depends mainly on the garment's pattern and fabric elasticity, which influence the clothing fit and freedom of movement. Skin sensorial wear comfort characterises mechanical sensations caused by the direct contact of clothes to skin (e.g. softness, smoothness).

For sportswear one can find that the physiological aspect is extremely important because of its major effect on the efficiency and performance of athletes. Thermal comfort refers to sensations of hot, cold, or dampness in clothes and is usually associated with environmental factors such as heat, moisture, and air velocity [6]. Water/moisture vapour transmission and air permeability are important factors that affect the thermal comfort of sportswear. Fibre content and fabric geometry are two primary factors that may affect water/moisture vapour transmission [7]. Several studies have been conducted on the role of determining thermal parameters in the human body during the performance of exercise [8]. Investigators have found that hydrophilic textiles, such as cotton seem to have beneficial influences on the thermal physiological response as well as on overall comfort during and after exercise compared to hydrophobic textiles such as polyester, nylon and polypropyl-

ene. A rise in the core temperature, heart rate, amount of sweat, and metabolic heat production was found to be greater in subjects wearing clothing ensembles made of weak hygroscopic material versus clothing ensembles made of strong hygroscopic material in various exercise conditions [9, 11].

Textile material used in underwear in a normal work garment has a small, but insignificant influence on the wet heat dissipation during intermittent exercise in a cool environment [10]. Investigation of the influence of different types of sportswear made from cellulosic man-made fibers and polyester fibers on the energy cost of the effort of volunteers in sports conditions done by Malgorzata Zimniewska et al. [12].

The human body sweats during exercise to maintain its internal temperature, where its physiological activities can run efficiently. This process is called heat acclimatisation, which improves thermal comfort, increases heat tolerance and reduces heat strain [13]. On the other hand, the presence of moisture within clothing can increase the wearer's heat loss dramatically [14, 15]. Heat and moisture transport through clothing involves complex processes and is coupled with evaporation, condensation and the sorption and desorption of moisture [16 - 18]. Transfer of heat away from the body is

affected by various factors including air movement (i.e., wind), relative humidity, sunshine, and clothing. Clothing affects air circulation over the skin as well as evaporative cooling and moisture regulation. If moisture cannot evaporate from the skin, both the skin temperature and discomfort increase [19]. Adequate ventilation or air movement can reduce the insulation properties of clothing by 5 to 50% [20].

Researchers investigated the influence of different types of sportswear on the physiological parameters and energy cost of volunteers in sports conditions while wearing sportswear made from 100% TENCEL® fibres, 100% polyester fibres and TENCEL®/polyester blend. The study showed that garments made from a blend of Polyester and TENCEL® had the most favorable effect on the energy cost of physical work, as well as on the time of compensation and efficiency of the volunteers [21]. Other researchers compared the effect of wearing clothes made of natural fibres to clothes made of synthetic fibres on thermoregulation in humans. They found that the influence of the material type is especially seen during physical effort where muscular activity increases, resulting in an increase in heat produced by the body, which affects the heat balance in the human body [22, 23]. Some other research concerned measurements of body temperature, the heart rate, systolic and diastolic blood pressure, oxygen consumption, skeletal muscle activity and the reaction time [24 - 28]. Another research work focused on analysing the influence of clothing materials on human physiology and thermal comfort. They compared the effect of wearing clothes made of natural fibres (wool) and synthetic fibres (acrylic) on some psychomotor parameters of human volunteers during and after physical effort [29]. They found that the clothing material has an influence on the respiratory and cardiovascular system, whereas there was no effect on psychomotor parameters. In addition, the well-being feeling of wearing clothes made of acrylic fibres after the physical effort was worse compared to the woolen clothes [29]. Another study examined the effects of wearing compression tights on oxygen cost and sensation responses during running exercise compared to the classic elastic variety and conventional shorts. They found that wearing compression tights during running exercise may enhance the overall circulation and decrease muscle

**Table 1.** Sample characteristics.

| Samle No. | Fibre composition        | Fabric porosity | Fabric thickness, mm | Fabric surface weight, g/m <sup>2</sup> |
|-----------|--------------------------|-----------------|----------------------|---|
| 1         | 100% cotton              | 0.85            | 0.725 ± 0.01         | 168                                     |
| 2         | 65% polyester/35% cotton | 0.81            | 0.743 ± 0.01         | 203                                     |
| 3         | 100% polyester           | 0.79            | 0.598 ± 0.01         | 127                                     |

oscillation to promote lower energy expenditure [30, 31].

