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THE ROLE OF TEXTILE MATERIAL IN CLOTHING ON THERMOREGULATORY RESPONSES TO INTERMITTENT EXERCISE

Ruth NIELSEN[1*] & Thomas L.ENDRUSICK[2]

[1] National Institute of Occupational Health
S-17184 Solna, Sweden
[2] U.S.Army Research Institute of Environmental Medicine
Natick, MA01760-5007, USA

The physiological effect of different textile material used in the underwear of an ensemble in the development of over heating or chilling in humans during intermittent exercise in a cold environment was studied. Underwear prototypes manufactured from five different fiber type materials were tested as a part of a typical, standardized clothing system on eight male subjects (T_a=5°C, T_{dp}=-3.2°C and V_a=0.3 $m \cdot s^{-1}$). The test consisted of a twice repeated procedure of 40 min cycle exercise (54% of VO_2max) followed by 20 min of rest. Differences were found in both the amount of non-evaporated and evaporated sweat with the five different underwear configurations. No significant difference could be detected in esophageal temperature, skin temperatures, skin wettedness, and onset time of sweating. It is concluded that the 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.

1. INTRODUCTION

Working conditions have in many areas been improved parallel to the technological development in the society. However, exposure to a cool or cold work environment is still a daily reality for many industrial and outdoor workers. After-exercise-chill is a common reason for thermal discomfort in these environments [1, 2]. The phenomena is especially connected to dressed people performing intermittent exercise, as it is related to the interplay between the physiological reactions of the human body and the clothing system.

Common used clothing ensembles for cold environments comprises two or more clothing layers: underwear, possibly middle layers, and an outer clothing layer. Each layer has its own thermal function. The main part of the skin surface is not in contact with the ambient environment, but with the micro environment under the clothing and the underwear itself. Thus, underwear has a special function in relation to the sensation of the fabric-to-skin interface and may also be of importance for the resulting micro environment over the skin. Advertisements for thermal underwear claims benefits of different textile material in both insulating power,

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vapor transmission and wicking ability "leaving only dryness and warmth next to the skin even while you are perspiring heavily in winter or summer". From this it seems possible that a proper use of underwear could diminish or hinder the development of after-exercise-chill.

The thermal resistance of an undergarment is quite small as compared to the overall resistance of a total garment. In the literature [3] addition of thermal underwear to a clothing system is supposed to add little extra warmth or protection for the wearer, and in terms of differences in intrinsic thermal resistance these differences are insignificant as long as the fit and design is kept the same [4].

The latent heat dissipation from the skin to the environment takes mainly place as diffusion resulting from a difference in vapor pressure [5]. This diffusion is restricted by the resistance of the clothing layers. Water/sweat can also be transported in the textile fibers themselves, on the surface of the fibers or by capillary action in the yarn. The transport of water by capillary action is negligible in natural fibers; however, textiles made of polypropylene and treated polyester fibers, that do not take up water in the textile fibers, have a considerable ability to transfer water by capillary action. In natural fibers the water transport in the textile fibers themselves is most important. There are important differences in the water/sweat absorbing ability of textile fibers [6]. Textile fibers will absorb and desorb water when the humidity around them changes, and reach an equilibrium with their environments. Wool is able to take up and keep significantly more water/sweat in the fibers than any other textile and it takes thus longer time before the air in the textile cavities is exchanged with water during e.g. sweat bursts. Also the ab-/desorption processes means that an exchange of heat energi takes place between fibers and air. By measurements on a thermal manikin release of 20 $W \cdot m^{-2}$ by a light woolen garment when changing from a 5% to a 70% rh environment has been shown [4]. This has the same effect as an increase of 0.9 clo in the thermal insulation or walking into a room with a 6°C higher air temperature. The release of heat was considerably less when the same ensemble was made of cotton/polyester (11 $W \cdot m^{-2}$), and even smaller when it was made of polyester/polyamide (7 $W \cdot m^{-2}$).

