

Title page

Title: Practical on-site measurement of heat strain with the use of a perceptual strain index

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Practical on-site measurement of heat strain with the use of a perceptual strain index

Abstract

Objectives There have been increased interests in research on quantifying heat strain of construction workers and formulating corresponding guidelines for working in hot weather. The aim of this study was to validate a subjective measurement tool, the perceptual strain index (PeSI), for measuring heat strain in real-work settings.

Methods A total of sixteen construction workers were invited to participate in the field surveys. Empiric-based human monitoring was carried out with simultaneous micrometeorological (wet bulb globe temperature, WBGT), physiological (heart rate, HR), and perceptual (perceived exertion, RPE; thermal sensation, TS) measurements throughout the test. The relative heart rate (RHR), the physiological strain index (PSI_{HR}), and the PeSI were then calculated accordingly.

Results The PeSI exhibited moderate correlations to WBGT and RHR ($r=0.42$ and 0.40 , respectively), which indicated the PeSI was sensitive to the variants of WBGT and RHR. The results of regression analysis indicated that the PeSI changed in the same general manner as the PSI_{HR} , with a relatively large determination coefficient ($R^2=0.67$). The established perceptual strain zone illustrated that the PeSI ranging from 7 and 8 would be the exposure limit of construction workers in hot weather.

Conclusions The PeSI is a simple, robust, reliable, and user-friendly tool for heat strain assessment in occupational settings. The perceptual strain zone will provide practical guidelines for on-site heat strain monitoring for construction workers.

Keywords

perceptual strain; physiological strain; heat stress; stressors; construction workers

Abbreviations

HR	heart rate (beats/min)
PeSI	perceptual strain index
PSI	physiological strain index
RHR	relative heart rate
RPE	rating of perceived exertion
TS	thermal sensation
WBGT	wet bulb globe temperature (°C)

Introduction

Construction workers are susceptible to heat stress in summer because they have to perform strenuous physical work with prolonged exposure to hostile weather (Rowlinson and Jia 2014; Chan et al. 2012a), which poses high risks of heat-related illnesses and even potential lethality (Miller et al. 2011; Inaba and Mirbod 2007). The comprehensive understanding of the level of heat stress/strain of construction workers has considerable value in taking the corresponding measures to safeguard workers health and safety. A large body of scientific research on assessing heat stress/strain of construction workers has been formulated in the past decades. For example, a large number of environmental indicators have been developed and been adopted to formulate the “early warning” for working in hot weather (Miller and Bates 2007; Yi and Chan 2013; Zhao et al. 2009). Aside from the environmental indicators, the physical indicators, which indicate the physical stress of workers performing physical activities (Kjellstrom et al. 2011; Miller and Bates 2007), have been used to evaluate the physical workload of construction workers (Chan et al. 2012a; Wong et al. 2014; Maiti et al. 2008; Rowlinson and Jia 2014). However, the reliability and validity of these environmental/physical indicators are still debatable regarding different micro-environmental conditions and validation methods (Miller and Bates 2007; Yi and Chan 2013; Hartmann and Fleischer 2005). A marked limitation of these indicators is that the interpretation of their output has to be incorporated with human physique, clothing, and other boundary conditions (Budd 2008; Rowlinson et al., 2014). The use of a single environmental or physical indicator may hence underestimate the adverse effects of all the stressors, which further introduces large errors into the prediction of heat stress (Epstein and Moran 2006; Budd 2008). More importantly, the physiological and psychological consequences remain ambiguous relative to the use of these heat stress indicators.

Heat strain index is thus recommended as a holistic tool to assess the heat exposure limits elicited by a range of heat stressors. The Predicted Heat Strain Model and the Physiological Strain Index have been adopted to determine the maximum allowable exposure time and the optimal recovery time of construction workers in hot weather (Rowlinson and Jia 2014; Chan et al. 2012b). However, risks of error-in-use of tympanic/ear temperature thermometry in these studies have to be recognized when body core temperature involving invasive measurement and complicated calibration procedures cannot be obtained. Thus, direct measurement of physiological strain at the workplace is inconvenient and impractical owing to its intrusive measurement and cost issues (Rowlinson et al. 2014). Subjective measurement may be an alternative and feasible approach to assess workers' perceptual strain in workplaces.

