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ORIGINAL PAPER

Thermal comfort modelling of body temperature and psychological variations of a human exercising in an outdoor environment

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Abstract Human thermal comfort assessments pertaining to exercise while in outdoor environments can improve urban and recreational planning. The current study applied a simple four-segment skin temperature approach to the COMFA (COMfort FormulA) outdoor energy balance model. Comparative results of measured mean skin temperature ($\overline{T}_{Msk}$) with predicted $\overline{T}_{sk}$ indicate that the model accurately predicted $\overline{T}_{sk}$, showing significantly strong agreement (r=0.859, P<0.01) during outdoor exercise (cycling and running). The combined 5-min mean variation of the $\overline{T}_{sk}$ RMSE was 1.5°C, with separate cycling and running giving RMSE of 1.4°C and 1.6°C, respectively, and no significant difference in residuals. Subjects' actual thermal sensation (ATS) votes displayed significant strong rank correlation with budget scores calculated using both measured and predicted $\overline{T}_{sk}$ (r_s= 0.507 and 0.517, respectively, P<0.01). These results show improved predictive strength of ATS of subjects as compared to the original and updated COMFA models. This psychological improvement, plus $\overline{T}_{sk}$ and T_c validations, enables better application to a variety of outdoor spaces. This model can be used in future research studying linkages between thermal discomfort, subsequent decreases in physical activity, and negative health trends.

Keywords Human comfort · Skin temperature · Bioclimatic urban design · Heat stress · COMFA model · Physical activity

Introduction

A thermally comfortable outdoor space influences the type and amount of physical activity a person performs, and creation of comfortable spaces is necessary to meet the demand of outdoor recreational users (Brown and Gillespie 1986). Human thermal sensation (TS) models can be used as bioclimatic design tools to provide more satisfactory spaces for exercise and recreational activities, which increases the overall health and well-being of urban dwellers. The future growth of cities will undoubtedly cause further problems associated with cardiovascular and respiratory problems, as well as death and illness from heat and air pollutants during the warmest times of the year (Vanos et al. 2010). Detrimental impacts are further expanded to athletic performance, work and behaviour (Brotherhood 2008), with shorter exercise durations found at high air temperatures (T_a), and a linear decrease in exercise workrate in the heat (Tucker et al. 2006). Many studies have noted specifically that urban dwellers show overall decreased health and functionality in everyday life (Johansson and Rohinton 2006), and higher heat-related mortality (Golden et al. 2008; Gosling et al. 2009).

TS models are used to predict the energy budget of a human and subsequently estimate how a human 'feels' in their given environment. Most well-validated energy budget

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models, such as those by Fanger (1970) or Gagge (1971) have been developed from indoor laboratory studies (steady-state) that are non-complex (Hoppe 2002; Huizenga et al. 2001). Such models use one-dimensional approaches for heat and mass exchange from the human body, with a clothing system that is uniform over the whole body (Zolfaghari and Maerefat 2010). When conditions are complex and non-uniform, they show non-linear relationships with thermal acceptability and sensation (Zhang and Zhao 2008), which will vary from indoor conditions. Consequently, these studies may not be appropriate for measuring outdoor heat stress in the ambient environment under a multitude of real world stimuli (Brotherhood 2008), and may not account for sensation differences a human feels on bare versus clothed parts of the body (Zolfaghari and Maerefat 2010). Further review of various outdoor thermal comfort models can be found in Vanos et al. (2010).

Skin temperature (T_{sk}) is an essential variable when estimating thermoregulatory responses due to heat and vapour exchange at the skin surface. The main function of local T_{sk} and mean skin temperature ($\overline{T}_{sk}$) is to aid in regulation of bloodflow, with high core temperatures (T_{c}) promoting bloodflow, and low T_{sk} inhibiting bloodflow (Huizenga et al. 2001). It is difficult to measure accurately $\overline{T}_{sk}$ of a human due to temperature variations of the skin, which become more complex during exercise and sweating (Ramanathan 1964). Thermal comfort is determined largely by $\overline{T}_{sk}$ (Bulcao et al. 2000; Yao et al. 2007), with associated physiological responses, such as heart and sweat rates, closely linked to T_{c} (Bulcao et al. 2000). Fiala et al. 2001 found that the driving impulses for regulatory action were T_{c} and $\overline{T}_{sk}$; thus a temperature-based active system controls the regulatory responses of the body.

Actual thermal sensation (ATS) is the perception of heat or cold (what one feels). Yao et al. 2007 found that the conscious mind reaches conclusions about ATS directly from the temperature of the skin. One can sense a change in ATS through thermoreceptors located in the skin, with a high rate of temperature change (ΔT) causing a greater effect on ATS. Firing of receptors depends on the rate of ΔT, and the ATS threshold value (when ΔT is felt) depends on the rate of ΔT as well as on individual characteristics (Kenshalo 1970).

Multi-segment models incorporate the uneven distribution of temperature and thermoregulatory responses over the body surface. Many validation studies have revealed that using multiple segments can reproduce thermal responses in dynamic environments, which are more difficult to model than indoor climates (Fiala et al. 2007; Havenith et al. 2002; Huizenga et al. 2001; Richards and Havenith 2007). The first multi-segmented human thermoregulation bloodflow model was the Stolwijk model (Stolwijk 1971), which couples circulatory, thermoregulatory and energy balance systems. Six segments of the body (head, trunk, hands, arms, legs, feet) are used for $\overline{T}_{sk}$ prediction, which has been found to be valid for the 'average' person under low activity conditions (Munir et al. 2009). Recent studies by Fiala et al. (2007, Huizenga et al. (2001), Salloum et al. (2007), Tanabe et al. (2002) and Munir et al. (2009) have been completed using this model.

The COMFA energy budget model (Brown and Gillespie 1986, 1995) is the foundation of the current study, and applies Fanger's 1970 model to predict the energy budget of a human using microclimatic, clothing and physiological data (Vanos et al. 2010). The version of COMFA recently evaluated and improved by Kenny and co-workers (Kenny et al. 2009a, 2009b) for use on exercising individuals is employed in the present study for energy budget prediction. The purpose of this paper is to apply an improved multi-segmented skin temperature (T_{sk}) approach to the COMFA model and evaluate its accuracy in predicting thermoregulatory responses. Statistical verification of predicted mean skin temperature ($\overline{T}_{Psk}$) with measured mean skin temperatures ($\overline{T}_{Msk}$) was completed, as well as T_{c} comparison with current literature, to test the validity of the multi-segment COMFA model. $\overline{T}_{sk}$ prediction is essential for thermal comfort, and becomes increasingly important under a range of thermal circumstances and higher metabolic outputs. This paper also contributes to research efforts to understand the psychological agreement of exercising subjects with respect to modelled energy budgets. Through comparative assessment of ATS responses by the subjects with predicted thermal sensation (PTS), the accuracy of subjective predictions using the adjusted COMFA model was validated.

