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Human responses in heat – comparison of the Predicted Heat Strain and the Fiala multi-node model for a case of intermittent work

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ABSTRACT

Two mathematical models of human thermal regulation include the rational Predicted Heat Strain (PHS) and the thermophysiological model by Fiala. The approaches of the models are different, however, they both aim at providing predictions of the thermophysiological responses to thermal environments of an average person. The aim of this study was to compare and analyze predictions of the two models against experimental data. The analysis also includes a gender comparison. The experimental data comprised of ten participants (5 males, 5 females, average anthropometric values were used as input) conducting an intermittent protocol of rotating tasks (cycling, stacking, stepping and arm crank) of moderate metabolic activities (134–291 W/m^2) with breaks in-between in a controlled environmental condition (34 °C, 60% RH). The validation consisted of the predictions' comparison against experimental data from 2.5 h of data of rectal temperature and mean skin temperature based on contact thermometry from four body locations. The PHS model over-predicted rectal temperatures during the first activity for males and the cooling effectiveness of sweat in the recovery periods, for both males and females. As a result, the PHS simulation underestimated the thermal strain in this context. The Fiala model accurately predicted the rectal temperature throughout the exposure. The fluctuation of the experimental mean skin temperature was not reflected in any of the models. However, the PHS simulation model showed better agreement than the Fiala model. As both models predicted responses more accurately for males than females, we suggest that in future development of the models it is important to take this result into account. The paper further discusses possible sources of the observed discrepancies and concludes with some suggestions for modifications.

1. Introduction

It is important to have models for heat stress prediction in order to reduce thermal risk and prevent heat induced illness in different exposure situations. The use of models to predict and quantify heat stress and strain have contributed to a reduction in morbidity and mortality in industrial, military, sports, and leisure activities (Havenith and Fiala, 2016). Mathematical modelling of the human thermal regulation goes back more than 70 years for applications in mainly occupational settings (Burton, 1937; Stolwijk, 1971; Gagge et al.,1986, 1971; Fanger, 1973; Azer and Hsu, 1977; Fiala et al., 1999, 2001, 2003; Malchaire et al., 2001; Tanabe, 2002; Malchaire, 2006). More than 100 heat stress indices and models have been developed during this time, with varying complexity and easiness to use (Havenith and Fiala, 2016). Heat stress indices and models are categorized as rational, empirical or direct. Rational indices are centred on calculations involving the heat balance equation; empirical indices are based on establishing equations from the physiological responses of human subjects (e.g. sweat loss), and direct indices are founded on the measurements of instruments used to simulate the response of the human body (Parsons, 2003). There are many different approaches of models to address heat stress prediction with various objectives and applications. One of the most commonly used rational indices is the Predicted Heat Strain (PHS), which is based on the heat balance equation and is also an international standard (ISO7933:2004; Malchaire et al., 2001; Malchaire, 2006). A rational physiological model representing human thermoregulation was developed by Fiala et al. (1999, 2001, 2012), Fiala and Havenith (2015), and covers to wide range of human thermal exposure and responses.

The Predicted Heat Strain (PHS, ISO 7933) index predicts changes in physiological parameters and was validated against data on physiological responses of subjects in hot conditions. The simulation model

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Table 1
Metabolic rate of the activities during the exposure. Mean and standard deviation. The metabolic rate includes all types of energy use. Mechanical work was accounted for by 20% in the cycling exercise in both models.

Step	Activity	Start time	End time	Metabolic heat production [W m^{-2}]	Mechanical work [W m^{-2}]
1	Psychological test	−00:15:00	−00:00:59	80	0
2	Cycling	0:00:00	0:17:59	287 (SD 23.4)	58 (20%)
3	Rest	0:18:00	0:20:59	80	0
4	Stacking	0:21:00	0:38:59	129 (SD 14.8)	0
5	Rest	0:39:00	0:41:59	80	0
6	Stepping	0:42:00	0:59:59	220 (SD 14.2)	0
7	Psychological test	1:00:00	1:14:59	80	0
8	Arm crank	1:15:00	1:32:59	143 (SD 12.9)	0
9	Rest	1:33:00	1:35:59	80	0
10	Cycling	1:36:00	1:53:59	287 (SD 23.4)	58 (20%)
11	Rest	1:54:00	1:56:59	80	0
12	Stacking	1:57:00	2:14:59	129 (SD 14.8)	0
13	Psychological test	2:15:00	2:29:59	80	0

