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Feasibility analysis of heart rate monitoring of construction workers using a photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker

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A B S T R A C T

With increasing concerns regarding occupational safety and health, managing excessive physical workloads of workers is critical to prevent workers' fatigue, injuries, errors, or accidents at physically demanding workplaces such as construction. In this regard, heart rate (HR) is an effective physiological indicator of workers' physical demands. Currently, off-the-shelf wearable activity trackers (e.g., wristband-type) can monitor a worker's HR with its embedded photoplethysmography (PPG) sensor. However, PPG signals can be highly affected by signal noises resulted from user's movements, and thus the exact HR extraction from a wristband-type PPG may not be sufficiently accurate during intensive construction tasks. In this paper, we investigate the accuracy of a PPG sensor embedded in a wristband-type tracker to see if it can be used for construction. Through field data collection from seven construction workers, we conduct a comparative HR analysis between a PPG sensor and an electrocardiography (ECG) sensor in a chest strap used as ground truth. The results show that a PPG-based HR sensor in a wristband-type activity tracker has a potential for practicable HR monitoring of construction workers with 4.79% of mean-average-percentage-error (MAPE) and 0.85 of correlation coefficient for whole datasets (4.44%, 4.52%, and 5.33% of MAPEs and 0.89, 0.70, and 0.61 of correlation coefficients during light works with <90 bpm of HRs, moderate works with 90–110 bpm of HRs, and heavy works with >110 bpm of HRs, respectively). Because there is still room for improvement of the accuracy, particularly during heavy works, we also investigate the factors affecting the accuracy of HR monitoring using inequality statistics. From this secondary investigation, we found the major sources of error including noises from motion artifacts. With advanced noise-cancellation techniques, it is expected that that field HR monitoring using wearable activity trackers can be used to evaluate worker's physical demands from diverse construction tasks in a non-intrusive and affordable way. As a result, our work will help manage excessive workloads (e.g., flexing work/rest plans) so that a worker can sustain his/her given tasks during working time in a safer and healthier way.

1. Introduction

Over the past several decades, increasing concerns regarding workers' health promotion has arisen due to the high incidence of workers' illnesses and injuries, as well as the industrial health-care burden [23,38,47]. Particularly in a labor-intensive industry such as construction, excessive physiological demands from physically demanding tasks raise potential risks including workers' fatigue, injuries, errors, or accidents, as well as a possible decline in productivity in the long run [21,58]. For example, the U.S. construction industry has approximately 0.2 million cases of construction workers' injuries and illnesses, which amounts to 80 thousands cases of days away from work in 2013 [12]. Monitoring workers' physiological conditions can thus be a critical prerequisite of early detection and screening of personal physical status; this monitoring allows us to identify workers' excessive physical demands from tasks at the worksite and provide timely information for proactive management of high physical workloads (e.g., duration and intensity of work) [1,13,21].

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Specifically, a heart rate (HR) is an affordable physiological measurement and a reliable indicator of workers' physical demands related to muscular activities [25,28,56]. Due to the effectiveness of HR, many wearable health devices provide a user's HR monitoring on a real-time basis. In particular, a wristband-type activity tracker has the potential to monitor workers' HR in the field because, given its light weight and comfort, it does not hinder movements or actions, and given its relatively low cost (e.g., less than $150 per unit), it does not greatly increase the expense of worksite health care [29,40].

These wristband-type activity trackers are usually equipped with a photoplethysmography (PPG) sensor for HR monitoring, which is based on a spectrographic technology composed of light-emitting diodes (LEDs) and a photo detector for optical detection of blood-flow rate caused by the heart's activity [4,34]. However, the exact HR extraction from a PPG during intensive physical activities remains challenging. In particular, the PPG signals are sensitive to motion artifacts, which are signal noises resulted from voluntary and involuntary movements of the users during data acquisition (e.g., changes in the location of the optical sensor on the body, changes in pressure of the sensor-skin interfaces, etc.) [50,53]. Therefore, the accuracy of the PPG-based HR monitoring needs to be tested before it is used for intensive construction tasks. To address this issue, we examine the accuracy of PPG-based HR monitoring using a wristband-type activity tracker for construction workers during their physically demanding tasks. We also investigate major factors affecting the accuracy of HR monitoring for construction workers. To do this, we collect field HR data from workers at the real construction site from both a PPG sensor in a wristband-type activity tracker and an electrocardiogram (ECG) sensor in a chest strap. ECG-based HR is used as ground truth because an ECG sensor provides accurate HRs by directly measuring the electoral signals from heart's activity [2,50]. We then conduct a comparative analysis between HRs from both a PPG and ECG to investigate whether the PPG sensor is suitable to measure workers' HR while working in construction.

2. Measuring heart rate (HR)

HR is the most widely used form of physiological information for personal health conditions [2,21]. This section explores the importance and usefulness of HR monitoring, as well as methods for measuring HR.

