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Validation of the Predicted Heat Strain Model in Hot Underground Mines

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Abstract

Heat-related illnesses (HRI) are relatively common in both hot surface and underground mining operations. When workers are exposed to extreme heat or strenuous work in a hot environment, they become prone to heat stress. Heat strain is the result of the body's response to external and internal heat stress. It is therefore vital for the conditions leading to heat strain be detected and treated in a timely manner. Heat-related illnesses are manifested by exhaustion and heat stroke. The predicted heat strain (PHS) [ISO 7933 (2004)] model has been developed to predict the health condition of the worker in terms of core body temperature and water loss. The PHS model tested in this study is based on eight physical parameters that are measured at different intervals during a work shift. They include air temperature, humidity, radiation, air velocity, metabolic rate, clothing insulation, posture, and acclimatization. The model predictions are then compared with a direct physiological measurement, such as core body temperature. We present the results of an extensive study that monitored and predicted body's response to heat stress under different environmental and working conditions. The PHS model provided reliable results in most instances in comparison with other prediction methods currently in use in the field.

Keywords Predicted heat strain · Hot underground mines · Heat strain · Heat stress

1 Introduction

A large number of underground mining occupations are characterized by physically demanding activities generally take place in harsh working environments. Mineworkers are typically exposed to heat and physical exertion that can result in heat-related illnesses (HRI) such as heat cramps, heat syncope (fainting), heat exhaustion, and heat stroke. Several other sources of heat in underground mines have been identified that increase the incidence of heat-related illnesses among the mining workforce, including geothermal gradient (increasing rock temperature with depth), seasonal climate, auto-compression, mining methods, groundwater, diesel equipment liberated heat, blasting, and human metabolism, among others [1–3]. The implementation of mine ventilation and cooling systems is the primary means of providing a comfortable working environment. However, the adoption of heat stress indices and models that predict the physiological response of the human body in hot conditions will significantly reduce the risk of heat strain/stress by allowing intervention prior to advanced heat-related illness or exhaustion. One of the most accepted indices to evaluate the potential for thermal stress is the predicted heat strain (PHS), which has become the main driver for establishing heat management guidelines in the military, construction, sports, and other industries [4].

The predicted heat strain (PHS) [ISO 7933 (2004)] is a rational index derived from the thermal balance equation. Since its formulation in 2004 to improve the previous required sweat rate (SWreq) [ISO 7933 (1989)] index, the PHS index allows for in-depth analysis of physical work environments to quantify and predict physiological parameters of an average individual in terms of core, skin and rectal temperatures, and the sweat rate in a minute-by-minute basis. The PHS index project brought together researchers from laboratories in eight European research centers in the field of thermal physiology [5] and finally replaced the previous SWreq version by addressing limitations that were observed for more than a decade with respect to its applicability. The PHS index project

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developed an integral approach towards the evaluation and prevention of the risks associated with thermal environment by concentrating on important specific aspects such as the influence of various clothing sets on the evaporation and convection heat transfer, the distribution of heat temperatures in the human body and its relation to several primary climatic parameters, and the definition of limit criteria for sweat rate, dehydration, and maximum core temperatures. The calibration of the PHS model was performed using algorithms selected from the most recent scientific literature and was subsequently validated by a large data set obtained from laboratory and field experiments (672 and 237 sets of data, respectively) conducted by the eight partner laboratories [5, 6].

In the present study, predictions of the core temperatures were made using a PHS program developed by Jacques Malchaire (last modified in June 2016, personal communication). The program analyzes and interprets the heat stress using formulae based on ISO Standard 7933:2004 [Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using the calculation of the predicted heat strain].