makes it possible to predict sweat rate, core and mean skin temperatures for an average person. However, it does not divide detailed spatial information (i.e. body segments) for sweat rate and skin temperature. An objective is to calculate duration exposure limits for use in occupational settings based on rectal temperature and sweat loss. The PHS simulation model was built on the previous required sweat rate index (SWreq) (Malchaire et al., 2001) and includes some additional aspects, such as calculation of the respiratory heat loss, distribution of heat storage in the body, exponential averaging for mean skin temperature and sweat rate, limits for non-acclimatized subjects and added mean body and rectal temperature to predicted core temperature (Malchaire et al., 2001; Malchaire, 2006). The simulation model was validated based on laboratory and field data within the European Program BIOMED II. Data from 909 experiments (672 laboratory and 237 field experiments) were gathered to a common database (Malchaire et al., 2001, 2002). One of the most innovative elements of the PHS simulation model included new algorithms for the prediction of the effects of body movements and wind on the heat exchange through clothing (Havenith et al., 1999; Parsons et al., 1999). The main limitation of the simulation model is its validity for clothing insulation in the range of 0.1–1 clo excluding highly insulating work wear (Wang et al., 2013). Furthermore, care should be taken when using available internet software with the integrated models as the algorithms of the standard model could have been modified according to the authors own interpretations and may have not been verified (d'Ambrosio Alfano et al., 2007, 2015; Ueno et al., 2009). The simulation model developed and used in the present comparison (www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS/PHS_agenda_2.html) was based on the implementation of the model in Annex E from the international standard (ISO 7933).

The mathematical model of the human thermophysiology by Fiala (Fiala et al., 1999, 2001, 2012; Fiala and Havenith, 2015) is implemented in a commercially available software (version FPCm5.3, Ergonsim, Germany). It consists of two interacting systems: the controlled or passive system and the controlling or active system. The passive system represents the human body segmented in 20 elements and includes the physical characteristics of the human tissue and the heat and mass transfer occurring within and between the body elements as well as between the body surface and the environment. Currently, the model allows adjustment of the fitness level, acclimatization days, body size and percentage of body fat of a simulated person besides simulation of a standardized average person (Havenith, 2001; Fiala and Havenith, 2015). The active system predicts the thermoregulatory responses driven by the central and peripheral nervous system including vasomotion, shivering and sweating based on regression models. This model has been widely validated mainly for prediction of mean skin and core temperatures, showing in general an acceptable agreement in a wide range of environmental conditions, clothing and activity level for both steady-state and transient exposures (Fiala et al., 2001; Psikuta et al., 2012; Martínez et al., 2016).

The approaches to simulate heat exchange are different in the described models, however, they both aim at providing predictions of the physiological responses to hot thermal environments of the average person. The objective of this paper was to compare and evaluate predictions of the two models against experimental human data. The experimental data was acquired from an intervention study carried out in controlled environmental conditions at Lund University, Sweden. An aim was to compare the rational simulation model PHS and the more complex rational multi-node model of Fiala against experimental human data. In addition, performance of models for simulating female and male data was analyzed as well.

2. Method

2.1. Description of the experimental study

The experimental data originates from dataset selected from a study carried out at Lund University involving ten participants (five males, five females) who performed an intermittent work protocol consisting of different occupational activities scheduled along 3 h. The experiments were carried out in the climatic chamber at a constant air temperature of 34 °C, relative humidity of 60% and air speed of 0.4 m s^{-1}. Participants were wearing a T-shirt, shorts, socks and sport shoes providing low thermal insulation. The basic thermal insulation and the evaporative resistance of the clothing ensemble considered for the simulation were 0.18 clo and 3.71 m^{2} Pa W^{-1}, respectively. Thermal insulation was measured at Empa with a thermal manikin (Sweating Agile Manikin) (Psikuta, 2009) and the evaporative resistance was taken from Wang et al. (2014), for a similar clothing ensemble. Table 1 shows the duration and metabolic rate of the different activities as considered for the simulated exposure using data from 2.5 h of the work protocol as measurements started after the initial psychology test which was a part of the experimental study protocol. This period of low activity in the chamber was used as a baseline exposure for the model predictions. Each exercise bout of 18 min was followed by a three-minute break to change activity, weigh the subject and conduct other tasks according to the experimental protocol. The sweat rate was calculated from weight change between each exercise bout. Oxygen uptake was continuously measured for every activity by Metamax I (Cortex, Germany).

The activities are described below (see Table 1):

- Psychological test: assessing different aspects of cognitive performance.
- Cycling: physical activity on a cycling ergometer at 100 W at 60 revolutions per minute.