International Journal of Industrial Ergonomics 40 (2010) 406–413

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

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

Transient sweat response of the human head during cycling

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ARTICLE INFO

Article history:
Received 3 February 2009
Received in revised form
5 January 2010
Accepted 26 February 2010
Available online 28 March 2010

Keywords:
Sweat rate
Thermal comfort
Data-based modelling
Dynamics

ABSTRACT

This research aims at quantifying transient spatial gradients in sweat production on a human head while cycling.

Six test persons were studied. Each test lasted 30 min while a change in work rate was applied after 5 min (from 80 to 150 W for males and from 50 to 125 W for females). Two conditions were analyzed in this research: warm (28.3 ± 0.1 °C, 38 ± 0.6% RH and 0.1 ± 0.1 m/s air velocity) and standard (16.1° ± 0.2 C, 45% ± 0.6 RH and 2.4 ± 0.2 m/s air velocity). Sweat production of the head was measured as a function of time on the right temple, left temple and forehead. This allowed modelling the dynamics of the sweat production response. Constant steady state sweat production, time delay in sweat production, time constant of sweat production and steady state gain of sweat production were quantified and analyzed.

Time constants of sweat production were shorter in the warm condition compared to the standard condition. Mean and SEM time constant of sweat production varied from 561 ± 144 s (frontal region) to 1117 ± 230 s (left temple) and 1080 ± 232 s (right temple) in the warm condition. While, at the standard condition, the time constant of sweat production varied from 873 ± 121 s at the frontal region to 1431 ± 195 s at the left temple and 1727 ± 196 s at the right temple. Additionally, also constant steady state sweat production was 0.4–0.7 mg min^{-1} cm^{-2} higher in the warm compared to the standard condition ($P < 0.05$). However, no differences ($P > 0.05$) were observed for steady state gain and time delay of sweat production between the standard and warm condition.

The results of this research can be used to enhance physiological insight of the sweating process and it can also help to develop sweating thermal manikins that behave more realistically to thermal changes. Knowledge of sweat production might also be valuable when designing active controlled headgear since the reaction time of the actuator should take the dynamics of sweat rate into account as a function of work rate and thermal environmental conditions.

Relevance to industry: Understanding of the dynamic behaviour of sweat production in relation to work rate under different environmental conditions allows the design of model based controllers in headgear that actively minimize sweat production. This could help a user's desire to wear a helmet as well as his ability to concentrate.

1. Introduction

The human head can dissipate up to 50% of the produced latent and sensible heat loss when insulating clothing is worn (Rasch et al., 1991). Its importance in the thermoregulation of the human body is therefore unquestioned. In warm environments this results in large sweat production on the human head in order to maintain thermal neutrality. The amount at which sweat is produced varies between different body parts (Kuno, 1956; Johnson et al., 1997; Machado-Moreira et al., 2008a; Havenith et al., 2008) and the distribution changes with changing non-thermal (work rate) and thermal conditions (Desruelle and Candas, 2000). Machado-Moreira et al. (2008b) showed spatial differences in sweat production on the human scull when sweat production was measured at nine locations in wind still situations. In previous work, we did not find differences in sweat productions

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doi:10.1016/j.ergon.2010.02.005

at four locations on the human scull at an air velocity of 3/ms when a bicycle helmet was worn, although a trend towards more sweat production at the rear of the scull was observed (De Bruyne et al., 2008).

Understanding spatial and temporal gradients in latent heat loss of the human head allows optimisation of headgear for thermal comfort, if these measures are validated by thermal comfort studies as performed by Liu et al. (1997). Additionally, thermal manikins that are used to evaluate heat accumulation between a head and headgear could be optimised in a realistic way. These thermal manikins have been used by Liu and Holmér (1997), Hsu et al. (2000), Davis et al. (2001), Bruhwiler, 2003; Bruhwiler et al. (2004, 2006), Brühwiler (2009), Buyan et al. (2006) and Bogerd and Bruhwiler (2008) and do not consider the dynamics of (latent) heat loss.

Researches towards spatial gradients in latent heat loss on a human head (Machado-Moreira et al., 2008b; De Bruyne et al., 2008) have analyzed static experimental results (constant steady state sweat production). These studies did not consider the dynamics of the sweat response such as the time delay between a change in work rate and the onset of sweating and the time constant describing how fast the sweat rate changes. The human thermoregulatory system is often shown as a negative feedback control system with a core temperature as set-point. (Mekjavic and Eiken, 2006). Using this approach, time delay is the reaction time for the sweat production to react on a change in work rate to maintain thermal balance. A time constant is the reaction speed of the sweat production to react on a change in work rate. Steady state gain of sweat production shows the amount of sweat that is produced if work rate is changed with one unit (Watt).

The aim of this research was to investigate the dynamic behaviour of sweat production on three locations on the human head in standard to warm conditions as a response to a change in work rate for studying the dynamics of sweat production in more detail.