Methods

Field surveys, participants and physiological data collection

Twelve physically active and healthy subjects (six female, six male) between the ages of 19 and 23 years participated in the current study, which is a comparatively young subset of the population. All subjects were healthy and active in their daily lives, and accustomed to exercising at moderate to intense training levels approximately 4–5 times per week. Descriptive characteristics of participants are listed in Table 1. Each volunteer completed the Physical Activity Readiness Questionnaire (PAR-Q) form as per the American College of Sports Medicine guidelines (ACSM 2006) and an informed consent form, with a protocol approved by the University of Guelph Research Ethics Board. Subjects abstained from strenuous activity, caffeine, and the use of sunscreen or lotion prior to the test, did not eat in the hour preceding the test, and were not permitted to drink fluid during the testing.

Table 1 Descriptive characteristics of subjects participating in field studies (n=12). *BMI* Body mass index, *SD* standard deviation

Variable	Mean	SD	Minimum–maximum
Female (n=6)			
Age (years)	21.5	1.38	19–23
Height (cm)	170.9	4.77	165.1–179.1
Weight (kg)	62.1	3.22	60.0–68.2
BMI[a]	21.4	0.76	20.45–22.51
Male (n=6)			
Age (years)	21.8	1.72	20–24
Height (cm)	186.5	5.94	180.0–195.6
Weight (kg)	81.8	9.53	72.7–97.7
BMI[a]	23.5	2.70	20.7–27.6

[a] 'Normal' BMI range is 18.5–24.9 (ACSM 2006)

Each cyclist and runner completed two exercise sessions. Cycling tests were completed on 16 and 30 July 2009, while running tests were completed on 16 and 30 September 2009, between the hours of 1100 hours and 1900 hours. All tests were completed at the University of Guelph campus (43.3°N, 80.2°W, 377 m above sea level) on large, uniform grass multipurpose fields.

Subjects exercised at a moderate intensity of 60–69% maximum heart rate (max HR). This intensity is equivalent to a rate of perceived exertion (RPE) (Borg 1982) of 12–13 ("somewhat hard"), in accordance with recommendations (ACSM 2006) of 30-min of moderate exercise 4–7 times per week for the average person. In order to have each subject exercising in their individual intensity range of 60–69% max HR, the Karvonen formula (Karvonen et al. 1957) was used to find a specific target HR (THR).

$$THR = (220 - age - RHR) \times (Intensity) + RHR \tag{1}$$

where RHR is resting heart rate, which was measured in a relaxed state on a day prior to the testing day.

Stationary cycling ergonometers (Monark, Ergomedic 874E; Healthcase International, Langley, WA), provided by the Department of Human Health and Nutrition Sciences (University of Guelph), were used for the cycling tests. The ergonometers were set in close proximity (10 m) to a portable weather station, and measured power output (W), speed (m s^{-1}), and revolutions per minute (RPM) of the cyclists. Runners exercised within the range of 10–50 m from a weather station on the open grass field. The subjects provided their carotid pulse over a 10-s period every 5-min during the test.

Metabolic activity (M_{act}), or energy expenditure (EE), in W m^{-2}, of both the cyclists and runners was estimated through use of the method of Strath et al. (2000) solving for EE from HR after adjusting for age and fitness. This estimation was completed by expressing the data as a percent of HR reserve (%HRR) and percent of VO_2 reserve (%VO_{2R}). A drawback of using this method is that training state and individual HR characteristics can affect the HR-VO_2 relationship; however, this method allows researchers to more accurately quantify physical activity (Strath et al. 2000), which is appropriate for the current study.

Each participant had fast response thermocouples (SA1-T Omega Engineering, Stamford, CT) attached to their left calf, right thigh, right upper arm and left chest (Ramanathan 1964). The mean measured skin temperature ($\overline{T}_{Msk}$) was calculated using the Ramanathan 4-point weighting method (Eq. 2), recommended and applied in field studies similar to the current study (e.g. Hodder and Parsons 2007; Mitchell and Wyndham 1969; Mora-Rodriguez et al. 2008; Sparks et al. 2005). This equation yields mean skin temperature values comparable to the 'elaborate' 7-point Hardy-Dubois weighting scheme, and is suitable for environment and heat exchange studies (Ramanathan 1964).

$$\overline{T}_{sk} = 0.3T_{chest} + 0.3T_{arm} + 0.2T_{leg} + 0.2T_{thigh} \tag{2}$$

T_{sk} readings were recorded using a 21X datalogger (Campbell Scientific Instruments, Logan, UT) for the cycling tests and a portable datalogger (HH147, Omega Engineering, Stamford, CT) secured on a waist belt during the running tests. All T_{sk} data were collected at 10-s intervals and calculated as 5-min averages over the sampling period. Using a structured three-question survey, participants were asked to rate their ATS on a 7-point psychophysical scale (hot, warm, slightly warm, neutral, slightly cool, cool, cold) (Fanger 1970), preferred change (PC) in sensation (i.e., would you like to feel much warmer, warmer, slightly warmer, no change, slightly cooler, cooler, much cooler), and RPE (Borg 1982) every 5-min. Subjects were asked to focus on overall feelings of exertion and sensation, rather than specific areas of the body.

Meteorological data acquisition

Net radiation was measured using a CNR1 net radiometer (Kip and Zonen, Delft, the Netherlands) mounted parallel to the ground surface, with four flux components (incident and reflected or emitted short- and long-wave radiation) measured simultaneously. Absorbed radiation was measured using a cylindrical radiation thermometer (CRT) as modified by Kenny et al. (2009a) mounted at 90° to the ground surface, painted to have an albedo of 0.37 and an emissivity of 0.95. It was ensured that no shadows were cast on either of the radiation instruments. Wind velocity (v_w) was measured using a cup anemometer (03102 R.M. Young Wind Sentry Anemometer, Campbell Scientific). *RH* and T_a

were measured using an HC-S3 Temperature and Relative Humidity probe (Campbell Scientific). All instruments were mounted on a tripod (Hoskin Scientific, Burlington, ON) 1.5–2.0 m above the ground surface. Meteorological data were collected with a CR21X datalogger (Campbell Scientific) at 10-s intervals and calculated as 5-min averages.