From a theoretical point of view the difference in water absorbing and water transporting ability of textiles such as wool, cotton, polyester and polypropylene, can be expected to produce both differences in wetting-time of underwear and other clothing layers, and differences in energy exchange caused by condensation and evaporation processes, and thus finally contribute to the degree of sweating during exercise, the after-exercise-chill and cold discomfort generally. The purpose of the present study was on persons performing intermittent exercise in an environment causing both periods of sweating and chilling, to investigate if underwear manufactured in different textile material resulted in different thermoregulatory responses.

2. MATERIALS AND METHODS

2.1. Garment Description

Underwear manufactured in a 1-by-1 rib knit from 5 different fiber type materials (cotton (F1), wool (F2), polypropylene (F3), and polyester with two different kinds of surface treatment (Capilene=F4 & Thermax=F5)) were evaluated. Measurements of fabric thickness were performed on samples of cloth [7]: F1=0.94 mm, F2=0.97 mm, F3=0.84 mm, F4=0.79 mm, F5=0.69mm.

All five underwear prototypes were tested as a part of a typical, standardized clothing system on human subjects. The clothing system comprised the two-piece long-sleeved/long-legged underwear, a Battle Dress Uniform (BDU) shirt and trousers (50% cotton/50% nylon), woolen socks, gym shoes, and woolen gloves (Figure 1). Before any testing was done, all clothing systems were laundered 5 times without soap in a washing machine and drip-dryed in between.

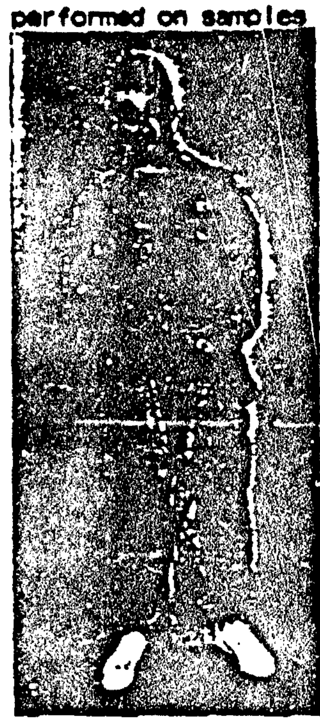


Figure 1. Clothing system

2.2. Subjects

Eight healthy males volunteered for the present series of experiments. They had an average (±s.d.) age of 25 ±3.7 years, weight of 71 ±7.2 kg, height of 176 ± 3.3 cm, DuBois surface area (A_{Du}) of 1.86 ± 0.104 m^2, $\dot{V}O_2$max of 3.48±0.637 l $O_2 \cdot min^{-1}$ and percentage body fat of 14 ±4.6%.

2.3. Experimental Protocol

Conditions were chosen so as to mimic real-life situations under which sweating and after-exercise-chill would develop, and where this type of clothing would be worn. Testing occured in a climatic chamber at an air temperature (T_a=T_o) of 5.2 ±0.31°C, a dew point temperature (T_{dp}) of -3.2 ±0.48°C (~64 % rh), and an air velocity of 0.32 $m \cdot s^{-1}$.

The clothing was stored in the antechamber at an air temperature of 29°C and 20 % relative humidity at least two hours before the experimental procedure began, and the dressing of the subject took place in this chamber. Each subject reported to the laboratory at the same time of the day for all experiments. After arrival he was weighed in the nude and then hooked up with chest electrodes for heart rate, thermocouples for esophageal and skin temperatures (calf, thigh, chest, lower back, upper back, upper arm, forearm, hand, and forehead). Each piece of clothing was weighed on a balance (Sauter, model K12), put on the subject and when he was completely hooked up, a dressed weight was recorded (Sauter, model KR120). Upon entering the test envirorment the subject were hooked up with dew point sensors [8] on the skin underneath the garment (back, chest and thigh) before he mounted a cycle ergonometer placed on a Potter balance (model 23B). Approximately 10 min after entering the test chamber the subject began the 2-hour test. The test comprised a twice repeated cyclus of 40 min cycle exercise (60 rpm; 2.0 ±0.40 kp) followed by 20 min of rest. Each subject always worked at the same work level, that had been choosen so it would be close to 55% of his $\dot{V}O_2$-max. Esophageal, skin and air temperatures, as well as dew point temperatures at the skin and in the ambient air were monitored on a HP200 computer every minute during the test and stored for analysis. Changes in body weight were sampled from the Potter balance every 20 seconds on a HP85 computer and HR was recorded every 10 min. $\dot{V}O_2$ and $\dot{V}CO_2$ were measured by open circuit spirometry using an automated system (Sensormedics Horizon MMC) the last 5 min of the first exercise and rest period, respectively. Two minutes after cessation of the test the subject left the test chamber and undressed immediately in the antechamber. He was weighed in the nude and each piece of clothing was weighed.

