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Wearable sensors for monitoring on-duty and off-duty worker physiological status and activities in construction

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ABSTRACT

Total Worker Health® (TWH) integrates occupational health and safety with the promotion of workers' off-duty wellbeing. Wearable sensors (e.g., activity trackers and physiological monitors) have facilitated personalized objective measurement of workers' health and wellbeing. Furthermore, the TWH concept is relevant to construction workers, especially roofing workers, as they encounter high on-duty health and safety risks and have poor off-duty lifestyles. This study examined the reliability and usability of wearable sensors for monitoring roofing workers' on-duty and off-duty activities. The results demonstrated the usability of these sensors and recommended a data collection period of three consecutive days for obtaining an intraclass correlation coefficient of ≥ 0.75 for heart rate, energy expenditure, metabolic equivalents, and sleep efficiency. The participants exhibited significant variations in their physical responses, health statuses, and safety behaviors. Moreover, several issues were identified in the application of wearable sensors to TWH evaluations for construction workers including roofers.

1. Introduction

Construction activities involve intensive workloads and are physically demanding. It is therefore not surprising to see that the industry suffers from high rates of musculoskeletal and cardiovascular diseases, in addition to injuries and fatalities [1]. Construction industry's rate of non-fatal injuries is approximately 40% greater than the average rate in the United States (U.S.) [1]. Among various high-risk industries, construction industry contributed the largest proportion of deaths in 2010 (approximately 17%) [1]. These health and safety concerns are associated with absenteeism and presenteeism, which have led to fewer improvement of worker productivity in construction [2]. Construction workers also often have poor overall health and lifestyle factors, such as poor eating, physical fitness, and sleeping habits [3]. Cardiovascular diseases, high blood pressure, and obesity are major health-risk factors for construction workers [1]. Based on the National Health Interview conducted from 2004 to 2011 among the United States (U.S.) workers, the obesity of construction and extraction (i.e., gas and oil well–-drilling) workers actually increased among Hispanic and White male construction trade workers when compared with statistics from 2004 to 2007 and 2008 to 2011 [4]. These seemingly personal lifestyle choices can impact a worker's performance or exacerbate the physical demand from work. On the other hand, these choices are restricted by work activities at times, as shift-based work and overtime can interfere with a worker's ability to exercise or physically participate in leisure activities [5]. A deep understanding that looks into the interactions between construction workers' on- and off-duty activities is necessary for the development of effective interventions which reduce injuries and illnesses, and at the same time improve worker wellbeing.

Such a concept was coined and trademarked by the U.S. National Institute for Occupational Safety and Health as Total Worker Health® (TWH). This concept is based on understanding and integrating efforts to improve occupational health and safety with interventions that can improve workers' off-duty lifestyles [6]. The TWH approach aims to evaluate the relationship between triggers of unsafe worker behaviors and the workers' off-duty wellbeing and lifestyles [7]. Several proof-of-concept TWH studies including development of measurement tools for the health protection and promotion score research have been done in the health care and manufacturing sectors. In [8], through semi-structured interviews with small- and medium-sized business representatives, it was found that a work site intervention combining work site health promotion with occupational safety and health (i.e., the concept of TWH) is valid in terms of acceptability and feasibility. In [9,10], with a subjective measurement, a new integration score which measures feasibility, acceptability, and meaningfulness of TWH was developed and verified. In [11], six tools to measure TWHs validity

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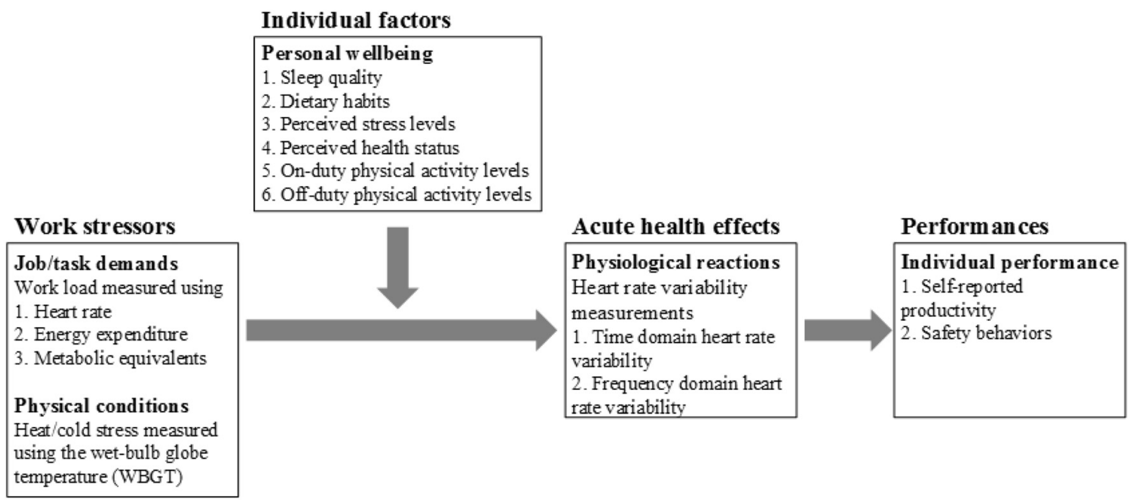

