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Evaluation of physiological strain in hot work areas using thermal imagery

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ABSTRACT

Background: Monitoring core body temperature to identify heat strain in workers engaged in hot work in heat stress environments is intrusive and expensive. Nonintrusive, inexpensive methods are needed to calculate individual Physiological Strain Index (PSI).

Objective: Thermal imaging and heart rate monitoring were used in this study to calculate Physiological Strain Index (PSI) from thermal imaging temperatures of human subjects wearing thermal protective garments during recovery from hot work.

Methods: Ten male subjects were evaluated for physiological strain while participating in hot work. Thermal images of the head and neck were captured with a high-resolution thermal imaging camera concomitant with measures of gastrointestinal and skin temperature. Lin's concordance correlation coefficient (rho_c), Pearson's coefficient (r) and bias correction factor (C-b) were calculated to compare thermal imaging based temperatures to gastrointestinal temperatures. Calculations of PSI based thermal imaging recorded temperatures were compared to gastrointestinal based PSI.

Results: Participants reached a peak PSI of 5.2, indicating moderate heat strain. Sagittal measurements showed low correlation (rho_c=0.133), moderate precision (r=0.496) and low accuracy (C_b=0.269) with gastrointestinal temperature. Bland-Altman plots of imaging measurements showed increasing agreement as gastrointestinal temperature rose; however, the Limits of Agreement (LoA) fell outside the $\pm$0.25 C range of clinical significance. Bland-Altman plots of PSI calculated from imaging measurements showed increasing agreement as gastrointestinal temperature rose; however, the LoA fell outside the $\pm$0.5 range of clinical significance.

Conclusion: Results of this study confirmed previous research showing thermal imagery is not highly correlated to body core temperature during recovery from moderate heat strain in mild ambient conditions. Measurements display a trend toward increasing correlation at higher body core temperatures. Accuracy was not sufficient at mild to moderate heat strain to allow calculation of individual physiological stress.

1. Introduction

Heat stress is the heat load a worker is exposed to and is composed of environmental factors (such as air temperature, humidity, air velocity and radiant heat), metabolic heat, and clothing and Protective Personal Equipment (PPE) factors. Heat strain is the individual physiological response to heat stress. Heat strain as a response to heat stress is highly variable in individuals, with factors such as underlying health, acclimation, lifestyle and genetics affecting the occurrence of heat stress disorders (Nagano et al., 2010). High heat stress may lead to high heat strain, potentially resulting in a number of heat related illnesses including heat stroke, which is life threatening. During the 2-year period covering 2012–2013, 20 cases of heat illness or death involving 18 private employers and two federal agencies produced citations for lack of federal OSHA enforcement. Thirteen of these cases resulted in a worker's death and two or more employees experienced symptoms of heat illness in seven of the cases (Arbury et al., 2014).

Heat stress resulting from exposure and worker exertion within hot workplace environments is common in many occupational groups, including smelter workers. The increased risk of heat strain in these occupational groups means that early and accurate detection and mitigation of physiological strain is essential for protecting the health of these workers (American Conference of Governmental Industrial Hygienists, 2015).

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There are three types of thermal strain indices currently in use (Parsons, 1999):

- Environmental indices measure ambient heat stress, which may be used as an indicator for potential heat strain among workers. Currently used environmental indices include the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) Screening Threshold, Occupational Safety and Health (OSHA) Heat Index and Wet Bulb Globe Temperature (WBGT).
- Thermoregulatory heat transfer models such as the ACGIH TLV Detailed Analysis include clothing/PPE and metabolic rate adjustments, which may be used to evaluate the potential for heat strain among Similarly Exposed Groups (SEGs).
- Physiological models such as the Physiological Strain Index (PSI) provide individual, real-time estimates of heat strain (Moran et al., 1998).

Real-time monitoring of PSI in occupational settings is currently limited due to the intrusive nature of gathering core temperature measurements, which requires use of a rectal temperature probe or ingestion of an intestinal telemetry temperature sensor (hereafter referred to simply as sensor) to measure rectal or gastrointestinal temperature, respectively. Due to these limitations, thermal indices are the primary control measure used in hot work environments. However, due to individual variability among workers, thermal indices are designed to be conservative and may unnecessarily restrict work as a result. A less intrusive method for monitoring core body temperatures for PSI calculation would allow monitoring and detection of individual heat stress response before the worker experiences symptoms of heat strain.

