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Predicting Deep Body Temperature (T_b) from Forehead Skin Temperature: T_b or Not T_b?

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Abstract: There is a need to rapidly screen individuals for heat strain and fever using skin temperature (T_{sk}) as an index of deep body temperature (T_b). This study's aim was to assess whether T_{sk} could serve as an accurate and valid index of T_b during a simulated heatwave. Seven participants maintained a continuous schedule over 9-days, in 3-day parts; pre-/post-HW (25.4 °C), simulated-HW (35.4 °C). Contact thermistors measured T_{sk} ($T_{forehead}$, T_{finger}); radio pills measured gastrointestinal temperature (T_{gi}). Proximal-distal temperature gradients ($\Delta T_{forehead–finger}$) were also measured. Measurements were grouped into ambient conditions: 22, 25, and 35 °C. T_{gi} and $T_{forehead}$ only displayed a significant relationship in 22 °C (r: 0.591; $p < 0.001$) and 25 °C (r: 0.408; $p < 0.001$) conditions. A linear regression of all conditions identified $T_{forehead}$ and $\Delta T_{forehead–finger}$ as significant predictors of T_{gi} (r^2: 0.588; F: 125.771; $p < 0.001$), producing a root mean square error of 0.26 °C. Additional residual analysis identified $T_{forehead}$ to be responsible for a plateau in T_{gi} prediction above 37 °C. Contact $T_{forehead}$ was shown to be a statistically suitable indicator of T_{gi} in non-HW conditions; however, an error of ~1 °C makes this physiologically redundant. The measurement of multiple sites may improve T_b prediction, though it is still physiologically unsuitable, especially at higher ambient temperatures.

Keywords: deep body temperature; skin temperature; heat strain; heatwave; contact thermography

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1. Introduction

Two principal methods have been proposed to predict deep body temperature (T_b) from the measurement of heat loss from the skin surface. One method measures the conductive heat loss pathway [1] and requires sensor contact with the skin surface. The second is a non-contact method, monitoring radiative heat loss with infrared thermography. Common to both methods are their inaccuracy in estimating absolute T_b. Mekjavic and Tipton [2] concluded the prediction of T_b from one skin region, namely the forehead, is inaccurate, resulting in false positives and negatives. They suggest that other facial sites, such as the inner canthus of the eye, may prove superior to forehead skin temperature (T_{sk}). They also recommend that T_{sk} gradients between proximal and distal sites, such as the forehead (proximal site) and fingertip (distal site), may provide an improvement in the prediction of T_b. Namely, the proximal–distal skin temperature gradient (ΔT_{sk}P-D) reflects perfusion of distal sites and may indicate whether the elevated temperature is due to heat strain or fever, the former causing peripheral vasodilatation, and the latter vasoconstriction.

Recently, the need to rapidly screen individuals using T_b prediction in industry has become more important for a number of reasons. Disregard for the control of greenhouse gases has resulted in global warming, with potentially devastating consequences for future generations. Among these consequences are summer heatwaves (HWs), originally infrequent and occurring only during the peak summer months, they are now increasing

in frequency, magnitude, and duration [3]. In an industrial environment, HWs may affect the health and well-being of workers [4] and result in reduced labor productivity [5–7] as a result of occupational heat strain. It has been suggested that HWs may have a cumulative effect on workers, resulting in a residual effect several days after the ambient temperature returns to normal [5]. To try and mitigate the debilitating effects of HWs in the working environment, many countermeasures are available to reduce metabolic heat production and enhance heat loss, if only in the short term. The countermeasures include the availability of cold drinking water, cool and ventilated rooms during rest breaks, and cooling vests [7]. However, the possibility of monitoring workers for impending signs of heat strain, such as monitoring T_b, has largely been ignored; a system of reactive rather than preventative monitoring is more common.

Additionally, the recent pandemic of the Severe Acute Respiratory Syndrome Coronavirus 2 (SARs-CoV-2), resulting in a global coronavirus disease starting in 2019 (COVID-19), caused a lockdown of industrial activity during peaks of the COVID-19 waves in 2020. The manufacturing industry maintained some operations and has consequently taken the recommended precautions (i.e., masks, distancing, etc.) to safeguard the workforce. Some companies have implemented the monitoring of workers' surface temperatures using infrared thermography (IRT) to estimate T_b. Those identified by the scanners as having elevated body temperature, for whatever reason, are not allowed entry.