Predicted values from the PHS index were then compared with temperature readings obtained by a thermometer-based ingestible capsule (VitalSense® Core Temperature Capsule) that measures core temperature and transmits data in real time to a sensor electronics module (SEM) wireless device. The VitalSense capsule is 8.6 mm in diameter, 23 mm in length, and weighs 1.6 g with a temperature accuracy of ± 0.1 °C, over a range of 25 to 50 °C [7]. Once activated and ingested, individuals are required to be within a reception range of approximately 1 m from a portable monitor (EquiVital Life Monitor, Hidalgo Ltd. Cambridge, UK) that contains the SEM device. Core temperatures and other vital signs such as skin temperature, heart rate, and respiration rate are measured and reported at a rate of four times per minute to the monitor. Several research studies have supported the VitalSense capsules as a valid and reliable technique for the measurement core body temperature in humans, especially in field-based settings [8–12]. Physiological data are downloaded from the SEM wireless device for analysis and comparison. The main objective of this study is to conduct an in-depth examination of the relationship between the VitalSense capsule and the PHS index, and to uncover the existence of any inconsistencies and differences between the two approaches.

2 Methodology

2.1 Participants and Mining Activities

All two experimental data sets—the VitalSense capsule and PHS index—presented in this study were derived from testing ten participants. Male participants recruited for this study were permanent and part-time workers at the mine who were asked to perform physically demanding tasks. The skill level and degree of difficulty of each activity were quite diverse and none of them had professional or elite physical training background. Table 1 shows the anthropometrical characteristics of all participants considered in the study.

Mobile and real-time monitoring from the VitalSense system enabled the acquisition of physiological data for extended periods of time, while the ingestible pill was kept in the stomach. It allowed representative measurements of participants' daily routines, whether they were performing underground work, such as drilling or mucking, or supporting other mining activities during the day, including surface-level tasks. Table 2 summarizes the percentages related to activities at the underground and surface levels. Air temperature and relative humidity were input values for the PHS index. On average, underground air temperatures were slightly lower than at the surface level, while underground relative humidity values were slightly higher than those observed at the surface.

The studies were held at the Resolution Copper and San Xavier underground mines during consecutive seasonal periods from 2016 to 2018. Both mines are located in Arizona, a desert state in the USA largely characterized by its high temperatures and relative dryness. Experiments were conducted during daytime shifts (range times varied from 7 a.m. to 3:30 p.m.), where all participants were required to wear personal protective equipment consisting of helmet, goggles, gloves, special footwear, and overalls. The rock temperature at Resolution Copper underground is about 80 °C; however, the air properties measurements were taken in cooled working areas.

A brief description of the physical demands of every working activity is provided below:

- Main workers: regularly required to stand and walk for extended periods of time through all operative underground levels of the mine. For maintenance supervisors, physical activity is moderate to heavy while operating the tools and materials.
- Drilling: driving and operating mobile drilling machines. Moderate physical strength is required to drill, wire, and place explosives in a generally noisy and dusty work environment. Use of a jackhammer drill was performed also at the surface level.
- Mucking: the process of removing the broken material from the mining faces with a mucking machine. Operators are required to stand by the machine for long periods of time
- Shoveling: using a shovel as a tool for digging, taking up, removing, and throwing loose material.
- Other activities: physical activity required for cutting steel and maintenance work at the surface level.

Table 1 Anthropometrical characteristics of all participants in the study

	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m^2)	Living in AZ (years)
Males $n = 10$					
Mean	21.16	65.8	180	23.89	7.93
STDEV	1.85	4.5	0.02	1.88	7.82

2.2 Predicted Heat Strain Experimental Procedure

Required environmental parameters used as inputs for the predicted heat strain model were measured after the initial participant health questionnaire was filled and every 60 min thereafter without interfering with the course of activities. The thermal insulation for the clothing ensemble considered was 0.5–0.8 clo, according to insulation values obtained with a thermal manikin for a similar clothing ensemble [13]. Air temperature and relative humidity were continually measured by a digital LCD Thermo-Hygrometer; the airspeed was measured by an airflow anemometer (Airflow Developments Ltd., England), the globe temperature was calculated from the air temperature, and solar radiation was obtained according to formulae derived in a thermal study for outdoors and indoors environments [14]. The globe temperature and solar radiation were also collected from the "Weather Underground" website.

2.3 Core Temperature Capsule Procedure

VitalSense core temperature capsules (EQ-ACC-023) and EquiVital monitor (EQ-02-SEM-007) were used in this research. Participants were asked to use a chest belt (EQ-02-B2-1-TBD) to attach the monitor to the body and provide mobile monitoring capability. The VitalSense capsule was activated by placing it in front of the monitor activation port. Following activation, the capsule was swallowed, and transmission of temperature data began reading every 15 s. Capsules were administered to participants between 7 a.m. and 10 a.m. The experiment was completed when the data communication was no longer maintained or when the capsule was passed.