Modelling thermal comfort using the COMFA model

The energy budget for each participant was calculated at 5-min intervals during the exercise session based on the COMFA outdoor energy balance model (Brown and Gillespie 1986; Kenny et al. 2009a). The COMFA model requires the following inputs: T_a (°C), RH (%), v_w (m s^{-1}), static clothing resistance (r_{co}, s m^{-1}), static clothing vapour resistance (r_{cvo}, s m^{-1}), M_{act} (W m^{-2}) and total absorbed radiation (R_{abs}, W m^{-2}). Integral changes to the COMFA model involving clothing resistance (r_c), r_{cvo}, tissue resistance (r_t) and $\overline{T}_{sk}$, as proposed by Kenny et al. (2009b), were incorporated in the current study.

Skin temperature

Under normal everyday circumstances, the average human will wear ensembles that result in both bare and covered segments of the body. Thus, simulating a clothing resistance over the whole body may result in large inaccuracies for TS predictions. The current study employed a multi-segment method using four segments (Table 2) with respect to location of skin thermocouples and accounting for covered or bare body parts. This new method is in accordance with thermal energy budget models by Stolwijk and Hardy (1966), Fiala et al. (2001), Huizenga et al. (2001), van Marken Lichtenbelt et al. (2004), and Munir et al. (2009). Each body segment was assumed to possess a distinct T_{sk}, r_c, and aerodynamic resistance (r_a) to estimate convective heat exchange (C). r_c was also incorporated into sensible evaporation, and therefore evaporative heat loss (E). A distinct surface temperature (T_s) value was found for each segment and used in the estimation of emitted longwave radiation (L). Each segment was weighted using the coefficients in Table 2 to solve for total C, E and L, in W m^{-2}.

Table 2 Body segments and respective surface areas applied to convective heat exchange equations in the COMFA model

Segment	Fractional surface area[a]
Head/torso	0.321
Arms	0.202
Pelvis/thighs	0.285
Calves/shins	0.192

[a] Average weighting coefficient (Tikuisis et al. 2001)

T_{sk} was calculated for each segment as follows (Brown and Gillespie 1986):

$$T_{sk} = \left(\frac{T_c - T_a}{r_t + r_{c_i} + r_{a_i}}\right)(r_{a_i} + r_{c_i}) + T_a \tag{3}$$

where r_t, r_{c_i} and r_{a_i} are tissue, clothing and aerodynamic resistances, respectively (s m^{-1}), and 'i' refers to the segment. The mean predicted skin temperature ($\overline{T}_{Psk}$) was then found in the same manner as $\overline{T}_{Msk}$ using Eq. 2 in order to incorporate uneven influence of important portions of the body influencing skin temperature changes (Ramanathan 1964).

For trials on the first 3 days (warm, fair weather; T_a=16–25°C), all subjects wore white cotton T-shirts with regular athletic shorts and shoes. On day 4, subjects were permitted to wear clothing suitable for the cooler weather (T_a=8–10°C).

Clothing insulation values (I_{cl}) (clo) were assigned to each segment in accordance with ISO9920 (2007) based on clothing type and fabric. When subjects wore layered clothing, the I_{cl} was found using Eq. 4 (ISO9920 2007), where a clo is an arbitrary unit of clothing insulation (1 clo=186.6 sm^{-1}=0.1555 m^2 °C^{-1}W^{-1}).

$$I_{cl_i} = 0.161 + 0.836 \sum I_{clu} \tag{4}$$

I_{clu} is the effective thermal insulation of individual garments making up the segment ensemble, and r_{co}=I_{cl}× 186.6 sm^{-1}.

Core temperature

Sweating response is commonly expressed using a mean body temperature, calculated from $\overline{T}_{sk}$ and T_c (Shibasaki et al. 2006) since both temperatures stimulate thermoregulatory responses (Bulcao et al. 2000). Cardiovascular strain is exhibited through high $\overline{T}_{sk}$, sweat loss, and T_c (Sparks et al. 2005). The T_c increases as warm up progresses, followed by a levelling off after 15–20 min of exercise (Saltin and Hermansen 1966), and reaching an equilibrium value according to Eq. 5 (Malchaire et al. 2000). The COMFA model was found unable to account for the initial 'lag' in T_c rise compared to measured values, which was more evident at higher M_{act} (Kenny et al. 2009b). In order to avoid over-prediction of T_c in the initial stages of exercise, this study adopted a method of predicting T_c for t=0, 5 and 10-min using an exponential equation (Malchaire et al. 2000; Saltin and Hermansen 1966), as shown in Eq. 6.

$$T_{c_{eq}} = 36.6 + 0.002M_{act} \tag{5}$$

$$T_c = T_{c_0} + (T_{c_{eq}} - T_{c_0})(1 - exp(\frac{t}{\tau})) \tag{6}$$

where t is the time increment, τ is the time constant of 10-min, $T_{c_{eq}}$ is core temperature at equilibrium (after 15-min), found by Eq. 5, and T_{c_0} is core temperature at t=0, using Eq. 5 due to the subjects being at a rested equilibrium state prior to beginning exercise. Only after beginning exercise and changing their metabolic state did the time constant equation come into effect.

Results and discussion

Overview of participant and microclimate data

In the statistical analyses, the 12 subjects were treated uniquely in each experiment, as significant differences in all microclimate conditions were present, as well as possible changes in heat acclimation and physical fitness. Between days ANOVA showed no difference in the M_{act}, HR, or T_{c}; however, significant difference was present in $\overline{T}_{sk}$ ($P<0.05$).

The mean HR of the cyclists during exercise was 143 BPM (range=78–188 BPM), while that of the runners was 150 BPM (range=108–186 BPM), displaying individual variability among subjects at the range minimum. The mean speed of the cyclists during exercise was 9.3 $\mathrm{m s^{-1}}$ (range=6.7–18.0 $\mathrm{m s^{-1}}$), while that of the runners was 3.3 $\mathrm{m s^{-1}}$ (range=2.5–3.8 $\mathrm{m s^{-1}}$). The mean M_{act} during exercise for combined cycling and running tests was 516 $\mathrm{W m^{-2}}$ (range=99–742 $\mathrm{W m^{-2}}$), while that of cycling was 499 $\mathrm{W m^{-2}}$ (range=99–742 $\mathrm{W m^{-2}}$), and running was 533 $\mathrm{W m^{-2}}$ (range=315–732 $\mathrm{W m^{-2}}$). RPE values while exercising were similar for both cycling and running (RPE range=6–19 and 6–16, respectively).

