How is Performance in the Heat Affected by Clothing?

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Abstract: Adequate heat balance is critical to human performance in the heat. If heat balance cannot be maintained, the core temperature increases and body water dehydration leads to exhaustion and limit the performance. Clothing heat transfer properties, thermal insulation and water vapour resistance, modify heat exchange and may indirectly affect performance. Work in protective clothing quickly becomes exhaustive in impermeable garments, but can be easily completed with much less strain in permeable garments. Athletes, in particular in sports of endurance type, may produce more than 1000 W/m^2 in an event lasting several hours. Physical examination of the heat balance of a runner reveals that a 20 % lower water vapour resistance of a covering running suit allows the runner a longer run time or a higher speed per km before critical physiological strain is reached.

Keywords: performance, heat Stress, core temperature, skin temperature, water vapour resistance

1. Introduction

Physical or muscular performance is associated with overcoming various forms of external physical loads or resistances such as for example lifting your center of gravity in high jump or overcoming the resistance of wind or water in cycling or swimming. Most focus in exercise and sports physiology is on the physiological and psychological factors that determine performance [1]. It is well known that environmental factors such as climate and altitude can modify performance, mostly in the form of a degradation [2]. Much less is known about how clothing affects performance in particular on a quantitative level at high work intensities as in sports. In occupational physiology research has tried to quantify the impact of worker´s clothing and equipment on physiological strain and several indices have been proposed over the years for this purpose. A few of them have become international standards [3-5]. Focus in the evaluation, however, has been the physiological strain and how it can be reduced. Very few studies have tried to quantify the thermal effect on performance and productivity [6, 7].

This paper analyses the physics and physiology behind physical performance, in particular with reference to the impact of clothing and its properties.

2. Human heat balance

Heat balance is required for sustained work performance. If balance is not maintained heat is stored in the body and the tissue temperatures increase. Increasing tissue temperatures, in particular core temperature, is associated with increasing physiological strain and at some critical level exhaustion is reached and work intensity cannot be maintained. Work has to be stopped or intensity may be reduced. Albeit the capacity of the physiological temperature regulation system is individual and trainable, the stress is entirely determined by physical factors of the environment.

Equation 1 is a mathematical description of the heat balance of the body.

$$S = M - W - RES - E - R - C - K \qquad (1)$$

Metabolic energy production (M) minus the effective, external, physical work (W) is the internal heat production. Heat exchange takes place in the respiratory tract (RES), on the skin by evaporation (E), radiation (R), convection (C), and conduction (K). Tissue heat content (S) may change depending on the values of the equation. The details of the equation and its solution are given in for example [8].

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Definitions, symbols and units are given and explained in Table 1.

External work is determined by the kind of activity, but is in most cases very small and negligible, in particular during walking and running. In sports like swimming, cycling and mountaineering, external work needs to be considered. Respiratory heat exchange is related to breathing minute volume, which relates to metabolic rate. RES is

Table 1. Symbols and units for heat balance calculations

A_{Du}	body surface area, m^2
C	convective heat exchange, W/m^2
E	evaporative heat exchange, W/m^2
I_T	total insulation of clothing and boundary air layer, $m^2 °C/W$
K	conductive heat exchange, W/m^2
M	metabolic energy production, W/m_2
p_a	ambient water vapour pressure, kPa
p_{sk}	water vapour pressure at skin temperature, kPa
p_{sks}	saturated water vapour pressure at skin temperature, kPa
R	radiative heat exchange, W/m^2
R_{eT}	evaporative resistance of clothing and boundary air layer, Pam^2/W
RES	respiratory heat exchange by convection and evaporation, W/m^2
S	Body heat storage rate, W/m^2
t_o	operative temperature of the environment, °C
t_{co}	core temperature, °C
t_{sk}	mean skin temperature, °C
W	rate of external energy production, W/m^2

small or even negative in hot environments but increases in cold to 10-15 % of metabolic rate. Conductive heat losses are negligible in most types of physical activity.

