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Original Article

A free software to predict heat strain according to the ISO 7933:2018

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Abstract: Our primary objective in this study was to design and implement the FAME Lab PHS Calculator software (PHS_{FL}) (www.famelab.gr/research/downloads), a free tool to calculate the predicted heat strain of an individual based on ISO 7933:2018. Our secondary objective was to optimize the practicality of the PHS_{FL} by incorporating knowledge from other ISO standards and published literature. The third objective of this study was to assess: (i) the criterion-related validity of the PHS_{FL} by comparing its results against those obtained using the original ISO 7933:2018 code; and (ii) the construct validity of the PHS_{FL} by comparing its results against those obtained via field experiments performed in human participants during work in the heat. Our analysis for criterion validity demonstrates that PHS_{FL} provides valid results within the required computational accuracy, according to Annex F of ISO 7933:2018. The construct validity showed that root mean square errors (RMSE) and 95% limits of agreement (LOA) were minimal between measured and predicted core temperature (RMSE: 0.3°C; LOA: 0.06 ± 0.58°C) and small between measured and predicted mean skin temperature (RMSE: 1.1°C; LOA: 0.59 ± 1.83°C). In conclusion, the PHS_{FL} software demonstrated strong criterion-related and construct-related validity.

Key words: Predicted heat strain (PHS), Hyperthermia, Heat stress, Occupation, Work, Labor, Thermal

Introduction

It is well-established that human capacity to perform both physical and mental tasks is impaired in hot environments and that this relationship is driven by core (T_c) and mean skin (T_{sk}) temperatures as well as hydration status[1–4]. For instance, a study in agriculture workers showed that there is a 2.1% increase in irregular work breaks for every degree Celsius increase in T_{sk}[5]. Furthermore, a recent systematic review showed that 35% of workers experience occupational heat strain during a work shift under heat stress, while 15% of the workers who frequently work under occupational heat stress experience kidney disease or injury[3]. However, despite these important health ramifications associated with work or exercise in hot environments, it is not always possible to perform the necessary physiological assessments in workers due to, for instance, lack of equipment, expertise, resources, time, and/or inability to recruit volunteers. Consequently, over the last century more than 160 thermal stress indices have been developed to estimate the thermal stress and/or strain experienced by a person[6, 7]. However, the majority of those thermal indices take into account only exogenous (e.g., environmental conditions) parameters without considering endogenous factors (e.g., metabolic heat production and clothing)[6, 8]. Therefore, the results derived using these indices may not accurately correspond to the thermal

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strain experienced by a person[9–11].

The ISO 7933:1989 was developed to determine and interpret thermal stress by calculation of the required sweat rate for heat balance[12]. Subsequently, a European Union project (BMH4-CT96-0648)[13] was funded to address some of the shortcomings[14, 15] of the ISO 7933:1989 and to improve its prediction accuracy. The resulting standard (ISO 7933:2004[16]) was updated using large datasets collected from different laboratories[15]. The ISO 7933:2004 introduced the programming code for the Predicted Heat Strain (PHS) model, which was designed to predict the heat strain experience by a group of individuals under a set of known environmental and physiological conditions[13]. Recently, the ISO committee published the ISO 7933:2018[2] "*…for the analytical determination and interpretation of the thermal stress (in terms of water loss and core temperature) experienced by a subject in a hot environment and to determine the "maximum allowable exposure times", with which the physiological strain is acceptable for 95% of the exposed population*".

The popularity of the PHS is increasing until today, primarily due to the afore-mentioned complexities for performing physiological assessments in human participants. Since its inception, a total of 611 articles have used and/or referred to the PHS model (metrics taken on Jan 11, 2019 from Google Scholar). The same statistics demonstrate that about three scientific articles used and/or referred to the PHS model every two weeks during 2018. Despite the increasing popularity of the PHS model, the calculations described in the ISO 7933:2018 are cumbersome and time-consuming. For instance, it has been stated that the first ISO 7933:1989 "*…was so sophisticated that it was simply not understood nor used in industry*" and that "*…this situation was likely to be worse as the complexity increased for the Predicted Heat Strain*"[14].

To address the limited practicality of the PHS and to increase its usage in industry, our primary objective in this study was to design and implement the FAME Lab PHS Calculator software (PHS_{FL}), a new software to calculate the PHS of a group of individuals based on ISO 7933:2018. Our secondary objective was to optimize the practicality of the PHS_{FL} by making it easy for physiologists, industrial hygienists, and occupational physicians to calculate the required environmental and physiological parameters through other ISO standards (7726:1998[17], 8996:2004[18], and 7730:1994[19]) and published literature[20, 21]. The third objective of this study was to assess: (i) the criterion-related validity of the PHS_{FL} by comparing its results against those obtained using the original ISO 7933:2018 code[16]; and (ii) the construct validity of the PHS_{FL} by comparing its results against those obtained via field experiments performed in human participants during work in the heat.

