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

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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_t) and evaporative resistance (CF_e), respectively. Then, CF_t 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_t 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_t of ISO 7933 (CF_t7933) and ISO 9920 (CF_t9920), 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_e9920a and CF_e9920b (PHSmA) and modified PHS integrated with CF_e9920a and CF_e9920b (PHSmB). We calculated the rectal temperature, water loss, and exposure time limit by PHS, PHSmA, and PHSmB and compared the results.

Results: CF_t7933 and CF_t9920 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_c) diminished the effects of V_ar on CF_t7933, CF_t9920, CF_e7933, and CF_e9920b. However, CF_e9920a was not influenced by I_c. The predicted rectal temperature and water loss difference were larger between PHS and PHSmA, 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 PHSmA, PHSmB 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

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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 (Iₜ) and evaporative resistance (RₑT). 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 (Vₑ), 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 micro-environmental 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].

Iₜ and RₑT 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 Iₜ and RₑT under wind or active conditions from static conditions, some studies on correction factors for dynamic total thermal insulation (CFᵢ) [1, 13–20] and evaporative resistance (CFₑ) [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 CFᵢ and CFₑ 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 CFᵢ for over 0.6 clo of clothing insulation (Eq. 30 in [14]) and nude (Eq. 29 in [14]) under walking and wind. CFᵢ for nude in [14] was later changed to Eq. 3 in [16] by Havenith et al. Havenith and Nilsson [21] proposed the equations for CFₑ from the empirical relation of change in iₑ 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 CFᵢ in addition to Holmér et al. [14]. CFₑ 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 CFₑ 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, CFₑ was revised to that of the present ISO 9920 [28]. For static conditions, the Lewis relation and static moisture permeability index (iₑst) were used to estimate evaporative resistance from thermal insulation for both ISO 7933 [22] and ISO 9920 [27]. For dynamic conditions, CFₑ was derived from the empirical relation between CFᵢ and dynamic moisture permeability index (iₑdyn) in ISO 7933 [22]. On the other hand, in ISO 9920 [27] two equations were provided to calculate CFₑ: one was an empirical equation including relative air velocity and walking speed, and the other was an empirical relation including CFᵢ.

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] concerning relative air velocity, 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_v,t) from static total thermal insulation (I_T), t_s and Lewis relation were applied in ISO 7933 [22] and ISO 9920 [27]. In our calculation, t_s 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_T. 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

### 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_v,t) from static total thermal insulation (I_T), t_s and Lewis relation were applied in ISO 7933 [22] and ISO 9920 [27]. In our calculation, t_s 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_T. 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

| Correction factor | I_cl | ISO7933 [22] | ISO9920 [27] |
|-------------------|------|--------------|--------------|
| CF_i              |      |        |        |
| Nude              | 0 < I_cl < 0.6 | Exp (− 0.472 V_w + 0.047 V_a^2 − 0.342 V_w + 0.117 V_a^3) (= Corr_i) 
|                   | 0.6 ≤ I_cl ≤ 1.0 | (0.6 − I_cl) Corr_i + I_cl Corr_i / (0.6 × I_cl) 
|                   | ≥ 0.6 | Exp (0.043 − 0.398 V_w + 0.066 V_a^2 − 0.378 V_w + 0.094 V_a^3) (= Corr_i) 
| CF_e              | All range | Corr_i Corr_l − 6.5 Corr_l + 4.9) (3) 
|                   |       | (If t_dyn = t_s / (0.6 × Corr_l^2 − 6.5 × Corr_l + 4.9) > 0.9, then t_dyn = 0.9) 

I_cl thermal insulation of air layer in nude, I_cl intrinsic thermal insulation of clothing, V_w relative air velocity, V_a walking speed, t_s static total thermal insulation at 0.6 clo, t_s instant total thermal insulation at I_cl, Corr_i correction factors for dynamic thermal insulation in nude, Corr_i correction factors for dynamic total thermal insulation over 0.6 clo of I_cl, t_s static moisture permeability index, t_s dyn dynamic moisture permeability index
Table 2: Ranges of validity for ISO 7933 [22] and ISO 9920 [27]

| Parameter | ISO 7933 [14] | ISO 9920 [27] |
|-----------|---------------|---------------|
| Ta        | 15–50 °C      | -             |
| Tr –Ta    | 0–60 °C       | -             |
| M         | 52–232 W·m⁻²  | -             |
| Vw        | 0.0–3.0 m·s⁻¹ | 0.15–3.50 m·s⁻¹ |
| Vr        | 0.0–1.5 m·s⁻¹ | 0.0–1.2 m·s⁻¹  |
| Icl       | 0.1–1.0 clo   | 0.0–1.4 clo   |

T<sub>a</sub>, air temperature; T<sub>r</sub>, mean radiant temperature; M, metabolic rate; V<sub>w</sub>, relative air velocity; V<sub>r</sub>, walking speed; I<sub>cl</sub>, intrinsic thermal insulation of clothing.

