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Collective sensing of workers' gait patterns to identify fall hazards in construction

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ABSTRACT

Current hazard-identification efforts in construction mostly rely on human judgment, a reality that leaves a significant number of hazards unidentified or not well-assessed. This situation highlights a need for enhancing hazard-identification capabilities in dynamic and unpredictable construction environments. Given the fact that hazards cause disruptions in workers' behaviors and responses, capturing such disruptions offers opportunities for identifying hazards. This study proposes a collective sensing approach that senses and assesses workers' gait abnormalities in order to identify physical fall hazards in a construction jobsite. Laboratory experiments simulating an ironworkers' working environment were designed and conducted to examine the feasibility of the proposed approach. A wearable inertial measurement unit (WIMU) attached to a subject's ankle collected kinematic gait data. The results indicated that the aggregated gait abnormality score from multiple subjects have a strong correlation with the existence of installed fall hazards such as obstacles and slippery surfaces. This outcome highlights the opportunity for future devices to use workers' abnormal gait responses to reveal safety hazards in construction environments.

1. Introduction

The development of wearable sensing technology enables the collection and analysis of individual worker's bodily and physiological responses to work on a job site, an opportunity that was previously unattainable [1–3]. Collecting and analyzing worker's data is especially valuable in the pursuit of increasing safety on a construction site since identifying at-risk workers and safety hazards represents the first step towards mitigating risks. The hazard identification in a construction environment is still a challenging issue due to the lack of resources [4] and the dynamic work environments involved [5]. Construction takes place both indoor and outdoor—often at the same time—and tasks often generate unpredictable work environments such as surface contamination by dust and mud [5]. Different also tasks take place in the same space [5], which yields frequent overlaps in the construction work environment and site changes due to the interaction between various activities. With such dynamic environments, construction sites contain a significant quantity of unidentified or not well-assessed hazards that expose construction workers to additional safety risks during required operations [6,7].

The standard approach to identifying a hazard in construction mainly functions on the basis of the judgment of safety managers or individual workers [6]. However, these approaches still encounter three main challenges in a construction environment: 1) Safety managers must assess multiple areas, a fact that decreases their effectiveness in addressing new safety risks as hazards arise; 2) individuals have different levels of knowledge and experience in identifying hazards; 3) dynamic work environments add complexities that decrease individuals' ability to recognize hazards on the jobsite. Therefore, innovative approaches to identifying hazards would help address such limitations and enhance hazard-identification capabilities to prevent accidents in a construction site.

Among the various types of accidents, slips, trips and falls (STFs) are the primary sources of injuries among construction workers [8,9], and these events result in enormous economic and human losses [10]. With such high risk of STFs, many previous studies have sought to automatically detect STFs through wearable sensing technology [11–15]. In clinical spheres, Bourke and his colleagues developed a threshold-based fall-detection algorithm that uses an accelerometer [11] or gyroscope [12]; their research showed a feasibility of automated detection of fall of patients with wearable sensor. Lai et al. [13] proposed a method for detecting patients' injuries using multiple accelerometers; their outcomes revealed an opportunity of identifying injured body area and estimating severity through data from accelerometers. In the construc-

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tion-safety realm, Lim et al. [14] implemented an artificial neural network model to detect slip and trip events using acceleration data recovered from a smartphone. Dzeng et al. [15] investigated whether it was possible to detect fall portents—*i.e.*, near-miss falls—using embedded IMU sensors in a smartphone. Combined, these studies reveal the feasibility of using wearable sensors to detect occurred STFs in both daily-living or working environments. However, considering the fact that not all fall hazards will result in STFs, current approaches based on retrospectives have limited performance for robust identification of current hazards or future risks. Thereby, different approach that can identify a possible source of STFs (*i.e.*, fall hazards) without experiencing STFs would be necessary to increase the hazard identification performance in construction.

Previous studies revealed that the human body responds to physical environmental changes [16,17]. Accordingly, considering the fact that STFs often begin with bad interactions between a foot and floor-surface conditions, potential sources of STFs could foreseeably be identified by studying changes in a worker's gait pattern (*i.e.*, foot movement patterns) alongside the changes' spatial locations. In this context, this study investigates whether and how measuring workers' gait patterns can help locate fall hazards in a construction jobsite. Specifically, this study used wearable inertial measurement units (WIMU) to collect workers' gait patterns as the subjects responded to fall hazards in a laboratory settings and then computed spatiotemporal gait features to quantify the workers' gait-pattern changes. In order to effectively translate the degree of gait disruption from multiple gait features into a single value, this study defined an IMU-based Gait Abnormality Score (I-GAS); this score first uses the Mahalanobis distance [18] to measure the magnitude of gait disruption generated from fall hazards and then compares the outcome to reference gait data from non-hazardous locations/laboratory setups. Using the different laboratory experimental setups—which simulated ironwork environments—this study verified the existence of gait disruptions at hazard location and showed the feasibility of identifying fall hazards using the proposed I-GAS. Consequently, the results of this study contribute to identifying fall hazards in a proactive manner. The developed technique can thereby help construction managers eliminate the risk of hazards without depending exclusively upon observations or hazard reporting from a construction worker.