2. Materials and methods

2.1. Subjects and experimental conditions

All experiments were performed by six test subjects (one female, five males) who participated as a volunteer. After being informed, each subject provided written consent to the procedures, which were approved by the Commission for Medical Ethics of the University of Leuven. The mean physical characteristics of the subjects were 22 ± 0.5 yr of age, 21.2 ± 0.7 of BMI and $3.57 \pm 0.16\ \mathrm{l\,min^{-1}}$ maximum oxygen consumption (VO_2max). The six participants had physical characteristics of: 22 ± 0.5 yr of age, 21.2 ± 0.7 of BMI and $3.57 \pm 0.16\ \mathrm{l\,min^{-1}}$ maximum oxygen consumption (VO_2max). As only six volunteers participated in this experiment, we choose a group with similar physical characteristics (BMI and VO_2max) and age and that were in good health. As such, we tried to avoid large individual differences in sweat production to obtain clear results. This does however implicate that other age groups or people with different physical characteristics might have a different response that could be studied in future researches. Clothing could have been a disturbing factor as it could influence the heat loss from different body parts. Test persons wore therefore the same cloths during the standard and warm condition (see below for definition of temperature conditions): a short sleeved T-shirt (0.36 clo, ASHRAE, 2005) and short shorts (0.36 clo, ASHRAE, 2005). The test persons performed a cycling experiment under two different environmental conditions in a climate chamber (4 m × 12 m × 5 m). The first condition reflects the average Belgian climate between the warmer months May and September when recreational cycling is popular with an average ambient temperature of $16.1^\circ \pm 0.2$ C and an average wind speed of 2.4 ± 0.2 m/s. Relative humidity was $45.0 \pm 0.6\%$. This first condition is named a 'standard' (Belgian weather) condition in this paper. The second condition reflects a warm Belgian summer day with an ambient temperature of 28.3 ± 0.1 °C and no wind speed (0.1 ± 0.1 m/s). Relative humidity was $37.6 \pm 0.6\%$ in the warm condition. This second condition is named a warm (Belgian weather) condition. For both conditions, no sweat production is expected based on the environmental setting since the standard condition is too cold for sweat production for a resting person and the warm condition is comfortable for a resting person. As such, sweat production was assumed to be the result of increased metabolic heat production due to an increase in work rate for which the two test conditions provide a different disturbance. More detailed information about the climate chamber can be found in De Bruyne et al. (2008). Each experiment was repeated three times to anticipate for occasional outliers. Each experiment lasted 30 min and started after the subjects had stayed 15 min at rest in the tested environmental condition (standard or warm condition). In total 36 experiments were conducted (6 × 2 × 3).

Preliminary to the test, a statistical power analysis showed (81.2%, while 80% is acceptable) that a number of six test persons were sufficient to allow the experiment to detect the differences in sweat production for two environmental conditions. This test was performed using preliminary results where the mean constant steady state sweat production at the standard condition was $0.75\ \mathrm{mg\,min^{-1}\,cm^{-2}}$ (SD 0.40) and the mean steady state sweat production in the warm condition was $1.25\ \mathrm{mg\,min^{-1}\,cm^{-2}}$ (SD 0.40). Additionally, differences between the female and males were insignificant for steady state of sweat production ($P > 0.05$), time delay of sweat production ($P > 0.05$), time constant of sweat production ($P > 0.05$), and steady state gain of sweat production ($P > 0.05$). The results of the female were as such included in the overall results.

2.2. Experimental protocol

Each subject completed six experiments: namely three repetitions under the warm condition and three repetitions under the standard condition. The conditions were in random order and there was at least 23 h between each experiment. This research aimed at studying the dynamic sweat production for recreational cycling in function of work rate. Work rate was adjusted for this type of cycling (cycling at a low effort level and cycling at moderate effort level). Additionally, the difference between both work rates needed to be high enough to allow a clear differentiation in sweat production, but was not allowed to be too high to avoid non-linearity between the input of work rate and the output of sweat production. As such, a work rate of 80–150 W was chosen for men and a work rate of 50–125 was chosen for females. During each experiment, the test persons started cycling for 5 min at 80 W (50 W for female, low work rate level), followed by a step to 150 W (125 W for female, high work rate level) which was maintained for 25 min. The experiments were performed on a cycle ergometer (Tunturi T8 Alpha 300 Cycle). The need of a step experiment was due to the use of the dynamic modelling as will be explained later.

Heart rate was measured using a heart rate monitor (Polar, using T-ware interface). Sample frequency of heart rate was 0.2 Hz. Sweat production of the head was measured at three places: left temple, right temple and forehead (Fig. 1). Frontal and temples were chosen since sweat production on these sites are often considered as discomfort by cyclists. Both right and left temple were chosen to see if symmetry in sweat production could be observed. The three sites did also allow to position sweat capsules without the disturbance of