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Table 3: Input parameters of PHS, PHS<sub>mA</sub> to calculate difference in predicted core temperature and accumulated water loss

| Individual condition | V<sub>r</sub> | V<sub>w</sub> | I<sub>cl</sub> |
|----------------------|------------|-------------|-------------|
| 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 | Ta, 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<sub>inst</sub>, 0.38 | Calculation program, PHS, PHS<sub>mA</sub> | Calculation time, 1 h |

V<sub>r</sub>, relative air velocity; V<sub>w</sub>, walking speed; I<sub>cl</sub>, intrinsic thermal insulation of clothing; Ta, air temperature; RH, relative humidity; M, metabolic rate; I<sub>inst</sub>, static moisture permeability index; PHS, predicted heat strain; PHS<sub>mA</sub>, 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.

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Results

CF<sub>i</sub> and CF<sub>e</sub> 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<sub>i</sub> and CF<sub>e</sub> for relative air velocity were largest in nude, second in 0.3 clo, and least in larger than 0.6 clo. However, CF<sub>i</sub> and CF<sub>e</sub> 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<sub>i</sub> and CF<sub>e</sub> were larger than CF<sub>i</sub> and CF<sub>e</sub> in both for relative air velocity and walking speed. For a nude condition at 3.0 m·s⁻¹ of relative air velocity, CF<sub>i</sub> was larger than CF<sub>i</sub> by more than three times. For larger than 0.6 clo, CF<sub>i</sub> and CF<sub>e</sub> were almost the same and were about two times larger than CF<sub>i</sub> (Fig. 2a). For the effect of walking speed, CF<sub>e</sub> and CF<sub>e</sub> were also as large as CF<sub>i</sub> (Fig. 2b). We compared the combined effect of relative air velocity and walking speed on CF<sub>i</sub> and CF<sub>e</sub> 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 ± 10 °C at ± 1 °C intervals. The other calculation conditions of metabolic rate, height, weight, heat acclimation, I<sub>inst</sub> value, and drink availability are the same as listed in Table 3.
the same (Fig. 3a–c). For CF\(_e\), both the contours of the ratios of CF\(_e^{9920a}\) and CF\(_e^{9920b}\) to CF\(_e^{7933}\) were almost parallel to the y-axis, which means that both CF\(_e^{9920a}\) and CF\(_e^{9920b}\) change similarly in terms of walking speed (Fig. 3d–i). The ratio of CF\(_e^{9920a}\) to CF\(_e^{7933}\) 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\(_e^{9920b}\) to CF\(_e^{7933}\) 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–
D). Under condition A, in high ambient temperature and RH region, the predicted rectal temperature by PHSmA 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 PHSmA did not differ as much as condition A or B.

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

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 $CF_{o9920}$ 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 $CF_{o9920}$ to $CF_{e7933}$. The ratios of $CF_{e9920}$ 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 $CF_{e9920}$ to $CF_{e7933}$. The line of $mdyn$ of 0.9 is illustrated in the figures.
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_{lim,Tr=38} 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
velocity was lowered in an unfastened garment zip. Thus, how one wears clothing could also influence $C_F_i$ with relative air velocity. $C_F_i$ of Lu et al. (nude) [37] was close to those of $C_F_i^{7933}$ (nude) and $C_F_i^{9920}$ (nude). $C_F_i$ of Lu et al. (moderate) [37] was also close to $C_F_i^{9920}$ ($\geq 0.6 \text{ clo}$).

$C_F_i^{7933}$ and $C_F_i^{9920}$ 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 $C_F_i$ of a nude body was smaller than a clothed body under the same relative air velocity (Fig. 6a). However, with walking speed, $C_F_i$ in nude conditions and clothing conditions were almost the same for $C_F_i^{7933}$ and $C_F_i^{9920}$ (Fig. 6c). The experimental results also showed that $C_F_i$ dependence on walking speed was not related to $I_c$ (Fig. 6c).

