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 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.

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

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.

$$R + C = \frac{t_{sk} - t_o}{I_T} \tag{2}$$

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.

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

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.

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

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.

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