



# Intermittent wetting clothing as a cooling strategy for body heat strain alleviation of vulnerable populations during a severe heatwave incident

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## ABSTRACT

Many documented studies have demonstrated the human mortality rate increases during severe heatwaves. There remains a need for further explore ecologically valid cooling strategies to alleviate body heat strain during extreme heatwaves. The main aim of this work was to explore whether intermittent wetting clothing can be served as an ecologically valid cooling strategy to mitigate heat stress on inactive vulnerable populations not having access to air-conditioning during a severe heatwave. Ten young male subjects underwent two 90-min separate trials: a dry clothing trial (i.e., CON) and a wetted clothing cooling trial (i.e., WEC). A set of light summer wear was chosen and intermittently wetted by tap water at intervals of every 30 min. Physiological and perceptual responses of subjects were examined and compared. All trials were performed in a chamber with an air temperature of  $43 \pm 0.5$  °C, RH =  $57 \pm 5\%$  and an air velocity of  $0.15 \pm 0.05$  m/s (WBGT =  $37.35$  °C). Results demonstrated that WEC, compared with CON, could significantly reduce both the mean skin temperature and the core temperature throughout the 5–90th min and 25–90th min of the trial, respectively ( $p < 0.05$ ). Besides, WEC could also remarkable reduce local skin temperatures at those body sites covered by wet clothing ( $p < 0.05$ ). In comparison, no significant difference was found between WEC and CON on perceptual responses. Further, it was also found from PHS simulations that conditions with a partial water vapour pressure  $\leq 3.1$ – $3.5$  kPa would not induce pronounced core temperature rises at 43 °C. Finally, it may be concluded that intermittent wetting clothing could be served as an ecologically valid cooling strategy to reduce thermo-physiological strain of vulnerable populations while seating during humid heatwaves and thereby improve their health and safety.

## 1. Introduction

Heatwaves (i.e., prolonged periods of extremely hot weather) are becoming increasingly frequent and intense in recent years due to global warming and climate change (Li et al., 2015). It is now well established that human mortality and morbidity rates increase significantly during extreme heatwaves (Robine et al., 2008; Knowlton et al., 2009; Shaposhnikov et al., 2014; Guo et al., 2017). In the year of 2003, the deadliest heatwaves in Europe led to over 70,000 deaths (Robine et al., 2008). The California's 2006 heatwave killed at least 140 people and led to 1182 hospitalizations (Knowlton et al., 2009). The 2010 severe heatwave killed 55,736 people in Russia (Shaposhnikov et al., 2014). More recently in 2015, heatwaves in India and Pakistan claimed more than 4500 lives (Murari et al., 2015). Obviously, heatwaves have become a global concern, and they severely threaten

human health and safety (Li et al., 2015; Mora et al., 2017).

In extremely hot environments ( $T_{air} \geq 40$  °C), people like the poor and the homeless in backward areas do not have a chance to access air-conditioning. Hence, they have a high risk of suffering heat stress during prolonged heatwave incidents. In fact, statistical data showed that those populations account for a large proportion of heat-induced death tolls (Åström et al., 2011; Gronlund, 2014; Gubernot et al., 2014). Besides, extreme heatwaves put strains on the electrical power grid and cause power outages in some regions which renders electrically powered cooling devices (e.g., air-conditioning, electric fans and water pumps) useless. Thus, there is a great need to seek effective cooling strategies to combat heat stress on vulnerable people during extreme heatwave incidents (Gubernot et al., 2014). Presently, most government agencies just published qualitative guidelines for helping the general populations manage health and safety in heatwaves (CDC,

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2013). Some commonly suggested instructions may include drinking lots of water when the weather is hot, terminating work in the hottest hours of the day and wearing thin and light clothing (Gubernot et al., 2014). Unfortunately, the effectiveness and feasibility of the above qualitative measures remain uninvestigated. Therefore, there is a great need to scientifically explore effective but feasible cooling strategies to mitigate heat stress on vulnerable populations during heatwaves.

Based on the human heat balance equation (i.e.,  $M - W = (K + C + R + E_{sk}) + (C_{res} + E_{res}) + S$  [ $W/m^2$ ], where  $M$ ,  $W$ ,  $K$ ,  $C$ ,  $R$ ,  $E_{sk}$ ,  $C_{res}$ ,  $E_{res}$  and  $S$  are the metabolic heat production, mechanic work, conductive heat transfer, convective heat transfer, radiative heat transfer, evaporative heat transfer from the skin, convective respiratory heat transfer, evaporative respiratory heat transfer and the heat storage, respectively), the alleviation of heat strain (e.g., reducing the body heat storage  $S$ ) in hot environments may be implemented from three aspects, i.e., provide a relatively comfortable working environment to the individuals (e.g., using air conditioning), reduce the body metabolic heat production (e.g., adjusting exercise/work intensities) and create a comfortable clothing microenvironment around the human body (e.g., using personal wearable cooling systems). Air conditioning (AC) is regarded as an effective cooling strategy to mitigate heat stress, but it tends to bring about huge cooling energy consumptions. Besides, the use of AC systems induces ecological and environmental protection issues (Zhang et al., 2015). More important, it is not easily accessible for many population groups such as people living in economically backward areas. Lowering down the body energy expenditure seems less useful under extremely hot environments because the body heat gain in such conditions always outweighs the body heat dissipation. Documented studies (Yang and Yan, 2014; Lu et al., 2015; Song and Wang, 2016) on personal wearable cooling strategies (e.g., personal cooling clothing [PCC]) have demonstrated that PCC systems are effective in alleviating heat strain while working in various hot environments. Hence, personal wearable cooling clothing has great potential for heat stress mitigation on the general population during heatwaves. To our knowledge, whether personal wearable cooling clothing could effectively reduce body heat strain of vulnerable groups during extreme heatwaves remains unknown.

The most commonly used personal cooling device (PCD) at homes and in offices is electric fans. Electric fans (e.g., ceiling fan, desk fan and floor fan) help individuals dissipate body heat through forced convection under a range of indoor environmental conditions (CDC, 2013; Scheatzle et al., 1989; Ravanelli et al., 2015; Yang et al., 2015; Schiavon et al., 2017). The U.S. Environmental Protection Agency (EPA) suggests that the indoor temperature upper limit to use electric fans is 35.6–37.2 °C with no relative humidity values given (CDC, 2013). Controversially, several researchers recommend wider and higher temperature upper limits (i.e., > 40 °C) to use electric fans in low relative humidity conditions (Scheatzle et al., 1989; Ravanelli et al., 2015). Electric fans are usually less portable and hence, it is impractical for active populations to use electric fan cooling.