Research by Bourlai et al. (2012) used thermal imaging of the skin of the head and neck to estimate body core temperatures of participants before, during, and after treadmill exercise in a heated room with participants wearing wild land firefighting garments. The estimated body core temperatures showed a strong correlation with GI temperature during exertion within a heated enclosure, with a bias of only −0.07 °C (1.4 °C). However, the results of this research have not been confirmed in an occupational setting.

Thermal imagery may prove useful in rapid screening when used for determination of core temperature immediately upon cessation of hot work. Therefore, the use of thermal imagery of the skin of workers in comparison to gastrointestinal temperature for evaluation of physiological strain in hot occupational environments was investigated during this study. Although studies like that of Bourlai et al. are useful in establishing a correlation between thermal imaging and body core temperatures, the work of investigating, validating, and establishing such correlations in an actual occupational setting remains undone. The goal of this project was to validate the use of thermal imagery temperatures of the skin of workers in comparison to gastrointestinal temperature for evaluation of physiological strain in a real-world occupational setting.

2. Material and methods

Inclusion of human participants in this study was approved by the University of Utah Institutional Review Board (IRB; Approval #00082999). Prior to enrolling participants in the study, written informed consent for the pre-study questionnaire, monitoring for the study, and a post-sampling questionnaire were obtained.

2.1. Study design and participant recruitment

This cross-sectional study investigated the evaluation of physiological strain using thermal imagining of the skin of the head and neck of smelter and foundry workers rather than rectal or intestinal temperature in hot occupational environments. The study location consisted of a copper smelter located in the western United States. The site was selected for the hot work environment and work activities that necessitate thermal protective clothing.

The study population consisted of copper smelter furnace tappers. These tappers work rotating 12-h shifts on a 28-day schedule and are responsible for opening, maintaining and closing furnace holes as needed to control blister and matte copper levels within the furnace. Tapper PPE includes nonflame resistant coveralls, Nomex® arm sleeves, Nomex® hood, aluminized leathers, helmet, face shield, aluminized hood and full face respirator; all of which decrease the efficiency of the body's natural thermal compensation through evaporation of sweat. Work is production driven, but self-paced and a sufficient number of employees are on duty for tappers to rotate as necessary based upon workers' perceived exertion. Tappers are provided climate-controlled rest areas for recovery. Employee interviews indicated hot work periods vary from 30 min to several hours depending upon furnace hole conditions. Ambient conditions within the work area are variable and highly dependent upon external environmental conditions. At the time of sampling, ambient conditions were qualitatively judged by the tappers to be mild. According to the nearest National Weather Service station, seasonal highs ranged from 4 to 13 °C, lows ranged from −6 to 5 °C, and average relative humidity was between 54% and 86%. However, due to the high temperatures of the molten copper—in excess of 1200 °C—temperatures at tapper work positions exhibited a strong gradient and were significantly above ambient conditions. Additionally, the tappers were exposed to high levels of infrared radiation, which is known to contribute to thermal load.

The primary participant inclusion criterion was current employment as a copper furnace tapper. Exclusion criterion was potential contraindications associated with the ingestion of the sensor. Recruitment took place in the smelter's work center and being included in the study was entirely voluntary. Participants were not provided with any incentives, but still received their regular rate of pay.

After obtaining a participant's informed consent as required by the IRB, a self-administered questionnaire was given to evaluate eligibility and obtain a brief medical history. Questions concerning potential contraindications associated with the ingestion of the sensor (i.e., gastrointestinal surgery, felinization of the esophagus, esophageal stricture, hypomotility disorders, etc.) were evaluated by a physician associated with the study. No contraindications were reported, therefore, no physician clearances were required. Self-reported demographic information was captured including age, weight, height, sex, time of gastrointestinal thermometer ingestion, smoking history, and exercise frequency. The median age was 40.7 years. The median height was 178 cm with a median weight of 98 kg, yielding a median BMI of 30.8. Participants reported a median frequency of 3.0 aerobic and 2.7 strength sessions per week. Current smokers represented 30% of the participants, while 30% were former smokers and the remaining 40% had never smoked. None had consumed alcohol within 24 h of reporting to work. While demographic information was not utilized in the analysis, it is crucial for describing the participant population. Demographic characteristics of the participants are found in Table 1.

Following completion of the questionnaire, participants were instructed to refrain from consuming alcohol for 24 h prior to the study-monitoring period. During monitoring potential