In view of increasing reliance on the prediction of T_b from T_{sk}, the present study evaluated whether contact measurements of T_{sk} can provide a suitable surrogate for direct measurement of T_b; for the purpose of screening workers for SARs-CoV-2 virus infection and impending heat strain during summer HW. It was hypothesized that T_{sk} would produce a significant association with T_b, but measurement of more sites to generate a ΔT_{sk}P-D will produce a stronger association, as hypothesized by Mekjavic and Tipton [2].

2. Materials and Methods

This study was part of a program of research conducted within the framework of the European Commission Heat Shield project, investigating the effect of HWs on the health, well-being, and labour productivity of workers in five key European industries (manufacturing, agriculture, construction, logistics, tourism). During four previous HWs, conditions within an industrial manufacturing plant employing 1500 workers (odelo d.o.o., Prebold, Slovenia) were monitored [5]. Due to the difficulty of continuous 24-h physiological monitoring of workers during a HW, a study was conducted simulating the industrial process in controlled laboratory conditions [8], using data from the HWs measured in central Slovenia. Consequently, measurements of T_{sk} and T_b were conducted hourly throughout a 9-day study, including both normothermic and simulated HW conditions, to assess the association with T_b using indirect measurements.

2.1. Participants

A sample size of seven participants was deemed to provide sufficient power to detect a statistical significance, assuming an α of 0.001 and β of 0.99 (G*Power Version 3.1.9.6, Bonn, Germany) using an effect size of effect size (d) of 1.8834 (f = 0.9417), based on the results of a previous study [8,9]. Seven young, healthy males (mean (SD); age: 21.1 (1.1) years; body stature: 180 (6.1) cm; body mass: 81.5 (15.6) kg; body mass index: 25.1 (4.4) kg·m^2) participated in the study, which had received prior approval (Approval no. 0120-402/2020/4: 20 October 2020) by the Committee for Medical Ethics at the Ministry of Health (Republic of Slovenia). All were non-smokers, engaged in regular physical activity recreationally, and were free from known cardiovascular, respiratory, and autonomic disease. Prior to the commencement of the study, the participants were informed of the details of the experimental protocol and were familiarized with the procedures, before signing an informed consent agreement. The participants were aware that they could terminate participation in the study at any time during the 10-day duration.

2.2. Protocol

The study was conducted at the PlanHab facility (European Space Agency ground-based research facility) at the Olympic Sports Centre Planica (Rateče, Slovenia). Participants were confined to the facility for 9-days and had access to their rooms, a common area, laboratory, and dining area. They were provided with three meals and two snacks each day (breakfast, lunch, afternoon snack, dinner, evening snack) and could drink water ad libitum.

On arrival at the facility, the participants were acquainted with the entire facility and were familiarized with all the experimental procedures. They were instructed to refrain from venturing outside the designated areas of the facility, as the temperature and humidity were regulated only in the designated areas, using heaters controlled by temperature regulators. Ambient humidity within the laboratory remained constant at ~45%. The protocol was designed to mimic the routine daily activities in a manufacturing plant, as well as some of the activities at home. Participants were awakened each day at 0700 hrs. After breakfast, they entered the laboratory at 0840 hrs, which was arranged as a series of workstations equipped with personal computers. The work shift lasted until 1800 with breaks for snacks and lunch. Upon completion of the work shift, participants had dinner and then retired to their common area or individual rooms. Lights out was at 2300 hrs. This was the daily routine for nine consecutive days.

During the 9-day confinement, the temperatures within the living quarters and workplace (i.e., laboratory) were regulated, as displayed in Table 1. The first 3 days (pre-HW) represented normal conditions. The simulated HW was initiated at midnight at the end of day 3, with temperatures increasing in all areas. At midnight on day 6, the nighttime/daytime temperature profile was re-adjusted to the same profile as in the first 3 days (post-HW). Experiments took place in ambient conditions of a 19.8 ± 1.8 Wet-Bulb Globe Temperature (from www.wunderground.com; accessed on 14 January 2022).

Table 1. Temperature during daily work and rest periods. Temperature is presented as a mean (SD) of each 3-day testing condition.