2.1. Importance of HR monitoring

Because HR is affected by an individual's general fitness level, duration of work tasks, and level of workloads, and is relatively easy to monitor in a cost-effective and non-invasive way, it has been used as an effective indicator of exercise or work intensity during the performance of many activities [1,2,60]. Diverse criteria for physical workloads have been introduced by distinguishing HR at rest, maximum HR, and HR during physical work [1,28,33,41]. Specifically, %HR Reserve (%HRR; relative heart rate), which converts a target HR into the percentage of the difference between maximum HR and HR at rest [33], has been successfully applied in physical workloads assessment by offsetting individual physical characteristics (e.g., different resting HR among individuals) [22,25,28,56]. Additionally, HR has been widely used to estimate human energy expenditure (EE), which is an effective physiological measurement of physical demands from a metabolic perspective [10,20], by examining the linear relationship between HR and oxygen uptake (VO2) and the constant relation between VO2 and EE [15,52]. Therefore, HR monitoring at the worksite has the potential to evaluate a worker's physical demands from diverse construction tasks in order to manage workloads. Doing so ensures that a worker can sustain his/her given tasks in a safer and healthier way throughout a whole working day.

On the other hand, the factors affecting HR include not only personal differences (e.g., physical fitness level) and mode of exercise/work (e.g., body position and activity intensity) but also neural and hormonal affects (e.g., emotion), internal body changes (e.g., alcohol, drugs, fear, and sleep deprivation), environmental stresses (e.g., heat, humidity, cold, wind, altitude, and air quality), and protection from the degenerative process of heart disease (e.g., fatigue) [2,37]. Therefore, continuous HR monitoring can be used to detect any abnormal HR, which could result from a worker's health problems such as fatigue, cardiovascular disease (e.g., heart valve problems, arrhythmia, heart attack, and stroke), or heat-related injuries (e.g., heat stroke and heat exhaustion) [2,11]. Specifically, according to increasing concerns on worker's heat-related injuries, HR has been widely used as an important variable to represent the Physiological Strain Index (PSI), an indicator of thermal-strain risks [11,35,44]. For example, PSI over 7.0 that corresponds to approximately 158 bpm of HR and 38.6 °C of core body temperature can be classified as the ‘at high thermal-strain risks’ where exposure to heat needs to be immediately reduced [35]. As a result, field HR monitoring can provide an opportunity for understanding and managing workers' physical conditions (e.g., physical demands, thermal-strain risks, etc.) from not only heavy workloads of tasks but also unfavorable site conditions and personal health status.

2.2. HR monitoring method

To measure HR, an electrocardiogram (ECG) is commonly used because it is regarded as the most reliable method [50]. ECG sensors measure the bio-potential generated by electrical signals that govern the expansion and contraction of heart chambers [2,50]. It measures electrical activity of the heart through continuous waveforms that show the contraction and relaxation phases of the cardiac cycles [40]. Based on electrical signals originating from the heart, an ECG sensor detects beat-to-beat intervals (i.e., distance between two subsequent R waves; R-R intervals) to calculate HR as beats-per-minute (bpm). Although HR monitoring can be affected by dry skin, dirty electrodes, or poor strap placement, if used appropriately, ECG sensors measure HRs accurately [50]. Despite this accuracy, ECG monitoring is difficult to conduct in occupational settings because it has to create an electrical loop through the body, often requiring a chest strap, which can be uncomfortable for users. The ECG sensor has also been introduced in an activity tracker worn on the wristband (e.g., Samsung Simband™). However, the wristband remains inadequate for measuring HR while workers are working. Workers are required to touch their non-wristband hand to the sensor in the wristband to create an electrical loop through the body. This motion interrupts the continuity of work or exercise.

Therefore, most wristband-type wearable activity trackers use a photoplethysmography (PPG) sensor for HR monitoring. A PPG sensor applies a light-based technology that consists of a light source and a photodetector, with red, infrared, or green LEDs [53]. Specifically, most off-the-shelf wearable activity trackers for PPG-based HR monitoring (e.g., Basis Peak™, Fitbit Charge HR™, etc.) use two green light sources because of its robustness against signal noises [50]. Using this technology as shown in Fig. 1, the PPG sensor detects different light

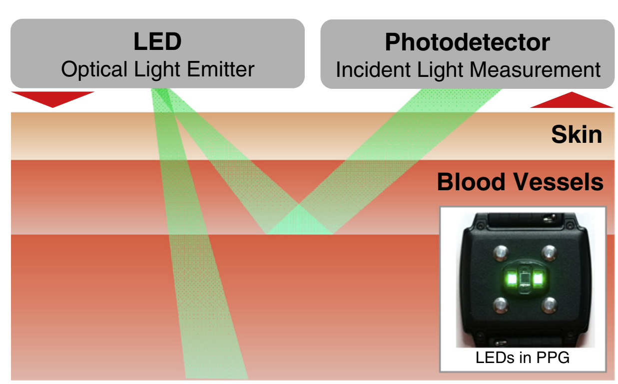

Fig. 1. Description of a PPG sensor.