3. CALCULATIONS

Metabolic energy production (M) was calculated from the measurements of oxygen consumption ($\dot{V}O_2$) as

$$M = (0.23RQ+0.77)\cdot \dot{V}O_2 \cdot k \cdot 60 \cdot A_{Du}^{-1} \qquad (W\cdot m^{-2})$$

in which RQ is the respiratory exchange ratio, $\dot{V}O_2$ is the oxygen consumption in $l\ O_2 \cdot min^{-1}$, and k is the energy equivalent of oxygen ($5.873\ W\cdot h\cdot l\ O_2 \cdot min^{-1}$).

Mean skin temperature ($\bar{T}_{sk}$) was calculated as an area-weighted average of the measurements (modified from [9]):

$$\bar{T}_{sk} = 0.05T_{hand}+0.07(T_{forearm}+T_{upper\ arm}+T_{head})+0.20T_{calf}+0.19T_{thigh}$$
$$+0.175(T_{chest}+(T_{upper\ back}+T_{lower\ back})/2) \qquad (^{o}C)$$

Evaporative heat loss from the skin (E_{sk}) over the total experimental period was determined from the continuous monitoring of weight loss on the Potter balance corrected for weight of respiratory water loss (E_{res}) [10]. No dripping took place, because all excessive sweating was absorbed in the clothing. Total non-evaporated sweat loss (Sw_{ne}) was measured as the difference between clothing weight before and after the experiment. Total sweat loss (Sw_{tot}) was calculated as the sum of E_{sk} and Sw_{ne}.

Vapor pressures at the skin surface and in the ambient air were determined from the local dew point temperature recordings using the Antoine equation.
Local skin wettedness, w, on back, chest and thigh was calculated as:

$$w = 100\cdot(P_{sk}-P_a)/(P_{ssk}-P_a) \qquad (\%)$$

where P_{sk} is the vapor pressure at the skin surface, P_{ssk} is the saturated vapor pressure at the local skin temperature and P_a is ambient water vapor pressure.
An average skin wettedness for thigh and torso area was estimated using each local skin surface area's fraction of the total body surface area:

$$w = 100\cdot(0.175\cdot w_{chest} + 0.175\cdot w_{back} + 0.19\cdot w_{leg})/0.54 \qquad (\%)$$

3.2. Statistical analysis

Repeated-measures analysis of variance (ANOVA) was used to determine whether the factor 'textile material' had any significant effect on physiological reactions or sweat accumulation in the clothing. In the event that ANOVA revelled significant main effect Tukey's critical difference was calculated and used to locate significant difference between means. Data are presented as means$\pm$s.d. All differences reported are significant at the $P<0.05$ level. A paired t-test was used to test if there was any difference between physiological reaction in the first and second test period.

4. RESULTS

Work intensity (W) was at average 64 ±11.6 $W \cdot m^{-2}$ during the 40 minutes bicycle periods. Metabolic energy production (M) did not vary between clothing systems, and were at average (n=40) 344 ±51.2 $W \cdot m^{-2}$ during exercise and 65 ±11.6 $W \cdot m^{-2}$ during rest.