Heat transfer from skin to ambient air takes place by convection through fabrics and garment openings and by radiation between fibers, fabrics and ambient surfaces. In its simplest form it can be described by equation 2. IT is the thermal resistance (or insulation) of the clothing and boundary air layer around the body. Insulation is principally a function of the thickness of still air layers between fibers, fabrics, layers and garments in the clothing. The boundary air layer on top of clothing adds some insulation. Increased air velocity in general reduces insulation.

$$R + C = \frac{t_{sk} - t_o}{I_T} \qquad (2)$$

Evaporative heat exchange is a complex process that may engage diffusion, convection, condensation, absorption and re-evaporation. In the simplest case, sweat is assumed to evaporate at the skin surface and heat is transported as water vapour in air through clothing and by ventilation of clothing. Equation 3 describes this process. R_{eT} is the water vapour resistance of the clothing and boundary air layer around the body. Water vapour resistance is principally determined by the porosity of fabrics and the thickness of air layers (cf, insulation). Increased air velocity in most cases reduces vapour resistance.

$$E = \frac{p_{sk} - p_a}{R_{eT} * 10^{-3}} \qquad (3)$$

Water vapour pressure at the skin surface results from sweating and its evaporation. The highest value of p_{sk} is achieved when the skin is fully wet and the value is equal to the vapour pressure of saturated air at the actual skin temperature.

If internal heat production differs from heat losses, there is a change of heat content in body tissues affecting temperatures of the skin as well as the core. The change in these temperatures can be related to S by equation 4. The values of the weighting factors, a and b, are 0.2 and 0.8 in heating and 0.35 and 0.65 in cooling of the body. Core temperature can now be calculated for different combinations of skin temperature and S.

$$S = 0.98 \cdot Wt \cdot \frac{d(a \cdot t_{sk} + b \cdot t_{co})}{dt} \cdot \frac{1}{A_{du}} \qquad (4)$$

The values of t_{sk}, p_{sk} and t_{co} are determined by the physiological, thermoregulatory process of the body and must lie within critical ranges to be compatible with for example thermal comfort or heat or cold tolerance.

JFBI Vol.1 No. 1 2008 doi:10.3993/jfbi06200802

3. Protective clothing and performance

Figure 1 shows the effects of water vapour resistance on body temperatures and sweat evaporation. This subject performed light work for up to one hour in long sleeved underwear and a protective coverall made of two types of fabric with different vapour permeability [9]. One fabric was impermeable and the other was permeable (Goretex) to vapour transfer. The design was identical. Measured values for evaporative resistance were 180 and 37 Pam^2/W. Air temperature was 45 °C and relative humidity 15 % (1.44 kPa). Heat can only be lost by sweat evaporation, as ambient temperature is higher than skin temperature. The following data were achieved as the average of four subjects. Metabolic heat production was 150 W/m^2. Heat gain by radiation and convection was about 40 W/m^2. Respiratory heat exchange is neglected. In other words evaporative heat loss must contribute 190 W/m^2 for at balance.

Table 1. Critical values for some physiological parameters related to heat balance in the cold, in moderate climates (“comfort” zone) and in the heat. Values for p_{sk} is the saturated water vapour pressure at the given skin temperature. Skin temperature is also dependent on air temperature and clothing (cf. figure 1).

physiological parameter	unacclim.	acclim.	“comfort”	unacclim/ untrained	acclim./ trained
t_{sk} °C	30	28	34-36	36-38	36-39
p_{sk} kPa	4.2	3.8	5.3-5.9	5.9-6.6	6.3-7.0
t_{co} °C	37	37	37	39	40