In this work, three samples of commercial sportswear were selected to represent three different fibre compositions. All samples were made of single jersey knitted fabrics with 100% cotton fibres, 35/65 cotton polyester blend fibres and 100% polyester fibres. Thermal characteristics, air and moisture permeability properties were measured for all samples. Then group of volunteers, all sportspersons, were selected to wear the samples in order to evaluate their physical performance during the exercise assigned.

## Materials and methods

Fabric thermal resistance, thermal conductivity, thermal absorptivity, heat flow, relative water vapour permeability and air permeability are physical properties that need to be measured to obtain a better understanding of heat and water transportation through fabric. Three groups of knitted fabric samples made from fabrics that are commercially used for sportswear were chosen for this work. The fibre composition of each group was 100% cotton fibres, 65/35 polyester/cotton blend fibres and 100% polyester fibres. The selection criterion of the fabric types was based on choosing fabrics with the same structure, same finishing process, relatively close fabric thickness and relatively close fabric porosity. All samples were dyed knitted fabrics with the same fabric structure - single jersey. The average fabric porosity, fabric thickness and fabric weight per unit area for the three groups of samples are listed in *Table 1*.

### Measuring the thermal comfort properties of garments

Thermal properties are among the most important features of textiles. Most of the studies carried out have been devoted to measuring static thermal properties such as thermal conductivity, thermal resistance, and thermal diffusion. Kawabata & Yoneda pointed out the importance of the so-called 'warm-cool feeling' [32]. This property tells us whether a user feels 'warm' or 'cool' upon the first

brief contact of the fabric with the human skin. Also, Hes introduced the term 'thermal absorption' as a measure of the 'warm-cool feeling' of textiles [33, 34]. The three samples of this study were tested using the computer-controlled ALAMBETA device to measure thermal resistance, thermal conductivity, thermal absorptivity, fabric thickness and heat flow. The ALAMBETA device enables rapid measurement of the steady-state and transient-state thermal properties of any plain compressible non-metallic materials such as textile fabrics, plastic or rubber foils, and paper products [35, 36].

### Measuring relative water vapour permeability in %

The samples were tested in a steady state isothermal condition to measure the relative water vapour permeability (RWVP%) using a PERMETEST device, which was developed by Hes [37, 38]. The PERMETEST is a new fast response measuring instrument (skin simulator) that measures the water vapour permeability of textile fabrics, garments, nonwoven webs and soft polymer foils by measuring the evaporative heat resistance utilising heat flux sensing. The temperature of the measuring head is maintained at room temperature for isothermal conditions. Then heat supplied to maintain the temperature of the measuring head, where the water supplied gets evaporated, is measured. The heat supplied to maintain a constant temperature with and without the fabric mounted on the plate is measured.

### Evaluating the physical effort of the athletes

Seven professional athletes, healthy males, were selected out of 16 professional athletes volunteering their services to undergo the testing. All volunteers were informed about the aim of the examination and its risk, and they agreed to participate in the study. Each subject was initially screened for major medical problems or prescription medication via a written questionnaire. A subject was deemed fit if he did not have a serious medical condition and if he regularly