	Work (0840–1800 hrs)	**Rest/Sleep (1800–0840 hrs)**
	Temperature (°C)	**Temperature (°C)**
Pre-HW	25.4 (0.3)	22.3 (0.5)
HW	35.5 (0.3)	26.3 (0.8)
Post-HW	25.5 (0.7)	23.1 (0.7)

HW: Heatwave. Pre-HW: Testing days 1–3. HW: Testing days 4–6. Post-HW: Testing days 7–9.

2.3. Measurements

Each morning the participants ingested a calibrated telemetric radio pill (Body Cap, Caen, France), a thermistor was secured to their forehead ($T_{forehead}$), and a distal phalanx pad was attached to the middle finger (T_{finger}) (iButton, Type DS1921H, Maxim/Dallas Semiconductor Corp., Dallas, TX, USA). These devices provided continuous measurement of gastrointestinal temperature (T_{gi}) and T_{sk}, respectively, on each day. Validation of the calibrated telemetric radio pill against rectal thermistor during rest, water immersion, and steady-state exercise revealed no significant differences; furthermore, the system produces effective validity and test-retest reliability [10,11]. Additionally, the validation of iButton thermistors against calibrated thermocouples revealed no significant difference during steady-state, though response time to changes in temperature was slower than thermocouples [12].

2.4. Analyses

T_{gi} and T_{sk} were measured continuously, and an average of the last 10 min was taken in each hour for 23-h, every day. This averaging period was chosen to avoid potential artefacts by using a stable 10-min period. Each day, telemetric pills were ingested at

0700 hrs, immediately after waking up, and T_{sk} iButtons were attached to the skin in the evening at 2230 hrs. Temperature measurements were recorded during three distinct ambient conditions: 22 °C, 25 °C, and 35 °C. ΔT_{sk}P-D, an index of blood flow [13], was calculated between the forehead and fingertip ($\Delta T_{forehead–finger}$). When measured at the forearm–finger or calf–toe, a value $\geq$2 °C represents vasoconstriction and $\leq$0 °C represents vasodilation [14,15]. In the present study, in which the ΔT_{sk}P-D was assessed from T_{sk} at the forehead and fingertip, the thresholds for vasoconstriction and vasodilatation may likely be dissimilar to those reported by previous studies using the forearm–fingertip skin temperature gradient as an index of perfusion. Holm, et al. [16] have previously investigated the use of the forehead–fingertip skin temperature gradient as an index of mortality in hospital patients.

Means, standard deviations, and coefficient of variation (CoV) were calculated for T_{gi}, $T_{forehead}$, and T_{finger} (Table 2).

Table 2. Mean (±SD), and coefficient of variation (CoV) of Tsk and Tgi measurements at each ambient condition.

Ambient Condition	Measurement	Mean (SD)	CoV (%)
22 °C	T_{gi}	36.7 (0.4)	1.2
	$T_{forehead}$	34.2 (1.4)	4.1
	T_{finger}	33.2 (0.5)	1.5
25 °C	T_{gi}	37.0 (0.4)	1.0
	$T_{forehead}$	33.9 (1.3)	3.7
	T_{finger}	33.8 (0.5)	1.4
35 °C	T_{gi}	37.3 ± 0.2	0.6
	$T_{forehead}$	35.9 ± 0.7	1.9
	T_{finger}	35.5 ± 0.6	1.7

T_{gi}: gastrointestinal temperature. $T_{forehead}$: forehead temperature. $T_{fingertip}$: fingertip temperature.

The data, following calculation of normality by a Shapiro–Wilk test, were assessed using either a Pearson's Correlation Coefficient or a Spearman's Rank Correlation Coefficient. Additionally, a multiple linear regression using $T_{forehead}$, T_{finger} and $\Delta T_{forehead\text{-}finger}$ was conducted. All statistical tests were completed using an alpha value of $p < 0.05$ and conducted using IBM SPSS Statistics (Version 26, Armonk, NY, USA).

In addition to the multiple linear regression, root mean square error (RMSE) was also calculated between measured T_{gi} and predicted T_{gi} as produced from a regression equation, using the following equation [17]:

$$\mathrm{RMSE} = \left[\sum_{i=1}^{N} \frac{\left(Z_{f(i)} - Z_{O(i)} \right)^2}{N} \right]^{1/2} \quad (1)$$

where,

Z_f = forecast value
Z_o = observed value
N = sample size

3. Results

All participants completed the 9-day confinement. There were no untoward effects of the 3-day HW. The physiological responses and labor productivity during the simulated normal weather and HW periods have been presented elsewhere [8].