Core temperature as represented by T_{es} was not influenced by the fiber material of the underwear worn (Figure 2). T_{es} was at average for all tests 36.6 ±0.19°C in the first minute of exercise. After 20 minutes of exercise a steady-state value of 37.4 ±0.18°C was reached. During the rest period T_{es} decreased quickly to reach a value of 36.8 ±0.20°C in the last minute. The course of T_{es} over the second exercise/rest period was similar to the course over the first period and similar temperature values were measured at the end of the two periods.

Mean skin temperature ($\bar{T}_{sk}$) did not vary between underwear conditions (Figure 2). The average values (n=40) at the beginning of the exercise and at the end of each period were 31.0 ±0.61, 30.9 ±1.01, 29.1 ±0.62, [illegible]3 ±1.01 and 28.7 ±0.63 °C. All values except for F5 during exercise and F2 at rest were significantly lower at the end of the second period than the corresponding values in the first period.

Average skin wettedness (w) did not show any difference between underwear conditions (Figure 2). Average values (n=40) at the beginning of the

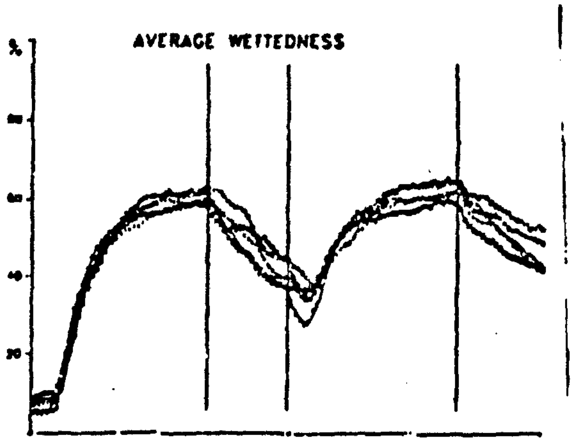
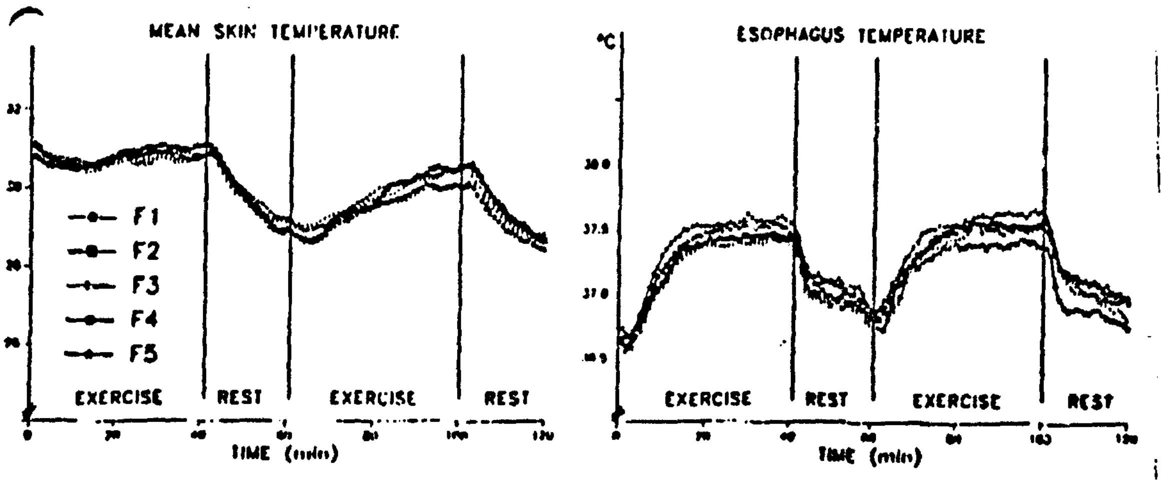


Figure 2. Average (n=8) skin wettedness, mean skin temperature and esophagus temperature during the test for each underwear condition.



exercise and at the end of each period were 7 ±6.2, 60 ±11.3, 41 ±13.1, 62 ±10.6 and 45 ±14.4 %. Wettedness were slightly higher in the second exercise and rest period compared at the first period.