A potential personal cooling strategy to provide body cooling to both inactive and active populations is to wear personal cooling clothing (PCC). Presently, existing PCC systems include phase change material (PCM) cooling clothing, air cooling clothing (ACC), liquid cooling clothing (LCC), evaporative cooling clothing (ECC) and hybrid cooling clothing (HCC) that combines at least two aforementioned cooling techniques (Heled et al., 2004; Lu et al., 2015; Mokhtari and Sheikhzadeh, 2014; Wang and Song, 2017). Various types of PCC were found to bring significant body cooling benefits in hot environments (Lu et al., 2015; Mokhtari and Sheikhzadeh, 2014; Wang and Song, 2017). Nevertheless, it should be emphasized that a number of ergonomic problems brought by PCC (e.g., weight and movement restriction of PCC, convenience of use, expense and logistics) largely limit the actual wearable usability of PCC for vulnerable populations (Parsons, 2009; Sampson et al., 2013; Chan et al., 2015). For example, most ACC, LCC and HCC systems are normally complicated and expensive, and also

some PCC systems are non-portable due to the use of connected immovable compressors for providing cold air/liquid (Mokhtari and Sheikhzadeh, 2014). PCM cooling clothing suffers from drawbacks of cold storage requirement for PCM solidification, and also, miscellaneous replacements of PCMs during usage to realize prolonged cooling. In view of the above issues, there is an urgent need to seek ecologically valid personal cooling strategies with less ergonomic problems for the general public to mitigate heat stress during heatwave incidents.

Further, for such vulnerable populations as the poor, the homeless and those who do not have access to cooling devices and locations, an ecologically valid cooling strategy is important to manage individual health and safety while being exposed to prolonged heatwaves. It has been well recognized that water evaporation is a natural and ecologically valid strategy for body cooling. In cold conditions, wet clothing (i.e., another type of PCC containing water, referred as passive cooling clothing) can induce the body ‘chilling effect’ and thereby, increases the risk for an individual to develop hypothermia. Laboratory trials discovered wet clothing could absorb a large amount of body heat or promote great body heat losses, and thus results in a great body heat debt in cold environments (Craig, 1972; Havenith et al., 2013; Bakkevig et al., 1994; Richards et al., 2008; Wang et al., 2016). Greatly enhanced evaporative (due to the promoted moisture evaporation) and conductive heat transfer (due to the reduced clothing thermal insulation) through wearing wet clothing may be the explanation of the above phenomenon (Elson and Eckels, 2018). In hot conditions, the only documented human trial study (Heled et al., 2004) has demonstrated that spraying tap water on subjects in impermeable nuclear, biological, and chemical (NBC) clothing was effective in reducing body heat strain under an extremely hot environment (i.e., 40 °C, 40% RH). Nevertheless, the effectiveness of water spraying of normally clothing (e.g., light summer wear) on the heat strain alleviation of vulnerable populations remains unclear. Given these observations, it is also expected that using wet clothing in heatwaves may also promote evaporative heat transfer, and thus brings significant cooling to individual persons in heatwave events. Besides, this strategy is practical and easy to enforce due to its simplicity, i.e., the wetting of clothing may easily be achieved by using accessible water sources such as water reservoirs, water pools or water hydrants on the street.

Therefore, a study was conducted to investigate the effectiveness of intermittent wetting clothing on body heat strain alleviation in a simulated extreme heatwave event. Human trials were conducted in a controlled climate chamber with an extremely high air temperature and a high relative humidity (i.e., 43 °C, 57%). Thermophysiological responses and subjective perceptions of ten healthy male subjects in wet and dry summer wear were examined and compared. It was hypothesized that intermittent wetting clothing is able to improve both human thermophysiological responses and subjective perceptions in extreme heatwave incidents. Besides, due to the neglect of the contribution of environmental relative humidity (RH) to the magnitude of heat waves (Guo et al., 2017; Russo et al., 2017; Mora et al., 2017), the RH effect on the human thermophysiological load was also investigated using the PHS (Predicted Heat Strain) model (ISO, 7933, 2004).

## 2. Methods

### 2.1. Subjects

Ten healthy male subjects voluntarily participated into this study. Their average age, height, weight, body surface area and body mass index (expressed as mean  $\pm$  standard deviation) were  $23.2 \pm 2.4$  yr,  $1.73 \pm 0.02$  m,  $64.1 \pm 4.8$  kg,  $1.76 \pm 0.06$  m<sup>2</sup> and  $21.5 \pm 1.5$  kg/m<sup>2</sup>, respectively. Subjects were informed not to drink alcohol, tea, coffee, or perform intense activities at least 24-h before any scheduled trial. They were briefed of the purpose, experimental process, and potential risks associated with the trials, and a written consent was

obtained from the subjects prior to their participation. This study strictly complied with the rules of use of human subjects and was approved by the local ethical committee of Soochow University (Suzhou, China).

## 2.2. Clothing ensemble and test condition

A set of ordinary light summer wear including a short-sleeve polyester t-shirt, cotton short pants, briefs and sandals, was examined. The intrinsic thermal insulation ( $I_{cl}$ ) of the entire summer wear was 0.50 clo (1 clo = 0.155 m<sup>2</sup> K/W) and the permeability index ( $i_m$ ) of the whole clothing ensemble was 0.80 (i.e., very good permeability).

All trials were conducted in a climate chamber with air temperature of 43.0 ± 0.5 °C, RH = 57 ± 5% and air velocity of 0.15 ± 0.05 m/s. Thus, the partial water vapour pressure inside the chamber was 5000 Pa. The environmental condition selected could represent a harsh humid heatwave condition (also a dangerous health condition) (Russo et al., 2017).

## 2.3. Test protocol and calculations

In order to examine the effect of intermittent wetting clothing on the alleviation of body heat strain, the summer wear (i.e., both the t-shirt and short pants) was either wetted intermittently using tap water at every 30-min time intervals (denoted as WEC) or was not wetted by the tap water throughout the trials (denoted as CON). Each subject underwent two trials, i.e., in CON and WEC, in a randomized and counter-balanced order. Each trial was conducted at the same time of the day with a 48-h interval to eliminate the circadian variation impact. A total of 20 trials were conducted (i.e., 10 subjects × 2 trials).

