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Development of an early-warning system for site work in hot and humid environments: A case study

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ABSTRACT

This study presents an early-warning system for working in hot and humid environment. The developed system can monitor workers' heat strain level when they have to work under such hostile conditions continuously. Health alert messages with corresponding intervention measures will be prompted to workers to safeguard their wellbeing. Heat strain is evaluated by a subjective index perception rating of perceived exertion (RPE) and an objective heat strain indicator heart rate. A database containing 550 sets of synchronized work-related, environmental, and personal data were used to construct the prediction model. Artificial neural networks were applied to forecast the RPE of construction workers. Statistical measures including MAPE, RMSE and R^2 confirm that the established model is good fitting with high accuracy. The proposed system could be automated by integrating smart sensor technology, location tracking technology, and information communication technology, which could be in the form of GSM based environmental sensor, smart bracelet, and smart phone application, to protect the wellbeing for those who have to work in hot and humid conditions.

1. Introduction

Construction is a large, complex, and dynamic sector that generates employment for millions of people worldwide. However, this sector has the most fatalities and high incidence of non-fatal occupational injuries and illnesses on days away from work. Based on the estimates of International Labour Organization (ILO), at least 60,000 fatal accidents occur each year in construction sites around the world, which represent one fatal accident every 10 min [1]. In addition, the ILO estimates that the construction workers in industrialized countries are 3 to 4 times greater than other employees to die from accidents at work [2]. Aside from the dangers of being the front-liners on a jobsite, workers in the construction industry also confront potential health hazards (e.g., temperature extremes, radiation, chemicals, dusts, vibration, and noise) throughout the building process. Furthermore, about 30% of construction workers in some European countries suffer from pain and musculoskeletal disorders [3]. The occupational illnesses of construction workers have not been accurately measured, but an educated guess indicates that construction workers suffer both acute (short-term) and chronic (long-term) illnesses from their exposure to environmental hazards [4]. The health and safety of construction workers aroused greater attention from governments, industry community practitioners, and the academia.

Heat stress is a well-known occupational hazard in the construction industry [4], and climate change together with the increased frequency and intensity of extreme heat events have made risks more severe and widespread [5-8]. Heat stress causes physiological and psychological discomforts, deteriorates performance and productivity, increases incident rates, and even threatens survival [9-11]. Increased thermoregulatory, cardiovascular and perceptual strains on the body promote confusion, irritability, and other emotional stress, which may cause workers to distract attention from tasks or ignore safety procedures [12]. Published reports in the United States suggest that work in construction occupation is associated with an increased risk of heat-related death and illness [13,14]. In Japan, a total of 47 deaths due to heat stroke were reported as industrial accidents in hot environments during 2010. The construction industry is found to be more susceptible to heat stress than other industries, which is accounted for 64% of all lethal cases [15]. News reports archived in Hong Kong show alarming incidences of heat stress and verifiable reported deaths in the construction industry [16]. A recent survey revealed that 5% of construction workers had suffered from heat stroke and 23% had experienced symptoms of heat stroke [17]. In Taiwan, construction workers were identified as the most vulnerable population

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in which high temperature impacts on health and productivity [18]. The risk of heat stress experienced by construction workers may even be higher in the Middle East where ambient air temperatures often reach 45 °C and higher with 90% humidity [19]. Considering the high frequency of heat-related incidents in the construction industry, understanding how heat stress results in heat-related illnesses and how it affects construction workers is important in planning for intervention strategies.

To prevent heat stress, a series of fundamental practice notes and guidelines (e.g., appropriate work arrangements, shelters at work or rest places to reduce radiant heat gain, ventilation in indoor working environment, air-conditioned rest rooms, and provision of drinking water or sports drinks) have been promulgated [20-23]. Likewise, the issue of working under hot weather has been a concern of academic researchers. The limits of human tolerance in terms of physiological parameters (e.g., core temperature, heart rate, skin temperature) have been evaluated at different levels of heat exposure [24-26]. Upper tolerance limits in terms of environmental indicators (e.g., temperature, humidity, wet bulb globe temperature, thermal work limit) have been explored in literature [27] and adopted by regulatory organizations [28-30]. Recently, attempts and efforts were made to establish a safety evaluation model for assessing the risk of heat stress in the workplace. Evaluating safety is not only an important means for implementing the policy but also provides a base for establishing a scientific and standardized management of enterprises [31]. For example, Ren et al. [32] established an evaluation framework for assessing the hazards of heat stress in the workplace in an underground mine. Zheng et al. [33] studied safety evaluation and early warning rating of hot and humid environment. However, no systematic and in-depth studies have been conducted with respect to safety evaluation and early warning in hot and humid environment for the identification, evaluation, control, and management of human behavioral factors. The performance of work activities befitting safety and accident prevention is a continuing and dynamic process. The key to achieving these objectives lies with workers' concentration. The cognitive condition of concentration can be viewed through the concept of mindfulness [34]. Mindful work organization and performance can be achieved through the improvement of workers' alertness to and awareness of the hazardous nature of the operations.