Subjects and Methods

Design and implementation of the PHS_{FL} software (objective 1)

The PHS_{FL} software was developed using the Visual Basic programming language (Microsoft; USA). In its core, the software is based on equations and formulas elaborated in the ISO 7933:2018[2].

Optimizing the practicality of the PHS_{FL} software (objective 2)

After developing the basic code of the PHS_{FL}, published information was used to make certain additions to improve the user friendliness of the software. These additions are described in detail in the following sub-sections. It is important to note that all modifications of the original software described in ISO 7933:2018 are optional, as the user can choose which features he/she wants to use and which not.

Additions to the ISO 7933:2018 programming code

i) Metabolic rate using heart rate (ISO 8996:2004)

We added an option to predict metabolic rate as a function of an individual's heart rate, age, sex, and body mass according to the ISO 8996:2004[18] (Table 1). It is important to note that, according to ISO 9886:2004[22] "the increase of heart rate due to thermal strain is on the average 33 beats·min^{-1} per degree of temperature rise of the body core". Therefore, we modified our code to subtract the thermal cardiac reactivity from the user-defined heart rate (using the user-defined core temperature) in the calculation of metabolic rate. Though correcting heart rate for thermal cardiac reactivity is advisable for the unbiased estimation of metabolic rate, the above-mentioned value of 33 beats/min/°C may vary between individuals from 17 to 60 beats/min/°C[22–24].

ii) Metabolic rate using heart rate

We added an option to predict metabolic rate as a function of an individual's sex, age, body mass, body stature, mean heart rate, and heart rate at rest, according to ISO 7933:2018[2, 23, 25]. As mentioned above, this part of the code is modified to subtract the thermal cardiac reactivity from the user-defined heart rate in the calculation of metabolic rate.

Table 1. Calculation of metabolic rate as a function of an individual's heart rate, sex, age, and body mass

Age (yr)	Body mass (kg)				
	50	60	70	80	90
Women					
20	2.9*HR-150	3.4*HR-181	3.8*HR-210	4.2*HR-237	4.5*HR-263
30	2.8*HR-143	3.3*HR-173	3.7*HR-201	4.0*HR-228	4.4*HR-254
40	2.7*HR-136	3.1*HR-165	3.5*HR-192	3.9*HR-218	4.3*HR-244
50	2.6*HR-127	3.0*HR-155	3.4*HR-182	3.7*HR-207	4.1*HR-232
60	2.5*HR-117	2.9*HR-145	3.2*HR-170	3.6*HR-195	3.9*HR-219
Men					
20	3.7*HR-201	4.2*HR-238	4.7*HR-273	5.2*HR-307	5.6*HR-339
30	3.6*HR-197	4.1*HR-233	4.6*HR-268	5.1*HR-301	5.5*HR-333
40	3.5*HR-192	4.0*HR-228	4.5*HR-262	5.0*HR-295	5.4*HR-326
50	3.4*HR-186	4.0*HR-222	4.4*HR-256	4.9*HR-288	5.3*HR-319
60	3.4*HR-180	3.9*HR-215	4.5*HR-249	4.8*HR-280	5.2*HR-311

All information included in Table 1 was obtained from the ISO 8996:2004.

iii) Metabolic rate using the compendium of physical activities

We added an option to predict the metabolic rate using the compendium of physical activities[26]. The compendium of physical activities presents all activities in metabolic equivalents; we converted those values to W/m^2 by multiplying them with 58.15, as descripted in ISO 7730:1994[19].

iv) Clothing insulation using previous literature

We added an option to predict clothing insulation based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)[27] to describe the clothing insulation of various garments such as, shirts, sweaters, jackets, trousers, skirts, dresses, sleepwear, robes, and underwear.

v) Mechanical efficiency and power

Mechanical efficiency (η) represents the fraction of the overall metabolic energy converted to external mechanical power (work), while the remaining metabolic energy (1−η) is converted to internal heat warming up the body.[21] The ISO 7933:2018[2, 16] states that "*in most industrial situations, the effective mechanical power is small and can be neglected*". However, Fiala[21] concluded that "*… the human mechanical efficiency is not constant in reality, but rises with increasing activity levels*". In this light, we added an option in the PHS_{FL} to calculate the mechanical efficiency based on a formula provided by Fiala[21], as well as an automatic computation of mechanical power using the following formula:

$$\eta = 0.2 * \tanh\left(0.39 * \left(\frac{act}{58.15}\right) - 0.60\right)$$

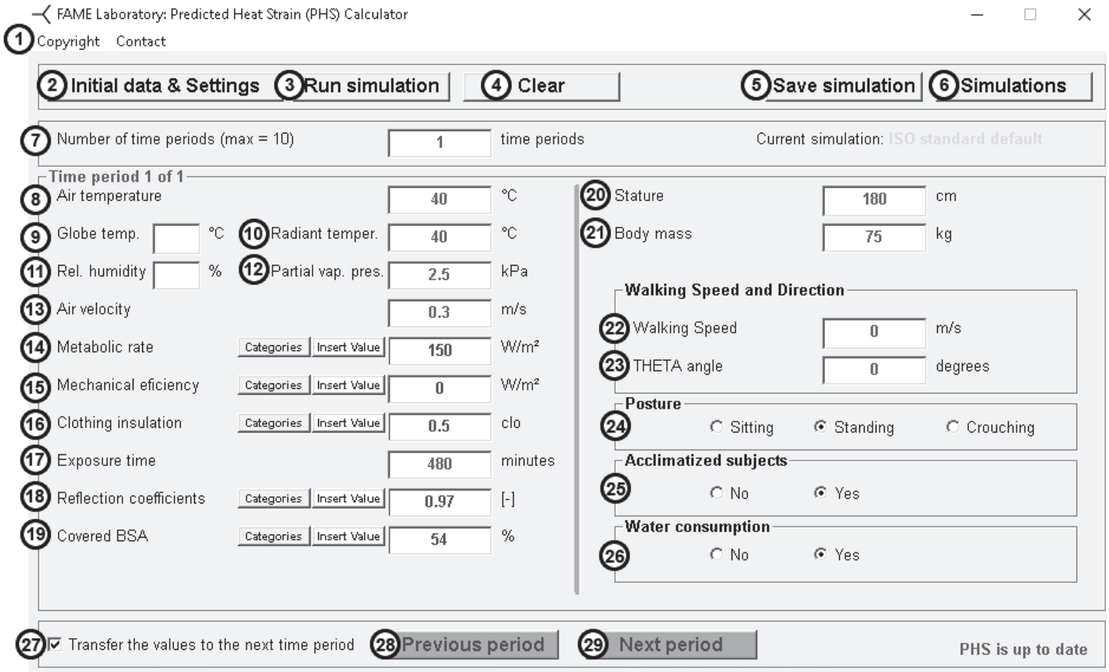
η=mechanical efficiency (%)
act=activity (W/m^2)

Fiala's equation has been modified to calculate activity in W/m^2, instead of metabolic equivalent. The transformation between metabolic equivalent and activity in W/m^2 (1 MET=58.15 W/m^2) was obtained from ISO 7730:1994[19].

It is important to note that, effective mechanical power is of great importance as it is a main parameter of the heat balance equation and neglecting it can lead to erroneous diagnosis and decisions. For instance, in a hypothetical case where a construction worker (body stature: 180 cm; body mass: 75 kg) repairs a roof, which is equal to a metabolic rate of 232.6 W/m^2[26], in a hot (air temperature: 30°C; globe temperature: 45°C) and humid (relative humidity: 60%) environment, he will reach 39°C T_c after 200 min of work. On the other hand, if we take into account the effective mechanical power, which in this case is equal to 34 W/m^2, his T_c after 200 min will be 37.8°C, resulting in a T_c difference of 1.2°C between the two identical scenarios.

vi) Different time periods

It is logical to assume that the environmental, physiological, and/or clothing parameters included in the PHS calculations may vary throughout the simulated exposure time. For instance, an individual performs work in the morning (when environmental heat stress is low) and continues working until the afternoon (when environmental heat stress is high). To this effect, we added an option to calculate the PHS for successive time periods that may



⑦ Number of time periods (max = 10) 1 time periods

Current simulation: ISO standard default

Time period 1 of 1

⑧ Air temperature 40 °C

⑨ Globe temp. °C ⑩ Radiant temper. 40 °C

⑪ Rel. humidity % ⑫ Partial vap. pres. 2.5 kPa

⑬ Air velocity 0.3 m/s

⑭ Metabolic rate 150 W/m²

⑮ Mechanical eficiency 0 W/m²

⑯ Clothing insulation 0.5 clo

⑰ Exposure time 480 minutes

⑱ Reflection coefficients 0.97 [-]

⑲ Covered BSA 54 %

⑳ Stature 180 cm

㉑ Body mass 75 kg

Walking Speed and Direction

㉒ Walking Speed 0 m/s

㉓ THETA angle 0 degrees

Posture

㉔ ○ Sitting ● Standing ○ Crouching

Acclimatized subjects

㉕ ○ No ● Yes

Water consumption

㉖ ○ No ● Yes

㉗ ☑ Transfer the values to the next time period ㉘ Previous period ㉙ Next period

PHS is up to date

Fig. 1. Main screen of the FAME Lab Predicted Heat Strain software.

Numbers indicate the 29 different options/buttons on the main screen that are explained in Table 2.