2.4 Statistical Analysis

Core temperatures from the VitalSense capsule and the PHS index were averaged at 1-min intervals during each working session for statistical comparison. Paired samples t test and the 95% confidence intervals (95% CI) were used to assess the relationship between the two temperature measurements. The level of significance was set at 5% ($\alpha = 0.05$) to evaluate the statistical differences, where a p value < 0.05 was considered statistically significant. Mean bias and limits of agreement (LoA) were investigated by plotting the temperatures differences between methods against their means according to the Bland-Altman method of measurement for multiple observations per subject [15]. It was not possible to properly correlate the results of the two methods due to missing VitalSense data readings. The Pearson product-moment correlation was used to established data correlation. All data are reported as mean ± standard deviation.

3 Results

For all 1-min time periods, the average PHS Index core temperature (T_{PHS}) was 37.14 °C ± 0.50 °C (95% confidence interval [CI] = 37.12 to 37.15 °C) and for VitalSense capsule core temperature (T_{OBS}) was 37.15 °C ± 1.15 °C (95% confidence interval [CI] = 37.13 to 37.18 °C). The largest differences in core temperature between both measurements were found 5 min immediately after the capsule was ingested. For every pair of 8143 core temperature data points, the T_{PHS} value was subtracted from the T_{OBS} value (Fig. 1). In this situation, the paired t test yields no significant result between the T_{PHS} and the reference T_{OBS} on core temperature across both experiments datasets (a mean bias of 0.014 °C, 95% CI − 0.010 to 0.038 °C; $p = 0.250$; t stat = 1.15; t critical 2-tail = 1.96), suggesting that both methods worked equally through all participant readings.

Table 2 Air temperature and relative humidity averages at underground and surface levels

Parameter	Total mine	Full year		Summer (July and August)	
		U.G. activities	Surface activities	U.G. activities	Surface activities
Air temperature (°C)	25.28 ± 6.27	25.08 ± 6.68	25.82 ± 5.56	26.34 ± 6.37	30.30 ± 3.83
Relative humidity (%)	27.77 ± 15.8	28.03 ± 17.2	27.10 ± 12.4	38.60 ± 7.5	37.53 ± 7.5
%time	100%	81.4%	18.6%		