The 24 field tests were conducted on four non-rainy days under varying temperature and cloud conditions (Table 3). These conditions were of appropriate range to test for the model's potential to predict temperatures under dynamic outdoor exposures.

Skin temperature

Mean and local skin temperature measurements are most appropriately evaluated and discussed by direct comparison of field measurements with corresponding predicted temperatures. Predicted mean skin temperature values ($\overline{T}_{Psk}$) showed significantly strong agreement with measured ($\overline{T}_{Msk}$) values (r=0.859, $P<0.01$), as shown in Fig. 1. The mean $\overline{T}_{Psk}$ and $\overline{T}_{Msk}$ ± one standard error (SE) during exercise were 31.2±0.20°C and 31.3±0.24°C, respectively.

Statistical evaluation of the difference between $\overline{T}_{Psk}$ and $\overline{T}_{Msk}$ at each time interval from 0–30 min was conducted using the root mean square error (RMSE). The mean 5-min variation of the $\overline{T}_{sk}$ RMSE (n=168) was 1.5°C. Separate cycling and running tests (n=84) had $\overline{T}_{sk}$ RMSE of 1.4 and 1.6°C, respectively. Residuals (differences) between the exercise types did not differ significantly, with a mean absolute residual of $\overline{T}_{Psk}$ from $\overline{T}_{Msk}$ of 1.2°C, and an average residual SE of 0.08°C.

Figure 2 displays the change of $\overline{T}_{Msk}$ and $\overline{T}_{Psk}$ with time, as well as RMSE over time. This figure shows that the model slightly under-predicted $\overline{T}_{sk}$ throughout the exercise period, and to a greater extent at t=0. This trend reversed at 25-min, where the model began to over-predict $\overline{T}_{sk}$. A possible explanation for this can be seen in the RMSE line for running (dashed line in Fig. 2b), which rises at 23-min. Further investigation found an increase in M_{act} at 25–30 min due to higher HR, thus the model predicted $\overline{T}_{sk}$ to be greater than measured. Exploration of residual values at 25–30 min exposed four outliers of approximately 3–4°C, which can be attributed to low $\overline{T}_{Msk}$ values, rather than high $\overline{T}_{Psk}$. This is most likely due to an increased likelihood of experimental error dealing with the skin thermocouples at the end of the exercise session.

Pearson correlation analysis was conducted to assess the relationship of select meteorological variables with $\overline{T}_{Msk}$ while the subjects were exercising (Table 4). Convection, T_{a} and T_{RT} displayed the strongest relationships (r=−0.902, 0.839, and 0.817, respectively, $P<0.01$) with $\overline{T}_{Msk}$. Convective heat loss to the air is greatest when a high T_{sk} results in a net flux of heat from the skin surface to the overlying air, and thus relies on the surrounding T_{a}. Hence, when T_{a} is close to T_{sk}, the convective heat loss will be less, and not participate as much in the overall budget. The elevated air temperatures on cycling days created a shallower temperature gradient and thus a weak relationship

Table 3 Summary of meteorological conditions recorded on-site expressed as a mean over each test period. T_a Air temperature (°C), e ambient vapour pressure (kPa), v_w wind speed (m $\mathrm{s^{-1}}$), T_{RT} cylindrical radiation thermometer temperature (°C), v_a activity speed (m $\mathrm{s^{-1}}$), K_t total incoming solar radiation (W $\mathrm{m^{-2}}$), L_a total atmospheric longwave radiation (W $\mathrm{m^{-2}}$), τ sky transmissivity

Date	Time	T_a	e	v_w	K_t	L_a	T_{RT}	τ
16 July 2009	1325–1650 hours	24.4	1.43	2.8	689	188	26.7	0.61
30 July 2009	1320–1640 hours	24.3	1.43	2.7	575	225	26.3	0.43
16 September 2009	1245–1535 hours	16.7	0.95	1.9	631	169	19.7	0.71
30 September 2009	1230–1530 hours	8.9	0.69	2.5	283	302	10.4	0.21

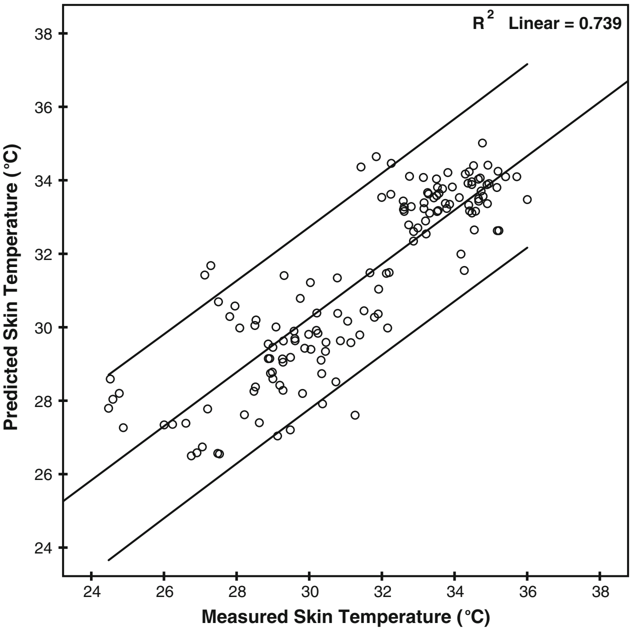

Fig. 1 Scatter plot displaying the relationship of skin temperatures predicted by the COMFA model to measured skin temperatures; 95% confidence intervals

of convection with $\overline{T}_{sk}$ (r=−0.057, P<0.01). In comparison, the cooler T_a and low R_{abs} on running days resulted in a strong negative relationship (r=−0.684, P<0.01), which allowed for a significantly greater convective heat loss from the body. T_a has a strong predictive relationship on $\overline{T}_{Msk}$ (Mairiaux et al. 1987) as found by Kenny et al. (2009b; R^2 linear=0.676), and in the current study (R^2 linear=0.704), with $\overline{T}_{Psk}$ by the model showing an even stronger relationship with T_a (R^2 linear = 0.878); hence, T_a is critical for accurate $\overline{T}_{sk}$ prediction. Additionally, the activity speed (v_a) present during running tests, plus lower ambient vapour pressures, resulted in significantly higher levels of evaporation during the latter 2 days (P<0.05).