A Perceptual Strain Index (PeSI) developed by Tikuisis et al. (2002) may be a holistic strain index that considers both perceived exertion and thermal sensation. This index has been verified to differentiate the levels of uncompensable heat strain under different heat exposures in the controlled climatic chamber and a field study (Tikuisis et al. 2002; Hostler et al. 2009; Petruzzello et al. 2009; Wright et al. 2013; Snook et al. 2014). Having extended its application under compensable heat strain in a controlled climatic environment (Yang and Chan, 2015), there is a pressing need of verifying the reliability of the PeSI in field studies that involve varying environmental and work-related parameters. In view of this, the goal of this study was to examine the reliability and validity of the PeSI for heat strain assessment in real-work settings. Correspondingly, the objectives of this study were formulated as: 1) to identify

the sensitivity of the PeSI to heat stressors (i.e., environmental and work-related conditions); and 2) to reveal how the PeSI reflects physiological strain.

Methods

Participants

A total of 16 local male construction workers participated in the field study. Prior to the field studies, a short health survey was administered to investigate whether the participants had history of diagnosed health problems (including diabetes, hyperlipidemia, hypertension, cardiovascular disease, and neurological problem) and major signs or symptoms of heat-related illness (such as pallor, fainting, headache, confusion, vertigo, drenching sweats and decrease in sweating, a rapid pulse, cramp, nausea, and shortness of breath). Exclusive criteria included construction workers with history of diagnosed health problems, heat-related illness, and regular medication intake. The summer in Hong Kong lasts from June to August. Given that the field study was conducted between July and August 2014, all participants had acclimated to work in a hot weather for approximately one month. Each participant was asked to provide basic personal information, including name, age, and trade. Body weight (including the dressed uniform) was measured by using a digital scale with 0.1 kg precision (Tanita, Japan). Height was measured to the nearest centimeter with a wall-mounted ruler. The demographic information of the participants was as follows (mean and standard deviation.): age 21.7 (1.9) years old, height 173.7 (5.1) cm, and body weight 65.0 (11.8) kg. Efforts had been made to recruit workers from a broad spectrum of trades and ultimately, participants engaged from four trades participated in this study. The number of participants engaged in formwork, rebar work, leveling, and plumbing/painting works was 6, 6, 2, and 2, respectively. Plumbing/painting workers worked at both outdoors and semi-outdoor areas under shade, whereas the others worked outdoors under direct sunlight. Four construction sites located in the open areas were available for this study. All participants performed their usual work at the ground floor or a platform. All participants were requested to write the consent

form after they were clearly briefed with the purposes and the procedures of the field study. On a voluntary basis, the participants could withdraw at any time. The study was fully approved by the Human Subjects Ethics Sub-committee of the authors' host organization.

Field studies

Each field study lasted from 8:00 am to 4:30 pm. Each day included two sessions, one each in the morning and afternoon. To avoid the confounding effects of different clothes on perceptual sensation (i.e., the uniform worn in the morning might become wet because of sweating), two types of summer work uniforms (each of which consisted of a short-sleeved shirt and a pair of long pants) were randomly assigned to the participants in the morning and afternoon, respectively. Work uniforms in proper sizes were provided to the participants according to their body sizes. The other personal protective equipment, such as safety helmet and safety shoes, was equipped as usual. Corresponding to a typical dress code of wearing a short-sleeved t-shirt, a pair of long pants, socks and thick soled safety shoes, the clothing insulation factor of each type of dress code was approximately 0.75 clo (BS 7963 2000).

Prior to the test in the morning, the participant was requested to wear the assigned work uniform and was equipped with a heart rate belt with its monitor (Polar Wearlink®, the USA). At the beginning of the test, the participant was asked to rest for 30 min at an air-conditioned room with the temperature maintained at approximately 22 °C to stabilize their heart rate. During this period, the participant was briefed about the objectives and procedures of the study and was requested to sign the consent form.

