Ueno *Journal of Physiological Anthropology* (2020) 39:23
https://doi.org/10.1186/s40101-020-00235-9

Journal of Physiological Anthropology

ORIGINAL ARTICLE Open Access

Comparison of correction factor for both dynamic total thermal insulation and evaporative resistance between ISO 7933 and ISO 9920

Satoru Ueno

Abstract

Background: Thermal insulation and evaporative resistance of clothing are the physical parameters to quantify heat transfer and evaporative dissipation from the human body to the environment, respectively. Wind and body movement decrease thermal insulation and evaporative resistance of clothing, which is represented as correction factors for dynamic total thermal insulation (CF_i) and evaporative resistance (CF_e), respectively. Then, CF_i and CF_e are parts of the key parameters to predict heat strain of workers by computer simulation. The objective of this study was to elucidate the difference of CF_i and CF_e between ISO 7933 and ISO 9920 and compare the difference of predicted rectal temperature, water loss, and exposure time limit calculated by using each correction factor.

Methods: CF_i of ISO 7933 (CF_{i7933}) and ISO 9920 (CF_{i9920}), and CF_e of ISO 7933 (CF_{e7933}) and two kinds of CF_e of ISO 9920 (CF_{e9920a}, CF_{e9920b}) were compared in terms of relative air velocity, walking speed for three kinds of thermal insulation of clothing. Next, two modified predicted heat strain (PHS) models were developed: modified PHS integrated with CF_{i9920} and CF_{e9920a} (PHS_{mA}) and modified PHS integrated with CF_{i9920} and CF_{e9920b} (PHS_{mB}). We calculated the rectal temperature, water loss, and exposure time limit by PHS, PHS_{mA}, and PHS_{mB} and compared the results.

Results: CF_{i7933} and CF_{i9920} were almost similar in terms of V_{ar} and walking speed, while CF_{e9920a} and CF_{e9920b} were larger than CF_{e7933} when V_{ar} was more than 1.0 m·s^{-1}. Intrinsic clothing insulation (I_{cl}) diminished the effects of V_{ar} on CF_{i7933}, CF_{i9920}, CF_{e7933}, and CF_{e9920b}. However, CF_{e9920a} was not influenced by I_{cl}. The predicted rectal temperature and water loss difference were larger between PHS and PHS_{mA} as CF_e difference got larger. The duration time when limit of rectal temperature of 38 °C was reached ($D_{limTre38}$) calculated by PHS was significantly longer than PHS_{mA}, PHS_{mB} at higher V_{ar}.

Conclusions: Precise correction factors for evaporative resistance are required to predict rectal temperature, water loss, and work-time limits.

Keywords: Predicted heat strain (PHS), Thermal insulation, Evaporative resistance, Correction factor

Correspondence: ueno@h.jniosh.johas.go.jp
Japan Organization of Occupational Health and Safety, National Institute of Occupational Safety and Health, 6-21-1 Nagao, Tama-ku, Kawasaki, Kanagawa 214-8585, Japan

Background

Clothing decreases heat transfer between the human body and the environment through convection, conduction, radiation, and evaporation. The thermal characteristics of clothing are mainly represented by total thermal insulation (I_T) and evaporative resistance (R_{eT}). Thermal insulation and the evaporative resistance of clothing depend not only on the clothing itself (fabric and design, such as apertures or folds in the clothing), but also on several conditions, such as the wearer's activity level, relative air velocity (V_{ar}) applied to the wearer, and posture [1–5]. Air flow promotes heat transfer by increased air permeation through the clothing fabric and openings inside the clothing. Human subject experiment using an ergometer showed that forced draft decreased body core temperature and sweat rate by increasing evaporative heat loss [6, 7]. A wearer's activity also increases heat transfer by the exchange of air between the inside of the clothing and the environment by "pumping effects" [8] through openings in the clothing. The walking movement of thermal manikin facilitated heat dissipation by convection and evaporation. Experimental results of mean skin and core temperature of a walking manikin were closer to a walking human trial data than a standing manikin [9]. When sweat absorbs heat from the skin, it turns into vapor. Thereafter, vapor is transferred to the environment to a greater extent through higher ventilation due to air flow or a wearer's activity. Increased vapor transfer to the environment decreases the microenvironmental humidity inside the clothing, which promotes evaporation on wetted skin, leading to increased heat transfer between the body and the environment. In a hot environment, the avenue of heat transfer from the human body to the environment is mainly through the evaporation of sweat due to decreased heat transfer by convection from decreased temperature difference between the skin and the environment. When heat loss by sweating is suppressed by vapor-impermeable clothing, though it serves to protect the human body from hazardous materials, thermal physiological strain increases [10–12].

I_T and R_{eT} in dynamic conditions are required to calculate heat transfer to the environment and to predict core temperature, water loss, or skin temperature, etc., in thermal models. However, the limited availability of climate chamber, sweating thermal manikin with active simulation, and laminar air flow make it difficult to measure thermal insulation and evaporative resistance of clothing under various specific conditions for air velocity or activity. Then, to numerically predict I_T and R_{eT} under wind or active conditions from static conditions, some studies on correction factors for dynamic total thermal insulation (CF_i) [1, 13–20] and evaporative resistance (CF_e) [2, 15, 16, 21] have been carried out.

Havenith et al. [1] investigated the effects of both walking and wind on the insulation value of clothing ensembles by conducting human subject experiment. Nilsson and Holmér [13] evaluated the total insulation in the wind and by walking via a thermal manikin. The equations for CF_i and CF_e in ISO 7933 [22] were developed as part of the BIOMED EU-project led by Malchaire. Three papers [14, 15, 21] were produced in the project. By utilizing the data of Havenith et al. [1] and Nilsson and Holmér [13], Holmér et al. [14] proposed CF_i for over 0.6 clo of clothing insulation (Eq. 30 in [14]) and nude (Eq. 29 in [14]) under walking and wind. CF_i for nude in [14] was later changed to Eq. 3 in [16] by Havenith et al. Havenith and Nilsson [21] proposed the equations for CF_e from the empirical relation of change in i_m with change in heat resistance. Parsons et al. [15] summarized the results and proposed the computer code. Equation 30 [14] and Eq. 3 [16] were included in the present ISO 7933 [22]. In the revision of ISO 7933 [23], predicted heat strain (PHS) model was proposed by Malchaire et al. [24] and adopted in the International Organization for Standardization (ISO) as ISO 7933 [22]. PHS was validated using laboratory (672 experiments) and field (237 experiments) data [25]. Following the publication of ISO 7933 [22], the ISO committee ISO TC159/SC5/WG1 started the ISO 9920 [26] revision. For this work, Havenith [17, 18] reanalyzed more data from a cooperation between Nilsson and Havenith, from Kim and McCullough [19], and from Nilsson et al. [20] on CF_i in addition to Holmér et al. [14]. CF_e in ISO 9920 [27] was also changed from that of ISO 7933 [22]. By analyzing a more extensive data from Havenith laboratory compared to what was used in ISO 7933 [22], it was found that CF_e of ISO 7933 [22] seemed to have overestimated the effects of movement and wind on vapor resistance. After discussions in ISO TC159/SC5/WG1 and presentation of the data, CF_e was revised to that of the present ISO 9920 [28]. For static conditions, the Lewis relation and static moisture permeability index (i_{mst}) were used to estimate evaporative resistance from thermal insulation for both ISO 7933 [22] and ISO 9920 [27]. For dynamic conditions, CF_e was derived from the empirical relation between CF_i and dynamic moisture permeability index (i_{mdyn}) in ISO 7933 [22]. On the other hand, in ISO 9920 [27] two equations were provided to calculate CF_e: one was an empirical equation including relative air velocity and walking speed, and the other was an empirical relation including CF_i.