Subjects were required to swallow an ingestible core temperature pill about 3-h before each trial to enable the capsule to enter the intestine site (Kolka et al., 1997). Upon arrival at the laboratory, the existence of the core temperature capsule was checked, and then the subjects were asked to drink 300 ml tepid water (about 37.0 °C) to avoid the possible dehydration (Cheung and McLellan, 1998). They were dressed in briefs and sandals. Afterwards, they rested on an armless chair quietly at room temperature until their core temperatures fell into the range of 36.8–37.2 °C. During the resting period, subjects were asked to perform the following tasks, i.e., learning to perform the Stroop Colour-Word Test, understanding the test procedure and the meanings of subjective rating scales listed in the questionnaire. Once fully equipped and dressed, the subjects entered into the climate chamber (ESPEC Corp., Osaka, Japan). The subjects were assigned to a testing scenario (in CON or WEC) randomly and they seated on a hard, armless chair. A plastic utility pan filled with light paraffin oil (Yanwei Medicinal Chemistry Company, Wuyi, Heibei Province, China) was placed underneath the chair to collect the dripped sweat (this setup prevents evaporation of the dripped sweat because sweat is always underneath the liquid paraffin oil [specific gravity: 0.860 g/cm<sup>3</sup>] due to the specific gravity difference between the paraffin and the sweat [Alber-Wallerström and Holmér, 1985]). It is noteworthy that an intermittent cooling strategy was used in WEC trials, i.e., for every 30 min, the t-shirt and short pants were quickly taken off and immersed in clean water (the water temperature was close to the room temperature, i.e., 25 ± 2 °C) for 30 s and squeezed gently prior to putting them onto the subject again. To avoid any possible bias, the same action (i.e., taking off and putting on CON) was taken in CON trials with the same time length. The trials lasted for 90 min and should be terminated if one or more of following criteria were satisfied: i) the subjects' core temperature ( $T_{inst}$ ) climbed to 39.0 °C, ii) the heart rate reached > 95% of the maximal heart rate, iii) they were unbearable and required to stop, or iv) they finished the 90 min trial. After the trials, the subjects left the chamber and quickly took off all clothing and wearable equipment to get each piece of the items weighed.

The oxygen consumption was recorded using a cardiopulmonary

tester (MetaMax®3B, Cortex Biophysik GmbH, Leipzig, Germany) during the entire trial. Heart rate was obtained using a Polar® chest strap and a heart rate watch (Polar Electro Oy, Kempele, Finland). Core temperature was measured using ingested telemetric core temperature capsules and a data recorder (CorTemp, HQ Inc., FL) that was placed at the waist region of the subjects. Skin temperatures in the seven sites of the left body, i.e., the chest, abdomen, scapula, paravertebral, upper arm, thigh and calf, were recorded by seven thermistors (MSR®145B4, MSR Electronic GmbH, Seuzach, Switzerland). The mean skin temperature ( $\bar{T}_{sk}$ ) was calculated using the Ramanathan's four-point weighting equation (Ramanathan, 1964):  $\bar{T}_{sk} = 0.3T_{chest} + 0.3T_{upper\ arm} + 0.2T_{thigh} + 0.2T_{calf}$ . All physiological parameters were recorded every 30 s throughout the entire trials. Based on the mean core and skin temperatures, the body heat storage could be calculated accordingly using the equation  $S = (0.8\Delta T_{inst} + 0.2\Delta \bar{T}_{sk}) \times C_b$  (where,  $C_b$  is the specific heat capacity of the body tissue,  $C_b = 3.49$  kJ/kg/°C;  $\Delta T_{inst}$  and  $\Delta \bar{T}_{sk}$  are the intestine temperature and mean skin temperature changes during a certain time period, respectively). The nude and clothed body weight, and each piece of clothing and wearable equipment were measured at the beginning and the end of each trial using a high precision weighing scale (Mettler Toledo KCC150s, Mettler-Toledo AG, Greifensee, Switzerland, precision: ± 1.0 g). Besides, the nude body weight, each piece of the summer wear and equipment were also measured during the trials for both trials in CON and WEC, i.e., right after the clothing being taken off every 30 min (excluding the end point), and each piece of the wear in WEC trials was also measured after being immersed into water. After the cooling intervention and prior to putting the re-wetted clothing on the body, each clothing piece was measured separately again to determine the total amount of water absorption. No subject requested to drink or use toilet to pee throughout the entire trial. The dehydration rate was calculated as the ratio of the total sweat production (i.e., the nude body weight difference between the 0th and the 90th min of the trial) to the pre-trial nude body mass. Sweat production (in grams), the mass of the evaporated sweat (in grams) and the efficiency of sweat evaporation were determined and calculated every 30 min throughout the trials. Sweat production during a certain 30 min time interval is the difference of the nude body weight in the time interval. Accordingly, the mass of the evaporated sweat during each 30-min time interval was obtained by subtracting the sweat absorbed (i.e., the difference of clothing weight in a time interval) and the dripped sweat (i.e., the difference of the dripped sweat in a time interval) from the sweat production (i.e., the difference of the body weight in a time interval). The efficiency of sweat evaporation was derived from [(sweat production - sweat absorbed by clothing - dripped sweat) / sweat production] × 100%.

The Stroop Colour-Word Test (SCWT) was performed at the beginning and the end of each trial using four colour-word cards. During the trials, subjects were seated close to a table, where the colour-word cards were placed. The cards were randomly assigned to the subjects to avoid any possible bias due to familiarization. Subjects were required to tell the colors of all words in a card (12 words), and time used to finish the reading, (i.e., the reaction time, in seconds), was recorded by a stopwatch. Subjective perceptions, i.e., thermal sensation, comfort sensation and skin wetness sensation, were collected at an interval of 15 min throughout the whole trials. Thermal sensation was assessed on a 9-point scale, in which -4 corresponds to 'Very cold' and +4 to 'Very hot' (McNall et al., 1967). Comfort and wetness sensations were both scored using 4-point scales with the comfort sensation scale ranges from -3 (representing 'Very uncomfortable') to 0 (representing 'Comfortable'), and the wetness sensation scale ranges from 0 (representing 'Neutral') to 3 (representing 'Very wet') (Brazaitis et al., 2010; Kwon et al., 1998). All these perceptual scales are continuous.