The participant performed his usual daily work at the sites during a period of 135 min (e.g., from 9:00

am to 11:15 am in the morning, and from 13:30 pm to 15:45 pm in the afternoon). He was allowed to drink water and take a break as they desired during this period. Each participant might have different working durations dependent on their work routine and their resting time. Upon completion of the morning session, the participant was recommended to have lunch in the air-conditioned room to ensure that he could be cooled and dried without heavy sweating before participating in the afternoon test. Prior to the second session, the participant was asked to change to another type of work uniform. The procedures of the second session in the afternoon were similar to those in the morning.

Measurements and indices calculations

To investigate the heat strain of construction workers, empiric-based human monitoring was conducted with simultaneous micrometeorological measurements throughout the test. Heart rate was recorded throughout the entire field study at a sampling of one minute. A heat stress monitor (QUESTemp[°]36, Australia) was located near to the participant to measure the microclimatological parameters, such as dry bulb temperature, wet bulb temperature, globe temperature, relative humidity, wind speed, and wet bulb globe temperature (WBGT) at 1 minute interval. Heart rate and environmental parameters were reduced into five-minute averages as a data set.

When body core temperature measurement was not possible because of its invasive surgical procedures, the PSI_{HR} index was calculated for physiological strain assessment (Moran et al. 2001). This index has been validated for different individuals of different levels of physical fitness (Moran et al. 2001). The PSI_{HR} ranges from 0 to 5, representing no/little strain to very high strain (Moran et al. 2001). The algorithm of the PSI_{HR} is expressed by Eq. (1).

$$PSI_{HR} = 5 \times \frac{HR_i - HR_0}{HR_{max} - HR_0} \quad (1)$$

where HR_0 are the minimum heart rate prior to work; HR_i is the simultaneous heart rate during working period; HR_{max} is the maximum heart rate of the participant achieved and it is substituted into the equation if it exceeds 180 beats/min.

Along with the measurement of heart rate, participants were asked to report on the ratings of perceived exertion and thermal sensation every 5 minute to determine the level of perceptual strain. Perceived exertion was assessed by the using an 11-point single-item scale with anchors ranging from 0 “resting” to 10 “maximal” (Borg 1998). Thermal sensation was measured by a seven-point Likert scale ranging from 1 “very cool” to 7 “very hot” (Gagge et al. 1967). The modified mathematical expression of the PeSI (Tikuisis et al. 2002) is given by Eq. (2).

$$PeSI = 5 \times \frac{RPE_i}{10} + 5 \times \frac{TS_i - 1}{6} \quad (2)$$

where RPE_i and TS_i are the simultaneous perceived exertion and thermal sensation respectively during working period.

The relative heart rate (RHR) was used to present the physical workload that construction workers were subjected to (Eq. (3)) (Shimaoka et al. 1998; Maiti 2008). Categories of physical workload were classified as follows: light ($RHR < 30\%$), moderate ($30\% \leq RHR < 40\%$), and heavy ($RHR \geq 40\%$) (Adeodu et al. 2014).

$$RHR = \frac{HR_w - HR_r}{HR_{max} - HR_r} \times 100 \quad (1)$$

where RHR refers to the heart rate increases compared to rest expressed as a percentage of the rest to

maximal heart rate range, HR_w was HR measured during work, HR_r was the minimal HR during rest, and $HR_{max}=220-Age$ (Rodahl 1989).

Statistical analysis

In total, 568 sets of physical and microclimatological data with the corresponding physiological and perceptual responses were captured from 16 construction workers. To investigate the sensitivity of perceptual strain toward heat stressors (i.e., environmental stress and physical workload), bivariate correlations (Spearman's coefficient) were computed based on the whole data sets (N=568). Even under the same environmental or physical conditions, perceptual and physiological strain levels may markedly differ among individuals (Kántor et al. 2012). Thus, the mean values of perceptual strain were calculated and plotted against the mean values of the physiological strain index. Regression analysis was then conducted to illustrate the relationship between the PeSI and the PSI_{HR} . Statistical significance was set at $p<0.05$. Statistical analyses were performed using SPSS software.