Buttons entitled "Categories" open a new window providing additional options; the buttons entitled "Insert value" enables the user to insert a specific value.

include different environmental, physiological, and/or clothing parameters. To calculate the PHS during separate time periods, the last values of each time period are used as initial data in the subsequent period, the new input values are considered, while the remaining properties of the software (i.e., equations and code) remain unchanged. Hence, this approach predicts heat strain during different time periods by continuously performing the calculation with dynamically varying input parameters (environmental, clothing, and physiological).

Software description

The developed $\mathrm{PHS_{FL}}$ software package can be freely downloaded using the following link: www.famelab.gr/research/downloads. It runs using Microsoft Windows operating systems (XP/Vista/Win7/Win10). With the use of Windows emulators, the $\mathrm{PHS_{FL}}$ software can also run on Linux and Apple Macintosh platforms. The home screen includes 29 buttons and input-boxes (Fig. 1), which are described in detail in Table 2. According to the ISO 7933:2018, the $\mathrm{PHS_{FL}}$ software provides minute-by-minute values for rectal temperature (°C) and total water loss (g).

To improve its usefulness, the $\mathrm{PHS_{FL}}$ also provides minute-by-minute results for $\mathrm{T_c}$ and $\mathrm{T_{sk}}$. These values were included within the original code of the ISO 7933:2018, yet the final outputs did not provide these predictions. The data are provided in numeric format as well as in charts and can be exported in *.csv, *.txt, and *.bmp formats.

Assessing the criterion-related validity of the $\mathrm{PHS_{FL}}$ (objective 3a)

The criterion-related validity (comparing a measurement against some known quantity)[28] of the $\mathrm{PHS_{FL}}$ was assessed by comparing its results against those obtained using the original ISO 7933:2018 code[16]. For this purpose, we compared the results of the of the $\mathrm{PHS_{FL}}$ and the PHS when simulating five different scenarios (Table 3), as descripted in the Annex F of ISO 7933:2018[2]. Also, we slightly modified the programming code of the ISO 7933:2018[16]—without making any changes to the computations and formulas—to generate minute-by-minute data, instead of producing only the last value of each scenario. Specifically, mean differences (bias) and root mean squared errors (RMSE) were used to examine potential differences in all outputs between $\mathrm{PHS_{FL}}$ and the code described in the Annex E of the ISO 7933:2018. Statistical analyses were conducted using Excel spreadsheets (Microsoft Office, Microsoft, Washington, USA).

Table 2. Explanation of the 29 different options/buttons provided on the main screen of the PHS software, as shown in Fig. 1

#	Name	Description
1	Copyright	Opens a new window which provides general information about the copyright of the present software.
2	Initial data & settings	Opens a new window which allows the user to change the initial data and settings of the software.
3	Calculate	Calculates the predicted heat strain and opens a new window which shows the calculated results.
4	Clear	Clears all changes including results. By clicking the “Yes” button, all changes, including results, will be lost.
5	Save simulation	Saves all variables including time periods and initial data.
6	Simulations	Opens a new window which provides four options: a) import a preexisted simulation from a file; b) export the selected simulation; c) delete the selected simulation; d) load a saved simulation.
7	Number of time periods	Indicates the number of different simulation phases. Each time period can have different input parameters. The maximum number of allowed time periods is 10.
8	Air temperature	Represents the temperature of the air around the human body.
9	Globe temperature	Measured using a black globe temperature sensor.
10	Mean Radiant temperature	Describes the average radiant temperature of all the surrounding surfaces.
11	Relative humidity	Describes the ratio between the partial pressure of water vapour in humid air and the water vapour saturation pressure at the same temperature and the same total pressure.
12	Vapour pressure	Describes the actual amount of water in the air.
13	Air velocity	Describes the wind speed.
14	Metabolic rate	Describes the metabolic rate.
15	Mechanical efficiency	Describes the efficiency of a task.
16	Clothing insulation	Describes the thermal insulation provided by clothing.
17	Exposed time	Represents the amount of time (minutes) spent on the simulated work task.
18	Reflection coefficients	Describes the emissivity of the reflective clothing.
19	Covered BSA	Describes the fraction of the body surface area covered by reflective clothing.
20	Stature	Represents the height (cm) of the simulated individual.
21	Body mass	Represents the weight (kg) of the simulated individual.
22	Walking speed	Describes the walking/movement speed of the simulated individual.
23	THETA angle	Describes the angle between walking direction and wind direction.
24	Posture	Describes the body position of the simulated individual.
25	Acclimatized subjects	Describes the acclimatization status of the simulated individual. It is important to note that a human being needs up to two weeks of daily exposure to be fully acclimatized.
26	Water consumption	Describes the ability of the simulated individual to drink water freely during the exposure time.
27	Transfer the values to the next time period	Enabling this option results in all values being transferred to the next time period when pressing “Next period”.
28	Previous period	Moves to the previous time-period, if available.
29	Next period	Moves to the next time-period, if available. If option #27 is enabled, all values will be transferred to the next time period.