The PHS (Predicted Heat Strain) model (ISO, 7933, 2004) was used to estimate the core temperature time-course changes of a standard person (body height: 170 cm, body weight: 75 kg, body surface area: 1.8 m<sup>2</sup>) while seating in extremely hot conditions at different levels of

relative humidity. First, the predicted core temperatures of the studied scenario (i.e., in CON, 43 °C and 57% RH), calculated by the PHS model, were compared with the experimental core temperature data for the validation purpose. It was then applied to predict the core temperature time-course development at different levels of relative humidity, ranging from 20% to 70% in CON (inputs to the PHS model: air temperature = 43 °C, radiant temperature = 43 °C, air velocity = 0.15 m/s, metabolic rate = 93 W/m<sup>2</sup>,  $I_{cl}$  = 0.50 clo,  $i_{m}$  = 0.80).

#### 2.4. Statistical Analyses

Data were presented as mean  $\pm$  SD (i.e., standard deviation). A two-way repeated measure analysis of variance (ANOVA) was performed to examine the differences of physiological parameters (i.e., core temperature, skin temperatures and heart rate) between the two testing scenarios (i.e., CON and WEC), the time effect and the interaction effect between testing scenarios and time. If sphericity violations occurred, F-values were corrected using the Geisser-Greenhouse procedure. Paired Samples *t*-tests were then conducted in the case of the interaction effect to detect which pair(s) of the variables (i.e., reaction time, metabolic rate, sweat production, the mass of the evaporated sweat and the sweat evaporation efficiency) between the two scenarios differ significantly. The nonparametric Wilcoxon signed-rank test was performed to compare the differences of the subjective parameters (thermal, comfort and wetness sensations). All data analyses were performed using SPSS v.20 (IBM Inc., Armonk, NY), and significance levels were set as  $p < 0.05$  (marked as \*) and  $p < 0.01$  (marked as \*\*).

### 3. Results

All subjects successfully completed the 90-min trials. Reaction time showed no significant difference between the 1st min and the 90th min of the trials in both CON and WEC (i.e.,  $11.2 \pm 2.8$  s at the beginning vs.  $11.7 \pm 4.6$  s at the end of the trials in CON, and  $10.4 \pm 1.7$  s at the beginning vs.  $10.2 \pm 3.0$  s at the end of the trials in WEC,  $p > 0.05$ ), or between the two testing scenarios at the last minute of the trials ( $11.7 \pm 4.6$  s in CON vs.  $10.2 \pm 3.0$  s in WEC,  $p > 0.05$ ). No significant difference in the metabolic rate was observed between WEC (i.e.,  $1.6 \pm 0.3$  METs) and CON (i.e.,  $1.5 \pm 0.3$  METs,  $p > 0.1$ ).

#### 3.1. Dehydration rate, sweat production, sweat evaporation and sweat evaporation efficiency

Similar dehydration rates were observed between in CON (i.e.,  $1.44 \pm 0.03\%$ ) and WEC (i.e.,  $1.22 \pm 0.02\%$ ) ( $p > 0.05$ ). The averaged sweat production, the mass of the evaporated sweat and the efficiency of sweat evaporation during the three 30-min intervals are illustrated in Fig. 1 (i.e., from the beginning to the 30th min [0–30 min], from the 31th min to the 60th min [31–60 min], and from the 61th min to the end of the test [61–90 min]). Sweat production was significantly lower in WEC than CON during the 0–30 min and 31–60 min time periods,  $p < 0.05$ . No significant difference in the mass of the evaporated sweat between CON and WEC at any time interval ( $p > 0.05$ ). The efficiency of sweat evaporation was significantly higher in WEC compared with CON at the first two 30 min intervals ( $p < 0.05$ ).

#### 3.2. Local skin temperatures

Time course changes of local skin temperatures at the seven body sites in CON and WEC are shown in Fig. 2. At the end of the test, local skin temperatures at the chest, upper arm and the thigh in CON exceeded 38 °C (i.e., 38.1–38.3 °C), whereas only the upper arm temperature exceeded 38 °C in WEC (i.e., 38.1 °C). Local skin temperatures except for that in the calf region were all significantly reduced in WEC, i.e., from the 5th min to the end of the trial in the scapula, upper arm

