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Perceptual strain index for heat strain assessment in an experimental study: An application to construction workers

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ABSTRACT

Although the physiological strain index (PhSI) is universal and comprehensive, its restrictions are recognized in terms of invasive on-site measurements and the requirement of accurate instruments. The perceptual strain index (PeSI) has been proposed as a user-friendly and practical indicator for heat strain. However, the application of this index in assessing the heat strain of construction workers has yet to be examined and documented. This study aims to ascertain the reliability and applicability of PeSI in an experimental setting that simulates a stressful working environment (i.e., environment, work uniform, and work pace) experienced by construction workers. Ten males and two females performed intermittent exercise on a treadmill while wearing a summer work uniform at 34.5 °C and 75% relative humidity in a climatic chamber. Physiological parameters (core temperature, heart rate) and perceptual variables (thermal sensation, perceived exertion) were collated synchronously at 3 min intervals. The results of two-way repeated measures analysis of variance (clothing × time) revealed that the PeSI was useful in differentiating the heat strain levels between different work uniforms. Not only did the PeSI change in the same general manner with the PhSI, but it was also powerful in reflecting different levels of physiological strain. Thus, the PeSI offers considerable promise for heat strain assessment under simulated working conditions.

1. Introduction

Over the years, numerous indices have been established to model and predict human heat strain. Thus, it is important to determine the most appropriate index for a specific experimental or real life setting. Prior to the amplification of strategies to identify this index, it is necessary to discriminate between heat strain indices and heat stress indices. While heat stress is associated with the total heat load on the body imposed by cumulative environmental, physical, and individual factors (Bhanarkar et al., 2005; Moran et al., 2003), heat strain refers to the physiological and/or psychological consequences of heat stress (Sawka et al., 2003). In this regard, a heat stress index (i.e., wet bulb globe temperature, thermal work limit) assesses the aforementioned risk factors, while a heat strain index (i.e., heat balance equation, physiological strain index) objectively measures the physiological and/or psychological responses.

Many heat strain indices have been proposed to determine the effects of risk factors under various heat exposures. A heat balance equation that integrates all of the environmental and behavioral variables is considered the most comprehensive indicator (Epstein and Moran, 2006). However, its limitations have been widely recognized, including the assumption of some parameters within the equation (Epstein and Moran, 2006) and the complexity of mathematical calculations (Gonzalez, 2004). Robinson et al. (1945) developed a formula to calculate physical heat strain by summing four physiological components: heart rate, core temperature, skin temperature, and sweat rate. However, Yaglou (1949) criticized this formular, stating that the arbitrary summation overlooks the interrelationship among these variables and their relative importance on contributing to heat strain. A physiological strain index (PhSI) has been proposed to better represent the overall state of physiological strain (Moran et al., 1998a). First, it includes the two primary determinants of physiological strain associated with heat stress (core temperature and heart rate; Belding, 1970) into the equation. Second, it has the ability to differentiate the strain level between clothing types, climates, hydration levels, exercise intensities, gender, and age (Moran et al., 2002; Moran et al., 1999; Moran et al. 1998b). Moreover, this index quantifies the strain and easily compares different heat exposures; however, it arguably underestimates cumulative strain as a combination of the circulatory and thermoregulatory loads under exercise heat stress (Frank et al., 2001). Frank et al. (2001) asserted that the cumulative heat strain index (CHSI) is more comprehensive in assessing total

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physiological strain. Although these objective measurements are sophisticated and comprehensive for heat strain assessment (Epstein and Moran, 2006), the practicality and application of these strain indices in the workplace remain questionable, such as the invasive measurement of core temperature, the requirement of expensive equipment, and the physical interaction between the investigator and the participant (Gallagher et al., 2012). For instance, heat strain assessment in a hot environment seems difficult outside of laboratory settings and in the absence of direct core temperature thermometry (Pryor et al. 2011).

In addition to physiological strain, the rise in heat strain in hot conditions is also associated with elevated perceptual strain (Nybo & Nielsen, 2001). Prevalently used perceptual indices include, but are not limited to perceived exertion, thermal sensation, thermal comfort, and perceived skin wetness. The rating of perceived exertion (RPE) allows individuals to subjectively assess their overall feeling of physical stress, effort, and fatigue in relation to a specific task (Foster et al., 2001). However, only limited information on subjective sensation from thermal stress can be derived from this single index. Thermal sensation (TS) measures the perception of individuals in a certain thermal condition (van Hoof, 2008), while thermal comfort reports how the human mind expresses satisfaction when experiencing a specific thermal environment (ASHRAE 55, 1992). Nevertheless, these indices are mainly dominated by cutaneous or peripheral thermoreceptors (Kato et al., 2001), which could limit the verification of cardiovascular stress. Perceived skin wetness is discerned as a valid heat strain index, as it matches prime thermo-physiological measurements such as core temperature, skin temperature, heart rate, total sweat rate, thermal comfort, and wet sensation (Lee et al., 2011). However, this index is limited when workers wear vapor-impermeable clothing during heavy work (Lee et al., 2011).