$C_F_e$ of experimental data, $C_F_e^{7933}$, $C_F_e^{9920a}$, and $C_F_e^{9920b}$ were different in two ways. First, $C_F_e^{9920b}$ was larger than $C_F_e^{7933}$ in both nude and more than 0.6 clo (Fig. 6b, d). $C_F_e^{9920a}$ was also larger than $C_F_e^{7933}$. Experiment data of $C_F_e$ [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 $R_{vT}$ in the study of thermal manikin could explain the $R_{vT}$ difference [41]. Second, the $C_F_e^{9920a}$ did
not depend on $I_T$. This is contrary to experimental results showing that $CFve$ in nude decreased with relative air velocity to a greater extent than that in clothing. To resolve these discrepancies, more experimental study regarding $CFve$ dependence on relative air velocity and walking speed would be needed.

For the combined effect of relative air velocity and walking speed on $CFve$, Eq. 1.1, 1.2, 2.1, and 2.3 in Table 1 showed that relative air velocity and walking speed independently affected $CFve$. 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 term of relative air velocity and walking speed could be needed for CF equation.

A higher CF indicated 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, PHSmA predicted that water loss increases at a lower ambient temperature than PHS and reached a maximum sweat rate (SWmax) at lower ambient temperature. In PHS, PHSmA and PHSmB, SWmax is determined by metabolic rate and acclimation.

\[ \text{SWmax} = (M - 32) \times \text{surface area of human body} \times \text{factor of acclimation (6)} \]

where M stands for metabolic rate in W·m\(^{-2}\)\(^{-1}\)[25]. The surface area of human body was expressed in m². Factor of acclimation was 1.25 for acclimated person and 1.0 for unacclimated person. Before sweat rate reached SWmax, the rectal temperature did not increase. But after reaching SWmax, 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 PHSmA reaches SWmax and by PHS did not, only the predicted rectal temperature by PHSmA increases. This relation explained that the differences in the rectal temperature between PHS and PHSmA 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 indicated a smaller maximum evaporation rate. Duration time when limit of rectal temperature of 38°C is reached \((D_{\text{limTre38}})\) was different according to

The largest difference in CF among PHS, PHSmA, and PHSmB in condition A (Table 4) could result in DlimTre38 difference. The large amount of water loss due to a lower evaporation efficiency by a high CF increased the probability of reaching the maximum sweat rate and an elevated rectal temperature. Thus, at high CF, rectal temperature increased in a lower heat stress environment than for a low CF. Under heat stress conditions where body rectal temperature started to increase, an inaccuracy in CF led to a large prediction error for DlimTre38 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 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 that covers all kinds of clothing. Thus, it would be necessary to derive a CF or CF 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·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·s\(^{-1}\).

### Table 4 Correction factor for dynamic total thermal insulation and evaporative resistance of PHS, PHSmA and PHSmB for four conditions (conditions A–D)

| Individual condition | CF\(_I\) | CF\(_E\) |
|----------------------|---------|---------|
| Condition A          | 0.46    | 0.54    |
| Condition B          | 0.55    | 0.61    |
| Condition C          | 0.93    | 0.98    |
| Condition D          | 0.95    | 0.95    |

CF\(_I\), correction factor for dynamic total thermal insulation, CF\(_E\), correction factor for dynamic total evaporative resistance, PHS predicted heat strain, PHSmA modified PHS including CF\(_I\) of Eqs. (2.1–3) and CF\(_E\) of Eq. (4). PHSmB modified PHS including CF\(_I\) of Eq. (2.1–3) and CF\(_E\) of Eq. (5). Equations are shown in Table 1.
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 $38{\degree}C$ is reached (minutes); $CF_e$: Correction factor for dynamic total evaporative resistance (dimensionless); $CF_{ISO7933}$: $CF_e$ of ISO 7933 (dimensionless); $CF_{ISO9920}$: $CF_e$ of ISO 9920 using relative air velocity and walking speed (dimensionless); $CF_{ISO9920a}$: $CF_e$ of ISO 9920 using CF $i_{9920}$ (dimensionless); $CF_{ISO9920b}$: $CF_e$ 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; PHSmod: Modified PHS integrated with $CF_{9920a}$ and $CF_{9920b}$; PHSres: Modified PHS integrated with $CF_{9920a}$ and $CF_{9920b}$; $R_u$: Total evaporative resistance ($m^2\cdot kPa\cdot W^{-1}$).

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**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.

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**Availability of data and materials**

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

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**Competing interests**

The author declares that I have no competing interests.