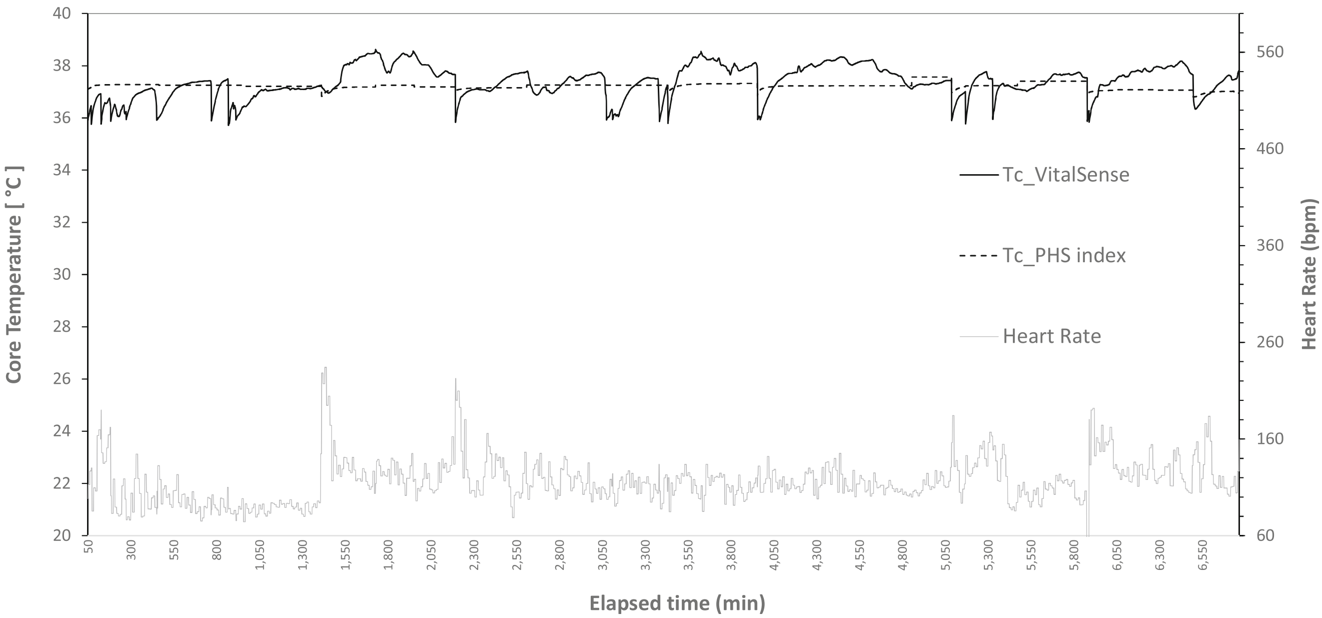

Fig. 1 VitalSense core temperature (observed), PHS index temperature (predicted), and heart rate vs time for the duration of the experiment

However, drilling at the surface was the only non-significant activity (see Table 3), while all the other activities displayed statistically significant differences (all p values < 0.001). Also, Pearson's correlation coefficient shows a weak positive correlation (Pearson $r = 0.32$, $p < 0.01$), according to Evans [16], between all measurements combined for T_{PHS} and T_{OBS} datasets. Inter-class correlation coefficients also indicate poor reliability; the ICC for all pair comparisons was 0.377 (95% confidence interval [CI] = 0.349 to 0.404).

The limits of agreement (LoA) technique was calculated as described by Bland and Altman for measurements of two methods with multiple and unequal observations by participants [15], determining that the mean and standard deviation of the difference of T_{OBS} and T_{PHS} are variable throughout the range of measurement (Fig. 2), with the 95% LoA between T_{OBS} and T_{PHS} as upper limit $Y = -68.54 + 1.81X$ and lower limit $Y = -67.44 + 1.84X$ for $Y = T_{OBS} - T_{PHS}$ and $X = (T_{OBS} + T_{PHS})/2$.

Examining the results presented in Table 3, several observations can be made. For instance, for the fifth activity "Maintenance on Surface" that was carried out in July 2017 (summer), the PHS index predicts the core temperature as one of its lowest (37.06 °C), while the VitalSense pill gives a higher value (37.23 °C). On the other hand, for the second activity "Drilling UG" that was performed in winter, the PHS index predicted the highest core temperature. In addition, among the six field activities evaluated, the PHS index is in close agreement with the VitalSense pill only for "Drilling on Surface," even though the p value (0.594) suggests that the correlation is not statistically significant.

For mining activities broken down into underground and surface works, results confirm no significant difference between the PHS index and VitalSense methods related to core temperatures in underground environments (a mean bias of −0.016 °C, $p = 0.249$), while the difference in core temperature means on the surface was significant (a mean bias of 0.15 °C, $p < 0.001$).

The acquisition of core temperature readings from the capsule monitor was successful in 95.5% of experiments (4.5% data loss). Sources of interference, such as the proximity to running machinery or incorrect wearing of sensor belt, account for the majority of lost data.

4 Discussion

The primary purpose of this study was to validate the use of the PHS heat stress index for estimating the core temperature of acclimated mine workers performing typical duties. The PHS index core temperature values were validated with an established and highly accurate technology, the VitalSense telemetric ingestible capsule. Although the paired t test finds no statistically significant difference between the two methods (mean bias of 0.014 °C, 95% CI −0.010 to 0.038 °C), the Pearson correlation coefficients and the Bland and Altman method provide a relatively weak correlation between both measurements. In this study, the subject's average workload ranged from moderate to intensive. The subjects were instructed not to deviate from their regular eating and resting habits, which resulted in a high degree of variability in the physiological data in comparison with other well-controlled laboratory settings. The PHS index overpredicted core temperatures for low values as measured by VitalSense (< 37.12 °C) and, conversely, underpredicted core temperature values for high values (> 37.12 °C). In general, the PHS index tends to underestimate critical values of thermal strain, which