The COMFA model is able to accurately predict physiological variables such as sweating response, T_{sk} or T_c, and is thus more accurate in heat stress prediction than the Humidex, or Wet Bulb Globe Thermometer, which has been found to show limited applicability (Epstein and Moran 2006). Physiological variables aid in determining thermal stress and potential strain of an individual in varying situations and locations; however, predicting strain during exercise and competition is more complex (Epstein and Moran 2006). Additional variables, such as fitness, physiological and psychological strain, core temperature and sweat rate may need to be considered and/or more accurately measured in such situations. Furthermore, sport-specific heat stress algorithms may be a useful application of the COMFA model based on carefully designed empirical research (Brotherhood 2008).

Core temperature

According to Fiala et al. (2001), core temperature is one of the most critical thermal characteristics of the human body, yet predictions based on Stolwijk's active system have been poorly correlated with data, especially for high levels of exercise and exercise in the heat, as found by Haslam and Parsons (1988). The COMFA model predicted T_c using Eqs. 5 and 6, with results displaying a mean value of 37.4°C (range 36.7–37.9°C, SE=0.02), with no significant difference between exercise types or testing days. Mean T_c at t=0 was 36.87°C, which is at thermal neutrality (36.8°C) (Parsons 2003).

Since T_c was not measured in the current study, a multi-study comparison of measured T_c in current and past literature with the modelled T_c by the COMFA was completed to validate the T_c predictions. Figure 3 displays trends of each study, revealing that the COMFA model adequately predicted T_c throughout the majority of the session for cycling and running tests combined. Compared to the current experiment, all studies presented in Fig. 3 had similar cycling exercise intensity and protocols, with T_c being measured using rectal probes. Ambient temperatures varied, yet were predominantly higher than the current experiment, and were completed in chamber or laboratory environments. Using the generalized HR-method for M_{act} estimation does not account for inconsistencies with the HR-energy expenditure relationship during dramatic changes, such as in the first few minutes when beginning exercise, and likewise when decreasing M_{act} (Strath et al. 2000). Applying Eq. 6 until equilibrium was reached at 15-min improved the ability of COMFA to predict T_c during exercise. This figure shows that, for the general application of the COMFA model to recreational design, and comfort

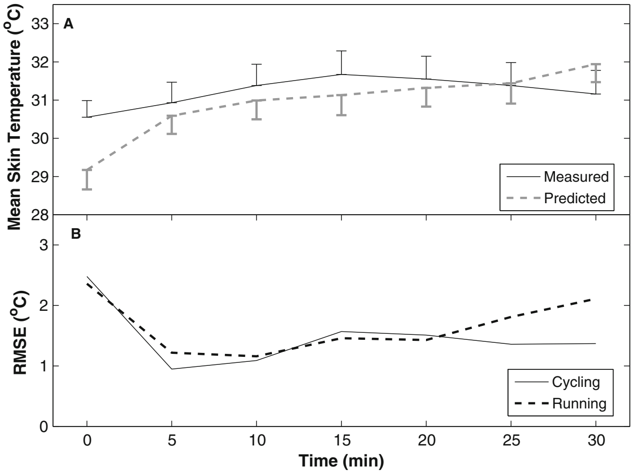

Fig. 2 **a** Average measured (T_{Msk}) and predicted (T_{Psk}) mean skin temperature. **b** RMSE variations during a 30-min exercise session. Error bars±1 standard error

Table 4 Pearson correlation coefficient (*r*) evaluation of select variables with measured skin temperature (T_{Msk}) while exercising for combined running and cycling, cycling (T_a=23–25°C) and running (T_a=8–18°C) tests. *C* Convective heat loss, R_{abs} absorbed radiation, T_a air temperature, T_{RT} radiant temperature—cylindrical radiation thermometer, v_w windspeed, *e* vapour pressure

Correlation (*r*) with T_{Msk}			
Variable	Combined (*n*=144)	Cycling (*n*=72)	Running (*n*=72)
C (W m^{-2})	-0.902^b	-0.057	-0.684^b
R_{abs} (W m^{-2})	0.765^b	0.375^b	0.097
T_a (°C)	0.839^b	0.351^b	0.355^b
T_{RT} (°C)	0.817^b	0.517^b	0.313^b
v_w (m s^{-1})	0.276^b	-0.169	-0.235^c
e (kPa)	0.847^b	0.130	0.380^b

[a] Correlation is significant at the 0.01 level (2-tailed)

[b] Correlation is significant at the 0.05 level (2-tailed)

and heat stress prediction for the general public, predicting T_c with an average M_{act} based on expected HR is sufficient.

Actual and predicted thermal sensation

Through the use of the revised budget values by Kenny et al. (2009b), ATS votes given by subjects and PTS predicted by the COMFA model were categorised based on a five-point TS scale from +2 (hot) to −2 (cold), where 'neutral' (0) ranges from a budget of −20 to +150 Wm^{-2} to account for 'activity skewing' (Kenny et al. 2009b). Figure 4 displays the range of COMFA budget values plotted against ATS votes during field tests (*n*=168), with one outlier value present. The median value for the 'neutral' (0) category was 83 Wm^{-2}, which clearly displayed overlap with categories 'warm' (+1) and 'hot' (+2), yet not with the 'cool' (−1) or 'cold' (−2). This overlap indicates the difficultly in predicting TS as the budget increases due to warm and/or radiantly strong environments, or with high metabolic rates. The 'cold' (−2) category should be interpreted with caution as only four data points were reported.

Figure 5 displays the frequency of ATS and PTS scores using both $\overline{T}_{Psk}$ and $\overline{T}_{Msk}$, with each displaying a normal distribution. Subjects ranked their ATS as neutral 57% of the time, while the PTS was neutral 39% and 38% using $\overline{T}_{Psk}$ and $\overline{T}_{Msk}$, respectively, which are comparable to frequencies found by Kenny et al. (2009a).