Fig. 1. Adapted Hurrell and McLaney's job stress, health, and performance model [37].

from two aspects, organizational and individual levels, were introduced. The research also provided a guideline for our research as of which variables should be measured in order to evaluate the validity of the TWH concept. In [12], the researcher conducted a survey on the feasibility and efficacy of TWH among patient-care workers. The researcher found that a TWH intervention hardly supported improvements in workers' health outcomes. While previous research works relied on the survey method when verifying the TWH concept, we collected both qualitative data through a survey and quantitative data with sensors in order to establish a more-well rounded study methodology. A few studies have considered the application of TWH and worksite health promotion programs for construction workers, who are exposed to significant health and safety risks [13–15]. We aimed to support the application of TWH in construction by leveraging wearable technologies to understand how the workers' off-duty lifestyles might intertwine with their physiological responses and on-duty performance. Both on-duty and off-duty factors (e.g., physical activities, hydration, and sleep quality) may influence workers' physiological strain, productivity, and safety behaviors.

Nowadays, novel worker and workplace monitoring technologies are available to provide rich data on factors that can affect both worker safety and productivity. Leveraging and understanding these data can potentially improve the sustainable development and retention of the construction workforce. Physiological status monitoring [16–18], inertial measurement units for gait stability measurements [19,20], ergonomics posture analysis [21], and electromyogram systems [22] have been applied to measure and predict the level of health hazards faced by workers in various construction and material handling activities. As the technologies became available, individuals are also being more receptive to the introduction of personal monitoring technologies such as the Fitbit device. It is an activity tracker that quantifies steps, stairs climbed, and distance traveled using a 3-axes accelerometer, and monitors heart rate using photoplethysmography. These monitoring technologies are largely available in the consumer market and are gaining tractions in workplace wellness programs for their capability to offer real-time health monitoring and feedback in intervention studies. To this end, we conducted a pilot study to investigate the feasibility and method of applying these emerging wearable sensor devices for the eventual implementation of construction safety and health management at the individual worker's level.

2. Background

Accelerometer-based activity trackers have been used to measure energy expenditure and sleep. There are several devices that consumers use for free-living activities. Such devices include Fitbit, Nikefule and Jawbone [23–25]. Other examples, like the ActiGraph and BodyMedia devices, have been developed for clinical research and are targeted as personalized medical devices [26–30]. These devices can be worn on the hip or wrist to estimate both energy expenditure and sleep. Some trackers such as Fitbit are also available to measure one's heart rate but devices like the Polar chest strap [31] and Zephyr products [16–18,32] are more intensively used to measure heart rate in the occupational health and safety research. Wearable technologies have been validated to compare with gold standard measurement for sleep [25], heart rate [17,33], and physical activity [23,24] measures. Heart rate has been adopted as a measurement to estimate workers' workload while its variability has been adopted to estimate the health outcomes related to workload or environmental stressor exposures [34,35]. Heat stress is one of the work stressors generated in a work environment and influences a worker's fatigue level and performance. As one of the indices to measure heat stress, WBGT is widely used, with the intention of examining a worker's heat tolerance limit [36]. The TWH concept offers a holistic approach towards the relationship between the health status of workers and their productivity. While past researches were limited to studying such relationships using survey instruments at the organizational level, wearable sensors could provide objective measurements on key TWH variables at the individual level. We herein resorted to the job stress and health model introduced by Hurrell and McLaney [37] to formally define these key variables and guide our utilization of wearable sensors as shown in Fig. 1. In our adaptation of the job stress and health model, we considered productivity and safety as the key performance outcomes as suggested by Cox et al. [38]. Unsafe behaviors are antecedents to injuries and accidents [39], and workers' stress and fatigue are known to be negatively related to safety behaviors [40]. We therefore project an individual's safety performance based on the person's safety behaviors, by evaluating the individual's frequency of non-neutral ergonomic postures.

The model in Fig. 1 assumes that acute health conditions influence workers' safety behaviors, especially their inattention to the ergonomic practices associated with material handling tasks. In other words, psychological fatigue induced by excessive workload may have an adverse effect on a worker's attention to ergonomic postures. In the model, workload (measured by HR) influences their physiological fatigue and stress, and this can be measured objectively by HRV. The degree of influence may differ according to each individual's sleep quality, and this can be quantified by measuring the individual's sleep efficiency using an activity tracker. In conclusion, a worker's fatigue level influences one's task performance at the individual level, and the worker's adherence to safe and ergonomic postures can be quantified as the