Experimental Thermal and Fluid Science 71 (2016) 103–113

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Skin temperature measurements by infrared thermography during running exercise

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form 5 October 2015
Accepted 5 October 2015
Available online 14 October 2015

Keywords:
Skin temperature
Running exercise
Infrared thermography
Human thermoregulation

ABSTRACT

The thermal interaction of human body and the environment during running activity is an important mechanism that may affect the athletic performance. Skin temperature plays the fundamental role of regulating the heat exchange by convection, radiation and evaporation. In this study, the skin temperature response to running exercise has been tested by infrared thermographic imaging, a highly reliable method for the real time, non-invasive monitoring of local cutaneous temperature over the body surface. Measurements performed for long-distance runners showed a fall in skin temperature during the initial stage of running exercise, regardless of the type of work (overground or treadmill) and environmental (outdoor or indoor) conditions. It is argued that this skin temperature decrease is associated with the cutaneous vasoconstrictor response to exercise. A continuous increase in load intensity (as occurs during an incremental treadmill exercise) may produce further reductions in skin temperature; conversely, a constant load running exercise is likely to promote the attainment of a relative minimum of skin temperature, followed by a gradual little rise over time related to thermoregulatory vasodilation.

1. Introduction

The thermoregulatory system of human body is aimed at maintaining a constant internal body temperature of about 37 °C. This steady temperature is the result of a balance between the metabolic heat production and heat dissipation to the environment. For a resting man, the typical heat production is about 100 W and it is often expressed in terms of heat production per unit area of skin (i.e., about 58 W/m^2 = 1 met). At rest, the main challenge to the regulation of body temperature derives from changes in environmental conditions. At low ambient temperatures, the rate of heat loss exceeds the metabolic heat production and the internal body temperature tends to decrease; in these conditions, skin blood flow is reduced to conserve heat. At high ambient temperatures, heat can be gained from the environment, core temperature rises and defense mechanisms (sweating) occur.

During physical exercise (for instance long-distance running), metabolic heat production may rise by 10–20 times as much (as compared with that of a sedentary person) and this rate of heat production may be sustained for several hours; a part (up to 30%) of metabolic heat production is converted into mechanical power, the rest has to be transported from the peripheral compartments of the body to the skin to be dissipated into the environment [1]. If the heat dissipating mechanisms (convection, radiation, and evaporation from skin, convection and evaporation through respiration) are unable to cope with metabolic heat production, heat starts to accumulate in the body, leading to an increase in body temperature. The duration and intensity of exercise, which affect the metabolic heat production, contribute significantly to heat accumulation in the body during exercise. As core temperature increases, heat dissipation increases sufficiently to balance heat production, and a steady state in core can be achieved if the environment allows adequate heat loss. Otherwise, the athlete is forced to decrease his/her speed (in order to reduce heat production), drop out of the race or, in the worst case, even collapse owing to hyperthermia. Even in running competitions of relatively short duration (10–15 km), extreme rises in body temperature may occur, particularly when the ambient temperature is high. During marathon races (42.2 km), runners commonly have a post-race core temperature ranging from 38.5 °C to 39.5 °C, but it can even exceed 40 °C during or after the race [2]. The ability to tolerate high core temperatures is related to genetic, training and acclimatisation factors as well as to the athlete's skin temperature, as warmer skin (and warmer environment) creates greater circulatory strain and lowers core temperature tolerance. For instance, large core-to-skin gradients and relatively low skin blood flows may explain tolerances for high core temperatures during long-distance running exercise [2].