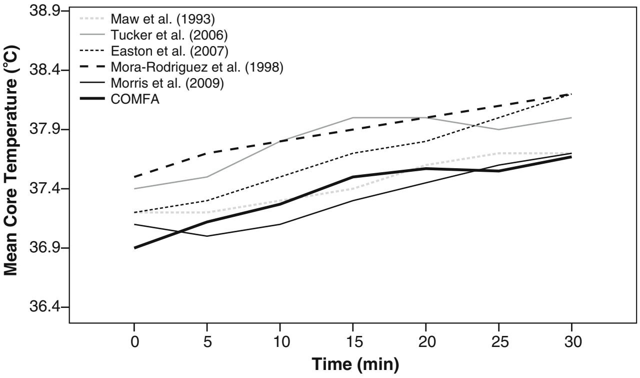

Fig. 3 Comparison of core temperature (T_c) results from literature with COMFA predictions. Lines represent the studies of Maw et al. (1993) (T_a=24°C, mean intensity $(\overline{I}) = 12 - 13$ *RPE* ('somewhat hard'), HR=142 BPM); Tucker et al. (2006) (T_a=25°C, $\overline{I} = 210$W, 16 RPE); Easton et al. (2007) (T_a=30°C, $\overline{I} = 63\%$ VO_{2max}, 70–100 RPM); Mora-Rodriguez et al. (2008) (T_a = 36°C, $\overline{I} = 60\%$ VO_{2max}, 169 W); Morris et al. (2009) (T_a=22°C; $\overline{I} = 70\%$ VO_{2max}, 14 RPE); and the COMFA model (T_a=8–25°C, $\overline{I} = 121$W, 60–69% $\mathrm{VO_{2max}}$, 9 METs, 12–13 RPE, 146 BPM, 78 RPM)

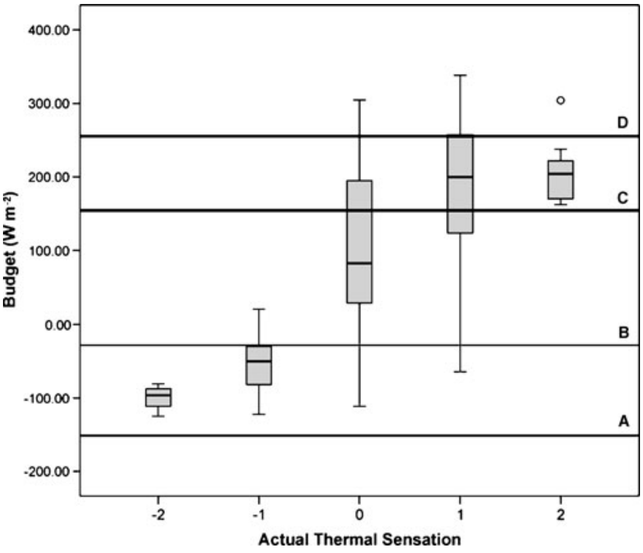

Fig. 4 Box and stem plot displaying the range of COMFA budget values with respect to actual thermal sensation (ATS) ratings given by subjects. *Boxes* Interquartile range; top of each box corresponds to 75th percentile; bottom corresponds to 25th percentile. *Stems* extend to highest and lowest scores in each range, excluding outliers (○). *Horizontal lines* Limits between each budget range (W m^{-2}) (A=−150; B=−20; C=150; D=250)

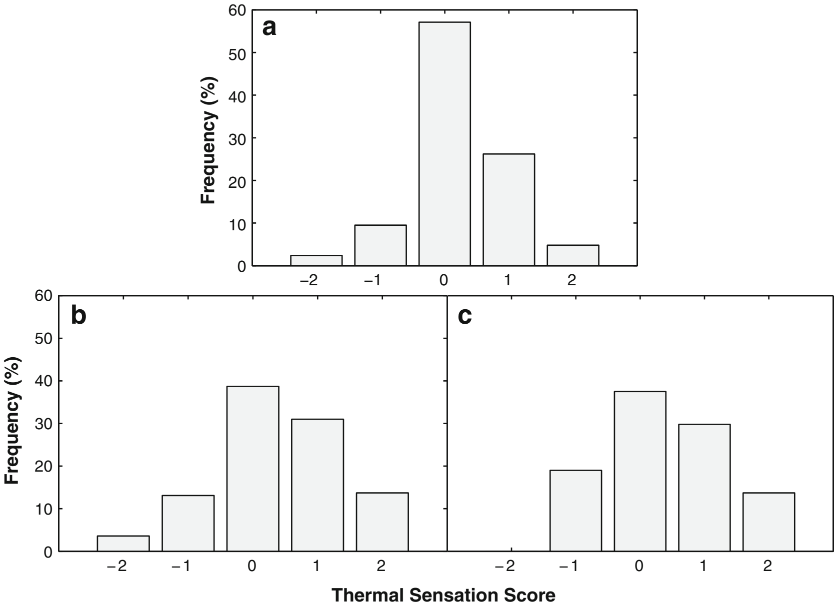

Fig. 5 Histograms displaying frequency distributions of **a** ATS given by subjects; **b** predicted thermal sensation (PTS) using predicted mean skin temperature by model ($\overline{T}_{Psk}$); **c** PTS using measured mean skin temperature ($\overline{T}_{Msk}$)

The bivariate associations between ordinal ATS and PTS data were assessed using a Spearman's rho rank correlation (r_s), with ATS votes from the subjects being compared to predicted and measured $\overline{T}_{sk}$. Correlation of ATS votes with PTS using $\overline{T}_{Psk}$ (r_s=0.564) was very close to PTS based on $\overline{T}_{Msk}$ (r_s=0.566), both showing significance at the P<0.01 level. Further analysis was completed through separation of days with cycling and running. PTS using $\overline{T}_{Psk}$ and $\overline{T}_{Msk}$ showed significant rank correlation with ATS during cycling (r_s=0.247 (P<0.05) and 0.268 (P<0.01)) and even more strongly with running (r_s=0.532 and 0.626, respectively, P<0.01). Thus, the model predicted the runners' TS with greater accuracy, which may be due to conflicting physiological and environmental parameters found between the activity types and study days.

Initially, a stark contrast was found in the mean overall budget values, which was 192 Wm^{-2} ('warm') for cyclists, and far lower at 23 Wm^{-2} ('neutral') for runners. Hence, on average, the cyclists were not comfortable, which resulted in more variation in subjective responses and ATS being more difficult to predict. The cause of this discomfort can be attributed to higher T_a and T_{RT} on the cycling days ($\overline{T}_a = 24.4$ and 12.8°C, $\overline{T}_{RT} = 26.5$ and 15.0°C, for cycling and running, respectively). According to Hodder and Parsons (2007), T_{RT} has the strongest influence on thermo-physiological significant indices, and is the most important input parameter for obtaining heat balance in summer-like conditions (Clark and Edholm 1985; Winslow et al. 1936). Furthermore, no activity speed is present during stationary cycling; thus, heat and vapour exchange through clothing is inhibited (Havenith et al. 2002), as is evaporative heat loss from skin. The estimated M_{act} for each activity were similar, with running M_{act} (533 Wm^{-2}) being slightly higher than that for cycling (499 Wm^{-2}); therefore, we are led to believe that the lower T_a and T_{RT}, with higher E during running, may have caused the runners to be more accepting of the conditions, allowing them to work harder yet still remain near the neutral zone of their budget.