3.1. Relationship between T_{sk} and T_{gi}

To assess the true relationship between $T_{forehead}$ and T_{gi}, measurements from every day were compared simultaneously, encompassing all ambient conditions. The range of temperatures observed was greater for $T_{forehead}$ (32.2–36 °C) than for T_{gi} (36.1–37.7 °C), whereas the average temperature of all measurements was higher for T_{gi} (T_{gi}: 36.9 ± 0.4 °C; $T_{forehead}$: 33.9 ± 1.4 °C), a significant difference ($p < 0.001$). A significant relationship was identified between the measurements of $T_{forehead}$ and T_{gi} (r = 0.653; $p < 0.001$).

3.2. T_{sk} and T_{gi} at Different Ambient Temperatures (HW vs. Non-HW)

The above correlation analysis of the relationship between $T_{forehead}$ and T_{gi} was repeated for the individual HW (35 °C) and non-HW (22 °C and 25 °C) ambient temperatures, as shown in Figure 1. A significant relationship was observed for the 22 °C (r = 0.591; $p < 0.001$) and 25 °C (r = 0.408; $p < 0.001$) ambient conditions, whereas there was no significant relationship at 35 °C (r = 0.263; $p < 0.185$). Table 2 displays mean (SD) T_{sk} and T_{gi} values measured in each ambient condition.

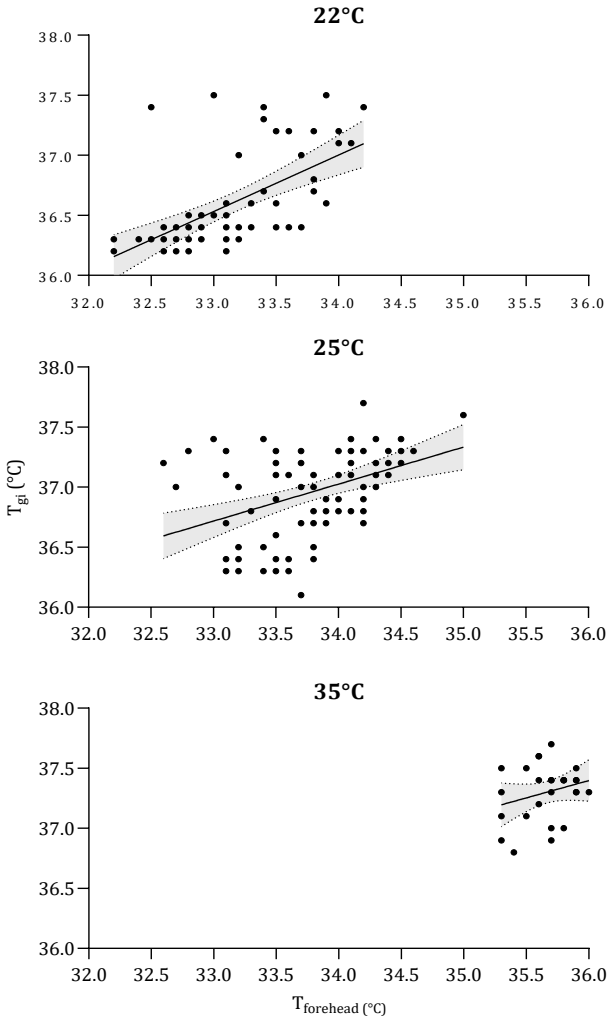

Figure 1. The relation between the temperature of the gastrointestinal tract measured with a radio pill (T_{gi}) and the temperature of the forehead using a contact thermistor ($T_{forehead}$). Measurements were obtained while participants were exposed to three ambient temperatures: 22 °C (upper panel), 25 °C (middle panel), and 35 °C (lower panel). Regression lines with associated 95% confidence bands for each temperature are also shown.