Results

The field studies were carried out within a WBGT range of 26 to 37 °C, with an average temperature (SD) of 31.9 (2.4) °C (Fig. 1a). According to Fig. 1b, RHR incorporated a range of workload from light (1%) to heavy (88%), with an average RHR of 20.2 (11.8) %. In the study periods, the most frequent RPE vote was 3 (31.9%), reflecting the fact that workers perceived the physical workload as moderate (Fig. 1c). Asking about thermal sensation, the responses mainly ranged from 4 (32.8%) and 5 (26.4%), indicating that the surrounding environment was more or less hot as perceived by workers (Fig. 1d). As regards to the PSI_{HR} , little and low strain ranging from 0 to 2 occurred most frequently, and very high strain (reaching four or above) occurred rarely (Fig. 1e). The PeSI values between 4 and 6 dominated, indicating that perceived strain was moderate during field surveys. Very high perceptual strain (reaching eight or higher) was reported in 11.5% of the cases (Fig. 1f).

To give a clearer description of the perceptual/physiological strain and their relations to the heat stressors, the percentage distribution of the strain values by strain category was also investigated for environmental and work-related parameters (Fig. 2). As expected, the relationships between the strain index and the stressor were positively correlated; the occurrence of a higher or stronger stressor was associated with more frequent responses to the higher strain level. For example, the percentage of the perceptual strain index in “high level” region (ranged from 8 to 10) increased remarkable, with percentages of 5%, 8%, and 18% which corresponded to light, moderate, and heavy workload, respectively (Fig. 2h). Meanwhile, regarding the percentage distributions of the PSI_{HR} , the percentages for “little strain level” (ranged from 0 to 1) decreased from 71% to 24% along with the increases in WBGT (Fig. 2e). The strength of these correlations was then assessed by Spearman correlation analysis.

All the presented correlations were significantly positive ($p < 0.001$). The correlation coefficients between the PSI_{HR} and the stressors were small ($r = 0.25$) for WBGT and large ($r = 0.99$) for RHR. RPE exhibited a stronger correlation to RHR ($r = 0.44$) than WBGT ($r = 0.36$), whereas TS had a stronger correlation to WBGT ($r = 0.43$) than RHR ($r = 0.34$). The sensitivity of the PeSI to variations in WBGT and RHR remained almost the same ($r = 0.42$ and 0.40 , respectively).

We also found that the PeSI values had a moderate correlation with the corresponding PSI_{HR} ($r = 0.42$, $p < 0.001$). We then investigated how the PeSI varied as a function of the PSI_{HR} . The PeSI values were averaged for each unit of PSI_{HR} . A power function describing the relationship between the PeSI and the PSI_{HR} was explored, with a relatively large determination coefficient ($R^2 = 0.67$). With this relationship, each level of perceptual strain within a certain range of the PeSI values was derived according to the corresponding physiological strain level proposed by Moran et al. (2001) (Table 1). On this basis, the exposure limit of the PeSI ranging from 7 and 8 with the corresponding RPE-TS combinations toward the heavy level of physiological strain ($3 < PSI_{HR} \leq 4$) was obtained. Using the similar concept proposed by Gallagher et al. (2012), RPE on the horizontal axis and TS on the vertical axis replacing the PeSI values were linked to each physiological strain level (Fig. 3).

Discussion

Although the validity of the PeSI was reported on the basis of experimental data for subjects under controlled conditions in a climatic chamber, this index has rarely been investigated in an actual outdoor environment. Given that outdoor working conditions exhibit greater variability and complexity and are more prone to human thermal and physical acceptability than enclosed spaces (Pearlmutter et al. 2014), it is critical to examine the validity of the PeSI in outdoor contexts. The key characteristics of a comprehensive and practical perceptual strain index that could be utilized by occupational settings are identified according to de Freitas et al. (2008), Moran et al. (2003), and NIOSH (1986): 1) being theoretically and empirically sound, 2) integrating the effects of all important heat stressors under a wide range of conditions, 3) reflecting exposure limits with sound physiological basis, and 4) being simple and easy to use, calculate, interpret, and understand. In this regard, the relationships between the PeSI and heat stressors/physiological strain were explored to verify the reliability of this strain index in real-life settings.