Table 3 Ratings by type of measurements across activities

Activities	Core temperature means (°C) at 95% confidence limit			
	PHS index	VitalSense pill	Pearson's correlation	*p*
1. Main workers	36.35 ± 0.05	37.19 ± 1.08	0.18	< 0.001
2. Drilling UG	37.78 ± 0.58	37.06 ± 1.20	0.47	< 0.001
3. Drilling on surface	37.10 ± 0.80	37.11 ± 1.15	0.49	0.594
4. Mucking	37.58 ± 0.17	37.22 ± 0.58	0.08	< 0.001
5. Maintenance on surface	37.06 ± 0.16	37.23 ± 0.81	0.49	< 0.001
6. Shoveling	37.12 ± 0.09	39.91 ± 0.43	0.63	< 0.001
Average	37.14 ± 0.50	37.15 ± 1.15	0.32	0.250

is in line with other studies [17] that reported underestimated rectal temperatures in the range of 37–38 °C. Examining all the data in Fig. 3, it appears that the PHS index values approach a horizontal asymptote in the last hours of the experiments and tend to remain flat thereafter. This suggests that the PHS method should be analyzed in multiple phases, i.e., when the task and environmental conditions change. This, however, differs from the original purpose of the PHS index created to predict an entire 8-h shift.

As expected, lower levels of core temperature were predicted for mine workers (mean $T_{PHS} = 36.35°$), and correspondingly, the heart rate levels experienced by the same workers (mean HR = 101 bpm) were also lower than for other activities. Interestingly, the values for light activities in Fig. 3 showed a higher discrepancy between predicted and observed core temperatures (T_{PHS} over-estimating core temperature in 0.82 °C), although anthropometric characteristics (age, weight, height, health test) were not significantly different from the rest of participants. One possible explanation may be the range of temperatures experienced by mine supervisors during long periods of walking through different levels of the mine was only captured in real time by the VitalSense capsule, in contrast to the PHS index which requires several input parameters reflecting the changing conditions in terms of work exposure and rest duration (VitalSense collects data more frequently