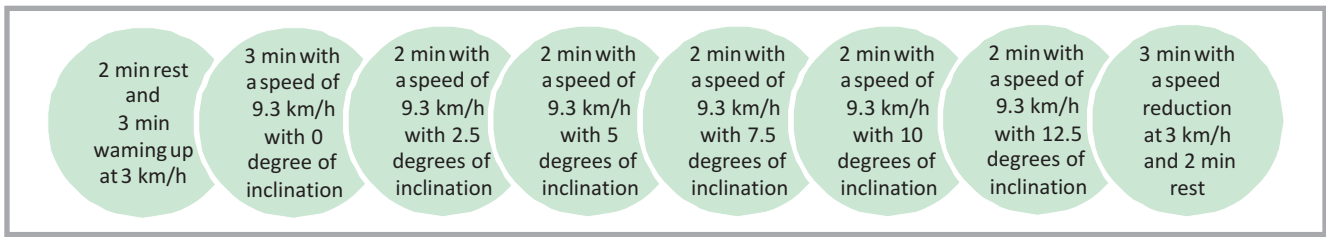


Figure 1. Experiment scheme.

trained on a treadmill. After the subject was accepted as a potential candidate, his fitness was assessed on a treadmill using a progressive speed test to make sure that all the seven athletes had reached almost the same level of fitness to reduce the variability of the physiological response.

Seven volunteers aged 18 to 20 years with a similar body constitution, within a weight range of 65 : 75 kg and height range of 171 : 180 cm. The subjects were instructed to have no food for the three hours prior the exercise session and not to participate in any physical exercise for 72 hours prior to the exercise session. On the other hand, the subjects were instructed to maintain their regular fluid and food intake during the course of the investigation and to be normally hydrated prior to each exercise session. During the exercise session, each subject was attached to a heart rate monitor (nSpire Health GmbH). Every subject wore one type of test clothing during one day of the experiment and other types of clothes in the following two days. Each type of set was worn on three different days in hot weather ( $30 \pm 2$  °C and RH  $60 \pm 5$  °C). Finally, seven full measurements were performed for each type of sportswear in accordance with the continuous 8 steps

of the experiment scheme, shown in **Figure 1**.

Each subject covered a distance of 2.35 km during the exercise session. The measurement monitored the parameters of the respiratory and circulatory system to estimate the physical performance of each subject wearing different types of sportswear fabrics. Physiological performance was tested using a nSpire Health GmbH device, which gives detailed information during an exercise session about oxygen consumption ( $VO_2$ ), carbon dioxide production ( $VCO_2$ ), the end-tidal partial pressure of oxygen ( $PETO_2$ ), the end-tidal partial pressure of carbon dioxide ( $PETCO_2$ ) and the heart rate.

## Results and discussion

### Thermal and moisture characteristics

The thermal properties of the three types of sportswear fabrics were measured, the average values of which are listed in **Table 2**. The results show that the sample with 100% polyester fibres has the lowest thermal conductivity ( $\lambda$ ), thermal absorptivity ( $b$ ), thermal resistance ( $r$ ) and heat flow ( $q$ ). In addition, air permeability (AP) and relative water vapor permeability (RWVP%) were measured for the three samples, listed in **Table 3**. Air per-

meability (AP) is defined as the rate of air flow passing perpendicularly through a known area under a prescribed air pressure. The relative water vapor permeability (RWVP) is defined as the rate of water vapour transmission through a fabric. The results listed in **Table 3** show that the sample with 100% polyester fibres is the most permeable and has the highest value of water vapour permeability compared to the others. Fabric porosity ( $FP$ ) for the three samples is calculated using data of the fabric thickness ( $h$ ), weight per unit area ( $W$ ), listed in **Table 1** (see page 83), and fabric density ( $\rho$ ), following the relation as follows:

$$FP = 1 - \left( \frac{W \text{ (g/cm}^2\text{)}}{h\rho \text{ (cm} \times \text{g/cm}^3\text{)}} \right)$$

Thermal conductivity ( $\lambda$ ) indicates the ability of fabric to conduct heat. In general, the thermal conductivity of fibres is higher than that of entrapped air in fabric [39]. Therefore, as the amount of entrapped air in the fabric structure increases, the fabric provides lower thermal conductivity and higher thermal insulation. Thus the results in **Table 2** show that the sample with 100% polyester fibres has the lowest thermal conductivity and, hence, a higher amount of entrapped air compared to the other two samples. Therefore this sample has better thermal insulation compared to the other two samples.