The key predictions of PHS are rectal temperature and sweat rate. Some researchers evaluated the predictions of PHS by comparing with physiological data. Kampmann et al. showed a pronounced underestimation of rectal temperature and correct estimation of sweat rate in moderate activity [29]. Parsons [30] pointed out that applying PHS in the assessment of rapidly changing environments and short exposures was not possible. Lundgren et al. also showed that intermittent work exposure challenged the accuracy of the PHS model [31]. They provided the data on the overestimation of PHS simulation on rectal temperature in heavy activity and cooling effect of sweating in recovery [30]. Wang et al. [32] demonstrated that rectal temperature and sweat rate predicted by PHS were higher than those of human subject data when wearing higher thermal insulating or higher evaporative resistance clothing than the scope of PHS model. From the perspective of occupational hygiene in terms of thermal environment, it is important to determine the maximum allowable exposure duration. In ISO 7933 [22], a maximum allowable exposure time is provided based on rectal temperature reaching 38 °C or a cumulative sweat loss limit based on acclimation state. In the determination of the duration time limit, environmental conditions, metabolic rates, and thermal characteristics of clothing should be inputted as important factors. CF_i and CF_e also play an important role in predicting heat strain under dynamic conditions. It was reported that CF_e of ISO 7933 [22] and ISO 9920 [27] were different, and the CF_e difference predicted the duration time limit difference for exposure [33]. To predict a suitable CF_e, it was necessary to further compare among ISO 7933 [22], two kinds of ISO 9920 [27], and experimental data.

The purpose of this paper was to compare the two kinds of CF_i or three kinds of CF_e for ISO 7933 [22] and ISO 9920 [27] with experimental results and to study the effect of differences in CF_i or CF_e on predicted rectal temperature, cumulative water loss, and duration time limit of exposure under constant conditions.

Methods

Correction factor

Two kinds of CF_i (CF_{i7933}: Eq. 1.1–3 and CF_{i9920}: Eq. 2.1–3) and three kinds of CF_e (CF_{e7933}: Eq. 3, CF_{e9920a}: Eq. 4, and CF_{e9920b}: Eq. 5) were summarized in Table 1. There were three functions of CF_i in terms of walking speed and relative air velocity according to the intrinsic thermal insulation of clothing (I_{cl}). Relative air velocity changes depending on conditions in ISO 7933 [22]: When the data on walking speed and walking direction to wind are provided, relative air velocity is calculated as the VECTOR difference between air velocity and walking speed. When walking direction is unknown, relative air velocity is air velocity if air velocity is larger than walking speed and otherwise walking speed. When both the direction of walking and walking speed were not known, relative air velocity is supposed as air velocity. To avoid complexity in the calculation of relative air velocity from air velocity or walking speed, relative air velocity was directly used to calculate CF_i or CF_e in this paper. To predict static total water vapor resistance (R_{eT}) from static total thermal insulation (I_T), i_{mst} and Lewis relation were applied in ISO 7933 [22] and ISO 9920 [27]. In our calculation, i_{mst} of 0.38 was used as normal clothing. Here, walking included only the effect of body movement by walking, excluding the effect of air velocity due to walking. First, we compared the independent effects of relative air velocity and walking speed between CF_{i7933} and CF_{i9920}. Table 2 shows the validity of ISO 7933 [22] and ISO 9920 [27] concerning relative air velocity, walking speed, and I_{cl}. First, when we calculated the effect of relative air velocity on CF_i, walking speed was fixed at 0.01 m·s^{-1} and relative air velocity varied from 0.0 to 3.0 m·s^{-1}. For walking speed effect, relative air velocity was fixed at 0.15 m·s^{-1} and walking speed varied from 0.0 to 1.2 m·s^{-1}. Second, we similarly

Table 1 Correction factors for dynamic total thermal insulation (CF_i) and evaporative resistance (CF_e) of ISO 7933 [22] and ISO 9920 [27]

Correction factor	I_{cl}	ISO7933 [22]	ISO9920 [27]
CF_i	Nude	$\mathrm{Exp}(-0.472\,V_{ar} + 0.047\,V_{ar}^2 - 0.342\,V_w + 0.117\,V_w^2)$ (= $Corrl_a$) …(1.1)	$\mathrm{Exp}(-0.533 \times (V_{ar} - 0.15) + 0.069 \times (V_{ar} - 0.15)^2 - 0.462\,V_w + 0.201\,V_w^2)$ (= $Corrl_a$) …(2.1)
	$0 < I_{cl} < 0.6$	$((0.6 - I_{cl}) \times Corrl_a + I_{cl} \times Corrl_T)/0.6$ …(1.2)	$((0.6 - I_{cl}) \times Corrl_a \times I_a + I_{cl} \times Corrl_T \times I_T(0.6)) / (0.6 \times I_T(I_{cl}))$ …(2.2)
	$I_{cl} \geq 0.6$	$\mathrm{Exp}(0.043 - 0.398\,V_{ar} + 0.066\,V_{ar}^2 - 0.378\,V_w + 0.094\,V_w^2)$ (= $Corrl_T$) …(1.3)	$\mathrm{Exp}(-0.281 \times (V_{ar} - 0.15) + 0.044 \times (V_{ar} - 0.15)^2 - 0.492\,V_w + 0.176\,V_w^2)$ (= $Corrl_T$) …(2.3)
CF_e	All range	$Corrl_T/(2.6\,Corrl_T^2 - 6.5\,Corrl_T + 4.9)$ …(3) (If $i_{mdyn} = i_{mst} \times (2.6 \times Corrl_T^2 - 6.5 \times Corrl_T + 4.9) > 0.9$, then $i_{mdyn} = 0.9$)	$\mathrm{Exp}(-0.468 \times (V_{ar} - 0.15) + 0.080 \times (V_{ar} - 0.15)^2 - 0.874\,V_w + 0.358\,V_w^2)$ …(4) $0.3 - 0.5 \times Corrl_T + 1.2 \times Corrl_T^2$ …(5)

I_a thermal insulation of air layer in nude, I_{cl} intrinsic thermal insulation of clothing, V_{ar} relative air velocity, V_w walking speed, $I_T(0.6)$ static total thermal insulation at 0.6 clo, $I_T(I_{cl})$ static total thermal insulation at I_{cl}, $Corrl_a$ correction factors for dynamic thermal insulation in nude, $Corrl_T$ correction factors for dynamic total thermal insulation over 0.6 clo of I_{cl}, i_{mst} static moisture permeability index, i_{mdyn} dynamic moisture permeability index

Table 2 Ranges of validity for ISO 7933 [22] and ISO 9920 [27]

Parameter	ISO 7933 [14]	ISO 9920 [27]
T_a	15–50 °C	-
T_r–T_a	0–60 °C	-
M	52–232 W·m^{-2}	-
V_{ar}	0.0–3.0 m·s^{-1}	0.15–3.50 m·s^{-1}
V_w	0.0–1.5 m·s^{-1}	0.0–1.2 m·s^{-1}
I_{cl}	0.1–1.0 clo	0.0–1.4 clo

T_a air temperature, T_r mean radiant temperature, *M* metabolic rate, V_{ar} relative air velocity, V_w walking speed, I_{cl} intrinsic thermal insulation of clothing

compared the independent effect of relative air velocity and walking speed among CF_{e7933}, CF_{e9920a}, and CF_{e9929b}. Third, we compared the combined effects of relative air velocity and walking speed on CF_i or CF_e. The relative value of CF_{i9920} to CF_{i7933}, CF_{e9920a} to CF_{e7933}, and CF_{e9920b} to CF_{e7933} was calculated for a two-dimensional area of relative air velocity from 0.0 to 3.0 m·s^{-1} and walking speed from 0.0 to 1.2 m·s^{-1}.