Occupational heat strain results from a combination of factors, which include environmental conditions, work demands, and individual characteristics. Earlier studies by Chan et al. [35,36] established a multiple linear model (MLR) to predict a worker's heat strain to different environmental factors, work-related factors, and personal factors. However, it was challenged that heat stress and heat strain may not be linearly correlated [37]. Furthermore, the combination of the large array of personal health and lifestyle factors and their complex interaction effects is far beyond the predictive power of a MLR [38]. More advanced analytical techniques are required to tackle these complex issues. Artificial neural networks (ANNs), a form of artificial intelligence technique, is one such approach which provides a high level of flexibility and competency in nonlinearities and complex behavior. ANN provides solutions to many complex problems in biology and medicine that are beyond the computational capacity of classical mathematical and traditional statistical techniques [39]. The application of ANN in data treatment is high, particularly where systems present nonlinearities and complex behavior [40].

Innovative devices and technologies [e.g., physiological status monitor (PSM) and Ultra-Wideband (UWB)] are being used to real-time location tracking and physiological status of construction workers for enhancing construction safety and productivity [41-47]. This research aims to develop an early-warning system for construction workers against hot and humid climates using modern technologies and ANN as the principal analytical technique. The objectives of this study are to (1) develop a model to predict a worker's heat strain in hot and humid environment; and (2) identify proper precautions against the hazards and risks in hot and humid environment to prevent and reduce the harmful effects of heat exposure. Since Hong Kong is in a subtropical climate zone where air temperature typically reaches 34.5 °C on its hottest summer days [48] and business environment of the construction industry in Hong Kong is highly competitive [49], the Hong Kong construction industry is selected as a prototype for developing a more focused methodology which if successful could also be applied to other regions.

2. Design of the early-warning system

2.1. Factors used to develop early-warning system

2.1.1. Heat strain assessment

Heat stress is defined by National Institute for Occupational Safety and Health as the sum of the heat generated in the body (metabolic heat) plus the heat gained from the environment minus the heat lost from the body to the environment [30]. Heat strain describes the overall physiological and psychological response resulting from heat stress [50]. International Standard Organization has identified the indicators for heat strain, including body core temperature, skin temperature, heart rate and the loss of body mass through sweating [51]. Heart rate is the earliest response of physiological strain [52], which was used to assess the strain of construction workers [53]. Previous studies reported that the normal heart rates for undertaking heavy tasks in the heat were in the range of 130–160 bpm [24,54]. According to ACGIH, an individual's heat stress exposure should be discontinued when his/her heart rate exceeds 180 beats per minute (bpm) minus the age of the employee sustained for at least 3 min [55].

Apart from the objective physiological parameters, heat strain can be evaluated by a subjective perception index rating of perceived exertion (RPE) which indicates the intensity of subjective effort, stress, or discomfort felt during physical activity [56]. RPE provides a useful indication of the capacity to continue a task [57]. The RPE scales use both verbal anchors and numbers that have been reported to possess both categorical and interval properties [58]. The Borg CR10 Scale was used in this study. The anchors ranged from 0 = "rest" to 10 = "maximal exertion."

Previous studies have demonstrated that the RPE is highly correlated with environmental factors such as temperature, relative humidity, air velocity, and solar radiation; personal factors such as age, body fat, and alcohol drinking/smoking habits; and work-related factors such as work duration and work intensity [59-62]. The wet bulb globe temperature (WBGT) which responds to all four elements of the thermal environment (i.e., air temperature, relative humidity, air velocity, and solar radiation) is adopted as an environmental parameter in this study. WBGT is so far the most widely used and accepted environmental index for managing occupational heat stress [63]. The body mass index (BMI) measures body fat based on height and weight. Alcohol drinking and smoking habits will be recorded under three categories according to the amount of weekly alcohol intake and cigarette consumption. According to the World Health Organization (WHO) [64], one "standard" drink contains 10 g of pure alcohol [e.g., 250 ml (3/4 can) of regular beer has 5% alcoholicity, 100 ml (1 small glass) of wine has 12% alcoholicity, 30 ml (1 pub measure) of hard liquor has 40% alcoholicity]. "Low-risk" drinking levels for men represent no more than four drinks on any single day, and no more than 14 drinks per week [65,66]. Thus, alcohol drinking habits are classified into three categories, namely "none," "no more than four drinks on any single day and no more than 14 drinks," and "more than four drinks on any single day and no more than 14 drinks." Based on the study by Chan et al. [67] on medical examination for construction workers, smoking habits were classified in three categories, namely "none," "no more than 35 cigarettes per week," and "more than 35 cigarettes per week". Workers of different trades may be subject to different degrees of physical demands. Energy expenditure, defined as a sum of internal heat produced and external work, is a common method to quantify the intensity of physical works in a hot environment [68]. Workload is classified into