Thermal absorptivity ( $b$ ) indicates the warm-cool feeling of fabrics [40]. When a human touches a fabric that has a different temperature from the skin, heat exchange occurs between the hand and fabric. If the thermal absorptivity of a fabric is high, it gives a cooler feeling at first contact [41]. Physically, thermal absorptivity ( $b$ ) is a function of the thermal conductivity, density and specific heat of a fabric ( $c$ ) as follows:  $b = (\lambda \rho c)^{1/2}$  [42]. However, this relation applies only for a short time of thermal contact between a fabric and skin. As time passes,

Table 2. Thermal properties of fabrics.

| Fabric type              | Thermal conductivity ( $\lambda$ ), W/mK | Thermal absorptivity ( $b$ ), $W \cdot m^{-2} s^{1/2} \cdot K^{-1}$ | Thermal resistance ( $r$ ), $K \cdot m^2/W$ | Heat flux density ( $q$ ), $W/m^2$ |
|--------------------------|--|---|---|------------------------------------|
| 100% cotton              | $22.7 \pm 0.07$                          | $56.0 \pm 1.62$   | $31.98 \pm 0.60$                            | $0.0104 \pm 0.00025$               |
| 65% polyester 35% cotton | $21.4 \pm 0.08$                          | $51.3 \pm 2.36$   | $34.44 \pm 0.47$                            | $0.0094 \pm 0.00024$               |
| 100% polyester           | $19.3 \pm 0.09$                          | $47.5 \pm 2.02$   | $27.74 \pm 0.63$                            | $0.0088 \pm 0.00025$               |

Table 3. Fabric relative water vapour permeability and air permeability for the three samples.

| Fabric type              | Vapour and air permeability |                                       |
|--------------------------|-----------------------------|---------------------------------------|
|                          | Air permeability, $l/m^2/s$ | Relative water vapour permeability, % |
| 100% cotton              | $1403 \pm 40.1$             | $56.14 \pm 0.289$                     |
| 65% polyester 35% cotton | $1416 \pm 18.1$             | $52.98 \pm 0.271$                     |
| 100% polyester           | $1670 \pm 13.3$             | $68.36 \pm 0.710$                     |

the heat flow ( $q$ ) loses its dynamical (transient) character and its level falls to a steady state [43] and thermal resistance ( $r$ ) takes place for the thermal characteristics. Thermal resistance indicates the effectiveness of fabric insulation. Physically, thermal resistance ( $r$ ) is a function of the thermal conductivity ( $\lambda$ ) and thickness ( $h$ ) of a fabric ( $r=h/\lambda$ ). The thermal resistance of a certain fabric is inversely proportional to its thermal conductivity [44]. At this point, it can be concluded that the sample with 100% cotton fibres has a higher thermal absorptivity ( $b$ ) and a higher heat flow ( $q$ ) as well, indicating a relatively cooler feeling when it touches human skin for a few seconds, which may give a more pleasant feeling compared to others. As time goes by, thermal resistance ( $r$ ) takes place, which indicates the fabric's insulation. Thus the sample with 100% cotton fibres has better thermal insulation compared to the others. This conclusion contradicts the previous one, which depends only on thermal conductivity. Therefore thermal conductivity can be used to evaluate a fabric's thermal insulation for the same fabric type. However, thermal absorptivity ( $b$ ), thermal resistance ( $r$ ) and heat flow give more details to evaluate thermal insulation for different fabrics because of considering the specific heat of a fabric and its thickness. This conclusion also agrees with the values of fabric porosity calculated, listed in **Table 1** (see page 83).

Statistical analysis of variance (ANOVA) was conducted for all properties measured to test the significance of differences between the three samples. The results listed in **Table 4** show that there are significant differences between the three samples for thermal absorptivity ( $b$ ), thermal resistance ( $r$ ) and heat flow ( $q$ ). Thus, at this point it is statistically proven that there is difference between the effective insulation of the three samples. In addition, there are highly significant differences between the three samples for air permeability (AP) and relative water vapor permeability (RWVP%).