Integration of CF_{i9920} and CF_{e9920a} or CF_{e9920b} to PHS

To investigate the effect of different correction factors on PHS, two modified PHS (PHS_{mA}, PHS_{mB}) were developed: PHS_{mA} with CF_{i9920} and CF_{e9920a}, and PHS_{mB} with CF_{i9920} and CF_{e9920b}. First, we calculated the difference of final rectal temperature and water loss calculated between PHS and PHS_{mA} under condition A, condition B, condition C, and condition D (Table 3) with a maximum calculation time of 1 h. In this study, we supposed continuous work for 1 h without taking a break. Other calculation conditions are presented in Table 3: moderate metabolic rate (145 W·m^{-2}), height (1.70 m), weight (65 kg), drink available, acclimated, i_{mst} (0.38), relative humidity (RH) (from 0 to 100%), and ambient temperature (from 30 to 40 °C). Moderate metabolic rate corresponds to sustained hand and arm work (hammering nails, filing) and arm and leg work (off-road operation of lorries, tractors, or construction equipment) [22]. Furthermore, 1.0 clo (1 clo, 0.155 m^2·°C·W^{-1}) of I_{cl} was used because 1.0 clo was the maximum thermal insulation of clothing, as shown in Table 2. Next, duration time when limit of rectal temperature of 38 °C was reached ($D_{limTre38}$) was compared between PHS_{mA} and PHS and between PHS_{mA} and PHS_{mB} at four conditions of relative air velocity and walking speed (conditions A, B, C, D) with a maximum calculation time of 8 h. Paired *t* test was used to test the significant difference between each model. Here, we supposed a worst-case scenario: continuous work for 8 h without taking a break. The total number of plots was 847, where RH varied from 0 to 100% at 10% intervals, ambient temperature from 30 to 40 °C at 1 °C intervals and mean radiant temperature from ambient temperature to ambient temperature + 60 °C at 10 °C intervals. The other calculation conditions of metabolic rate, height, weight, heat acclimation, i_{mst} value, and drink availability are the same as listed in Table 3.

Table 3 Input parameters of PHS, PHS_{mA} to calculate difference in predicted core temperature and accumulated water loss

Individual condition	V_{ar}	V_w	I_{cl}
Condition A	3.0 m·s^{-1}	0.1 m·s^{-1}	0.3 clo
Condition B	3.0 m·s^{-1}	0.1 m·s^{-1}	1.0 clo
Condition C	0.15 m·s^{-1}	0.1 m·s^{-1}	0.3 clo
Condition D	0.15 m·s^{-1}	0.1 m·s^{-1}	1.0 clo
Common condition	Input parameter		
T_a	Every 0.1 °C (30–40 °C)		
RH	Every 1% (0–100%)		
M	145 W·m^{-2}		
Height	1.70 m		
Weight	65 kg		
Acclimation	Acclimated		
Drink availability	Available		
i_{mst}	0.38		
Calculation program	PHS, PHS_{mA}		
Calculation time	1 h		

V_{ar} relative air velocity, V_w walking speed, I_{cl} intrinsic thermal insulation of clothing, T_a air temperature, *RH* relative humidity, *M* metabolic rate, i_{mst} static moisture permeability index, *PHS* predicted heat strain, PHS_{mA} modified PHS including equation (2.1–3) of correction factor for dynamic total thermal insulation and Eq. (4) of correction factor for dynamic total evaporative resistance. Equations are shown in Table 1

Results

CF_{i7933} and CF_{i9920} decreased similarly with relative air velocity and walking speed in nude and under the clothing thermal insulation of 0.3 clo and more than 0.6 clo (Fig. 1a). The reduction rates of CF_{i7933} and CF_{i9920} for relative air velocity were largest in nude, second in 0.3 clo, and least in larger than 0.6 clo. However, CF_{i7933} and CF_{i9920} did not differ in nude, the clothing thermal insulation of 0.3 clo and more than 0.6 clo in terms of walking speed (Fig. 1b). CF_{e7933} was smaller than CF_{e9920a} and CF_{e9920b} in both for relative air velocity and walking speed. For a nude condition at 3.0 m·s^{-1} of relative air velocity, CF_{e9920a} was larger than CF_{e7933} by more than three times. For larger than 0.6 clo, CF_{e9920a} and CF_{e9920b} were almost the same and were about two times larger than CF_{e7933} (Fig. 2a). For the effect of walking speed, CF_{e9920a} and CF_{e9920b} were also as large as CF_{e7933} (Fig. 2b). We compared the combined effect of relative air velocity and walking speed on CF_{i7933} and CF_{i9920}, CF_{e7933} and CF_{e9920a}, and CF_{e7933} and CF_{e9920b} in Fig. 3. For CF_i, the ratio of CF_{i9920} to CF_{i7933} was almost 1 in the large part of the calculated scope (relative air velocity 0.15–3.0 m·s^{-1}, walking speed 0.01–1.2 m·s^{-1}), indicating that CF_{i9920} and CF_{i7933} were almost