In the present study, the correlations of RPE-WBGT and TS-RHR were relatively weak ($r=0.36$ and 0.34 , respectively), even though the correlations of RPE-RHR ($r=0.99$) and TS-WBGT ($r=0.43$) were relatively strong. These results imply that RPE and TS may have a relatively weak correlation with the micrometeorological condition and physical workload, respectively. The PeSI fairly explained the variations of WBGT ($r=0.42$) and RHR ($r=0.40$). The PeSI incorporates physical and thermal sensations into a single index, which serves a comprehensive function in evaluating perceptual strain in both theoretical and empirical bases. The sensitivity of the PeSI to variants of thermal environment and physical workload are demonstrated in this study, that is, a higher level of perceptual strain occurs with

an increase in temperature or workload. Simplicity of the rating system and messaging is also desired for the implementation of a heat strain index. The PeSI based on RPE and TS is simple to calculate and interpret without impeding work performance, such that it has great potential application as a standard. Its form of output relative to each strain level can be readily interpreted and understood by users in occupational settings.

The ideal situation on heat strain assessment is to collect accurate physiological data from working people. However, this approach may be not practical because of its intrusive and complicated clinical procedures and excessive costs, despite the physiological devices will become more feasible and cheaper in future. In this regard, perceptual strain that can well reflect physiological strain will be of enormous benefit to replace physiological measurement in occupational settings. Occupational exposure standards should not only involve physiological consequences but should also consider subjective perceptions to heat stress (Cheung 2007) because perceptual strain may serve as a protective mechanism against the damaging effect of high core and brain temperatures (Cheung 2007; Nielsen and Nybo 2003). The relationship between the PeSI and the PSI_{HR} provides sound evidence that perceptual strain changes in the same general manner as physiological strain index. The PeSI that well reflects physiological strain may potentially become an early warning indicator of the increased physiological strain. On this basis, the perceptual exposure limit and its corresponding RPE-TS combinations toward a heavy physiological strain level are identified (Table 1). The newly established perceptual strain zone that gives clear descriptors of the perceptual strain level can provide a useful reference to form on-site heat strain monitoring guidelines for construction workers. Therefore, the perceptual strain zone would be of great benefit for use as a guideline by nonscientific population.

However, human physique (i.e., age, fitness), psychological factors (i.e., mood, motivation, and preference) and behaviors (i.e., smoking, and alcohol consumption) that can influence human thermoregulation and perception (Rowlinson and Jia 2014; Nikolopoulou and Steemers 2003; Knes and Thorsson 2006) are not described exactly in this study. Further research work should be performed with considering these facets and involving wider age groups and enlarged sample size.

Conclusion

The PeSI is sensitive to the variants of WBGT and RHR and changes in the same general manner as the PSI_{HR} . Moreover, this tool is a simple measurement of heat strain without operational complexities or associated error risks relative to the use of inaccurate equipment. Therefore, it can be considered to be a reliable and valid tool for heat strain assessment in real-work settings in terms of its theoretical and empirical soundness and user-friendliness. The established perceptual strain zone based on the relationship between the PeSI and the PSI_{HR} that offers an easy-to-understand measurement to approximate physiological strain can provide practical guidelines for real-time heat strain monitoring at construction sites.

Conflict of interest

The authors declare that they have no conflict of interest.