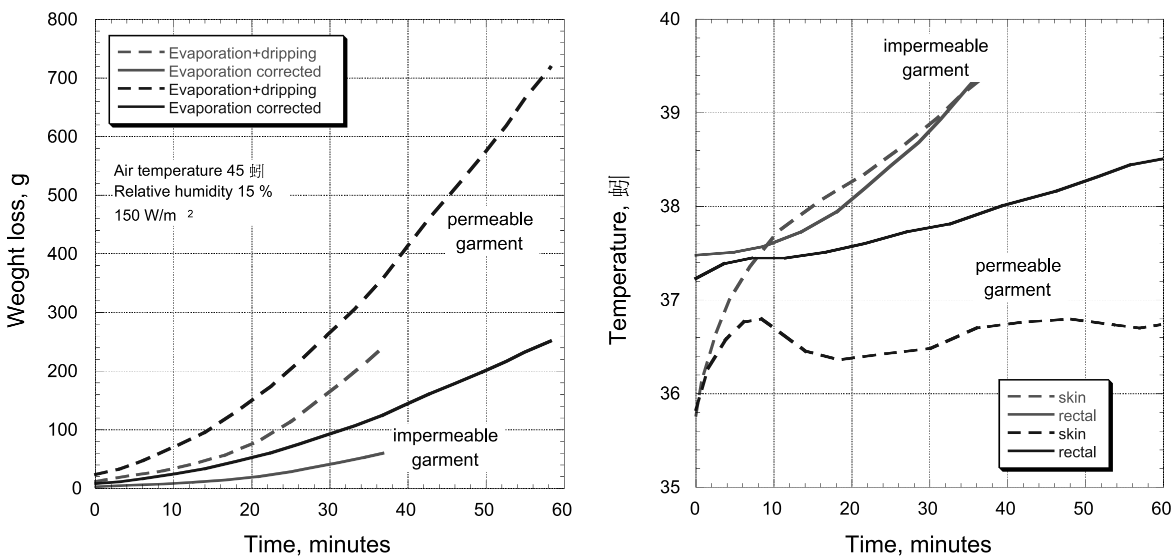

Figure 1 Sweating, dripping and evaporation during light treadmill work in the heat in two types of a gas protective suit (left panel). Right panel shows the mean skin and rectal temperature response. Modified and recalculated from [9].

Profuse sweating took place in these garments, most of it being trapped in underwear and dripping from the subjects. Calculated evaporative losses for the two suits are 31 and 131 W/m^2, respectively, leaving a net storage rate of about 148 and 59 W/m^2. This corresponds to a core temperature rise of about 3.5 and 1.4 °C, respectively, and compares favourably with the measured increases in rectal temperature. These were 2.0 °C for 35 minutes in impermeable suit (the subject stopped due to exhaustion) and 1.3 °C for 60 minutes in permeable suit (figure 1). The water vapour resistance is critical for performance and for physiological strain. If R_{eT} is reduced to 26 Pam^2/W heat balance may be achieved with negligible increase in core temperature.

4. Athletic performance and clothing

Athletes can sustain heavy work for long time combined with high internal temperatures. However, it seems that irrespective of the level of heat acclimatization exhaustion occurs when core temperatures reaches around 40 °C [10]. In less fit individuals heavy exercise is normally interrupted when core temperature is about 39 °C. In warm climates with air temperatures above 30 °C, skin temperature is likely to rise and reach values of 36-39 °C, partly depending on temperature and clothing. This sets the limit to the possible skin to ambience temperature gradient as well as the water vapour pressure gradient (table 1). In a hot dry climate the vapour pressure gradient remains high, which is favourable for evaporative heat exchange. In a warm, humid climate the temperature gradient remains positive, whereas the vapour pressure gradient may become very small. Accordingly, properties of clothing affect heat exchange and thereby performance, different depending on climate.

Athletic events are held under various climatic conditions around the world, sometime in countries with a warm and humid climate. So was the case with the summer Olympics in Atlanta in 1996 and with the world championship in orienteering in Japan in August 2006. In warm and humid climate conditions the heat exchange of the human body becomes more restricted due to pure physical laws [7].

Table 2 Heat balance and core temperature of a runner in a 16 km race running at his best pace in various clothing. Air temperature is 30 °C and relative humidity is 60 %. Respiratory heat losses are about 80 W/m^2. Clothing values are static, manikin values, corrected for wind speed (running speed) according to ISO 9920. The * indicates conditions with intolerable heat stress that force the runner to reduce speed or quit the race.

	Shorts+tshirt	Fully covering clothing	Fully covering clothing, reduced speed	Fully covering clothing, low R_{eT}	+ solar radiation
M, W/m^2	741	741	657	741	741
I_{Tot} clo	1,1	1.3	1.3	1.3	1.3
R_{eT} Pam^2/W	17	25	25	20	20
E, W/m^2	499	340	340	424	424
S, Wh	104	424	287	271	372
Run speed, km/h	16	16	14.2	16	16
Run time, min	60	*<<60**	67.6	60.0	<<60*
t_{co}, °C	1.1	4.4	3.0	2.8	3.8
Sweat loss g/h	1400		1100	1300	

A long distance runner consumes about 4 kJ kg^{-1} km-1. If running time is 16 km/h the metabolic rate (and heat production rate) is 741 W/m2 for a runner weighing 75 kg with a body surface is of 1.8 m^2. Running an hour at this speed in 30 °C and 60 % relative humidity with minimal clothing (mini shorts) would allow a reasonable heat balance and just a small rise in core temperature. Putting on a running dress (shorts and T-shirt) reduces evaporative cooling as well as convective cooling. Heat balance cannot be maintained and core temperature rises by 1 °C in an hour (table 2). A runner in orienteering is required to wear fully covered clothing (long legs and arms), which further reduces evaporative and convective cooling. Trying to keep the speed of 16 km/h results in a heat storage of 424 Wh over the hour and core temperature increases by more than 4 °C. This is beyond the limit of his tolerance and heat exhaustion may develop before the race is completed. A lowering of running speed to about 14 km/h is required to reduce heat storage rate and core temperature (Table 2) increase to tolerable levels (Table 1).