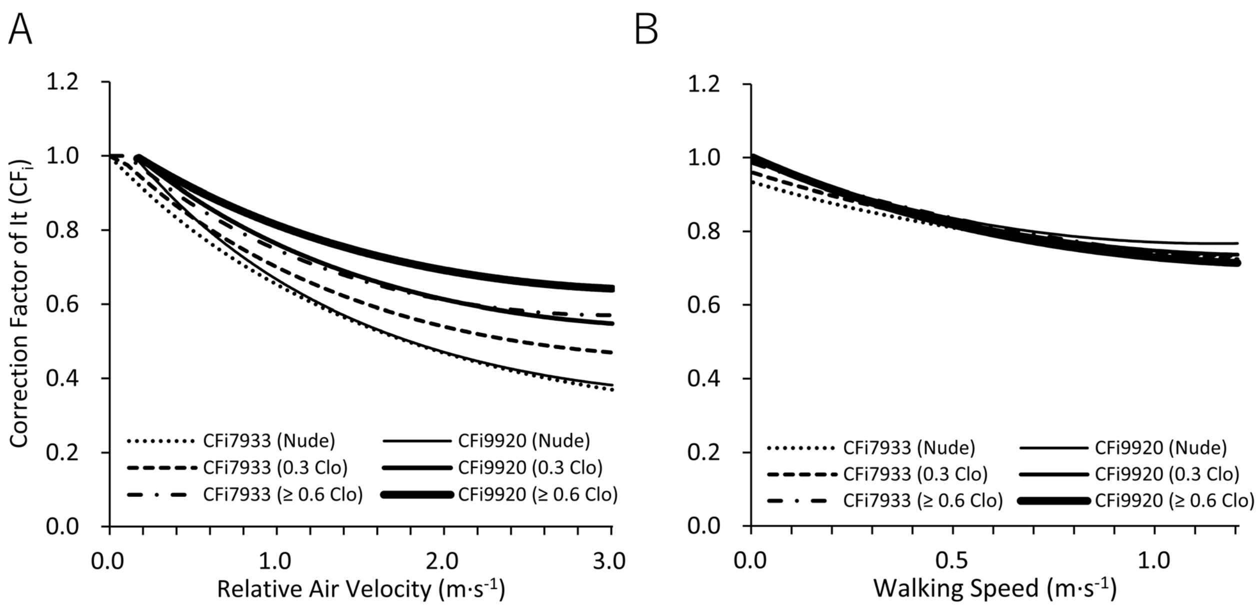

Fig. 1 CF_{i7933} and CF_{i9920} in nude, clothing thermal insulation of 0.3 clo and larger than or equal to 0.6 clo in terms of **a** relative air velocity and **b** walking speed

the same (Fig. 3a–c). For CF_e, both the contours of the ratios of CF_{e9920a} and CF_{e9920b} to CF_{e7933} were almost parallel to the y-axis, which means that both CF_{e9920a} and CF_{e9920b} change similarly in terms of walking speed (Fig. 3d–i). The ratio of CF_{e9920a} to CF_{e7933} was the largest in nude (Fig. 3d), next in 0.3 clo (Fig. 3e), and the smallest in more than 0.6 clo (Fig. 3f). The ratio of CF_{e9920b} to CF_{e7933} was not different in terms of clothing thermal insulation in the calculated scope (Fig. 3g–i).

Figure 4 provides the predicted rectal temperature (Fig. 4a–d) and water loss difference (Fig. 4e–h) between PHS and PHS_{mA} for a 1-h exposure with a scope of ambient temperature from 30 to 40 °C and RH from 0 to 100% in four conditions (conditions A–

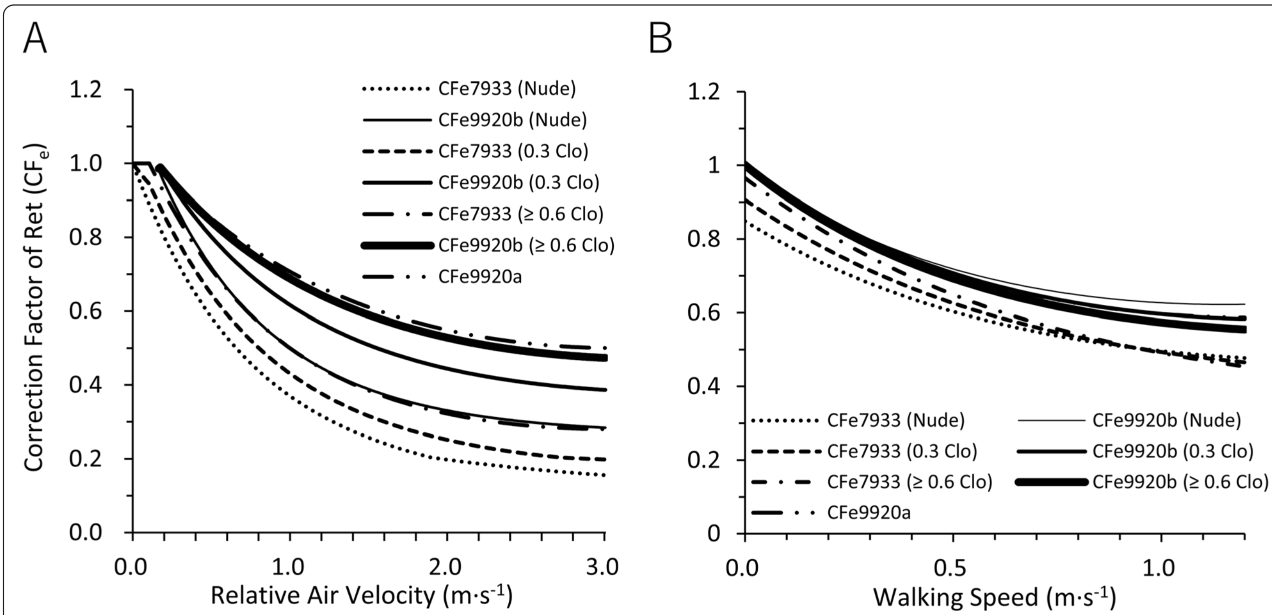

Fig. 2 CF_{e7933}, CF_{e9920a}, and CF_{e9920b} in nude, clothing thermal insulation of 0.3 clo and larger than or equal to 0.6 clo in terms of **a** relative air velocity and **b** walking speed