Assessing the construct validity of the PHS_{FL} (objective 3b)

The construct validity [the property of a measurement being associated with variables assessing the same (or similar) characteristic][28] of the PHS_{FL} was assessed by comparing its results against those obtained via field experiments performed in human participants during work in the heat. The experimental protocol for these field experiments was approved by the National Bioethical Committee of Cyprus in accordance with the Declaration of Helsinki (NBCC 27.01.61). The study involved monitoring a group of five experienced (8–16 yr of work experience) and acclimatized (i.e., continuously living in the area for the ≥90 previous days and performing other agriculture jobs on a daily basis) grape-picking workers during one full work-shift. Prior to their participation in the study, written informed consent was obtained from all volunteers after detailed explanation of all the procedures involved.

Baseline data [self-reported age; body stature (Seca 213; seca GmbH & Co. KG; Hamburg, Germany) and body mass (BC1000, Tanita corporation, Tokyo, Japan)] were collected one day prior to the experiment. During the field study, continuous heart rate, T_c and T_{sk} data were collected using wireless heart rate monitors (Polar Team2. Polar Electro Oy, Kempele, Finland), telemetric capsules (BodyCap, Caen, France), and wireless thermistors (iButtons type DS1921H, Maxim/Dallas Semiconductor Corp.,

Table 3. Tested conditions during the criterion-related validity simulations

Parameters (Units)	Simulated scenario				
	1st	2nd	3rd	4th	5th
Acclimatization	Yes	No	No	No	Yes
Posture	Standing	Standing	Standing	Standing	Sitting
Duration	480	480	480	480	480
Ta (°C)	40	35	30	30	35
Tg (°C)	40	35	45	30	50
Va (ms-1)	0.30	0.10	0.10	1.00	1.00
RH (%)	35	60	35	45	30
M (W)	300	300	300	450	250
W (W)	0	0	0	0	0
Icl (clo)	0.5	0.5	0.8	0.5	1.0
Tr (°C)	40.0	35.0	52.0	30.0	74.6
Pa (kPa)	2.58	3.37	1.48	1.91	1.69
Ap (fraction %)	–	–	30	–	20
Fr (-)	–	–	0.15	–	0.15

The five hypothetical scenarios presented in Table 3 were obtained from ISO/DIS 7933:2018. As mentioned in Annex F of ISO/DIS 7933:2018, in all cases stationary or undefined walking conditions are assumed.
Ta: air temperature; Tg: globe temperature; Va: air velocity; RH: relative humidity; M: metabolic rate; W: effective mechanical power; Icl: clothing insulation; Tr: mean radiant temperature; Pa: vapor pressure; Ap: fraction of the body surface area covered by reflective clothing; Fr: emissivity of the reflective clothing.

USA), respectively. Skin temperature data were collected from four sites (chest, arm, thigh, and leg) and were expressed as T_{sk} according the formula of Ramanathan (T_{sk}=[0.3 (chest + arm) + 0.2 (thigh + leg)])29). Furthermore, continuous environmental data [air temperature (°C), globe temperature (°C), relative humidity (%), and air velocity (m/s)] were collected using a portable weather station (Kestrel 5400FW, Nielsen-Kellerman, PA, USA). Thereafter, these environmental data were utilized to compute mean radiant temperature (by using air temperature, globe temperature, and air velocity) and partial vapor pressure (by using air temperature and relative humidity) based on formulas incorporating in the PHS code (Annex E) found in ISO 7933:20182).

Video recordings using a video camera (Hero 5 black, GoPro, CA, USA) installed in close proximity (up to 40 m) to the volunteers was used to calculate other parameters such as clothing insulation, covered body surface area, body posture, walking speed, and metabolic rate throughout the work shift. For this purpose, second-by-second video analysis was conducted using previous methodology5). More precisely, all clothes worn by volunteers were video-recorded and matched with known clothing insulation values found in the literature27). The same video recordings were used to calculate the fraction of the covered body surface area of workers by summing the regions of their body found to be covered by garments. The ratios of the area of the different body regions to the total body surface area were obtained from ISO 7933:20182). Metabolic rate was set to 327 W for males and 258 W for females according to previous literature30); individual characteristics for body mass and body stature were utilized to calculate body surface area using Dubois' formula31) and to express metabolic rate as W/m^2. Video analysis was used to identify when major changes in metabolic rate (i.e, lunch break) took place. Lunch break was characterized by 1.5 metabolic equivalents (87.2 W/m^2) according to the MET code 13030 of the compendium of physical activities26). The effective mechanical power (W/m^2) of the workers throughout their work shift was calculated using the method described under the section "additions to the ISO 7933:2018 programming code".