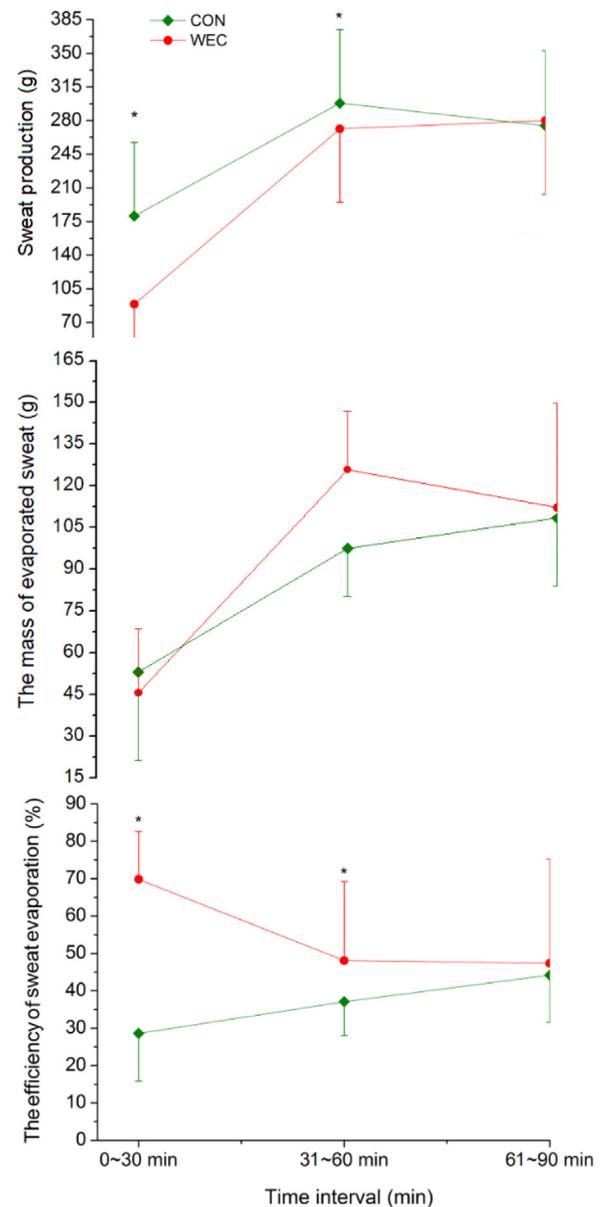
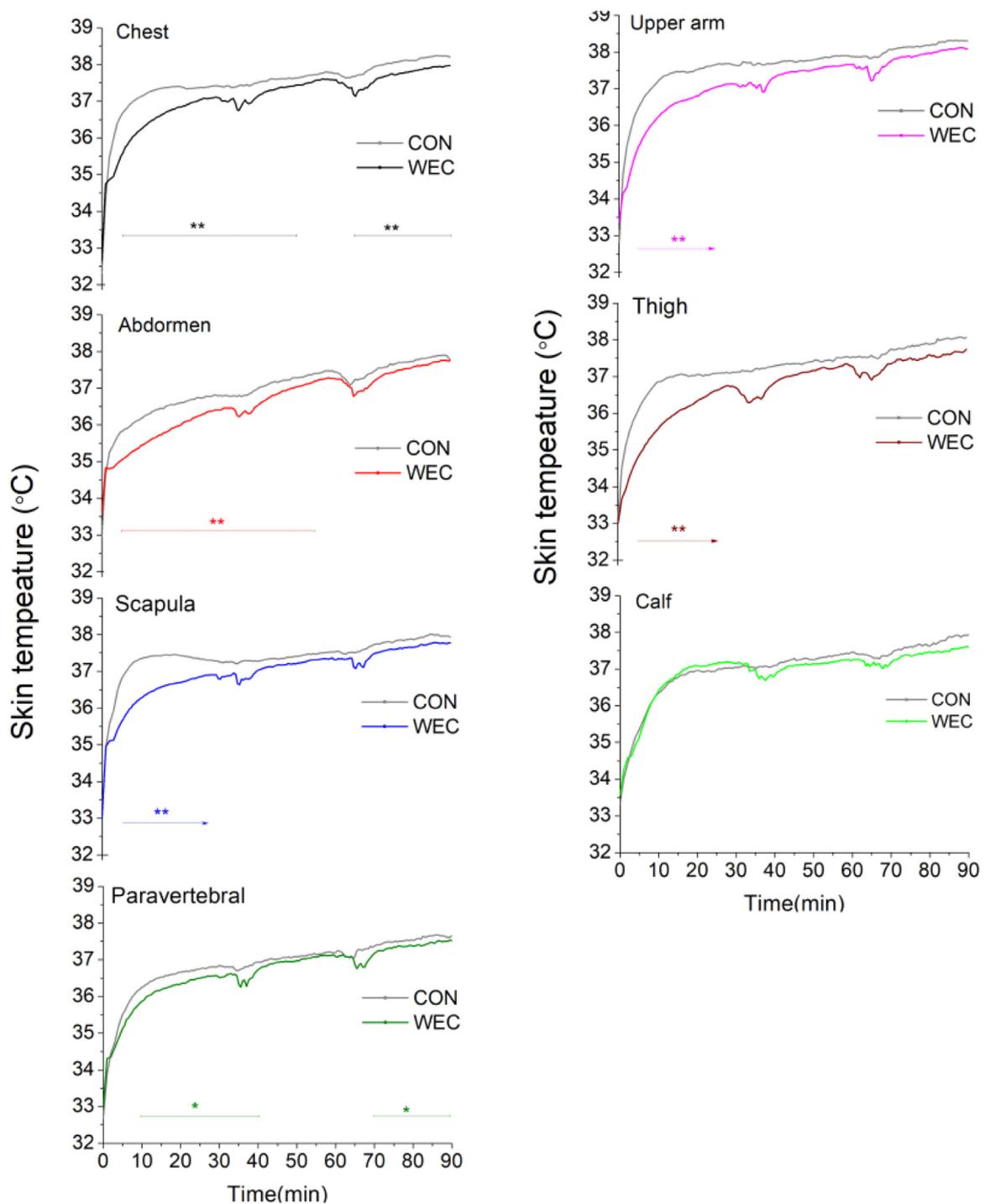


Fig. 1. The average sweat production, the mass of evaporated sweat and the sweating evaporation efficiency in WEC and CON during time periods of [0–30 min], [31–60 min] and [61–90 min].

and thigh regions, from the 5th min to the 50th min, and from the 65th min to the end of trial in the chest, from the 5th min to the 55th min of the trial in the abdomen, and from the 5th min to the 40th min, and from the 70th min to the end of trial at the paravertebral ( $p < 0.05$ ). To further illustrate the effect of intermittent wetting clothing on local skin temperature changes, time course changes in local skin temperature differences between WEC and CON were calculated (i.e., subtracting the skin temperature in CON from that in WEC, see Fig. 3). Three obvious reductions in local skin temperatures were observed at about the 5th min, 35th min and the 65th min of the trial, and the most significant reduction (i.e., ranging from  $-0.41$  to  $-1.32$  °C) occurred at about the 5–10th min of the trials ( $p < 0.05$ ). Skin temperatures were significantly higher at the scapula (i.e.,  $-1.2 \pm 0.4$  °C) and thigh regions (i.e.,  $-1.3 \pm 0.4$  °C) as compared to that in the paravertebral region (i.e.,  $-0.4 \pm 0.4$  °C,  $p < 0.05$ ).