While exercising outdoors at higher M_{act}, humans are more acceptant and expectant of uncomfortable conditions (Kenny et al. 2009a). Exercising at a high M_{act} is associated with physiological benefits (e.g., hormones, bloodflow, energy), as well as psychological mechanisms that may take precedence over many feelings of discomfort. This 'motivational effect' at higher M_{act}, or during intense training or competition, may overcome physiological perceptions and can result in heat injury (Brotherhood 2008; Roberts 2007).

Furthermore, increased discomfort was shown by higher measured local and mean T_{sk} values found during cycling tests. Blood redistribution occurs with respect to working muscles where muscle temperature increases more than T_c (Kerslake 1972). The cyclists showed increases in chest, thigh, calf and arm T_{sk} from t=0–30 min (mean ranges= 1.1, 2.3, 1.9, and 3.2°C, respectively), as compared to runners T_{sk} (mean ranges=0.8, −1.9, 1.6 and −0.7°C, respectively). Higher T_{sk} during the cycling trials were expected due to higher T_a and R_{abs}, yet the distribution of blood to muscles varies from that of running.

One of the main determinants of human thermal comfort is T_{RT} (Hodder and Parsons 2007; Kenny et al. 2009a; Matzarakis et al. 1999; Parsons 2003), which represents the sum of short- and long-wave radiation components in all directions (Kenny et al. 2008). T_{RT} was found to be closely related to T_a in the current study (r=0.993). A surplus of radiation inputs also increases T_c and T_{sk} (Tucker et al. 2006), as well as sweat gland activity varying with the intensity of radiant solar energy in different spectral bands (Ogawa et al. 1991), which affects evaporative heat loss.

There is demonstrably a complex interaction of microclimatic variables that potentially influence ATS; therefore, a multiple regression model for ordinal data was used to determine the best combination of gender, activity, T_a, v_r, M_{act}, K_t and L_a for predicting ATS scores (Table 5). Prior to completing the regression, the various predictors were tested for linearity with ATS, as well as multicollinearity to reduce variance inflation and incorrect relationship conclusions. This combination of variables significantly predicted the ATS votes using Pearson Chi-square ($P=0.00$), with the individual variables of L_a, T_a, M_{act}, and activity type significantly contributing to ATS responses ($P<0.05$). The proportion of the total variability accounted for by the multivariate model was 70%, as shown using the Nagelkerke Pseudo-R^2 test.

According to Havenith et al. (2002), the concept of ‘comfort’ may change while exercising due to a variety of factors, such as different hormones produced from the hypothalamus causing a sense of pleasure, which may broaden the range of what feels comfortable. However, under a warmer and radiantly strong ambient environment, sweating or vasodilation during cardiac activity may lead to hypotension, skin irritation, and intense warming of the skin (Maw et al. 1993). In the current study, increased $\overline{T}_{sk}$, and thus bloodflow to the surface, was found to increase convective and evaporative loss, both associated with the mentioned physiological responses. Hence, the ATS response by subjects when exercising is highly variable depending on the surrounding microclimate. Such mechanisms are difficult to quantify due to differing psychological and physical attributes, and were not considered in the original, sedentary based COMFA model by Brown and Gillespie (1986).

Accounting for psychological responses of exercising outdoors

There have been few attempts to understand the effect of the thermal environment on people’s use of outdoor spaces (Thorsson et al. 2004). The study of psychophysics attempts to relate physical stimulus with psychological sensation, such as the relationship between weather parameters or exercising with what a subject feels. Analysis of the subjective responses for preferred change (PC), RPE, ATS with a Spearman’s rho rank correlation test (r_s) showed that ATS was significantly related to PC, RPE and HR ($r_s=-0.801$, -0.540, 0.343, respectively). RPE was significantly related to HR and PC ($r_s=0.696$ and -0.488) all at the two tailed $P<0.01$ level. The RPE and HR correlation agrees with past research, showing RPE as a well-established tool in place of HR, blood lactate and $VO_{2\ max}$ monitoring (Batte et al. 2003). Subjects rated their PC as ‘0’ (no PC) 20% of the time, where 70% of ‘0’ responses were when the subjects were slightly warm (+1) or warm (+2); hence, at these times, subjects were not unsatisfied with their environments during exercise even when rated as ‘slightly warm’ or ‘warm’.

Feeling thermally comfortable deals with subtle and finely graded perceptual details, as opposed to thermal stress which deals with larger margins (Spagnolo and de Dear 2003). Exercise adaptation (improved fitness) and heat/cold acclimatisation vary throughout the year. Sedentary activities and the type of exercise being performed change perception and ATS responses, as shown by varying results in cycling and running tests of the current study. Significant inter-individual variation between budget output and ATS was found in the current study ($P<0.05$), as also found by Gavhed and Holmer (1996), which supports effects of age, height, weight, and varying psychology.

A purely physiological approach to determining TC is inadequate (Nikolopoulou et al. 2001), yet psychological research into the effects of thermal environments is still in its infancy (Parsons 2003). The psychological variables impacting ATS when exercising outdoors include, but are not limited to, expectations, perceived control, time of exposure (Thorsson et al. 2004), aesthetics, seasons, weather, socialising, perception, and readiness to exercise. Once the decision has been made to engage in physical

Table 5 Multiple ordinal regression model assessing the dependence of the subjects’ actual thermal sensation (ATS) votes on various predictors using a 7-point thermal sensation scale. L_a Atmospheric longwave radiation, T_a air temperature, v_r relative wind speed, K_t total incoming solar radiation, M_{act} metabolic activity rate, SE standard error

Model component		Estimate	SE	Significance
Location	L_a (W m^{-2})	0.009	.004	0.031[a]
	T_a (°C)	0.678	0.092	0.000[a]
	v_r (m s^{-1})	0.467	0.255	0.067
	K_t (W m^{-2})	0.000	0.001	0.582
	M_{act} (W m^{-2})	0.007	0.001	0.000[a]
	Activity	3.682	0.970	0.000[a]
	Gender	0.086	0.303	0.081
Goodness of fit	Chi-Square	df	Significant	
Pearson	2,282.81	971	0.000[a]	
Nagelkerke Pseudo R^2	0.700			

[a] Significant at a $P<0.05$ level

activity outdoors, certain facts of TC have been accepted (Nikolopoulou et al. 2001); in the same way, people engaging in recreational activities have already accepted the aspect of being slightly uncomfortable both thermally and metabolically.