3.3. Proximal-Distal Temperature Gradient Prediction

Mekjavic and Tipton [2] suggest that an index derived from measurements made at multiple sites might provide a more accurate temperature screening, primarily using areas where the skin is exposed (i.e., face and hands). When creating a T_{sk}P-D between the forehead and fingertip ($\Delta T_{forehead–finger}$), the correlation between this variable and T_{gi} was significant ($r = 0.637$; $p < 0.001$). Additionally, a multiple linear regression for prediction of T_{gi} using $T_{forehead}$, T_{finger}, and $\Delta T_{forehead–finger}$ produced a significant linear model using $T_{forehead}$ and $\Delta T_{forehead–finger}$ only ($r^2 = 0.588$; F: 125.771; $p < 0.001$):

$$\text{Predicted } T_{gi} = 29.349 + (0.225 \times T_{forehead}) + \left(0.154 \times \Delta T_{forehead-finger}\right) \quad (2)$$

This linear regression model describes a suitable fit between the measured and predicted values of T_{gi}. RMSE analysis of this regression equation established an error of 0.26 °C between the actual and predicted T_{gi}. Figure 2 displays the correlation between the measured and predicted T_{gi}, which exhibits a plateau at higher measured T_{gi}. A second-order polynomial trendline was chosen (solid line in Figure 2) to best represent the associated fit of the correlation ($r^2 = 0.63$).

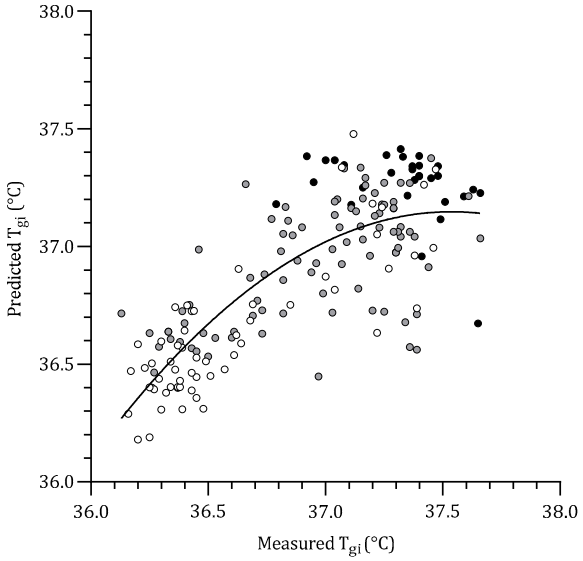

Figure 2. Relationship between measured temperature of the gastrointestinal tract (T_{gi}) and predicted T_{gi} using Equation (1). Measurements and predictions based on skin temperatures were obtained while participants were exposed to three ambient temperatures: 22 °C (white dots), 25 °C (grey dots), and 35 °C (black dots). A second-order polynomial trendline ($y = -0.4464x^2 + 33.512x - 591.75$) represents the best fit ($r^2 = 0.63$).

4. Discussion

Screening workers for elevated T_b has become of particular importance with the prevalence of two major global maladies, global warming and the COVID-19 pandemic. Both of which cause dangerous elevations in T_b and have potentially serious, if not fatal, consequences. Presently, workers in the industry are being screened primarily for elevations in T_b arising from a viral infection. However, in the future, any such valid methodology has the potential to be used for monitoring workers for heat strain, particularly during episodes of summer HWs. The assessment of the currently used approach for screening for elevated T_b was the aim of the present study. The principal finding was that neither single skin sites (i.e., hand, forehead), nor the T_{sk}P-D in combination with $T_{forehead}$, were able to provide a physiologically accurate index of T_b (i.e., gastrointestinal temperature). The methodological approach of predicting T_b from $T_{forehead}$ is therefore not valid.

4.1. Prediction of T_b Using Measurements of $T_{forehead}$ and $\Delta T_{forehead–fingertip}$

The statistical analysis in Section 3.1 revealed a significant correlation between the $T_{forehead}$ and T_{gi}, but the association with absolute T_b on this basis may vary by as much as 2 °C. Therefore, based on statistical analysis, $T_{forehead}$ appears to be a suitable index of T_b, however, this correlation is of limited physiological relevance as it may generate false positive/negative values. Of particular concern is the fact that the correlation becomes statistically non-significant during simulated HW conditions, conditions where an accurate prediction in an industrial setting would be required. The present study used contact thermometry to measure skin temperature, the method of choice in industry being $T_{forehead}$, obtained with infrared thermography (IRT). Using this technology, the measurement of surface T_{sk} may be adequate; however, as demonstrated by the results of the present study, the subsequent derivation of T_{gi} from the measurement of T_{sk} at one site, the preferred site being the forehead, is not physiologically valid.