Given that RPE and TS appear to be closely related to the predominant physiological parameters (i.e., heart rate, core temperature) of heat strain (Hostler et al., 2009; Aoyagi et al., 1998; Marino et al., 2004), the integration of these two subjective indices may be more appropriate in measuring human heat strain. Tikuisis et al. (2002) developed a holistic tool to assess perceived heat strain, namely, the perceptual strain index (PeSI), which combines both RPE and TS. In regard to the non-invasive measurement of heat strain and the unambiguous interpretation of the outputs of the PeSI, it is expected to offer a practical solution for assessing heat strain under various heat exposures. An applicable strain index should be sensitive enough to differentiate between similar exposures within a different variable (i.e., clothing, environment, metabolic rate) (Moran et al., 1998a). A reliable heat strain index should provide an accurate prediction of human physiological responses in consideration of activities, environmental conditions, clothing, and individual variations that correspond to different levels of heat stress (Tikuisis et al., 2002; Moran et al., 2003; Parsons, 2006). In view of this, the applicability and validity of the PeSI has been scrutinized in recent years. The PeSI enables differentiation of heat strain between fitness levels (Tikuisis et al., 2002), activity levels and protective garments (Petruzzello et al., 2009), but not hydration levels (Hostler et al., 2009). Meanwhile, moderate to high correlations of the PeSI and the PhSI have also been found in these studies, regardless of variations in heat exposure. These studies have provided solid evidence that the PeSI is capable of evaluating heat strain faced by firefighters.

However, less information has been reported regarding perceptual strain in an experimental setting, which simulates the working conditions of construction workers (i.e., environment, work pace, and work uniform). Therefore, the study objectives were to examine the applicability and reliability of the PeSI for heat strain assessment by 1) determining how sensitive the PeSI is to summer work uniform types, and 2) understanding how well the PeSI reflects physiological strain. The findings of this study will provide fundamental evidence for real life settings that require the PeSI as a reliable tool in evaluating worker heat strain.

2. Method

2.1. Experimental design[1]

Twelve university students (10 males and 2 females) participated in this study. All participants practiced sports two or three times per week and were considered physically active. They had no cardiovascular, esophageal, or other known diseases and were considered healthy. The average age, weight and height of the participants were 21 ± 3.35 years, 63 ± 6.49 kg, and 173 ± 6.93, respectively. Two work uniforms were provided to the participants who were asked to wear them in random order for two experimental days. Uniform A is newly designed with sophisticated consideration of superior heat-moisture performance of fabrics, smart design, and the specific requirement from industry. Uniform B is a commercially available and commonly worn uniform by construction workers. Each uniform consisted of a short-sleeved shirt and a pair of long pants.

Each participant reported to the laboratory at the same time on two separate days spaced at least one week apart, while wearing the same sports shoes and underwear. Four hours before the experiment, participants swallowed a calibrated ingestible capsule to measure intestinal temperature (CorTemp, HQI, America). Upon arrival, participants were briefed on the experimental protocol and were asked to sign a written consent form that was approved by the Human Subjects Ethics Sub-committee of the authors' host organization. Then, the participant put on the assigned uniform, and equipped with the CorTemp data logger and a heart rate belt (Polar T34 Transmitter, Finland).

Upon completion of the above preparation, participants entered into the climatically controlled chamber (Walk-in Chamber, Tai Wan), which maintained ambient conditions of 34.5 °C and 75% relative humidity for the experiments to simulate a stressful environment on construction sites (e.g., Wong et al., 2014). Climactic chamber experiments included 30 min of pre-exercise rest, a period of intermittent exercise on the treadmill and 30 min of passive recovery. The pre-exercise resting and passive recovery periods were exclusive in the present study. Intermittent exercise was adopted in the experimental settings to simulate the work pace because diverse construction work is largely intermittent by nature (Rappaport et al., 2003). Participants performed this exercise (consisting of intermittent running and active recovery; Fig. 1) on a motorized treadmill (h/p/cosmos® pulsar, Germany). The running test was terminated if the following exhaustion appeared: 1) core temperature reached 38.5 °C, 2) heart rate reached 95% of the age-predicted maximum heart rate (220-Age), or 3) the participant requested to stop. A registered nurse stationed inside the chamber throughout the whole exercise to provide medical care in case of emergency.

Core temperature (T_c), heart rate (HR), rating of perceived exertion (RPE), and thermal sensation (TS) data were compiled every 3 min during the treadmill exercise. The modified mathematical expressions of the PhSI and the PeSI are shown in Eqs. (1) and (4) (Tikuisis et al., 2002). The output of each strain index is expressed on a scale of 0–10, from low to high levels of heat strain (Moran et al., 1998a; Tikuisis et al., 2002). Additionally, the fractional

[1] The protocol of the experiment in this paper was elaborated in an unpublished paper named “Evaluating the physiological and psychological responses of wearing a newly designed work uniform” (under review). Only a part of the data has been used in this study.