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**References**

1. Havenith G, Heus R, Lotens WA. Resultant clothing insulation - a function of body movement, posture, wind, clothing fit and ensemble thickness. Ergonomics. 1990;33:67-84.

2. Havenith G, Heus R, Lotens WA. Clothing ventilation, vapor resistance and permeability index - changes due to posture, movement and wind. Ergonomics. 1990;33:989-1005.

3. Bouiski LM, Havenith G, Kuklane K, Parsons KC, Withey WR. Relationship between clothing ventilation and thermal insulation. AIHA J (Fairfax, Va). 2002;63:262-8.

4. Nielsen R, Olsen BW, Fanger PO. Effect of physical activity and air velocity on the thermal insulation of clothing. Ergonomics. 1985;28:1617-31.

5. Wu YS, Fan JT, Yu W. Effect of posture positions on the evaporative resistance and thermal insulation of clothing. Ergonomics. 2011;54:301-13.

6. Adams WC, Mack GW, Langhans GW, Nadel ER. Effects of varied air velocity on sweating and evaporative rates during exercise. J Appl Physiol. 1992;73:2668-74.

7. Saunders AG, Dugas JP, Tucker R, Lambert MI, Noakes TD. The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. Acta Physiol Scand. 2005;183:241-55.

8. Vogt JJ, Meyer JP, Candas V, Libert JP, Sagot JC. Pumping effects on thermal insulation of clothing worn by human subjects. Ergonomics. 1983;26:663-74.

9. Wang F. Effect of body movement on the thermophysiological responses of an adaptive manikin and human subjects. Measurement. 2018;116:251-6.

10. Holmér I. Protective clothing in hot environments. Ind Health. 2006;44:404-13.

11. Bernard T, Ashley C, Trentacosta J, Kapur V, Tew S. Critical heat stress evaluation of clothing ensembles with different levels of porosity. Ergonomics. 2010;53:1048-58.

12. Havenith G, den Hartog E, Martini S. Heat stress in chemical protective clothing: porosity and vapour resistance. Ergonomics. 2011;54:497-507.

13. Nilsson HO, Holmér I. Prediction of motion effects from static manikin measurements. In: A European seminar on Thermal Manikin Testing: 12 Feb, 1997; Solna: Proceeding of a European seminar on Thermal Manikin Testing; 1997:45-48.

14. Holmér I, Nilsson HO, Havenith G, Parsons K. Clothing convective heat exchange–proposal for improved prediction in standards and models. Ann Occup Hyg. 1999;43:329-37.

15. Parsons KC, Havenith G, Holmér I, Nilsson HO, Malchaire J. The effects of wind and human movement on the heat and vapour transfer properties of clothing. Ann Occup Hyg. 1999;43:339-46.

16. Havenith G, Holmér I, Parsons KC, den Hartog EA, Malchaire J. Calculation of dynamic heat and vapour resistance. In: Werner J, Hexamer M editors. Environmental Ergonomics IX. Aachen. Shaker Verlag Gmbh; 2000. p. 125-128. 9th International conference on Environmental Ergonomics. 30 July - 4 August, 2000, Dortmund, Germany: ISBN 3 8265 7648 9.

17. Havenith G, Holmér I, den Hartog EA, Parsons KC. Clothing evaporative heat resistance–proposal for improved representation in standards and models. Ann Occup Hyg. 1999;43:339-46.

18. Havenith G, Nilsson HO. Correction of clothing insulation for movement and wind effects. A meta-analysis. Environ in Eur J Appl Physiol. 2005/93: 506-85.

19. Kim CS, McCullough EA. Static and dynamic insulation values for cold weather protective clothing. In: Nelson CN, Henry NW editors. Performance of protective clothing: issues and priorities for the 21st century, Vol 7. ASTM STP 1386. American Society for Testing and Materials: West Conshohocken, PA, 2000. p. 233-47.

20. Nilsson HO, Antonsen H, Holmér I. New algorithms for prediction of wind effects on cold protective clothing. In: 1st European conference on protective clothing. Arbete och Hälsa 8, Stockholm, 2000. p. 17-20.

21. Havenith G, Nilsson HO. Correction of clothing insulation for movement and wind effects, a meta-analysis. Eur J Appl Physiol. 2004;92:636-40.

22. International Organization for Standardization (ISO). Ergonomics of the thermal environment - analytical determination and interpretation of heat stress using calculation of the predicted heat strain. (Standard No. ISO 7933: 2004), Geneva, Switzerland: ISO, 2004.