The recent proposal of Mekjavic and Tipton [2], which suggests additional sites to that of the forehead alone might provide a better outcome in the prediction of T_{gi}, was also evaluated by conducting a linear regression to calculate T_{gi} with the proximal-distal skin temperature gradient ($\Delta T_{forehead–finger}$), and skin temperatures. This regression proved statistically significant, resulting in smaller errors in the predictions of T_b. Furthermore, a polynomial curve fit the relationship between measured and predicted T_{gi} identified a plateau at higher levels of predicted T_{gi} (Figure 2). This suggests that the association appears to be accurate at lower temperatures; however, it begins to underestimate T_b as T_{gi} increases. Residual analysis of independent variables in the regression equation identifies $T_{forehead}$ as a contributor to this plateau due to increased variability and thus error at higher ambient temperatures. Additionally, whilst the average T_{gi} in the HW conditions was 37.3 °C, $T_{forehead}$ only reached 35.5 °C, which means it was incapable of linearly matching rises in T_{gi} during higher ambient conditions. The combination of these two sources of error likely caused the plateau in the relationship between measured and predicted T_{gi}, making it unsuitable to use $T_{forehead}$ as a prediction tool. It should also be emphasized that the industrial tasks simulated in the present study were that of checking the functioning of circuit boards; thus, a seated task. Any method for predicting heat strain in an industrial environment will need to be validated with tasks requiring elevated endogenous heat production, further increasing T_{gi} above $T_{forehead}$.

The ΔT_{sk}P-D between the forearm and fingertip has been demonstrated as an appropriate index of the perfusion of the fingers [13–15]. During exposure to a hot environment, as in the present study, a high distal (fingertip) T_{sk} would reflect vasodilatation, thus activation of the thermoregulatory heat loss mechanism. We hypothesized that if $T_{forehead}$ was a valid surrogate of T_b, when combined with an index of peripheral perfusion, such as ΔT_{sk}P-D, this could provide an index of heat strain. However, unlike T_{gi}, $T_{forehead}$ varied with ambient temperature, such that the observed variations in T_{gi} of ±1.5 °C, were accompanied by variations in $T_{forehead}$ of ±3.8 °C, casting doubt on the validity of $T_{forehead}$ as a valid surrogate measurement of T_b. Nevertheless, the $\Delta T_{forehead–finger}$ alone displayed a significant relationship with T_{gi}. Furthermore, a multiple regression combining ΔT_{sk}P-D with $T_{forehead}$ generated a regression equation, with an improved association with T_{gi}. The physiological validity of the derived regression model should be evaluated with a separate group of female and male subjects, of different ages, under conditions of elevated ambient temperatures, as would be experienced in the industry and during HWs.

4.2. Effect of Ambient Temperature on the Relation between Tsk and Tb

Mass screening of workers for elevated T_{gi} in an industrial setting may help to protect against heat stress or avoid the spread of viral disease. The ambient temperatures at which these measurements are taken may vary depending on the location of the measurement (indoor vs. outdoor), time of day (day shift vs. night shift), weather, and season. The large variation in T_{sk}, with little change in T_{gi}, is of concern with regard to the association of T_b with T_{sk}. In the present study, measurements taken in normal temperature (22

and 25 °C) ambient conditions provide a statistically significant relationship with T_{gi}, whereas measurements conducted during simulated HW (35 °C) conditions provided no statistically significant relationship. In the present study, increases in T_b were the result of high ambient temperatures. In contrast, a febrile temperature is the result of elevated endogenous heat production combined with decreased heat loss (vasoconstriction). Any method proclaiming to be able to predict T_b of active and/or febrile individuals regardless of the ambient temperature should be appropriately validated. Manufacturers of currently available scanners based on IRT technology do not provide the algorithms used to predict T_b based on $T_{forehead}$, nor do they provide any information regarding the validation of such algorithms. Due to the proven global importance of screening individuals for elevated T_b, it should only be a matter of time before this is regulated.

4.3. Accuracy of IRT to Contact Thermography

The aim of the present study was to assess the association of T_{sk} with T_b using contact thermography and not to validate IRT as a method for predicting T_b. However, IRT is the most commonly used method of measuring skin temperature in applied settings such as workplaces and hospitals, and its validity and accuracy should be considered in future T_{sk} predictions. The validity of IRT as a measurement of T_{sk} has been heavily debated, particularly with reference to its overestimation and comparison to a 'gold standard' of T_{sk} measurement. Maley et al. [18] propose that during hand rewarming, following cold water immersion, IRT overestimates T_{sk} measured by contact thermometry by 1.80 °C. However, this was countered by Havenith and Lloyd [19], who suggest that methodological issues such as camera accuracy and calibration commonly occur, and that contact thermometry cannot be considered a 'gold standard'.