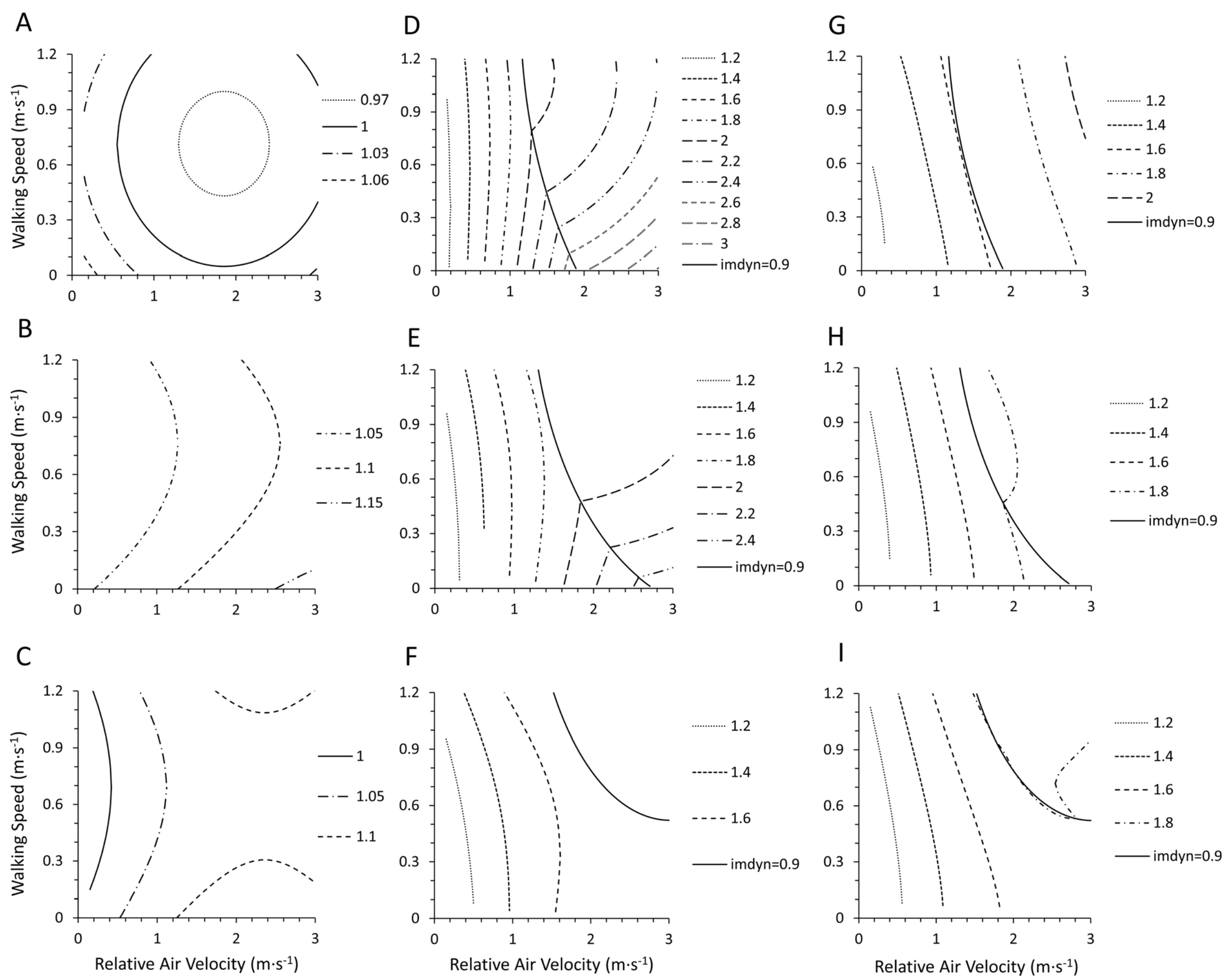

Fig. 3 The ratios of CF_{i9920} to CF_{i7933}, **a** in nude, **b** clothing thermal insulation of 0.3 clo, **c** clothing thermal insulation larger than or equal to 0.6 clo. The number of lines represents the ratio of CF_{i9920} to CF_{i7933}. The ratios of CF_{e9920a} to CF_{e7933}, **d** in nude, **e** clothing thermal insulation of 0.3 clo, **f** clothing thermal insulation larger than or equal to 0.6 clo. The number of lines represents the ratio of CF_{e9920a} to CF_{e7933}. The ratios of CF_{e9920b} to CF_{e7933}, **g** in nude, **h** clothing thermal insulation of 0.3 clo, **i** clothing thermal insulation larger than or equal to 0.6 clo. The number of lines represents the ratio of CF_{e9920b} to CF_{e7933}. The line of i_{mdyn} of 0.9 is illustrated in the figures

D). Under condition A, in high ambient temperature and RH region, the predicted rectal temperature by PHS_{mA} was higher than that by PHS. The maximum rectal temperature difference in the scope was about 1.4 °C (Fig. 4a). And the maximum water loss difference was about 400 ml (Fig. 4e). The region where the predicted water loss differed was almost the same area as that of the rectal temperature difference (Fig. 4e). Under condition B (Fig. 4b), the region where predicted rectal temperature and water loss differed was similar to condition A. The maximum rectal temperature difference was about 1.0 °C (Fig. 4b) and maximum water loss difference (Fig. 4f) was about 300 ml. Under condition C or D, both rectal temperature and water loss between PHS and PHS_{mA} did not differ as much as condition A or B.

The differences in $D_{limTre38}$ between PHS_{mA} and PHS and between PHS_{mA} and PHS_{mB} are shown in Fig. 5 for the four conditions (conditions A, B, C, and D). $D_{limTre38}$ differences between PHS and PHS_{mA} and between PHS_{mA} and PHS_{mB} were the largest under condition A and second largest under condition B. The largest $D_{limTre38}$ differences between PHS and PHS_{mA} were 454, 444, 377, and 309 min under conditions A, B, C, and D, respectively. The largest $D_{limTre38}$ differences between PHS_{mA} and PHS_{mB} were 434, 310, 89, and 71 min under conditions A, B, C, and D, respectively. $D_{limTre38}$ values of PHS were significantly larger than PHS_{mA} and PHS_{mB} by paired *t* test under the four tested conditions (P < 0.001). $D_{limTre38}$ values of PHS_{mB} were significantly larger than PHS_{mA} by paired *t* test under the four tested conditions (P < 0.001).

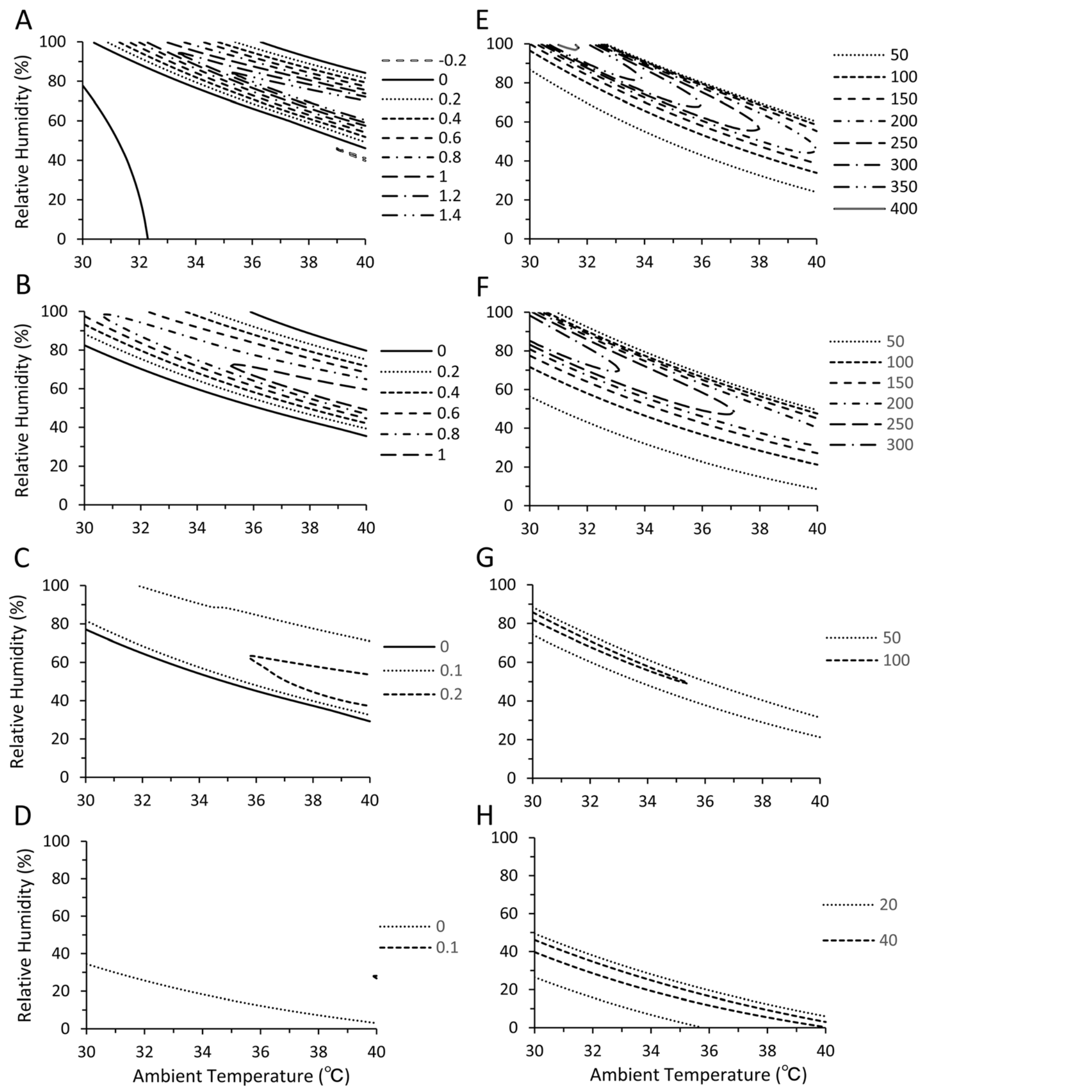

Fig. 4 Difference in predicted rectal temperature between PHS and PHS_{mA}, **a** under condition A, **b** condition B, **c** condition C, and **d** condition D in Table 3. The units of the line number are degrees centigrade. Difference in predicted water loss between PHS and PHS_{mA}, **e** under condition A, **f** condition B, **g** condition C, and **h** condition D in Table 3. The units of the line number are milliliters