23. International Organization for Standardization (ISO). Ergonomics of the thermal environment - analytical determination and interpretation of heat stress using calculation of the predicted heat strain. (Standard No. ISO 7933: 1989), Geneva, Switzerland: ISO, 1989.

24. Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, et al. Development and validation of the predicted heat strain model. Ann Occup Hyg. 2001;45:123-35.

25. Malchaire J, Kampmann B, Mehnert P, Gebhardt H, Piette A, Havenith G, et al. Assessment of the risk of heat disorders encountered during work in hot conditions. Int Arch Occup Environ Health. 2002;75:153-62.

26. International Organization for Standardization (ISO). Ergonomics of the thermal environment – estimation of the thermal insulation and evaporative resistance of a clothing ensemble. (Standard No. ISO 9920: 1995), Geneva, Switzerland: ISO, 1995.

27. International Organization for Standardization (ISO). Ergonomics of the thermal environment – estimation of the thermal insulation and evaporative resistance of a clothing ensemble. (Standard No. ISO 9920: 2007), Geneva, Switzerland: ISO, 2007.

28. Havenith G (personal communication).

29. Kampmann B, Brode P, Fiala D. Physiological responses to temperature and humidity compared to the assessment by UTCI, WBGT and PHS, Int J Biometeorol. 2012;56:505–13.

30. Parsons K. Occupational health impacts of climate change: current and future ISO standards for the assessment of heat stress. Ind Health. 2013;51(3):186–100.

31. Lundgren K, Martinez N, Johannson B, Piskuta A, Annasheim S, Kuklane K. Human responses in heat – comparison of the predicted heat strain and the Fiala multi-node model for a case of intermittent work. J Therm Biol. 2017;70(Part A):45-52.

32. Wang F, Gao C, Kuklane K, Holmér I. Effects of various protective clothing and thermal environments on heat strain of unacclimated men: the PHS (predicted heat strain) model revisited. Ind Health. 2013;51(3):266–74.
33. Ueno S, Sawada S, Bernard TE. Modifications to predicted heat strain (PHS) (ISO7933). In 13th International Conference on Environmental Ergonomics: 3–7 Aug, 2009. Boston, USA. Proceedings of the 13th International Conference on Environmental Ergonomics; 2009: 141–5.

34. Qian X, Fan J. Interactions of the surface heat and moisture transfer from the human body under varying climatic conditions and walking speeds. Appl Ergon. 2006;37:685–93.

35. Qian X, Fan J. A quasi-physical model for predicting the thermal insulation and moisture vapour resistance of clothing. Appl Ergon. 2009;40:577–90.

36. Morrissey MP, Rossi RM. The effect of wind, body movement and garment adjustments on the effective thermal resistance of clothing with low and high air permeability insulation. Text Res J. 2014;84:583–92.

37. Lu Y, Wang F, Wan X, Song G, Zhang C, Shi W. Clothing resultant thermal insulation determined on a movable thermal manikin. Part I: effects of wind and body movement on total insulation. Int J Biometeorol. 2015;59:1475–86.

38. Wang F, Del Ferraro S, Lin LY, Mayor TS. Localised boundary air layer and clothing evaporative resistances for individual body segments. Ergonomics. 2012;55:799–812.

39. Ueno S, Sawada S. Correction of the evaporative resistance of clothing by the temperature of skin fabric on a sweating and walking thermal manikin. Text Res J. 2011;82:1143–56.

40. Oliveira AV, Gaspar AR, Francisco SC, Quintela DA. Convective heat transfer from a nude body under calm conditions: assessment of the effects of walking with a thermal manikin. Int J Biometeorol. 2012;56:319–32.

41. Wang F, Havenith G, Mayor TS, Kuklane K, Leonard J, Młynarczyk M et al. Clothing real evaporative resistance determined by means of a sweating thermal manikin: a new round-robin study. In: Scientific Conference for Smart and Functional Textiles, Well-being, Thermal Comfort in Clothing, Design, Thermal Manikins and Modelling: Ambience14 & 10Xm. Tampere, Finland: University of Helsinki; 2014.

42. Lotens WA. The actual insulation of multilayer clothing. Scand J Work Environ Health. 1989;15:66–75.

43. Kakitsuba N. Investigation into clothing area factors for tight and loose fitting clothing in three different body positions. J Hum Environ Syst. 2004;7:75–81.

44. Anttonen H, Hiltunen E. The effect of wind on thermal insulation of military clothing. RTO-MP-HFM-168 – Soldiers in cold environments. NATO, Helsinki, 2000:1–12.

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