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Monitoring fatigue in construction workers using physiological measurements

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ABSTRACT

Fatigue is one of the factors leading to reduction in productivity, poor quality of work and increased risk of accidents in construction. Existing established methods of assessing fatigue include surveys and questionnaires, which are cumbersome to implement at construction sites. This study presents a novel approach for real time monitoring of physical fatigue in construction workers using wearable sensors. Changes in the heart rate, thermoregulation and electrical brain activity during a simulated construction task were monitored from 12 participants using a heart rate monitor, infrared temperature sensors and an EEG sensor. Borg's RPE was used as a subjective scale to collect the level of fatigue experienced by the participants. Boosted tree classifiers were trained using the features extracted from the heart rate and temperature sensor signals and used to predict the level of physical fatigue. Only physical fatigue was assessed as none of the participants developed any sign of mental fatigue during the study. The results show that physical fatigue can be monitored using wearable sensors. The classification accuracy, based solely on features extracted from average of skin temperature data, was 9% higher than based solely on heart rate data, and combining the information from both sensors resulted in the best accuracy of 82%. The results also show that monitoring thermoregulation from temple can be more useful compared to other studied monitoring sites, the classification accuracy based only on data from the temple was 79%. This accuracy is significantly higher compared to the classification accuracy based only on heart rate data (59%).

1. Introduction

The construction industry, one of the largest industries in the world, is also associated with high number of accidents. Based on a report released in 2005, the International Labor Organization (ILO) estimated there are at least 60,000 construction related fatalities around the world each year [1,2]. In the industrialized countries, the ILO estimates 35% to 40% of the fatalities to occur in the construction industry, which employs less than 10% of the total workforce [1]. Despite the construction industry's small share of the total workforce (4.8% [3]) in the United States, it had the highest number of fatalities, 984 fatalities (20.3%) in 2015 [4]. The same year, the incidence rate of nonfatal injuries in the construction industry, caused by overexertion was 10.6 per ten thousand workers, requiring a median of 13 days away from work [5]. Although safety performance in the U.S. construction industry improved significantly between 1973 and 2004 due to adoption of highly effective injury prevention strategies, there has not been any significant improvement in the injury statistics in the past decade, indicating that the industry has reached saturation with respect to the traditional injury prevention strategies and new safety innovations are needed [6,7].

Construction work typically involves physically demanding tasks often performed in harsh environmental conditions, which can cause fatigue and lead to poor judgment, poor quality of work, increased risk of accidents and reduction in productivity [8,9]. Fatigue has been associated with experiencing difficulties with physical and cognitive functions [10] and identified as a potential risk factor for slip-induced falls (40% of fatalities in 2014) [11], one of the "fatal four" causes of fatalities in the construction industry according to the Occupational Safety and Health Association (OSHA) [12]. 20% to 40% of different craft workers on a construction site routinely exceed generally accepted physiological thresholds for manual work [8]. Physical fatigue and impaired mental capacity pose a greater risk towards accidents in hot and cold environmental temperatures [13]. Although it is difficult to quantify the direct impacts of fatigue on construction safety due to lack of robust methods for real time fatigue monitoring, resulting in lack of fatigue related studies in occupational safety studies [14], it is one of the factors that has a negative impact on workers' safety and performance [15].

The objective of this study is to investigate if thermoregulatory changes (i.e., changes in the blood flow due to vasocontraction and vasodilation) could be used for assessing fatigue buildup, compared to the

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heart rate measurements, which have been used previously for fatigue monitoring and workload assessment [8,16–18]. Specifically, this paper focuses on monitoring thermoregulatory changes that occur during a simulated construction task and compares the accuracy of monitoring thermoregulation to monitoring heart rate for the purpose of assessing physical fatigue. The rest of the paper is organized as follows. Section 2 provides an overview on fatigue, fatigue measurement techniques and a background on human thermoregulation system. Section 3 describes the methodology for the experiment, sensors and sensing systems used, experimental procedures as well as the methods used in data analysis. Section 4 presents the results and explains the findings. Section 5 includes a discussion around the results, the limitations of this study, directions for future research and how the results could impact the field of construction safety. Section 6 concludes the paper.

2. Background and overview of related work

2.1. Methods for measuring fatigue

Fatigue refers to loss of efficiency or disinclination towards any kind of effort, yet it does not have a single definite state [19]. Although some support a unidimensional characterization of fatigue [20], it is usually described as physical fatigue and mental fatigue [19]. Mental fatigue results from prolonged periods of cognitive activity and leads to decrement in cognitive and behavioral performance [21,22]. Physical fatigue results from activities that require physical effort and is defined as the reduction in capacity to perform physical work [23]. Mental fatigue has been shown to impair physical performance [24]. However, light physical exertion seems to improve mental performance and heavy physical exertion leads to decrement in mental performance [25], suggesting a complex relation between physical and mental fatigue. Early attempts at quantifying fatigue involved different assessment scales that relied on subjective answers to a fixed set of questions relating to physical and mental fatigue [26,27]. Several construction related studies have also utilized different subjective feedback scales and questionnaires for assessing fatigue or workload [2,15,28–30]. There is no universally accepted standard for fatigue assessment and different studies have utilized different scales for fatigue assessment [28]. There are also expectation discrepancies caused between how one does feel and how one thinks one should feel, a problem inherent in subjective scales to assess fatigue [31]. Furthermore, collecting subjective feedback is cumbersome and not practical on construction sites, highlighting a need for methods that can continuously monitor fatigue with minimal intrusion to regular construction activities.