2. Research background

Fall accidents are the leading cause of fatalities and account for approximately 30% of all fatalities in construction [19]. Also, falls are one of the major causes of minor injuries in construction, and many workers have suffered a significant number of work disabilities (*e.g.*, contusions and fractures) from fall accidents [20]. Due to the high risks and related costs associated with fall accidents, many studies have sought to reveal and prevent the causes of falls in construction [20–23]. Courtney et al. [20] investigated disabling injuries in construction and identified the sources and types of worker injuries from falls. Cattledge et al. [21] analyzed nonfatal injuries from falls in construction and revealed that ladder and scaffold tasks are major sources of such injuries—these activities account for 50% of all nonfatal fall injuries in construction. Huang et al. [22] analyzed fall-accident records and identified high-risk trades, causes of accidents and other related information (*e.g.*, types of construction projects, fall height, worker's age, height of fall) in construction. Chi et al. [23] identified contributing factors of fatal fall accidents in construction and suggested prevention measures for fall accidents. These studies provide valuable insights about fall-causing environments and situations in construction.

However, hazard identification still relies on individuals' hazard-recognition abilities, which may vary according to experience and knowledge of hazards. In response, previous studies into hazard identification worked to increase individuals' recognition abilities through training programs or training in virtual environments [24–26]. Albert et al. [24] developed a maturity model for enhancing the hazard-recognition capabilities of construction workers and demonstrated the usefulness of the model by observing increases in hazard-recognition levels during construction. Bahn [25] studied the hazard-identification levels of construction workers and showed that length of work experience did not predetermine the hazard-identification performance of an individual. Sacks et al. [26] tested safety training in a virtual construction site and showed the effectiveness of using a virtual reality environment for worker's safety training. Each of these studies helped reveal the significance of worker training and preparation in construction safety.

While training is an effective way to enhance workers' hazard-identification performance, humans' recognition abilities are still subject to surrounding environmental factors (*e.g.*, noise and low light), especially in a dynamic environment such as construction. For example, a slippery surface—which is one of the leading causes of slip events—is challenging to detect in low-light conditions. Also, construction workers often must manually handle material (*e.g.*, carry, pull, or push) during tasks, which often interferes with visibility for hazard identification [5]. Thus, environmental factors during construction can easily undermine current hazard-identification performance, and workers are still at risk of injuries due to unidentified hazards.

It is well-known that existing hazards can cause a certain amount of disruptions in workers' behaviors, and these disruptions can evolve into accidents [27]. Also, falls often begin as a result of unexpected changes between a foot surface and the surface under the foot [28,29]. Thus, fall hazards cause disruptions to workers' gait movements, and these gait-pattern changes can foreseeably provide an insight into the existence of fall hazards. In such circumstances, gait analysis is widely studied to prevent fall accidents or to identify a potential faller in clinical applications [30–34]. In the past, such gait analyses were only available in the laboratory setting using a marker-based motion-tracking system [31,32] or a floor-pressure sensor system [33,34]; however, with the recent developments in wearable sensing technology and analysis techniques, ambulatory gait analysis has become available to outdoor environments through the use of wearable sensor systems. Accordingly, clinical researchers have begun to implement wearable sensor-based gait analysis methodologies to record spatiotemporal gait features (*e.g.*, stride times and stride distances) to then assess the abrupt changes in a patient's gait to measure the risk of falls [35–38]. A single or multiple WIMUs are attached to the subject's lower body parts for ambulatory gait analysis. Then, these sensors record kinematics of leg or foot movements using the accelerometer, gyroscope, and magnetometer imbedded within the WIMU. Previous studies confirmed the accuracy of measuring spatiotemporal gait features using a WIMU and revealed the opportunity for real applications [39–41]. Although these gait analysis techniques have been used to measure the fall risks of patients, no previous studies have used such gait analyses to identify fall hazards in construction environments.

In construction, several studies also used wearable sensing technologies to enhance safety on a construction site while mitigating the difficulties associated with current safety inspections, which depend on human recognition and judgment. Gatti et al. [2] tested a physical monitoring system to measure workers' physiological responses—such as heart rate, breathing rate—for safety monitoring. Cheng et al. [3] proposed the fusion of a location-tracking system and a physiological monitoring system for ergonomic analysis of a construction worker to prevent workers' musculoskeletal or other injuries. Also, different types of sensors, real-time locating systems (RTLS) [42], electromyography (EMG) [43], and electroencephalograms (EEG) [44] were evaluated for identifying hazard proximity and for measuring mental stress and the physical stability of a worker in a construction environment. WIMUs, which include an accelerometer, have been used to monitor a worker's activities and behaviors (*i.e.*, motion tracking) and demonstrated an ability to capture workers' behaviors in construction [45–48]. Joshua and Varghese [45] proposed an activity-recognizing method that is able