Onset of sweating was considered to take place when the dew point sensors at the skin recorded an increase in vapor pressure, and it began 9 ±2.74 min after the start of the exercise. No difference could be detected between the five different underwear conditions; neither was there any significant difference in the time to onset of sweating between the first and second exercise period; however, for F2 a strong tendency towards an earlier onset in the second exercise period was found.

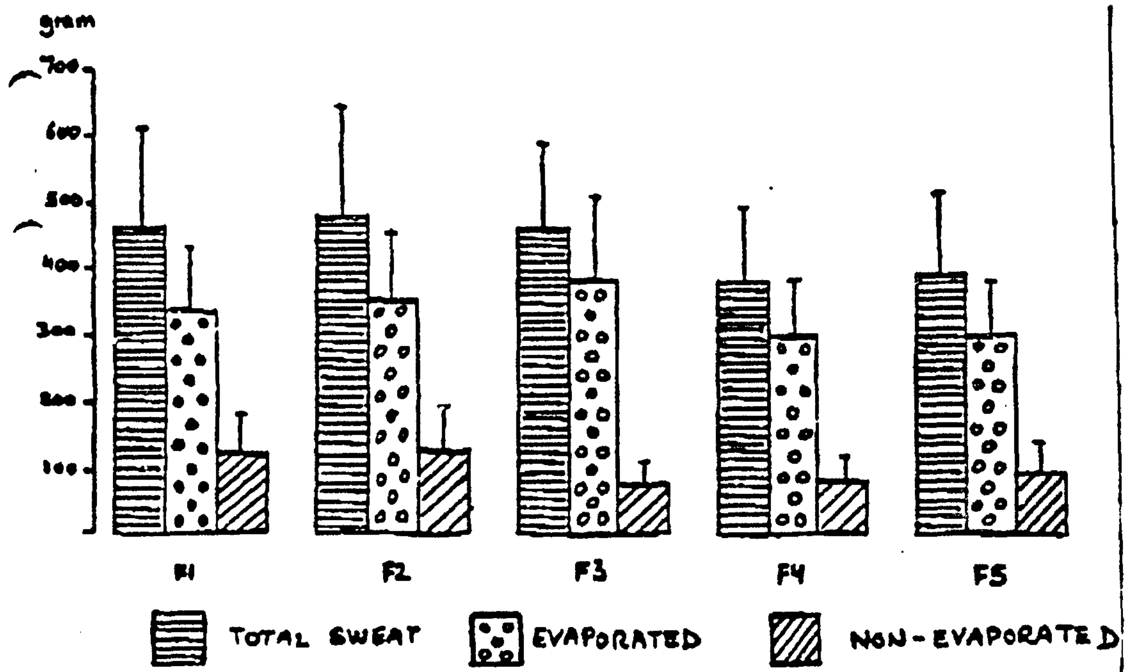


Figure 3. Total amount of sweat, evaporated sweat and non-evaporated sweat with the five clothing systems.

Total sweat loss (Sw_{tot}) was significantly lower with both F4 and F5 underwear compared at F1, F2 and F3 underwear (Figure 3).
Evaporation of sweat (E_{sk}) totalled over the test period was higher with F3 compared at F1, F4 and F5, and higher with F2 than with F5.
Total non-evaporated sweat loss (Sw_{ne}): The underwear material had a significant effect on the amount of sweat absorbed in the clothing ensemble worn (Figure 3). More sweat was absorbed when either F1 or F2 underwear were worn compared at F3, F4 or F5 underwear (F1 >F3, F4, F5; F2 >F3, F4, F5). Considering the underwear alone, both F1 and F2 underwear contained more sweat than all three types of man-made fiber underwear (F1>F3,F4,F5; F2 >F3,F4,F5). There was no difference between the amount of sweat absorbed in F3, F4 and F5 underwear; neither was there any difference between the amount of sweat absorbed in F1 and F2 underwear, respectively. There was no difference, and thus no underwear effect, in the amount of sweat found in the BDU-jacket and the BDU-trousers showed only a difference between F2 and F4 conditions (F2>F4). Socks, shoes and gloves contained after all experiments very little moisture (3, 6 and 6 g, respectively).