Unfortunately, offsetting the thermal stress with such psychological adjustments and acceptances can draw people into zones of thermal heat stress. Therefore, it is potentially dangerous when the ATS response is ‘comfortable’ and the model predicts the subject is too hot. In order to provide a ‘thermally safe’ outdoor space, we must design the space to agree with the PTS. Recent studies have attempted to associate psychological perception with outdoor use (Lin 2009); however, research on psychological aspects of exercising outdoors is limited in the literature. TC models should be employed to design outdoor recreational spaces that ensure thermal comfort for the majority of the users, regardless of our psychological adaptations/feelings associated with the ATS ratings, which are even more pronounced in motivated athletes.

In order to account for different climatic zones, cultures, and varying psychological and behavioural adaptations, the adaptive predicted mean vote (aPMV) has been tested using adaptive coefficients (Yao et al. 2009). This notion may be further applied to exercising, as an adaptive coefficient is needed to differentiate between low and high metabolically demanding activities outdoors, and can thus improve the agreement of ATS with PTS votes from both $\overline{T}_{Msk}$ and $\overline{T}_{Psk}$. In the current study, when $M_{\mathrm{act}}>400\ \mathrm{Wm}^{-2}$, the rank correlation of modelled PTS with ATS was 0.408, versus 0.723 at $M_{\mathrm{act}}<400\ \mathrm{Wm}^{-2}$ ($P<0.05$). These differences show the difficulty found in predicting ATS at higher metabolic rates, as compared to higher agreement found in studies on sedentary individuals ($M_{\mathrm{act}}=58\ \mathrm{Wm}^{-2}$) (e.g. Brown and Gillespie 1986; Fiala and Lomas 1999; Zhang and Zhao 2008)). Increased accuracy using adaptive coefficients for sport-specific heat stress prediction will aid in identifying individuals and areas at highest risk of heat stress/stroke. Such predictions are needed to balance perceived health risks against the costs of cancelling an event due to environmental hazard (Budd 2008). Additionally, focusing on human acclimatisation as an adaptive agent with respect to T_{c}, regulatory responses and the perception of thermal sensation, can extend the potential uses of TC models (Fiala et al. 2001).

Conclusion

The prediction of the human energy budget requires models to make use of human physiology and meteorological measurements of the environment to physically quantify thermal comfort or sensation. This study has investigated the accuracy of applying a multi-segment T_{sk} approach to the COMFA model to evaluate its validity with respect to $\overline{T}_{sk}$, T_{c} and ATS responses. Good agreement of measured and predicted $\overline{T}_{sk}$ was found, with the mean 5-min variation of the $\overline{T}_{sk}$ RMSE was 1.5°C, a mean residual of $\overline{T}_{Psk}$ from $\overline{T}_{Msk}$ of 1.2°C, and an average residual SE of 0.08°C. The ability of the COMFA model to accurately predict $\overline{T}_{sk}$ under dynamic outdoor conditions during exercise enhances its usability for TC prediction. This is due to $\overline{T}_{sk}$ being an important predictor of ATS (Bulcao et al. 2000; Yao et al. 2007) in addition to dominating thermoregulatory responses of sweating, vasoconstriction, vasodilation and shivering under variable conditions (Fiala et al. 2001).

This study also provided further understanding of the energy budget and TC of exercising subjects through the use of the COMFA energy budget model. A Spearmans rank correlation (r_{s}) was used to gauge the strength of the relationship of ATS with both $\overline{T}_{Msk}$ and $\overline{T}_{Psk}$ budget scores, which were found to be 0.507 and 0.517, respectively ($P<0.01$). When using $\overline{T}_{Psk}$, the frequency of PTS in agreement with ATS votes was 48%, with 93% within ± one TS score. Similarly, budgets predicted with $\overline{T}_{Msk}$ in the model were in agreement 49% of the time, and within ± one TS score 94% of the time. The correlation and frequency results highlight the model’s strength in predicting ATS under various outdoor conditions and high metabolic rates. Acceptance of broader thermal conditions outdoors (Johansson and Rohinton 2006), and perceived lack of environmental control greatly widens comfort limits (Spagnolo and de Dear 2003). This study demonstrates that, with outdoor conditions plus exercise, individuals were even more tolerant of thermally uncomfortable conditions with broader TS zones.

Psychological aspects in the outdoor climate have not been a major focus in human energy budget studies (Lin 2009), and future research must clarify and account for the variables associated with predicting TS of humans exercising while outdoors. Since the sensations related to thermal conditions can be divided into two categories (‘temperature sensation’ and ‘thermal comfort’) (Hensel 1981), an understanding of each, as well as local and whole body comfort and sensation, have been present in recent studies (Nakamura et al. 2008; Zhang et al. 2004). When human (dis)comfort is separated from TS, votes for each have been found to be highly associated (Nikolopoulou and Lykoudis 2006), which may result in the interchanging use of the two terms in the literature. Applying additional scales simultaneously to subjects excising outdoors—such as the TS scale and a comfort scale (‘+0’, just comfortable, to ‘+4’, very comfortable) (Zhang et al. 2004)—can help distinguish between discomfort caused by factors not associated with the metabolic-microclimate interrelation. Thus, an additional psychological measure in outdoor, physically dynamic studies may be an interesting area for future research.

Urban planners must correctly apply human comfort research and knowledge gained by human biometeorologists in order to develop sustainable and thermally comfortable urban areas (Vanos et al. 2010). Further research is required to integrate the knowledge of the human–climate behaviour relationship, and its implications for sustainable urban design. Heat-related mortality statistics warrant increased use of climate-sensitive design in urban areas in order to avoid heat stress, prevent decreased work and exercise, and reduce detrimental impacts on sports performance (Brotherhood 2008). Using a bioclimatic model developed for exercising individuals, such as the COMFA outdoor model, is a valuable tool for conscious design of outdoor spaces to improve the microclimate for the general population, and to promote increased recreational activity.

In conclusion, the multi-segment COMFA model accurately predicts the skin temperature of a human exercising in an outdoor environment, with PTS agreeing well with ATS, yet having a slight tendency to under-predict perceived comfort due to psychological influences associated with exercise and being outdoors. For design purposes, we should strive to meet PTS levels as much as possible in order to extend their length and enjoyment of exercise and decrease the likelihood of entering a dangerous heat zone. The improved strength of the COMFA model enables more accurate use for general application to a variety of outdoor spaces, with the goal of increasing user satisfaction through bioclimatic design. Further applications of this model include quantifying crucial weather parameters for heat events, estimating and mapping greenspace present and/or needed in built-up areas, and analysing thermal comfort and health trends of various urban regions.

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