Reducing clothing insulation and, in particular, water vapour resistance is another measure in order to improve heat balance and maintain performance.

Reducing vapour resistance by 5 Pa m^2/W (20 %) results in less heat storage and almost 2 °C lower increase in core temperature. This would allow the runner to increase the running speed to about 16 km/h and his performance is improved. The runner must be aware of this and select a garment with as low vapour resistance as possible, as the gain is significant, in particular during heavy exercise in warm humid climates.

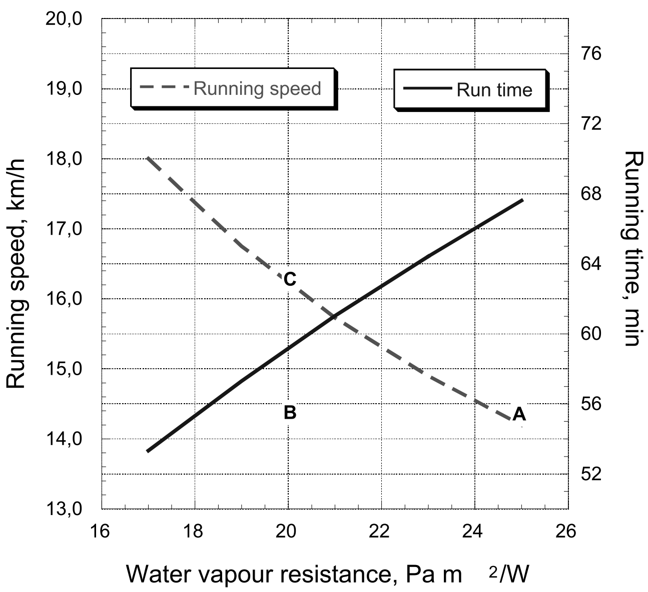

Figure 2 Running speed and performance time as function of clothing water vapour resistance. Relations are calculated for a 16 km race and the criteria is that the runner should finish with a core temperature of about 40 °C (cf. table 1). For explanation of letters; see text.

Figure 2 shows the decrement in speed and performance time over a 16 km race as function of the water vapour resistance of the garment. It is a challenge to fibre, fabric and garment manufacturers to find optimal combinations of the textile properties critical to performance.

Running in the sunshine adds approximately 100 Wh (or 56 W/m^2) [11]. With the conditions given in column 5, table 2; this would raise core temperature by another 1 °C. The runner cannot stand such a heat load and has to reduce running speed to cope with conditions or quit the race. Apart from avoiding solar heat load the runner can reduce speed (and heat production).

Not only high values of core temperature are detrimental to athletic performance, excessive water losses due to profuse sweating affects cardiovascular function and may compromise muscular work [12]. It is well known that in long lasting events (1 hour or more) the athletes or players need to and are encouraged to drink regularly to compensate for losses and reduce dehydration. The evaporative cooling required with high metabolic rates in warm climates requires high sweat rates. At high levels of sweating the fraction of sweat that evaporates diminishes and dripping occurs [13]. The water vapour pressure gradient from skin to ambient air, wind and the vapour resistance of clothing determine the possible cooling potential of evaporation. The smaller potential, the more sweat stays in clothing and drips from the body. At maximal vapour pressure gradient a lower vapour resistance allows more evaporation and, accordingly, contributes to more water losses (table 2). The runner in the previous example looses more than 1000 g/h from evaporation during the race (16 km) with a 25 Pam^2/W garment (running speed 14.2 km/h). The total water loss due to sweating may be some

10-20 % more. Selecting the 20 Pam^2/W garment allows him to keep the same speed, but now at a lower vapour pressure gradient (B in figure 2). He is not required to sweat as much to ensure the necessary evaporation and the total sweat loss (and water loss) will be lesser. In this case he is capable of running longer before getting too dehydrated. However, if he wants to win the competition over 16 km, he is likely to use the full potential of sweat evaporation and increase the running speed (table 2, column 5, C in figure 2). With proper water replacement programs dehydration seldom becomes critical. Evaporation and core temperature rise are, by far, the most critical elements in athletic events of endurance type in hot climates.

5. Conclusions

In conclusion, clothing plays an important role in human heat exchange. For various types of protective clothing water vapour resistances are usually high. Much relief in heat strain would be gained if this value could be reduced without compromising protection. However, also in athletic events with usually light clothing, benefits can be made. This is particularly true for sport with high to maximal activity levels of longer duration (1 hour or more). In the heat evaporative cooling becomes critical to the control of core temperature. Small differences in water vapour resistance may have significant effects upon running speed.

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