Any system for mass screening of workers based on the prediction of body temperature from forehead T_{sk} derived with IRT would need to utilize an infrared camera of high accuracy as differences occur commonly. Ng et al. [20] reported significant differences among the three infrared scanners used to measure $T_{forehead}$. The differences among these scanners were as high as ±2 °C. Such discrepancies among infrared cameras are also reflected in their ability to accurately measure T_{sk} when compared to contact thermography. Although a strong correlation between contact thermometry and non-contact IRT thermography has been reported [18,21], the authors reported that T_{sk} measured with IRT was 2.3 °C lower than that measured with a thermistor [21]. The above comparisons were made during a sleep study [21] and at rest [18]. During dynamic movement and exercise, as would be anticipated in an industrial setting, the agreement between contact and IRT measurements of T_{sk} is poor [22,23]. Irrespective of the validity achieved by IRT, the type of device specifications stipulated by the 'Journal Temperature Toolbox' [24], may be too stringent and impractical for many workplaces.

4.4. Prediction of Deep Body Temperature

Infrared scanners providing a predicted value of T_b based on a measurement of T_{sk} at a single site do so using proprietary algorithms, which are not available for scrutiny. This is unsatisfactory and unacceptable considering the impact elevated body temperature, whether due to viral infection or summer HW, has had not only on the industry but all aspects of our lives globally. The present study illustrates the errors in the association of T_b with T_{sk} that occur under controlled laboratory conditions, in which the measurements were conducted by trained individuals. It also emphasizes the need to discern between statistical and physiological significance. As an example, the correlation between $T_{forehead}$ and T_{gi} (Figure 1) may be statistically significant, indicating that an increase in one variable is observed as an increase in the other; this relation does not, however, provide an accurate assessment of T_b. Alternatively, using a regression equation of multiple measurement sites provided a significant prediction of T_{gi}, the physiological significance of which is made clear using RMSE. This analysis of the regression equation proposes that the error between actual and predicted T_{gi} is as low as 0.3 °C, enabling more accurate extrapolation of T_{gi}

from T_{sk} to occur. For measurements of T_b, the difference in values at one site could be the difference between a healthy temperature and heat strain or fever. It is most likely that future strategies of predicting T_b from exposed T_{sk} may need to incorporate several sites, and not just one, as suggested by Mekjavic and Tipton [2], as demonstrated in the present study for assessment of heat strain in workers during HW.

4.5. Limitations

As detailed above, differences lie in the mechanisms relating to changes in T_b, leading to differential heating and perfusion responses during either ambient heating or fever. The present study produced an equation for the prediction of T_b using several sites when participants were experiencing ambient heating at rest. Additional testing should consider the T_{sk} and T_b responses to the unique aspects of fever and exercise as methods of heating the human body. In addition, the participants in the present study, young, healthy males, did not appear to experience undue heat strain based on their T_{gi}. Though these participants were exposed to the conditions of a previously recorded HW [5], suggesting other non-thermal factors such as morphology, gender, acclimation, etc., should be considered in the prediction algorithm produced. Due to the relatively small and homogenous sample, the results of the present study should only be used as an example of the type of error associated with T_{sk} prediction. Finally, while the study design reflected certain applied conditions such as working schedules and tasks, the external validity should be cautioned and additional research with larger sample sizes in applied conditions advised.

5. Conclusions

Measurement of contact T_{sk} at the forehead appears to be a suitable site from which T_{gi} can be extrapolated at lower ambient temperatures. However, while statistically significant, this relationship cannot be considered physiologically appropriate due to an error of ~1 °C. The measurement of multiple sites, including a proximal-distal temperature gradient, may provide a more suitable prediction of T_b with a lower error (0.3 °C), however again this is not appropriate due to a plateauing of the prediction efficacy at higher temperatures, likely due to lower and more variable T_{sk} measurements. The methodological approach of predicting T_b from T_{sk} is therefore not physiologically valid in young males, particularly in higher ambient temperatures. In the future, indirect T_{sk} measurements should consider the effect of ambient temperature, the use of multiple sites, inclusion of a perfusion index, and the source of raised $T_{b,}$ in their algorithms.

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Data Availability Statement: Data available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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