The raw data collected were used to calculate hourly mean values. These averages were used to conduct five (i.e., one simulation per worker) eight-period (i.e., each period lasting one hour) simulations using the PHS_{FL} software. Pearson's correlation coefficient was used to examine the relationship between the recorded minute-by-minute T_c and T_{sk} values and those predicted via the PHS_{FL}. Paired-samples t-tests were used to detect potential differences between the recorded minute-by-minute T_c and T_{sk} values and those predicted via the PHS_{FL}. Furthermore, mean differences and root mean square errors were used to examine potential differences in T_c and T_{sk} between the recorded and those predicted via the PHS_{FL}. Finally, the Bland-Altman 95% limits of agreement and associated percent coefficient of variation were used to further assess and visualize the between-method differences. Statistical analyses were conducted using both the SPSS v25.0 (IBM, Armonk, NY, USA) and Excel spreadsheets (Microsoft Office, Microsoft, WA, USA). The level of significance for these analyses (construct validity) was set at $p<0.05$.

Results

Assessing the criterion-related validity of the PHS_{FL} (objective 3a)

The developed PHS_{FL} software predicts four variables (rectal temperature, T_c, T_{sk}, and total water loss), while the ISO 7933:2018 predict two variables (rectal temperature and total water loss). Also, both methods calculate the maximum allowable exposure times (maximum tolerable T_c and water loss not exceeded by 95% of the exposed people).

There were no differences (bias=0°C; RMSE=0°C) between the PHS_{FL} and the programming code obtained from Annex E of ISO 7933:2004 (Fig. 2). Furthermore, our analysis demonstrated that PHS_{FL} provides correct results within the required computational accuracy of 0.1°C for the predicted T_c and 1% for water loss, according to Annex F of ISO 7933:2018[2].

Assessing the construct validity of the PHS_{FL} (objective 3b)

Five grape-picking workers [3 females (age: 46.0 ± 6.9 yr; height: 157.9 ± 8.5 cm; weight: 55.9 ± 2.0), 2 males (age: 31.0 ± 14.1 yr; height: 177.6 ± 5.1 cm; weight: 81.5 ± 0.6 kg)] worked for eight consecutive hours in environmental temperature (28.5 ± 3.3°C) ranging from 18.6°C to 35.1°C. Heart rate (103.5 ± 12.6 bpm; range 75–172 bpm), T_c (37.4 ± 0.3°C; range 36.7–38.2°C), and T_{sk} (34.6 ± 1.5°C; range 30.9–36.6°C) suggested a moderate-to-high level of work intensity. Second by second video analysis showed that workers spent 81.4% of their work shift crouching, 12.0% standing, and 6.6% sitting. Furthermore, all of them wore clothes equal to 0.90 clo, while the clothing coverage (0.89 ± 0.2% of body surface area) ranged from 0.88% to 0.93% of their body surface area. All workers had an average walking speed of approximately 0.035 m/s (total walking distance/work shift duration→up to 1,000 m/28,800 s), throughout the work shift.

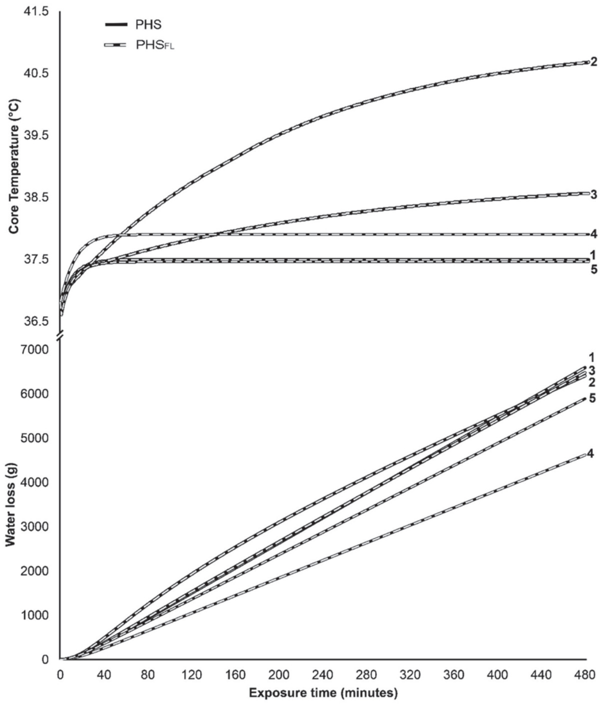


Fig. 2. Core temperature (top graph) and water loss (bottom graph) during the criterion-related validity scenarios presented in Table 3, as estimated using the two Predicted Heat Strain software packages (ISO 7933:2018 and PHS_{FL}).