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Fig. 3 Perceptual strain zone towards the physiological strain

Fig 1

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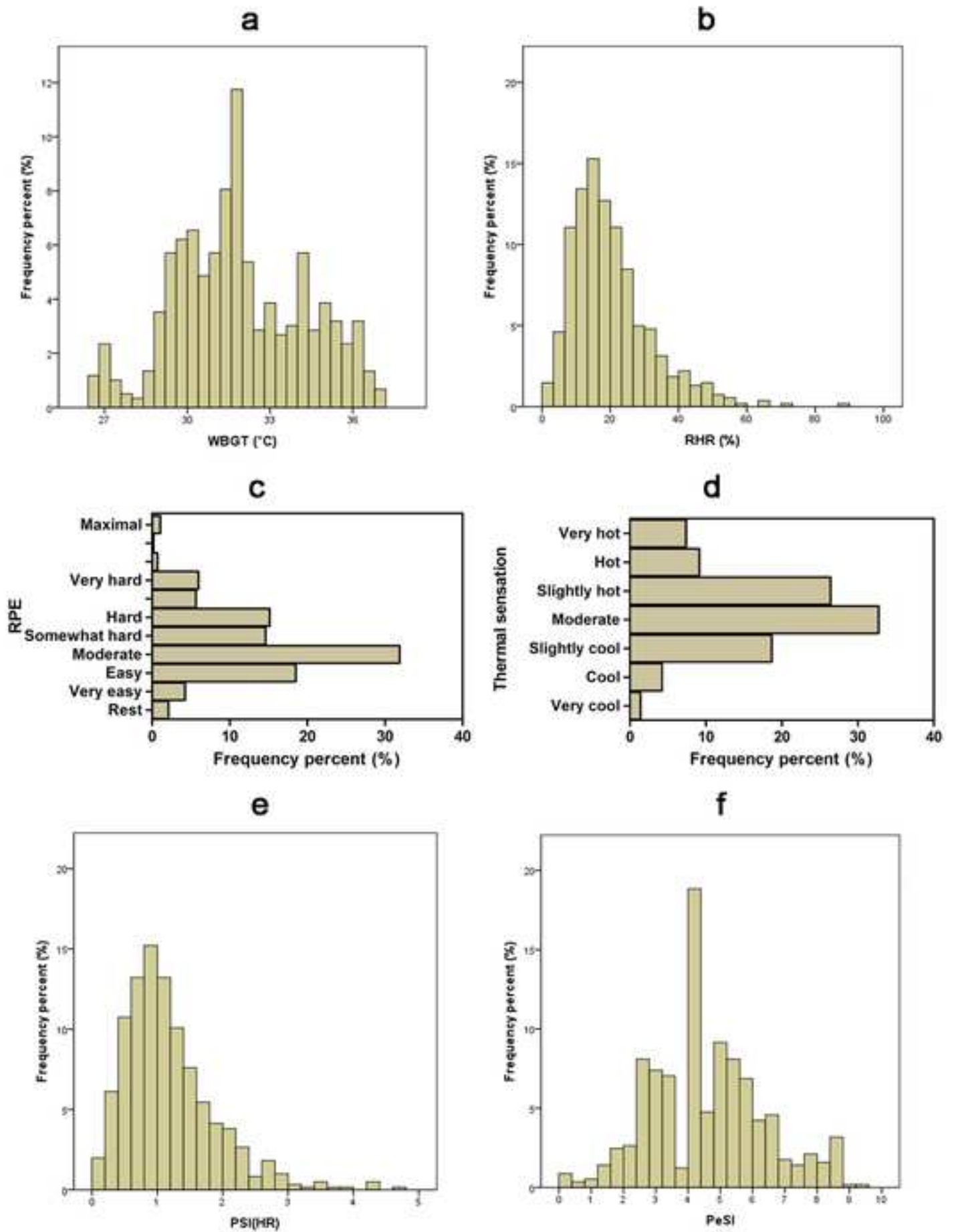