Water or vapour permeability is an essential property for fabrics used in sportswear. The human body has its own mechanism for cooling itself when overheating through sensible perspiration in the form of liquid sweat. Body heat evaporates the perspiration; however, if the vapor cannot escape to the surrounding atmosphere, the relative humidity inside the clothing will increase, which will cause

**Table 4.** ANOVA effect of dependance variable (fabric type) and athletes' physiological responses and performance.

|                     |                | Sum of squares | df | Mean square | F       | Sig.  |
|---------------------|----------------|----------------|----|-------------|---------|-------|
| VCO <sub>2</sub>    | Between groups | 14.650         | 2  | 7.325       | 55.370  | 0.000 |
|                     | Within groups  | 2.381          | 18 | 0.132       |         |       |
|                     | Total          | 17.032         | 20 |             |         |       |
| VO <sub>2</sub>     | Between groups | 0.729          | 2  | 0.364       | 3.501   | 0.052 |
|                     | Within groups  | 1.874          | 18 | 0.104       |         |       |
|                     | Total          | 2.603          | 20 |             |         |       |
| RER                 | Between groups | 0.539          | 2  | 0.270       | 104.229 | 0.000 |
|                     | Within groups  | 0.047          | 18 | 0.003       |         |       |
|                     | Total          | 0.586          | 20 |             |         |       |
| VO <sub>2</sub> /kg | Between groups | 149.687        | 2  | 74.843      | 8.284   | 0.003 |
|                     | Within groups  | 162.626        | 18 | 9.035       |         |       |
|                     | Total          | 312.312        | 20 |             |         |       |
| PETO <sub>2</sub>   | Between groups | 38.000         | 2  | 19.000      | 4.0156  | 0.033 |
|                     | Within groups  | 82.286         | 18 | 4.571       |         |       |
|                     | Total          | 120.286        | 20 |             |         |       |
| PETCO <sub>2</sub>  | Between groups | 689.238        | 2  | 344.619     | 86.844  | 0.000 |
|                     | Within groups  | 71.429         | 18 | 3.968       |         |       |
|                     | Total          | 760.667        | 20 |             |         |       |
| HR                  | Between groups | 740.095        | 2  | 370.048     | 11.774  | 0.001 |
|                     | Within groups  | 565.714        | 18 | 31.429      |         |       |
|                     | Total          | 1305.810       | 20 |             |         |       |

a wet feeling on the skin and an uncomfortable sensation [45, 46]. The sample with 100% polyester fibres has the highest relative water vapour permeability, followed by the one with 65/35 polyester cotton blended fibres. The sportswear made of 100% cotton fibres may absorb perspiration effectively but it keeps it close to the skin. When the wearer exerts physical effort (sports), the excess of sweat remains accumulated in the cotton fabric, causing thermal discomfort. Also the fabric might be soaked with sweat and has lost its thermal insulation.

#### Physiological response and performance

At this level, these properties are not sufficient to evaluate the three samples of sportswear. It was essential to evaluate the influence of the three samples on the performance of the athletes during the course of exercise. As mentioned previously, the physiological performance of the athletes was tested using a nSpire Health GmbH device to understand the influence of the fabric composition. The device gives detailed information during the course of exercise about oxygen consumption (VO<sub>2</sub>), carbon dioxide production (VCO<sub>2</sub>), the end-tidal partial pressure of oxygen (PETO<sub>2</sub>), the end-tidal partial pressure of carbon dioxide (PETCO<sub>2</sub>), and the heart rate.