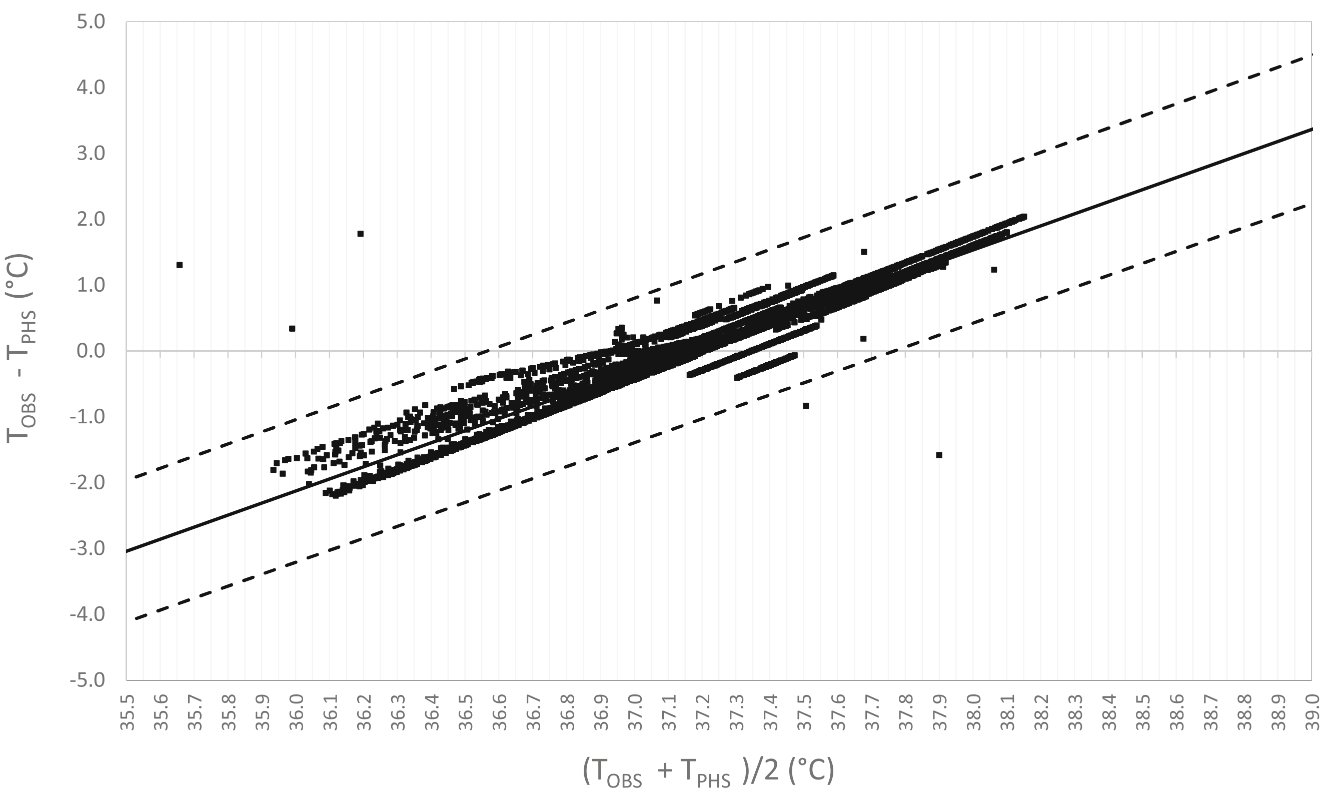

Fig. 2 Bland-Altman plots of observed core temperature (VitalSense capsule) and predicted core temperature (PHS index), with means (solid line) and limits of agreement (dashed lines)