Solid black and dashed white lines represent the ISO 7933:2018 and PHS_{FL} values, respectively (these lines overlap completely in all cases).

Both T_c and T_{sk} were strongly related with the predicted T_c (r=0.573, $p<0.001$) and T_{sk} (r=0.850, $p<0.001$) values (Fig. 3). No statistically significant differences were identified between the predicted T_c (37.4 ± 0.3°C) and the hourly measured T_c (37.4 ± 0.3°C) ($p>0.05$), throughout the work shift (Fig. 3). Importantly, no differences were found between the hourly predicted T_c (37.6 ± 0.1°C) and hourly measured T_c (37.6 ± 0.2°C) ($p=0.847$), during the last hour of the work shift (Fig. 3). On the other hand, we found statistically significant differences between the measured T_{sk} (34.9 ± 1.5°C) and predicted T_{sk} (35.5 ± 0.8°C) ($p<0.001$). However, it is important to note that there were no statistically significant differences between the measured and predicted T_{sk} values, throughout the majority of work duration (i.e., 1st, 3rd, 4th, 5th, 6th, 7th, and 8th working hours) (Fig. 3). Root mean square errors were minimal for T_c (0.3°C) and small for T_{sk} (1.1°C). The 95% limits of agreement between measured and predicted T_c and T_{sk} (Fig. 4) were 0.06 ± 0.58°C and 0.59 ± 1.83°C, respectively, indicating overestimation. The corresponding percentage coefficients of variation between measured and predicted T_c and T_{sk} were 0.8% and 2.6%, respectively.

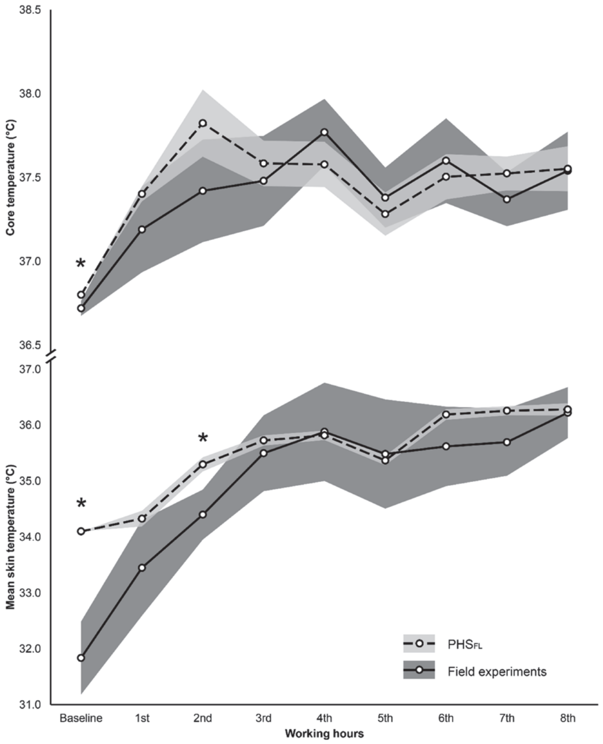


Fig. 3. Core (top graph) and mean skin (bottom graph) temperature (mean ± SD) as measured (solid lines with dark grey shading) during field studies or simulated (dashed lines with light grey shading) using the FAME Lab Predicted Heat Stain (PHS_{FL}) software. Asterisks indicate statistically significant differences at $p<0.05$.

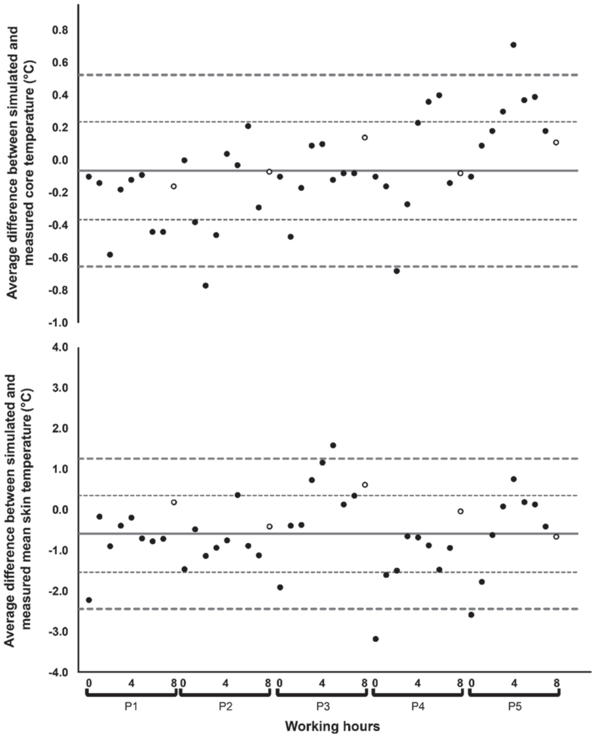


Fig. 4. Average differences between simulated and measured core (top graph) and mean skin (bottom graph) temperatures. Solid grey lines represent bias (average difference between the two methods). Fine dashed lines represent the standard deviations. Thick dashed lines represent the 95% limits of agreement. The full colored circles represent the hourly differences between simulated and measured temperature. White-filled circles correspond to the differences between simulated and measured temperature at the end of the work shift. Horizontal axis corresponds to the five 8-h work shifts [i.e., one per participant (P1, P2, P3, P4, and P5)] used in the study.