Discussion

In this study, we compared CF_i and CF_e between ISO 7933 [22] and ISO 9920 [27]. The vapor resistance value was reduced less in ISO9920 than in ISO7933. CF_i was close to each other, but CF_{e9920a} and CF_{e9920b} were larger than CF_{e7933}. To the best of our knowledge, there is no other study to compare correction factors of ISO 7933 [22] and ISO 9920 [27] in detail in terms of relative air velocity and walking speed. Next, we investigated the effect of CF_e differences on predicted rectal temperature and water loss under warm and humid conditions. When the difference between CF_{e7933} and CF_{e9920a} was large, the predicted rectal temperature and water loss were higher in PHS_{mA} than PHS at high ambient temperature and RH. $D_{limTre38}$ values by PHS were significantly larger than those of PHS_{mA} and PHS_{mB}.

Many researchers [1, 2, 14, 20, 21, 34–40] demonstrated the dependence of CF_i or CF_e on relative air velocity and walking speed mainly with human subject study or thermal manikin (Fig. 6a–d). In this paper, CF_i and CF_e of ISO 7933 [22] and ISO 9920 [27] were compared with experimental data including the recent research published after the issuance of ISO 9920 [27]. Concerning CF_i, CF_{i7933} and CF_{i9920} were close to experimental results both in nude and clothing conditions (Fig. 6a). CF_i of Qian (cloth) [35], Morrissey (garment zip fastened) [36] were close to CF_{i7933} (≥ 0.6 clo). Morrissey and Rossi [36] showed that CF_i with relative air

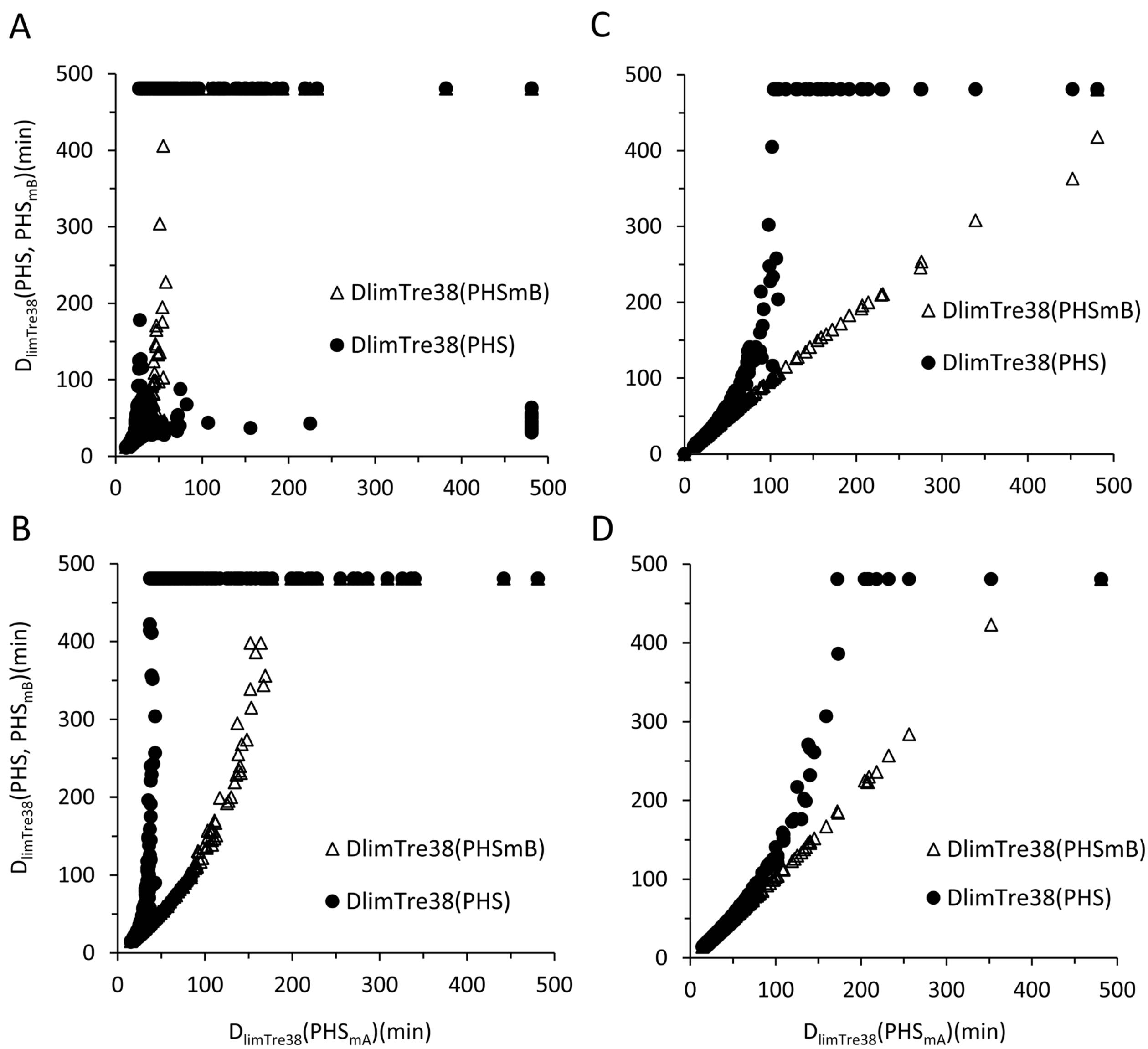

Fig. 5 Predicted time until rectal temperature reaches 38.0 °C ($D_{limTre38}$) of PHS, PHS_{mA} and PHS_{mB} under **a** condition A, **b** condition B, **c** condition C, and **d** condition D in Table 3. In each figure, the x axis represents $D_{limTre38}$ by PHS_{mA} and y axis by PHS and PHS_{mB}. The number of plots was 121, where relative humidity varies from 0 to 100% at 10% intervals and the ambient temperature from 30 to 40 °C at 1 °C intervals. The maximum calculation time was 480 min

velocity was lowered in an unfastened garment zip. Thus, how one wears clothing could also influence CF_i with relative air velocity. CF_i of Lu et al. (nude) [37] was close to those of CF_{i7933} (nude) and CF_{i9920} (nude). CF_i of Lu et al. (moderate) [37] was also close to CF_{i9920} (≥ 0.6 clo).