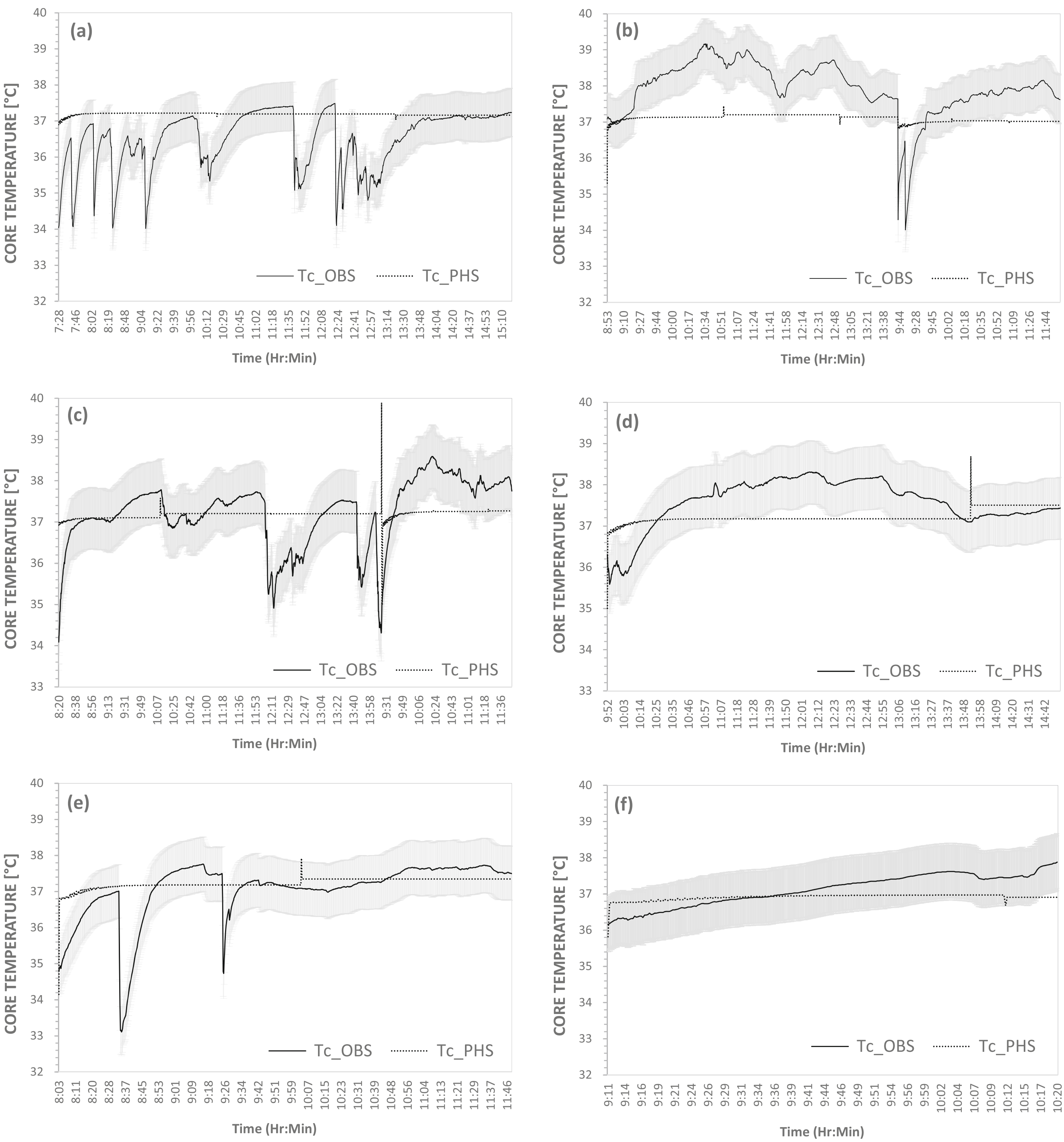

Fig. 3 Core temperatures observed (VitalSense capsule) and predicted (PHS index) for the six mining activities. **a** Main workers. **b** Drilling UG. **c** Drilling surface. **d** Mucking. **e** Maintenance on surface. **f** Shoveling

compared with the PHS parameters that were updated only every 60 min). Similar time-varying effects on work exposure have been noted by others [18].

The observed discrepancy between the two methods when core temperatures are lower than 37.12 °C is explained in part by the existence of dissimilar temperature readings at the start of experiments in both datasets. This is especially the case when the VitalSense capsule showed a steep increase in core temperatures immediately after the capsule was ingested. The temperature values continue to increase for about 5–10 min, adjusting to changes between the ambient temperature at the time of activation and when the capsule entered the stomach. Although very low core temperature values were flagged as data loss (hypothermia < 35 °C), the dynamic behavior of the

VitalSense readings T_{OBS} was lower than the T_{PHS} in the initial stage of the data acquisition. More importantly, less time was observed (< 1 min) in the case of the highest intensive activity (drilling underground) to start reading the first acceptable core temperature values, suggesting a correlation effect between delay and specific work activities.

Data collected during underground and surface activities provided the opportunity to study in more details the effect of outdoor and indoor environments on participants' core temperatures. In general, cooler environmental conditions were observed underground, especially during the summer, because the mine ventilation systems provided cooler air in the working areas. Results from core temperature measurements indicate that the PHS index and VitalSense pill methods showed better correlation for participants working underground, i.e., smaller differences between predicted and observed core temperatures, than subjects working on the surface level, albeit for small biases (− 0.016 °C and 0.15 °C mean bias in core temperatures, for underground and surface activities). These results suggest that the PHS index ability to predict core temperatures increases in environments where the heat load is less such as those found underground. It would also suggest that in this study, the statistical correlation was improved due to controlled changes in thermal conditions underground, rather than other factors such as age, gender, body mass index, or acclimatization of participants who belonged to a relatively homogeneous population. In other words, it appears that in this study, the PHS index showed very little sensitivity to different anthropometric characteristics.

5 Conclusions

This study assessed core temperatures provided by the predicted heat strain (PHS) index and a core temperature pill (VitalSense) for ten acclimatized participants at two underground mines. Comparisons were made between real-time experimental data and the PHS model. It was found that the PHS model showed no statistically significant difference with the VitalSense (mean bias + 0.014 °C, 95% CI − 0.010 to 0.038 °C) core temperature readings. However, the PHS index tends to underestimate higher core temperature values.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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