Oxygen consumption (VO<sub>2</sub>) is measured to indicate the volume of oxygen that is

used by human body to convert the energy from eaten food into molecular energy, called Adenosine Tri-Phosphate (ATP), which is used at the cellular level. During exercise, muscles work harder than normal and therefore they require more energy than normal. Hence, increasing the exercise intensity will lead to an increase in muscular oxygen demand and ultimately corresponds to an increasing VO<sub>2</sub>, which explains why breathing gets progressively faster and deeper as the exercise intensity increases [47, 48]. It is known that the absolute VO<sub>2</sub> peak is strongly influenced by a change in body size, thus it is more appropriate to normalise the VO<sub>2</sub> to the body mass since it will reveal the true oxygen consumption by fat free tissue [49].

Carbon dioxide output (VCO<sub>2</sub>) refers to the amount of carbon dioxide exhaled from the body per unit time. It continues to rise after the completion of exercise as the muscles continue to eliminate carbon dioxide before returning to baseline levels after several minutes. Note that carbon dioxide output can differ from carbon dioxide production by the body's metabolic processes, but in a steady state both are the same. The anaerobic metabolism supplies the excessive demand for energy, but it is accompanied by the production of carbon dioxide (CO<sub>2</sub>) and lactates. An excessive anaerobic metabolism reduces the stored energy faster than their renewal process. Carbon dioxide

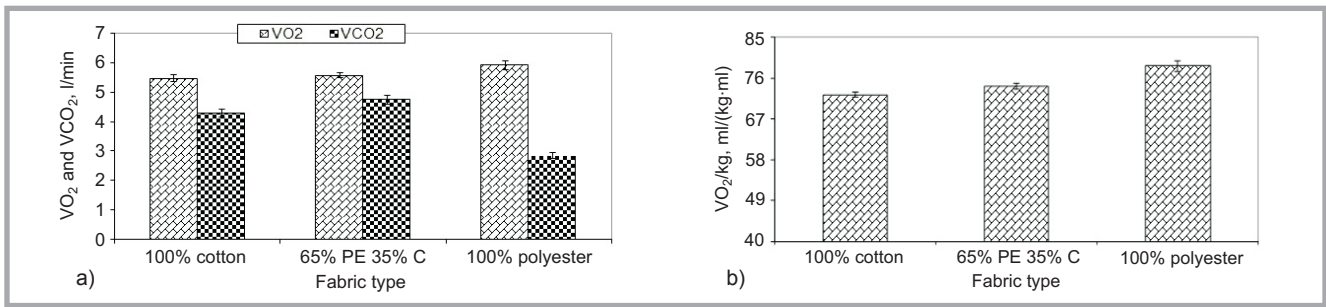


Figure 2. Mean values of gas exchange ( $VCO_2$ ,  $VO_2$  and  $maxVO_2/kg$ ) for the three fabric types.

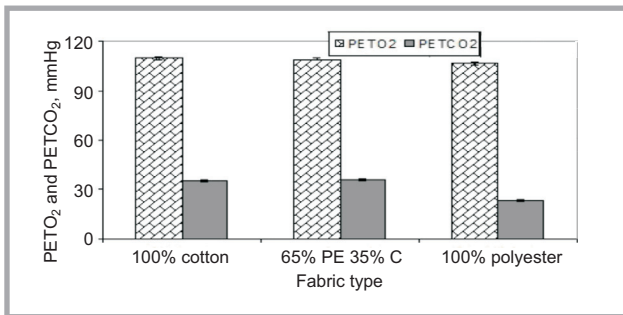


Figure 3. Mean values of blood gases with standard error-bars for the three fabric types.

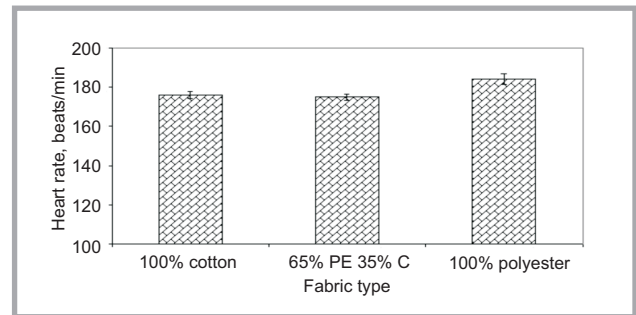


Figure 4. Mean values of the heart rate with standard error-bars for the three fabric types.

