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Accelerometer-based fall-portent detection algorithm for construction tiling operation

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ABSTRACT

Fall accidents are a major safety issue and a perennial problem in the construction industry. However, few studies have focused on detecting fall portents, identification of which may prevent falls from occurring. This study developed an accelerometer-based fall portent detection system that employed a hierarchical threshold-based algorithm. We designed tiling experiments to evaluate the performance of the proposed system. The participants performed the tasks under normal, inebriation, and sleepiness conditions on a scaffold while four accelerometers were attached to their chest, waist, arm, and hand. The results revealed that the traditional threshold-based algorithms had unacceptable accuracies of less than 30.66%. Most false warnings could be attributed to misidentifications of work-related motions. However, the work-related motions had a limited effect on the hierarchical threshold-based algorithm, which exhibited a satisfactory detection rate and accuracy of 76.86% and 79.13%, respectively.

1. Introduction

1.1. Fall accidents in the construction industry

The construction industry is one of the most hazardous industries, with a high number of employee injuries and fatalities. The majority of accidents can be attributed to falls. The Ministry of Labor (MOL, the highest administrative office responsible for labor affairs and safety in Taiwan) reported that falls contributed to approximately 52.46% (1260 of 2402) of construction-work-related fatalities from 2000 to 2014. Moreover, fall accidents represented approximately 61.39% (528 of 860) of fatalities from 2010 to 2014, with the percentage especially high in 2011 (67.07%; 110 of 164) and 2013 (64.50%; 124 of 192) [1]. The causes of fall accidents on construction sites seem to be largely unresolved, as indicated by fatality records. Fall prevention and safety management on construction sites are still insufficient or ineffective and require considerable improvement.

Fall accidents are a severe and perennial problem in numerous countries. The U.S. Bureau of Labor Statistics (BLS) reported that 36.00% of fatalities (1231 of 3419) were related to fall accidents in the U.S. construction industry from 2011 to 2014 [2]. The Singapore Workplace Safety and Health Report indicated that 30% of that country's construction fatalities are due to fall accidents [3]. Fall accidents cause the majority of fatalities in the European construction industry, accounting for 52% of all accidents [4]. Approximately 40% of fatal accidents are caused by falls in the Japanese construction industry [5]. Fall accidents also represent the largest proportion of work-related fatalities (181 of 606) in the Korean construction industry [6]. Furthermore, falls from scaffolds are one of the leading causes of the entire fall fatalities and injuries [7].

1.2. Near-miss accidents, accident precursors, and fall portents

The most frequently employed fall-prevention approaches such as safety facilities and personal protective equipment inspection only mitigate the injuries caused by a fall, instead of preventing the fall itself. If the precursors or portents of falls can be identified and detected, significant improvement in fall prevention may be possible [8]. Near-miss accidents are usually referred to as precursors of accidents [9], which are indicators of potential accidents or imminent signals that an accident will occur [10,11]. The causal pathways of near-miss accidents are similar to those of actual accidents [12]. Furthermore, near-miss accidents are a special precursor, which often result in no actual damage or injury but in some circumstances may result in great harm [13,14]. Thus, near-miss accidents may be considered an effective learning source and tracking method for fall prevention [15].

Identifying accident precursors has great potential to improve safety performance in the construction industry [8,15]. Wu et al.

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demonstrated that 90.9% of all accidents produced no injuries [16], whereas 8.8% resulted in minor injuries and only 0.3% caused major injuries [17]. Therefore, 300 near-miss accidents approximately result in thirty minor injuries and one major injury [18,19]. Additionally, near-miss accidents and minor injuries on construction sites occur at a much higher rate than more severe accidents [16,17], and tracking near-miss accidents in real time can help supervisors take appropriate actions before a potentially more severe accident can occur [16]. Similarly, Jones et al. discovered that the more near-miss accidents are identified, the lower the actual accident rate [11]. Near-miss accidents, accident precursors, and fall portents can thus be considered the conditions, events, and sequences that precede a fall accident [13], so detecting and identifying them may help prevent fall accidents from occurring [20–22].

Although near misses, precursors, and portents can provide essential information for safety management, identifying such events is difficult practically. Approximately 22 near misses per project were documented in one study: however, identifying the different types of near misses and then analyzing their relative frequencies and possible consequences was challenging [21,23], possibly because of a lack of legal requirements regarding near-miss-accident reporting and investigation. The lack of an effective system to identify near misses, precursors, and portents on construction sites may be the current critical deficiency of safety management [24]. Some researchers have begun to use text mining and network analysis technologies to extract precursors from unstructured accident reports [8,25].