Fig 2

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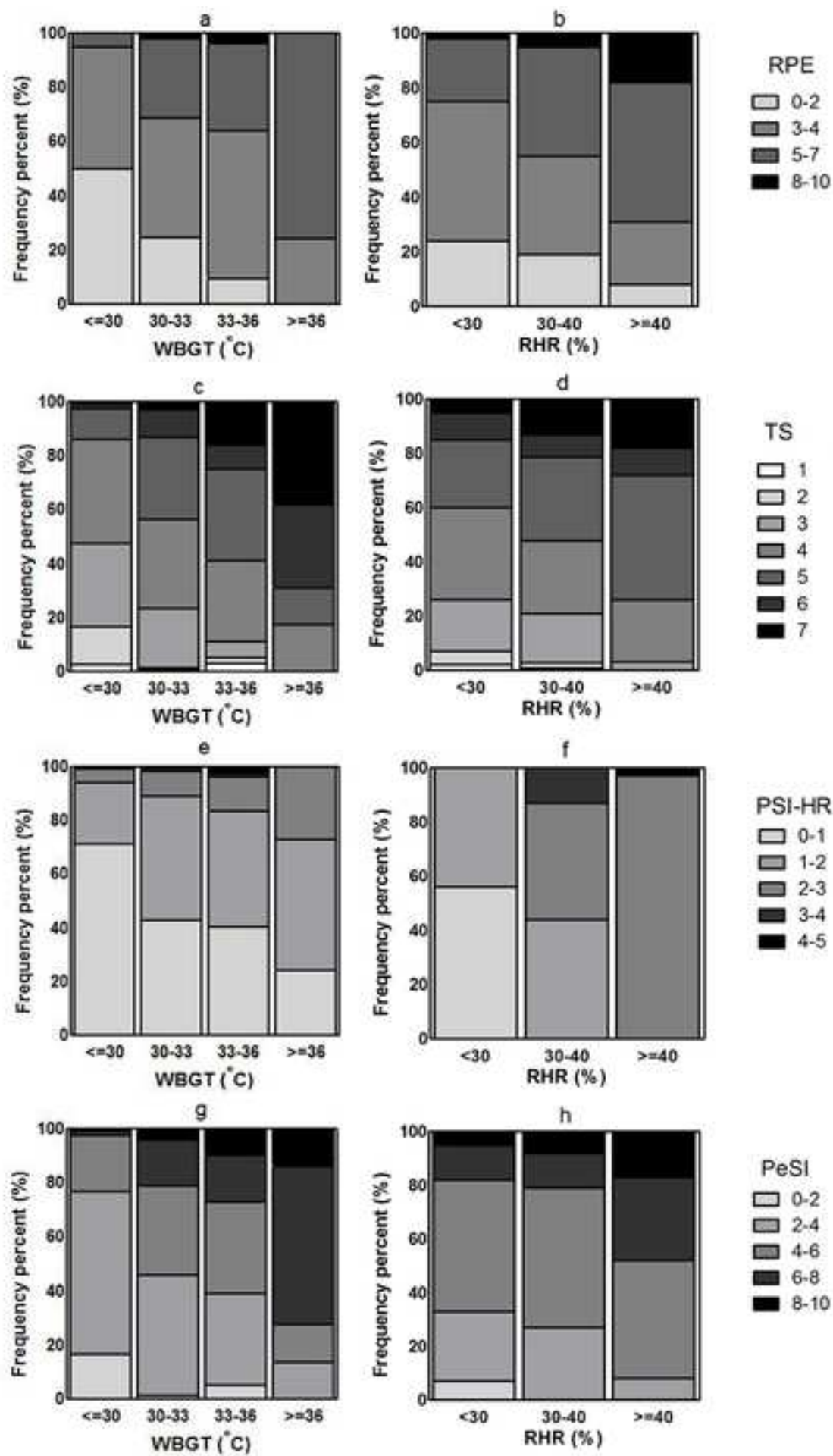


Table 1 Strain level of the PeSI and the corresponding exposure limit

PeSI	PSI _{HR}	Strain level	RPE-TS combinations for the exposure limit	
			RPE	TS
0-4	0-1	No/little strain		
4-6	1-2	Slight		
6-7	2-3	Moderate		
7-8 (exposure limit)	3-4	Heavy	4	7
			5	7
			6	6
			7	6
			8	5
			9	4
			10	4
8-10	4-5	Very heavy		