**Fig. 2.** Time course changes in local skin temperatures in CON and WEC. Note: \*\* in black colour means the significant difference between CON and WEC at the chest; \*\* in red colour denotes the significant difference between CON and WEC at the abdomen; \*\* in blue colour denotes the significant difference between CON and WEC at the scapula; \* in olive colour denotes the significant difference between CON and WEC at the paravertebral; \*\* in pink colour denotes the significant difference between CON and WEC at the upper arm; and \*\* in the cyan colour denotes the significant difference between CON and WEC at the thigh (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

### 3.3. Mean skin temperature, core temperature and heart rate

As shown in Fig. 4, the mean skin temperature was significantly lower in WEC compared with that in CON from the 5th min to the end of the trial ( $p < 0.05$ ). The maximum mean skin temperature difference between CON and WEC was registered at the 10th min of the trials (i.e., 0.9 °C). At the end of the trial, mean skin temperatures in CON and WEC reached  $38.2 \pm 0.1$  °C and  $37.9 \pm 0.3$  °C, respectively (i.e., the

mean temperature difference is 0.3 °C). Core temperature was also significantly reduced in WEC compared with in CON from the 25th min to the end of the trial ( $p < 0.05$ ). At the end of the trial, core temperatures in CON and WEC reached  $38.9 \pm 0.1$  °C and  $38.6 \pm 0.2$  °C, respectively (i.e., temperature difference: 0.3 °C). It is also interesting to note that the core temperature reached 38 °C ('potentially dangerous' level) in CON at the 52th min whereas in WEC it was at the 62th min of the test. Furthermore, it was observed that both the testing scenario and

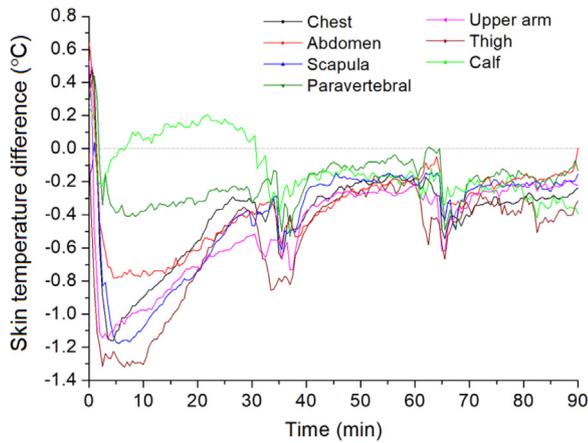


Fig. 3. Time course changes of in local skin temperature differences between CON and WEC.

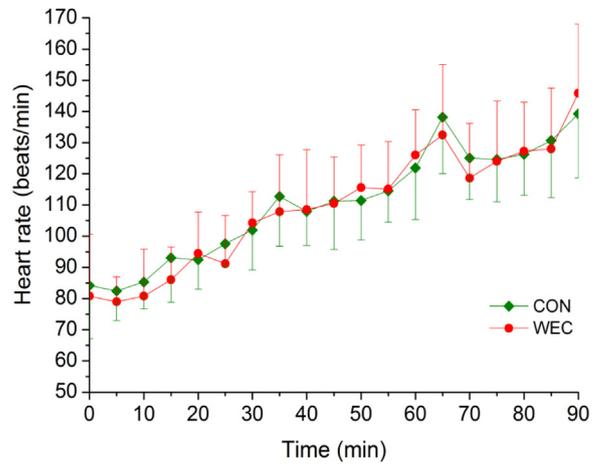


Fig. 5. Time course changes in heart rates in WEC and CON.

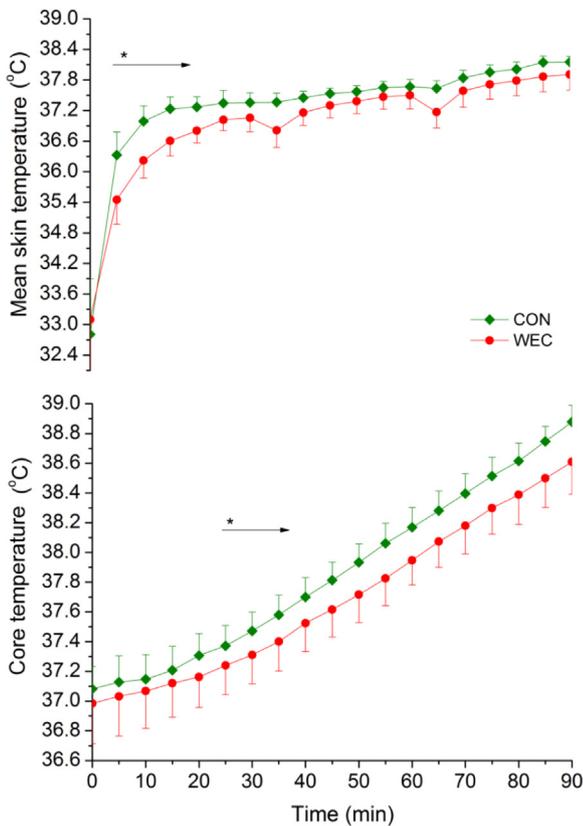


Fig. 4. Time course changes in mean skin and core temperatures in WEC and CON.

the time had a significant influence on mean skin and core temperatures ( $p < 0.01$ ), and interaction effect between them was registered as well ( $p < 0.05$ ).

As displayed in Fig. 5, heart rates increased to  $139 \pm 20$  beats/min and  $146 \pm 22$  beats/min in CON and WEC, respectively. It was found that time was the main factor affecting the heart rate ( $p > 0.05$ ). No significant difference in the heart rate was detected between the two testing scenarios during the entire trial ( $p > 0.1$ ).

### 3.4. Subjective perceptions

The responses of thermal sensation, comfort sensation and skin wetness sensation are shown in Fig. 6. At the end of the trial, subjective

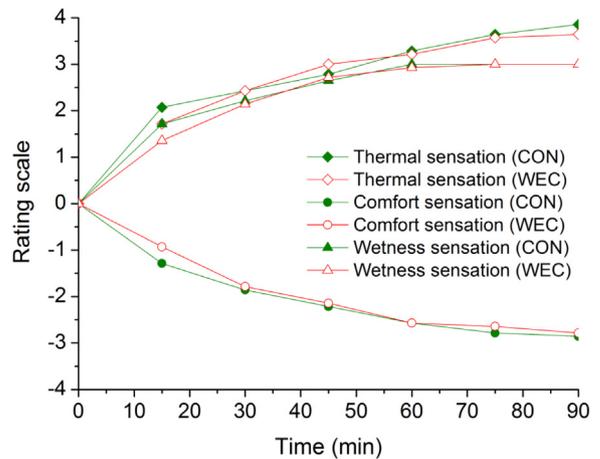


Fig. 6. The responses of thermal sensation, comfort sensation and skin wetness sensation in WEC and CON.

perception ratings nearly increased to the maximum values in both CON and WEC, i.e., thermal sensations reaching nearly ‘Very hot’ (i.e.,  $3.86 \pm 0.25$  in CON and  $3.64 \pm 0.43$  in WEC), comfort sensations climbing to nearly ‘Very uncomfortable’ (i.e.,  $-2.85 \pm 0.33$  in CON and  $-2.78 \pm 0.35$  in WEC) and wetness sensation increasing to ‘Very wet’ (i.e.,  $3.0 \pm 0.0$  in both CON and WEC). No significant differences in these subjective perceptions were observed between CON and WEC throughout the entire trials ( $p > 0.1$ ).