(CO<sub>2</sub>) and lactate production can interfere with the aerobic metabolism and lead to tiredness.

The End-Tidal Partial Pressure of Oxygen (PETO<sub>2</sub>) is measured at the end of exhalation in mm Hg. This value is typically around 100 - 110 mm Hg at rest. In normal individuals it will remain at or near this level with progressive exercise until the ventilatory threshold is reached, then it will increase due to the increase in minute ventilation.

The End-Tidal Partial Pressure of Carbon Dioxide (PETCO<sub>2</sub>) is measured at the end of exhalation (mm-Hg). This value is typically around 35 - 40 mm Hg at rest. In normal individuals it will remain at or near this level with progressive exercise until the ventilatory threshold is reached,

then it will decrease. Failure to decrease or an increase in this value is a sign of person with limited ventilatory capacity or neuromuscular impairment. The lower the values thereof the better for the athlete for both PETO<sub>2</sub> and PETCO<sub>2</sub>.

Results in Figure 2 show that the sample with 100% polyester fibres has the highest VO<sub>2</sub>/kg max (78.8 ml/(kgmin), VO<sub>2</sub> (5.91 l/min), and the lowest VCO<sub>2</sub> (2.84 l/min) and RER (0.48). The respiratory Exchange Ratio (RER) is a parameter that represents the ratio between VCO<sub>2</sub> and VO<sub>2</sub> (VCO<sub>2</sub>/VO<sub>2</sub>). Carbon dioxide production during aerobic metabolism comes from the chemical combination of carbohydrate or fatty acid with oxygen and the consequent production of carbon dioxide and water. The 100% cotton has the

lowest VO<sub>2</sub>/kg max (72.4 ml/(kg-min), and VO<sub>2</sub> (5.47 l/min) and the middle value of VCO<sub>2</sub> (4.28 l/min). This effect can be related to the better moisture management, which is reflected by its higher fabric relative water vapour permeability in %, 69.8%, fabric air permeability, and lower thermal conductivity, supporting the body's temperature regulation and leading to an increase in the athlete's cardiorespiratory fitness level and performance. From a physiological point of view, the higher the level of max VO<sub>2</sub>/kg and VO<sub>2</sub>, ATP and the lower the level of VCO<sub>2</sub> and RER the more favorable for the human organism. This will allow the body to conduct more intensive physical exercise without disturbing homeostasis and reaching fatigue. The advantage of using 100% polyester over the other samples is that it provides athletes with a higher VO<sub>2</sub> and lower VCO<sub>2</sub>.

Table 5. Correlation coefficients between the fabric thickness ( $h$ ), fabric porosity ( $FP$ ), relative water vapour permeability (%) of the fabrics, and between the fabric air permeability ( $AP$ ), thermal parameters and athletes' physiological responses and performance ( $VO_2/kg$ ,  $HR$ ,  $VCO_2$ ,  $VO_2$ ,  $RER$ ,  $PETO_2$  and  $PETCO_2$ ).

| Fabric properties | Athletes' physiological responses |       |       |                  |                 |                   |                    |
|-------------------|-----------------------------------|-------|-------|------------------|-----------------|-------------------|--------------------|
|                   | VO <sub>2</sub> /kg               | HR    | RER   | VCO <sub>2</sub> | VO <sub>2</sub> | PETO <sub>2</sub> | PETCO <sub>2</sub> |
| <b>h</b>          | -0.94                             | -1.00 | 0.99  | 0.98             | -0.97           | -0.46             | 1.00               |
| <b>Fp</b>         | -0.95                             | -0.75 | 0.70  | 0.66             | -0.92           | -0.91             | 0.78               |
| <b>AP</b>         | 0.97                              | 0.99  | -0.98 | -0.96            | 0.98            | 0.54              | -0.99              |
| <b>RWVP%</b>      | 0.99                              | 0.85  | -0.80 | -0.77            | 0.97            | 0.83              | -0.87              |
| <b>λ</b>          | -1.00                             | -0.88 | 0.84  | 0.82             | -0.99           | -0.79             | 0.90               |
| <b>b</b>          | -0.96                             | -0.78 | 0.73  | 0.69             | -0.94           | -0.89             | 0.80               |
| <b>r</b>          | -0.79                             | -0.96 | 0.98  | 0.99             | -0.83           | -0.15             | 0.95               |
| <b>q</b>          | -0.93                             | -0.72 | 0.66  | 0.62             | -0.90           | -0.93             | 0.75               |