CF_{i7933} and CF_{i9920} in nude conditions decreased with relative air velocity more than in clothing conditions. Qian and Fan [34, 35] and Lu et al. [37] also showed that CF_i of a nude body was smaller than a clothed body under the same relative air velocity (Fig. 6a). However, with walking speed, CF_i in nude conditions and clothing conditions were almost the same for CF_{i7933} and CF_{i9920} (Fig. 6c). The experimental results also showed that CF_i dependence on walking speed was not related to I_{cl} (Fig. 6c).

CF_e of experimental data, CF_{e7933}, CF_{e9920a}, and CF_{e9920b}, were different in two ways. First, CF_{e9920b} was larger than CF_{e7933} in both nude and more than 0.6 clo (Fig. 6b, d). CF_{e9920a} was also larger than CF_{e7933}. Experiment data of CF_e [2, 34, 35, 38, 39] which the standards should be based on were not consistent (Fig. 6b, d). The differences in experimental conditions or calculation methods of R_{eT} in the study of thermal manikin could explain the R_{eT} difference [41]. Second, the CF_{e9920a} did

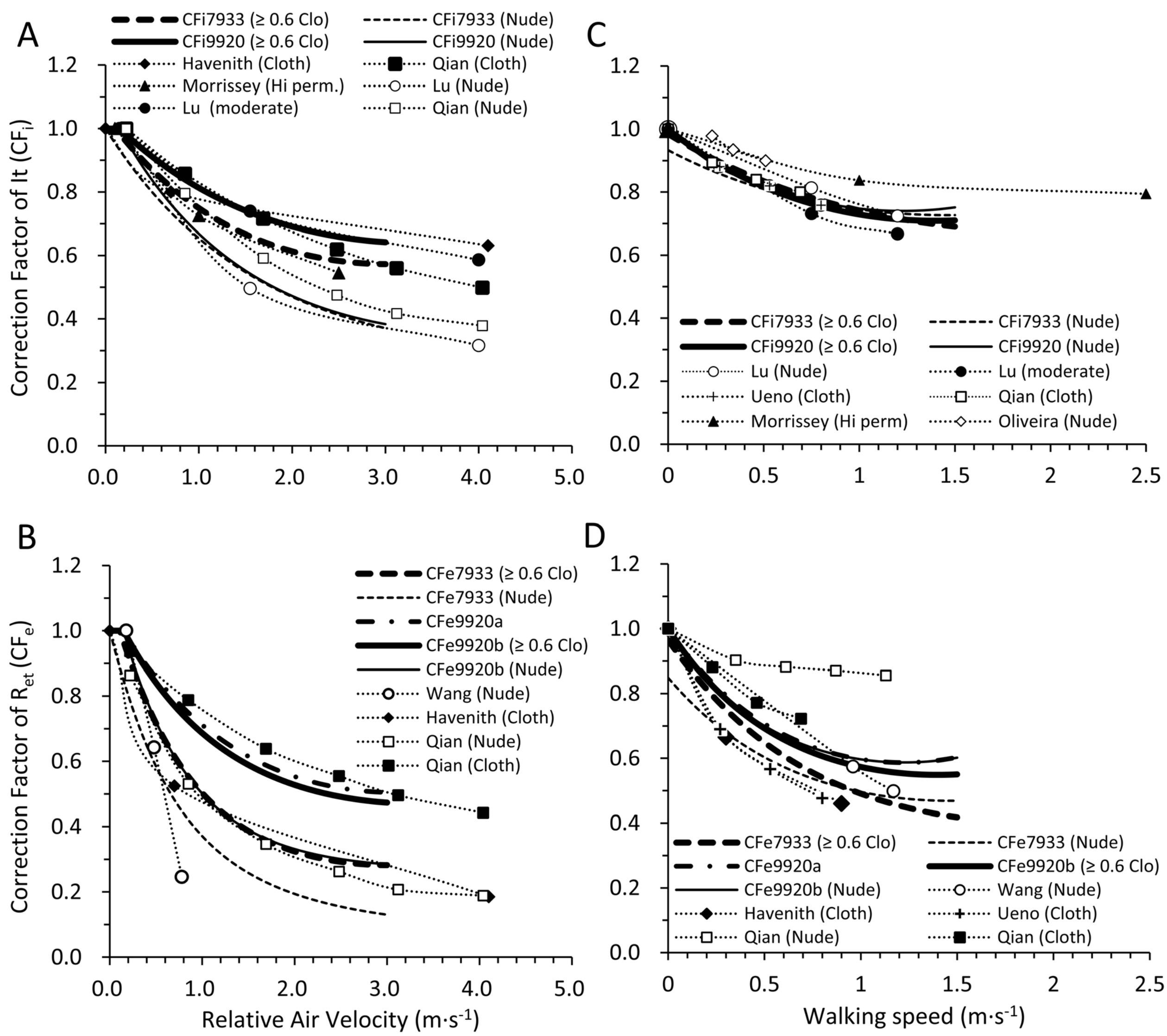

Fig. 6 Correction factors of ISO 7933, ISO 9920, and experimental results. **a** Correction factors of I_T in terms of relative air velocity, **b** correction factors of R_{eT} in terms of relative air velocity, **c** correction factors of I_T in terms of walking speed, and **d** correction factors of R_{eT} in terms of walking speed. The averages of intrinsic thermal insulation of the tested clothing used in the experiments were the following: **a** 1.1 clo (Havenith et al. [1] (cloth)), 0.0 clo (Qian and Fan [34] (nude)), 0.7 clo (Qian and Fan [35] (cloth)), 1.9 clo (Morrissey and Rossi [36] (Hi perm.)), 0.0 clo (Lu et al [37] (nude)), 1.8 clo (Lu et al. [37] (moderate)); **b** 1.1 clo (Havenith et al. [2] (cloth)), 0.0 clo (Qian and Fan [34] (nude)), 0.7 clo (Qian and Fan [35] (cloth)), 0.0 clo (Wang et al. [38] (nude)); **c** 0.0 clo (Lu et al. [37] (nude)), 1.5 clo (Lu et al. [37] (moderate)), 1.2 clo (Ueno and Sawada [39] (Workwear)), 0.7 clo (Qian and Fan [34] (Cloth)), 1.9 clo (Morrissey and Rossi [36] (Hi perm.)), 0.0 clo (Oliveira et al [40] (nude)); and **d** 0.0 clo (Wang et al. [38] (nude)), 1.1 clo (Havenith et al. [2] (cloth)), 1.2 clo (Ueno and Sawada [39] (workwear)), 0.0 clo (Qian and Fan [34] (Nude)), 0.7 clo (Qian and Fan [35] (cloth)). When only the total thermal insulation was given in the reference, the intrinsic thermal insulation was calculated using the equations in ISO 7933

not depend on I_T. This is contrary to experimental results showing that CF_e in nude decreased with relative air velocity to a greater extent than that in clothing. To resolve these discrepancies, more experimental study regarding CF_e dependence on relative air velocity and walking speed would be needed.

For the combined effect of relative air velocity and walking speed on CF_i, Eq. 1.1, 1.2, 2.1, and 2.3 in Table 1 showed that relative air velocity and walking speed independently affected CF_i. Heat exchange increased in the front trunk (chest, abdomen, pelvis) with a frontal wind. Meanwhile, heat exchange increases more in the arm and foot than the front trunk when walking in nude or light clothing [40]. In a combined condition of wind and walking, the effect of relative air velocity on I_T was larger than that of walking speed and affected that of walking speed [40]. To explain these effects, the interaction term of relative air velocity and walking speed could be needed for CF_i equation.