### 3.5. Effect of relative humidity on core temperatures

It can be easily seen from Fig. 7 that the PHS model accurately predicted the time-course core temperature development for the case of  $RH = 57\%$  (i.e., the ambient condition chosen for this work), though the initial core temperature was assumed to be  $36.8^\circ\text{C}$  in the model. Obviously, the relative humidity (RH) has a significant impact on the core temperature development. For  $RH \leq 40\%$ , the environmental heat stress has a limited impact on the body heat strain. In contrast, when the  $RH > 45\%$ , the core temperature increases remarkably with increasing environmental relative humidity. The critical relative humidity to induce uncompensable heat stress at the air temperature of  $43^\circ\text{C}$  is found to be between 35% and 40% (corresponds to partial water vapour pressures between 3.1 and 3.5 kPa).

## 4. Discussion

All subjects experienced severe thermophysiological and

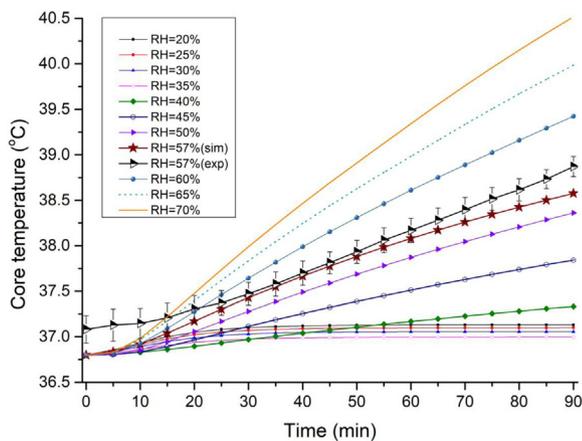


Fig. 7. Predicted time course core temperatures (i.e., rectal temperature) under various relative humidity levels at 43 °C. sim: simulation results; exp: experimental results.

cardiovascular strain (i.e., skin & core temperatures and the heart rate in CON reached  $38.2 \pm 0.1$  °C,  $38.9 \pm 0.1$  °C and  $139 \pm 20$  beats/min, respectively) and perceptual strain (i.e., thermal, comfort and wet sensations reached ‘Very hot’, ‘Very uncomfortable’ and ‘Very wet’, respectively) approaching the end of the trials. This has indicated that the studied ambient condition is an extremely harsh thermal environment for all subjects. Moreover, dehydration rates (i.e.,  $1.44 \pm 0.03\%$  in CON) exceeded the thirst threshold (i.e.,  $1.0 \pm 0.7\%$ ) (Parsons, 1988). Even so, the cognitive state of the human body was still well kept throughout the trials, indicated by the similar reaction time recorded at the beginning and the end of the trials.

In the studied extreme environment (i.e., 43 °C, 57% RH), the body heat dissipation via the sweat evaporation avenue was greatly restricted, resulting in high levels of body heat strain in both CON and WEC (Shvartz and Benor, 1972). In fact, the mean body heat storage in CON and WEC was  $8.3 \pm 0.6$  and  $7.6 \pm 0.5$  kJ/(kg K), respectively. Comparatively speaking, WEC could still significantly reduce the body heat strain (i.e., significantly lowered skin and core temperatures in WEC) compared with CON. This is mainly because a greater amount of water was evaporated (thus a higher evaporative body heat loss) in WEC than CON (Heled et al., 2004). Documented studies (Havenith et al., 2013; Akyol et al., 2014) showed that water from saturated clothing would first quickly evaporate to the ambient at a linear rate and then it slowed down during the drying out phase. It could be expected that the efficiency of sweat evaporation was significantly higher in WEC than CON at the first two 30 min intervals. No significant difference in the efficiency of sweat evaporation between WEC and CON in the third 30 min interval (i.e., the 60–90 min) was observed. The reason is probably because the secreted sweat completely saturated the clothing worn in CON at this stage (i.e., indicated by the ‘Very wet’ sensation shown in Fig. 6). For less severe heatwave conditions, in particular, less humid conditions (e.g., the partial water vapour pressure < 4.0 kPa), the intermittent wetting clothing cooling strategy would be function even better because the maximum evaporative capacity of the environment would be much greater than that of the studied heatwave condition. However, special attention should be paid to the frequency of applying the intermittent wetting clothing strategy because clothing dries much faster in such relatively dry heatwave conditions as compared to the presently studied condition. Therefore, the frequency of wetting clothing should be increased when using this cooling strategy to provide sustained evaporative cooling (e.g., every 20 min or 15 min).

In view of the high air temperature chosen for this study (i.e., 43 °C), the heat energy used for water/sweat evaporation could come from both the human body and the environment. Even so, the cooling