Figure 3 shows the blood gases, which is a measurement of how much oxygen and carbon dioxide is in the subject's blood, helping to determine the effectiveness of oxygen therapy. The test also provides information about the body's acid/base balance, which can reveal important clues about lung and kidney functioning and the body's general metabolic state. The values of PETCO<sub>2</sub> for the 100% polyester clothing varies between 18 and 25 mm-Hg, showing a high reduction in the PETCO<sub>2</sub> level compared to

the other types of clothing. **Figure 4** shows the relation between the heart rate (beat/min) for the three different type of clothing. The maximum heart rate was for the 100% polyester clothing, followed by the 100% cotton clothing, and the lowest value was for the blended one.

Statistical analysis of variance (ANOVA) was conducted for all measured properties to test the significance of differences between the three fabric types. The results listed in **Table 4** (see page 85) show significant differences between the three samples for  $PETO_2$  and  $VO_2$ . In addition, there are highly significant differences between the three samples for the remaining parameters.

The results in **Table 5** show the spearman correlation coefficients, calculated to study the correlation between attributes, which are assessed subjectively. The results show a high correlation between fabric thickness, fabric porosity, fabric air permeability, the relative water vapour permeability, fabric thermal properties and athletes' physiological responses and performance ( $VO_2/kg$ , HR,  $VCO_2$ ,  $VO_2$ , RER,  $PETO_2$   $PETCO_2$ ), except the relationship between  $PETO_2$  and  $h$ ,  $AP$  &  $r$ , which is not highly correlated. The other correlation values vary between ( $\pm 0.62$  and ( $\pm 1$ ), which indicates a high and perfect correlation, respectively.

## ■ Conclusions

The results showed that the sample with 100% polyester fibres demonstrated better physiological responses and performance by athletes compared to the other two fabric types. This result was related to the better moisture management, which was reflected in the amount of relative water vapour permeability (68%) and lower thermal conductivity, which support the body's temperature regulation. Better moisture management increased the athletes' cardiorespiratory fitness and performance. The results also showed that the subjects who wore the sample with 100% polyester fibres had the lowest carbon dioxide production ( $VCO_2$ ), end-tidal partial pressure of carbon dioxide ( $PETCO_2$ ) and a higher respiratory exchange ratio (RER), which indicated better physical performance. Statistical analysis showed a high correlation between fabric thickness, fabric porosity, fabric air permeability, the relative water vapour permeability, fabric thermal properties and athletes' physio-

logical responses, except the relationship between the end-tidal partial pressure of oxygen ( $PETO_2$ ) and fabric thickness ( $h$ ), air permeability ( $AP$ ) and thermal resistance ( $r$ ), which are not highly correlated. Also there was a high correlation between both the moisture and thermal properties of sportswear and between the athletes' cardiorespiratory fitness level and performance.

The sample made of 100% cotton fibres, which used to be favourable for sportswear, showed some shortcomings in terms of moisture management. Although perspiration is absorbed well, it remains close to the body, giving an unpleasant feeling, or thermal discomfort in other words. Fabric soaked with sweat begins to lose thermal insulation, leading to so-called post-exercise chill. On the other hand, the sample with 100% polyester transports perspiration quickly and effectively away from the body as its relative water vapour permeability was higher than the other two samples. In addition, it has the lowest thermal conductivity, thermal absorptivity, heat flow and has higher thermal diffusivity.

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