A higher CF_e induced a smaller maximum evaporation rate and higher wettedness in the skin, leading to a smaller evaporation efficiency. To correct a smaller evaporation efficiency and maintain a balance in heat transfer, the sweat rate increases. In our calculation, PHS_{mA} predicted that water loss increases at a lower ambient temperature than PHS and reached a maximum sweat rate (SW_{max}) at lower ambient temperature. In PHS, PHS_{mA} and PHS_{mB}, SW_{max} is determined by metabolic rate and acclimation.

SW_{max} = (M − 32) × surface area of human body × factor of acclimation (6) where M stands for metabolic rate in $W{\cdot}m^{-2}$ [25]. The surface area of human body was expressed in m^2. Factor of acclimation was 1.25 for acclimated person and 1.0 for unacclimated person. Before sweat rate reached SW_{max}, the rectal temperature did not increase. But after reaching SW_{max}, the rectal temperature started to increase in PHS model. Then, the time when the predicted rectal temperature started to increase was almost equivalent to the time when the predicted water loss reached the maximum sweat rate. When predicted sweat rate by PHS_{mA} reaches SW_{max} and by PHS did not, only the predicted rectal temperature by PHS_{mA} increases. This relation explained that the differences in the rectal temperature between PHS and PHS_{mA} were closely related to the differences in predicted water loss. Under every condition, the zone where rectal temperature differed almost overlapped the zone where sweat rate differed (Fig. 4). The difference in rectal temperature and water loss was larger under conditions A or B than conditions C or D. A larger difference in CF_e (Table 4) would contribute to a larger difference in predicted rectal temperature and water loss.

Our study showed that differences of $D_{limTre38}$ between PHS and PHS_{mA} were largest in condition A (Fig. 5). The largest difference in CF_e among PHS, PHS_{mA}, and PHS_{mB} in condition A (Table 4) could result in $Dlim_{Tre38}$ difference. The large amount of water loss due to a low evaporation efficiency by a high CF_e increased the probability of reaching the maximum sweat rate and an elevated rectal temperature. Thus, at high CF_e, rectal temperature increased in a lower heat stress environment than for a low CF_e. Under heat stress conditions where body rectal temperature started to increase, an inaccuracy in CF_e led to a large prediction error for $D_{lim\text{-}Tre38}$ values. Originally, predicting heat strain under such boundary conditions was required to avoid heat disorders. As such, the prediction errors due to an inaccurate CF_e should be lowered as much as possible under such boundary conditions. Since many kinds of clothing exist, it could be difficult to develop a CF_e that covers all kinds of clothing. Thus, it would be necessary to derive a CF_i or CF_e that is specialized for work clothing to prevent work-related heat disorders. Many other factors, except for wind or walking activity, such as how clothes fit, posture, and openings, were reported to affect I_T [42]. Further study is needed to estimate precise correction factor considering other factors.

The clothing area factor (f_{cl}), defined as the ratio of the clothing surface area to the body surface area, also plays an important role in the analysis of heat exchange between a clothed body and the environment. Though f_{cl} is decided only by static clothing thermal insulation, it is used in both static and dynamic conditions in ISO 7933 [22]. Since f_{cl} was shown to depend on clothes' fit or posture [43] and clothing shape was changed by wind [44], some corrections to f_{cl} should be considered.

Moreover, the scope of relative air velocity is limited to 3.0 and 3.5 $m{\cdot}s^{-1}$ for ISO 7933 [22] and ISO 9920 [27], respectively. When PHS is applied to outdoor work, the scope should be extended to an air velocity of more than 3.0 $m{\cdot}s^{-1}$.

Table 4 Correction factor for dynamic total thermal insulation and evaporative resistance of PHS, PHS_{mA} and PHS_{mB} for four conditions (conditions A–D)

Individual condition	CF_i			CF_e		
	PHS	PHS_{mA}	PHS_{mB}	PHS	PHS_{mA}	PHS_{mB}
Condition A	0.46	0.54	0.54	0.18	0.46	0.38
Condition B	0.55	0.61	0.61	0.26	0.46	0.44
Condition C	0.93	0.98	0.98	0.83	0.92	0.97
Condition D	0.95	0.95	0.95	0.88	0.92	0.91

CF_i correction factor for dynamic total thermal insulation, CF_e correction factor for dynamic total evaporative resistance, *PHS* predicted heat strain, PHS_{mA} modified PHS including CF_i of Eqs. (2.1–3) and CF_e of Eq. (4), PHS_{mB} modified PHS including CF_i of Eq. (2.1–3) and CF_e of Eq. (5). Equations are shown in Table 1

Conclusions

The correction factors for dynamic total thermal insulation (CF_{i9920}) and evaporative resistance (CF_{e9920a} and CF_{e9920b}) proposed in ISO 9920 [27] were compared with those of ISO 7933 (CF_{i7933} and CF_{e7933}) [22]. The vapor resistance value was reduced less in ISO9920 than in ISO7933. CF_i were close to each other; however, CF_e of ISO 9920 [33] was much larger than that of ISO 7933 [22]. The relation of one CF_e in ISO 9920 [27] on relative air velocity was not influenced by the intrinsic thermal insulation of clothing. The difference in CF_e lead to a difference in predicted rectal temperature and water loss in the critical region of ambient temperature and RH where predicted sweat rate reached maximum sweat rate. Duration time when limit of rectal temperature of 38 °C is reached ($D_{limTre38}$) was different according to the CF_e used in the calculation. A larger difference in CF_e results in a larger difference in $D_{limTre38}$ value. The development of a correct CF_e is required to predict appropriate work time limits in hot working environments.

Abbreviations

$D_{limTre38}$: Duration time when limit of rectal temperature of 38 °C is reached (minutes); CF_e: Correction factor for dynamic total evaporative resistance (dimensionless); CF_{e7933}: CF_e of ISO 7933 (dimensionless); CF_{e9920a}: CF_e of ISO 9920 using relative air velocity and walking speed (dimensionless); CF_{e9920b}: CF_e of ISO 9920 using CF_{i9920} (dimensionless); CF_i: Correction factor for dynamic total thermal insulation (dimensionless); CF_{i7933}: CF_i of ISO 7933 (dimensionless); CF_{i9920}: CF_i of ISO 9920 (dimensionless); ISO: International organization for standardization; I_T: Total thermal insulation ($m^2{\cdot}K{\cdot}W^{-1}$); PHS: Predicted heat strain; PHS_{mA}: Modified PHS integrated with CF_{i9920} and CF_{e9920a}; PHS_{mB}: Modified PHS integrated with CF_{i9920} and CF_{e9920b}; R_{eT}: Total evaporative resistance ($m^2{\cdot}kPa{\cdot}W^{-1}$)

Acknowledgements

The author expresses a deep appreciation to Prof. Bernard in South Florida University for discussing about correction factors of clothing and PHS.

Author's contributions

SU planned the study, wrote the program, analyzed the data, and drafted the manuscript. The author read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

The datasets used and/or software during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The author declares that I have no competing interests.

Received: 3 April 2020 Accepted: 6 August 2020
Published online: 24 August 2020

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