6. DISCUSSION:

Different fiber type material in the underwear of a clothing system has an effect on thermoregulatory responses during intermittent exercise in a cold environment. In the present study differences in sweat loss, evaporation of sweat and amount of non-evaporated sweat absorbed in the underwear were found. No differences were detected in chilling at rest, but with a longer rest period differences may develop.

It was choosen to use intermittent exercise rather than one exercise period followed by a period of rest. It was expected, and confirmed, that a dampening or watting of the clothing system occured over the course of the first period and this changed the course of the thermophysiological responses in the next period. Initially $\bar{T}_{sk}$ decreased slightly; however, after onset of sweating it increased due to insufficient evaporation of sweat as shown by the increase in skin wettedness. In the rest period $\bar{T}_{sk}$ decreased significantly and was at the onset of the second exercise period 2°C lower than at the start of the test. $\bar{T}_{sk}$ increased during the second exercise period and reached a steady state 0.5°C lower than the steady state level in the first exercise period. As other variables were constant this can be related to the dampening of the clothing system causing a lowering of the insulation value of the clothing system. This is supported by a similar lowering of $\bar{T}_{sk}$ in the second rest period and a slightly increased skin wettedness in the second period. During the first rest period skin wettedness showed that a drying out of the clothing took place, but after 20 minutes of rest the microenvironment was still humid (w=41%). Except in more extreme environments, the course of T_{es} is determined by the work level [11] and so in this study. The clothing only influences the thermophysiological responses at the body surface.

No differences were found in skin wettedness and $\bar{T}_{sk}$ due to different fiber type material of the underwear indicating that the humidity conditions in the microenvironment between skin and underwear were similar. Therefore, the observed differences in wet heat exchange must be caused by differences in the thermal processes taking place within the clothing system. The amount of sweat absorbed in the wool and the cotton underwear was as predicted from textile characteristics larger than the amount absorbed in the man-made textiles. These were all made of hydrophilic fibers, where the surface was made hydrophobic by a chemical treatment. The differences in total sweat production are for certain parts difficult to explain. Possible mechanisms are hypothesized below using sweat production with F4 and F5 as references.

Absorption of sweat in wool (F2) over the skin surface results in an incomplete evaporation and cooling of the skin, plus liberation of sorption heat at the skin. Both tend to increase $\bar{T}_{sk}$. The absorbed sweat is transported in the wool fibers further into the clothing where it evaporates and decreases the temperature between the clothing layers. This creates a steeper temperature gradient over the underwear and a greater dry heat flow. The tendency to increase $\bar{T}_{sk}$ may increase sweat production, and be the cause of the greater sweat production observed.

The increased sweat production with polypropylene underwear (F3) is found as increased evaporation. This may be explained by that sweat are wicked through the underwear, and evaporated further into the clothing. The incomplete evaporation at the skin would like with wool tend to increase $\bar{T}_{sk}$ resulting in a higher sweat production. However, a similar respons could be expected for F4 and F5 based on the information provided by the manufacturer. That the difference between polypropylene and the treated polyester fibers could be related to the slight difference in cloth thickness was considered, but as the differance between F3 and F4 are small, this cause is not likely.

6. CONCLUSIONS

In conclusion, different textile material in the underwear of a clothing system has an effect on thermoregulatory responses during intermittent exercise in a cold envirorment. However, thermal underwear does not keep its wearer completely dry as often claimed. In periods where sweating occur skin wettedness increases to similar levels independent of material of the underwear, and at rest mean skin temperature and skin wettedness decreases to the same values. However, the textile material of the underwear making the contact to the skin absorbs and contains less sweat when man-made hydrophilic fibers are used.

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