Discussion

In this paper we designed and implemented the PHS_{FL}, a new free software to estimate the heat strain of an individual under pre-known environmental conditions based on ISO 7933:2018. The PHS_{FL} software generates results identical to the ISO 7933:2018 code. According to our construct validity analyses, the PHS_{FL} estimates are comparable to those obtained via field experiments performed in human participants during work in the heat.

The PHS_{FL} software includes a number of features to optimize practicality and user-friendliness, including a method to simulate the heat strain of an individual who is exposed to varying environmental and/or physiological stress. In turn, our simulations showed that there were no statistically significant differences in T_c between the predicted and measured data. On the other hand, we showed that there were significant differences between the predicted and measured T_{sk} during the baseline measurements and the 2nd hour of the work shift. Despite these differences, we found strong linear relationships between the predicted and measured T_c and T_{sk} values. Moreover, the 95% limits of agreement suggest that a T_c of 38°C when measured with a gastrointestinal thermistor during field work in the heat would be estimated as low as 37.4°C or as high as 38.6°C using the PHS_{FL}. Similarly, a T_{sk} of 32°C when measured with skin thermistors during field work in the heat would be estimated as low as 29.3°C or as high as 33.5°C using the PHS_{FL}. These estimation limits are considerable (which is why actual measurements are vital for an accurate assessment), yet they provide a fairly good approximation of the heat strain experienced when working or exercising in the heat.

The PHS model was developed using a large dataset of field and laboratory tests[13]. The initial study conducted to develop and validate the PHS model[13] reported a moderate correlation coefficient (r=0.594) between the observed and predicted rectal temperatures in field experiments.

In laboratory experiments, where clothing and environmental conditions are more tightly controlled, the PHS has shown a strong association between the measured and predicted rectal temperatures (r=0.659)[13]. A subsequent study reported that the PHS model underestimates rectal temperature by 0.38°C (males: 0.18°C; females: 0.57°C) but provides an accurate estimate of T_{sk} (males: 0.05°C; females: 0.26°C)[32]. Given these extensive validation studies, we considered the PHS being validated, and we aimed to investigate the validity of the PHS_{FL}; that is, the added features of the PHS_{FL} (eg., time periods) that are not included in the PHS. Our field study results showed strong associations between the measured and predicted values from the PHS_{FL} for both T_c (r=0.573) and T_{sk} (r=0.850). Despite these positive results on construct validity, it is important to note that the PHS_{FL} is based on the ISO/DIS 7933:2018 code that was not developed to predict heat strain during successive sequences of exposure and incorporates a known error when a work period (Period 1) is followed by a prolonged period (Period 2) characterized by comparatively cooler environmental conditions and/or lower metabolic rate. In such conditions, the predicted rectal and core temperatures may (falsely) not return to baseline levels during Period 2. Additionally, it is important to note that the opposite may happen as well, since unrealistic T_c decline during resting breaks has been also observed[8]. Moreover, the ISO 7933 reports that the PHS model is not applicable in cases where protective clothing is worn[2], and this has been demonstrated by Wang *et al*[33]. Thus, the results from the PHS_{FL} during successive periods of exposure and/or when protective clothing is worn may incorporate errors.

Unfortunately, we were unable to investigate potential differences in sweat rate between predicted and collected data because our grape-picking workers consumed large amounts of grapes during their work shift which would introduce errors in our estimations. Also, our analysis is limited by the fact that our T_c and T_{sk} were calculated as hourly averages to minimize the influence of instantaneous events (eg., drinking cold water, dropping cold water on the body, eating grapes, moving to a different environment for limited amount of time).

In conclusion, we designed and implemented the PHS_{FL}, a free software (www.famelab.gr/research/downloads) and user-friendly software to estimate the heat strain of an individual under known and varying environmental conditions based on ISO 7933:2018. The PHS_{FL} software demonstrated strong criterion-related and construct-related validity. However, it is important to note that conducting simulations with the PHS_{FL} without the necessary basic understanding in thermal physiology may lead to misuse of the software and the potential generation of recommendations that can endanger the health of individuals exposed to heat. We hope that this software will help physiologists, industrial hygienists, and occupational physicians to optimize workers' health and enhance work effort and productivity.

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