effectiveness of WEC was still observed, which is indicated by the significantly reduced skin temperatures in local body regions covered by wet clothing. Skin temperatures at the scapula and thigh regions (i.e., tight fitting regions) showed larger reductions than that at the paravertebral region (i.e., loose fitting region). Obviously, clothing fitness plays a significant role in affecting the evaporative cooling effectiveness. Tight-fitting clothing brings more evaporative cooling benefits than loose-fitting clothing because tight-fitting clothing has a much greater evaporative body cooling efficiency than loose-fitting garments (Havenith et al., 2013; Wang et al., 2014; Elson and Eckels, 2018). The most pronounced skin temperature reductions occurred at the initial 5 min of the trials, which could be explained from two aspects. On one hand, remarkable water evaporation was expected in WEC. On the other hand, the body was still in the sweat development phase in CON and much less evaporation was taken place during the initial 5 min of the trials. This observation indicated that for people with impaired sweating function and perhaps the elderly (Foster et al., 1976), wetting the clothing worn through either water spraying or soaking the clothing into water could greatly help individuals reduce their skin temperatures and thereby, alleviate the body heat strain while staying (i.e., seating) in heatwave conditions. Attributing to the local skin temperature reductions in WEC, the mean skin temperature was observed to be significantly reduced in WEC nearly during the entire trials. With a larger temperature gradient between the body central core and the skin in WEC compared to CON, the core temperature was also found to be significantly reduced in WEC. It was also observed that the time at which the body central core started to receive evaporative cooling benefits has lagged behind that received by the body skin (i.e., core and skin temperatures were significantly reduced from the 25th min and the 5th min to the end of the WEC trials, respectively). This is obviously because it takes longer time for the body central core passes the internal heat through the underlying muscle and subcutaneous fat and reach the superficial skin layer, from where the metabolic heat is being dissipated to the external environment (Otte et al., 2002). At the 52nd min, the core temperature in CON almost reached 38 °C (i.e.,  $37.9 \pm 0.3$  °C), which falls within the ‘potentially dangerous’ range (i.e., 38.0–39.0 °C). The core temperature (in CON) rose further to  $38.9 \pm 0.1$  °C at the end of the trial, which almost reached the ‘dangerous’ level (i.e., over 39.0 °C) (Parsons, 1988). Applying WEC postponed the body core temperature rise to the ‘potentially dangerous’ level by 10 min (i.e., reaching 38 °C at 62th min), and this level continued till the end of the test (i.e.,  $38.6 \pm 0.2$  °C) (Parsons, 1988). Significantly lower sweat productions observed in the first two 30-min intervals in WEC than those in CON may be induced by the significantly alleviated heat strain in WEC. Similar time course heart rates were observed between WEC and CON, which was in accordance with the finding that the responses of the cardiovascular function mainly rested with the exercise/work intensities (Crandall and González-Alonso, 2010).

Although thermophysiological strain was significantly alleviated in WEC, subjective perceptions still could not be differentiated between WEC and CON. It has long been recognized that human perceptual responses are affected by a number of factors. Thermal sensation is closely related to the mean skin temperature (Gagge et al., 1969; Li, 2005). Wetness sensation is strongly linked to moisture accumulated on skin and clothing (Hatch et al., 1990; Li, 2005). In contrast, comfort sensation (i.e., thermal comfort) is normally affected by multiple factors such as the skin temperature, skin heat loss, and skin wetness (Havenith et al., 2002; Li et al., 2005). In this study, the mean skin temperature difference between CON and WEC (i.e., 0.9 °C) was insufficient to induce thermal sensation difference between the two studied scenarios (Chan et al., 2015). Insignificant differences observed in the skin wetness and comfort sensations between CON and WEC indicated that the chosen test condition was so extreme that subjects were unable to distinguish perceptual sensation differences (Sperlich et al., 2013). Particularly, both the skin wetness sensation and comfort sensation have almost reached their maximum ratings after just 60 min.

Interestingly, our results are in quite good agreement with experimental findings reported by Heled et al. (2004), where no significant difference on thermal comfort was found between the dry-ice cooling and water spray cooling in the extremely hot condition. In view of this, the hypothesis that the WEC cooling strategy could improve subjective perceptions was violated. However, it was still unclear whether there will be significant differences in perceptual responses in less humid heat-wave conditions.

With regard to the relative humidity effect on individual body heat strain, the environmental heat stress has a very limited impact to the body heat strain in relatively dry environments (RH < 40%), which is mainly because the environmental heat stress can be easily compensated by the evaporation of sweat. The critical relative humidity at 43 °C to induce uncompensable heat stress is likely to lie somewhere between 35% and 40%. For relatively dry heatwave conditions, there is no need to take further action on providing extra cooling on the individual while seating. Nevertheless, for vulnerable populations such as people with impaired sweating functions and the less fit elderly, there might be a need to introduce body cooling to accelerate body heat dissipation in order to maintain the body heat balance.

Further, it should be addressed that the cooling effect of the WEC strategy was highly dependent on the exercise intensities and environmental conditions (Chan et al., 2015). In the present study, a low activity intensity (i.e., about 1.6 METs) was used, and significant cooling benefits on thermophysiological responses were observed in WEC. However, the cooling effectiveness of WEC on people in high exercise/work intensities was still unknown, where more cooling benefits were required for reducing body heat strain. Though a highly humid environment was adopted in this study (i.e., the partial water vapour pressure of 5000 Pa), appreciable cooling benefits were still discovered. It was expected that WEC would be more effective in extremely hot dry environments, where evaporative heat loss is more promoted because of the enlarged water vapour pressure gradient between the body and the surrounding environment. Therefore, it could be concluded that the WEC could significantly reduce the thermophysiological strain of the human body while performing relatively low intensities under the studied heatwave condition. Nevertheless, cautions should be taken when applying the intermittent wetting clothing strategy to alleviate body heat strain while exercising/working at higher levels of intensity during similar extreme heatwaves.

A limitation of the present study is that only young male subjects were recruited, and a seating posture was used, restricting the results to females, populations with different ages and various actual work activities. Future studies should be performed to evaluate the effectiveness of the intermittent wetting clothing strategy in reducing the body heat strain on both sexes with wider age distributions (e.g., the elderly), and on the populations do not have access to air conditioning such as the outdoor workers while performing their daily activities in heatwaves.

## 5. Conclusions

This study explored the possibility of using intermittent wetting clothing to serve as an ecologically valid cooling strategy to alleviate heat strain of vulnerable populations while seating during an extreme heatwave. Results have revealed that the intermittent wetting clothing cooling strategy could effectively reduce body heat strain during the 90 min trials, as indicated by the significantly reduced local skin & mean skin temperatures as well as core temperatures in WEC. Further, in comparison to the widely used wet towel method (i.e., placing a wet towel on the head) seen in India and Pakistan and spraying water on the face and exposed skin, the proposed intermittent wetting clothing strategy is anticipated to be more effective in alleviating thermophysiological strain because it cools an individual person at a much greater body area. Besides, tight fitting summer clothing will offer a better evaporative cooling potential and thereby, an enhanced heat

strain alleviation is anticipated in tight-fitting garments as compared to loose-fitting clothing. Future studies are still required to examine the effectiveness of this promising ecologically valid cooling strategy in alleviating heat strain of the general populations not having access to air conditioning while performing other daily activities in extreme heatwaves, however.

## CRedit authorship contribution statement

**Wenfang Song:** Formal analysis, Investigation, Software, Validation, Visualization, Writing - original draft. **Faming Wang:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - original draft & Writing - review & editing. **Chengjiao Zhang:** Data curation, Investigation, Validation, Visualization.

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## Conflicts of interest

The authors declare that there is no conflict of interest involved.

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