In industries that require workers to be mentally vigilant, Psychomotor Vigilance Test (PVT) has been utilized to test the mental alertness of workers. PVT is a standard reaction time test, which has been utilized to monitor alertness of workers in various occupations, such as airport luggage screening [32], long distance driving [33], and nurses working long shifts [34]. Electroencephalogram (EEG) has also been utilized to assess mental fatigue in knowledge workers performing mental tasks [35], in long distance drivers [36,37], and athletes performing exercise in hot environments [38]. EEG has also been utilized to assess mental workload changes in construction workers during installation tasks requiring participants to climb a ladder, select proper nut and fastening the nut to a bolt [39]. Other sensors such as electrooculogram (EOG) have been used to monitor fatigue in drivers [40], and Skin Conductance Response (SCR) has been used to evaluate changes in mental workload during memorization task [41]. These previous studies in various fields have studied changes in mental alertness during tasks requiring mental focus. In the present study, both PVT and EEG are utilized to track declines in mental alertness during a physical activity, which does not require high level of mental focus in an attempt to study the relations between physical and mental fatigue development during construction work.

In industries that require workers to perform repetitive tasks using specific muscle groups, such as the manufacturing industry, localized muscular fatigue has been studied using surface Electromyography (sEMG). For example, sEMG has been used to monitor shoulder muscle fatigue in sewing machine operators [42], pillar drill operators [43] and during overhead drilling work [44]. In addition, sEMG has been used to monitor forearm muscular load in automobile assembly workers [45] and to monitor arm-shoulder fatigue during a nail hammering task [46,47]. Unlike the manufacturing industry, construction work also involves non-repetitive tasks and utilize multiple muscle groups [48], therefore the present study attempts to monitor overall physical fatigue in construction workers rather than localized muscular fatigue. However, overall physical fatigue is more complex than localized muscle fatigue; overall physical fatigue is difficult to quantify as it results from the interactions between local (muscular) and central factors (cardiovascular, metabolic, thermoregulatory changes, etc.) [49]. Previous studies have focused on physical workload monitoring of workers, mostly using heart rate [8,16–18]. A previous study, utilizing physiological measurements of heart rate and oxygen uptake on construction workers, showed that 20% to 40% of construction workers routinely exceed physical thresholds in the published guidelines [8]. Another study, using heart rate and oxygen consumption, showed that the energy expenditure of bar fixing tasks was more than bar bending tasks in a hot environment [16]. Recovery time after working to exhaustion in a hot environment was determined for rebar workers using heart rate, blood pressure and subjective ratings of fatigue [30]. However, several physiological and behavioral factors (e.g., relative body weight, smoking, etc.) influence the heart rate even for roughly equivalent tasks [50], making heart rate monitoring insufficient by itself for reliable monitoring of fatigue. For example, level of physical fitness [51], mentally stressful situations [52], energy drinks intake [53], cigarette smoking [54] and alcohol consumption [55] result in changes of heart rate. In addition, the day to day variability in heart rate limits its clinical usefulness and these fluctuations require comparisons with other physiological changes (e.g., thermoregulatory changes, metabolic changes etc.) to make a more meaningful use of heart rate monitoring for detecting physical overload [56]. Thermoregulatory changes have been linked with the development of fatigue during cycling exercise [57,58]. The present study uses monitoring of heart rate, thermoregulatory changes and subjective ratings of fatigue in order to study the development of physical fatigue. The present study also compares the usefulness of monitoring heart rate and monitoring thermoregulatory changes for the purpose of evaluating physical fatigue.

The recent advances in wearable sensing and computing have helped develop novel methods that can improve safety and health of construction workers. Several studies relating to workload assessment and physiological demands during work have also been conducted under different construction activities and environmental conditions [8,16,59–63]. An early warning system for monitoring heat stress in construction workers has been developed based on environmental and physiological monitoring data [2]. Location sensing and Physiological Status Monitoring (PSM) have been utilized for monitoring ergonomically safe and unsafe behaviors during construction activities [9]. PSM has also been utilized for analyzing the physical strain-productivity relation for construction tasks [64] and physiological condition monitoring of construction workers [59]. These previous studies have utilized heart rate monitoring and other physiological (energy expenditure, oxygen consumption, respiration rate etc.) and environmental information (temperature, humidity etc.) but have not yet investigated thermoregulatory changes that can occur during construction activities.

2.2. Background on human thermoregulatory system

Human thermoregulatory system maintains the core body temperature when exposed to conditions affecting thermal homeostasis. Vasocontraction and vasodilation are the primary mechanisms that

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