http://dx.doi.org/10.1016/j.expthermflusci.2015.10.006
0894-1777/

Nomenclature

A	body surface area (m^2)
c_{body}	body specific heat (J/kg K)
$c_{p,a}$	specific heat at constant pressure of air (J/kg K)
C_{res}	rate of convective heat loss from respiration (W)
C_{sk}	convective heat transfer rate from skin (W)
E_{max}	maximum evaporative heat transfer rate from skin (W)
E_{res}	rate of evaporative heat loss from respiration (W)
E_{rsw}	rate of evaporative heat loss by regulatory sweating (W)
E_{sk}	evaporative heat transfer rate from skin (W)
f_{cl}	ratio of the clothed surface area to the nude body area
f_i, f_0	weighting factors used in Table 1
h_c	convective heat transfer coefficient (W/m^2 K)
h_e	evaporative heat transfer coefficient (W/m^2 kPa)
h_{lv}	latent heat of vaporisation of water (J/kg)
h_r	radiative heat transfer coefficient (W/m^2 K)
$h = h_c + h_r$	total (convective + radiative) heat transfer coefficient (W/m^2 K)
$Lr = h_e/h_c$	Lewis ratio (K/kPa)
m	body mass (kg)
m'	pulmonary ventilation rate (kg/s)
M	rate of metabolic heat production (W)
n	number of skin temperature measurement sites
p_a	water vapour pressure in ambient air (kPa)
$p_{sk,s}$	saturated water vapour pressure at the skin (kPa)
q_{res}	total rate of heat loss through respiration (W)
q_{sk}	total rate of heat loss from skin (W)
R_{cl}	thermal resistance of clothing (m^2 K/W)
$R_{e,cl}$	evaporative heat transfer resistance of clothing (m^2 kPa/W)
R_{sk}	radiative heat transfer rate from skin (W)
S	rate of heat storage in the body (W)
t	time (s)
T_a	air ambient temperature (°C)
T_{body}	body temperature (°C)
T_{cl}	mean temperature of clothed body surface (°C)
T_{core}	temperature of the core body compartment (°C)
T_{ex}	temperature of exhaled air (°C)
T_{mr}	mean radiant temperature (°C)
$T_o = (h_r T_{mr} + h_c T_a)/(h_r + h_c)$	operative temperature (°C)
T_{sk}	mean skin temperature (°C)
$T_{sk,i}$	local skin temperature (°C)
V	velocity (m/s)
w	skin wettedness parameter
W	rate of mechanical work (W)

Greek symbols

α_{sk}	fraction of the body concentrated in the skin compartment
$\eta = W/M$	mechanical efficiency of the body
ω_a	humidity ratio of inhaled (ambient) air (kg_v/kg)
ω_{ex}	humidity ratio of exhaled air (kg_v/kg)

It is apparent from the above discussion that the analyses of the human thermoregulatory system in people at rest and under prolonged physical activity pursue different objectives. For resting people, the main issue to deal with is the evaluation of thermal comfort, while for exercising subjects the knowledge of internal body (core) temperature and skin temperature during an intense activity like long-distance running is of great importance to understand the sustainability of the required muscular work as well as to infer a possible association of the thermoregulatory response with the athletic performance.

During physical activity, core temperature is typically proportional to the metabolic rate and largely independent of a wide range of environmental conditions, while skin temperature is rather influenced by skin blood flow and environmental conditions [1,2]. Whereas internal (core) temperature measurements, typically performed by rectal or ingestible sensors, are invasive and can cause discomfort to runners, modern thermal imaging devices like infrared thermography are particularly suitable to precisely map the cutaneous temperature distribution and its evolution during exercise. A pioneering investigation of skin temperature during running by using infrared thermography was performed by Clark et al. [3]. They recorded skin temperature distributions and changes in two athletes standing and running outdoor and on a treadmill. During running, skin temperature distributions differed markedly from that observed before exercise. Torii et al. [4] used thermography to record skin temperature in the upper part of the body during bicycle exercise; they observed a fall in skin temperature for all the sample group (ten healthy men) during the muscolar exercise and attributed it to a cutaneous vascoconstrictor response to exercise rather than thermal factors, such as evaporation due to skin sweat. Thermographic imaging was employed by Zontak et al. [5] to study the hand temperature response for ten subjects exposed to graded load and constant load exercise (bicycle ergometry); the skin temperature showed a continuous decrease for the graded load exercise and a descending-ascending profile, followed by a quasi-steady-state period, for the constant load exercise. They argued that the thermographic skin response reflects the dynamic balance between hemodynamic and thermoregulatory processes.

More recent thermographic analyses during exercise were presented in Refs. [6–8]; these studies reported the skin temperature response to intermittent or graded treadmill running. Authors focused their attention to the upper part of the body (back and front torso) [6], anterior part [7], and posterior part [8] of the body, finding a general decrease in skin temperature over the monitored spots during running. In particular, thermal imaging presented in Ref. [7] documented the different temperature responses of thighs, forearms and trunk as well as the presence of hyperthermal spots over the entire body during the recovery; these findings are likely to be related to the cutaneous blood flow adaptation to the specific exercise.

The above mentioned literature studies demonstrated that thermographic imaging is particularly indicated to record the temperature distribution on the skin surface during physical activity. The emissivity for skin in the infrared region is nearly constant, with a value of 0.98 ± 0.01 [9], irrespective of race and unaffected by the presence of sweat [3]. Measurements can be taken continuously in time and local temperature changes can be detected with a high degree of accuracy. Moreover, image processing systems make it possible to obtain the average skin temperature of specific regions. Although their extensive use for diagnostic purposes, these systems have been rarely employed to investigate the skin temperature variation during exercise.

The aim of this work is to assess the skin temperature response to running exercise by thermographic imaging. Results obtained by infrared thermal images of runners subjected to outdoor running (on road and track) and indoor treadmill exercise (graded and constant load) are presented and discussed.