Some studies have focused on developing a near miss and accident precursor detection system using location-tracking technologies [4,15,16,26–34]. Carbonari et al. employed ultra-wideband (UWB) technology to detect whether a worker accessed potentially dangerous areas such as those where tools, materials, or other objects could fall from above [4]. Lee et al. established a mobile safety monitoring system consisting of a mobile sensing device for detecting workers approaching hazardous areas [26]. To avoid workplace congestion, Zhang et al. used global positioning system (GPS) data of workers to visualize the workforce location on a building information modeling (BIM) [27]. Furthermore, some researchers integrated a real-time location tracking system with statistic model for dynamic safety risk evaluation [28,29]. Li et al. established a chirp-spread-spectrum-based locating system [30], and further developed a stochastic state sequence model to predict discrete safety states (i.e., hazardous, risky, admonitory, and safe). The proposed model could identify the hazard to an individual worker based on their route through a real-time location system on construction sites [29].

Location-tracking technologies can also be applied to equipment (e.g., trucks and excavators) for improving both safety and productivity management [31]. Wu et al. used a designed Zigbee RFID sensor network to track near-miss accidents based on the real-time locations of labor, machines, and materials on a construction site, and the network could be applied to prevent fall, struck-by, caught in/between, and electric shock accidents [15,16]. Golovina et al. used GPS, equipment blind spot measurement, and proximity alert technology to prevent struck-by accidents between workers and construction equipment [32]. In addition to the aforementioned sensor-based location-tracking technologies, visualization technologies (i.e., image-based location) can also monitor the movements of workers and equipment [33]. Zhu et al. applied multiple surveillance videos to predict future positions of construction workers and mobile equipment [34].

Several monitoring techniques have been proposed to improve safety or jobsite management using location-tracking technologies, such as RFID, GPS, UWB, and visualization technologies to monitor whether a worker is entering a hazardous area. However, such technologies cannot monitor and identify whether a worker is physiologically fit for work. A lack of body and posture stability is one of the primary factors contributing to fall accidents [35]. Near misses and injuries can follow abnormal physiological statuses or adverse symptoms, and workers who have such symptoms are at a great risk of having an accident [36]. Some researchers have begun to evaluate the relationship between motion behaviors and accidents [22,35,37]. For instance, Cheng et al. integrated location tracking and motion capture technologies to evaluate the productivity and safety status of construction workers [37]. Abnormal physiological behaviors such as loss of balance, sudden sways, or unsteady footsteps may also be suitable portents or precursors to fall accidents.

1.3. Individual monitoring system with inertia sensors

Due to the heavy physical requirements of construction activities and their unhealthy lifestyles (e.g., alcohol abuse, night shifts, and insufficient rest periods), construction workers are liable to fatigue, muscle pains, and loss of balance (LOB). When their physiological status continuously deteriorates because of inappropriate rest, injuries or fatal accidents can occur [38]. Most high-elevation workers have experienced discomfort such as unsteady footsteps and waist pain, and their self-reported rates of such discomforts are considerably higher than those of ground-level workers [39]. Numerous researchers have identified a strong correlation between fall accidents and LOB [40–43]. Poor body postural stability has been revealed to be one of the major factors increasing fall risk [35,44]. The strong correlation between fall accidents and LOB demonstrated in the literature indicates that the real-time monitoring and analysis of the balance of workers may help identify fall portents and thus prevent falls.

Several researchers have successfully employed inertia sensors such as accelerometers and gyroscopes to distinguish different types of motions, and they have argued that inertia sensors have advantages of low cost, portability, small size, and ease of operation for monitoring daily activities [45–50]. Such sensors can measure velocity, acceleration, orientation, and gravitational forces, and the acceleration data can be used to monitor the physiological condition of a human body [51]. In the construction industry, inertia sensors could be used for the safety, productivity, and health monitoring of workers [38]. Jebelli et al. evaluated the postural stability of construction workers using inertia sensors and force plates, and the results demonstrated that the acceleration data can indicate the fall risk associated with the different tasks construction workers must perform [35]. Tsai employed a mobile phone with a built-in accelerometer to monitor construction workers and prevent fall accidents [52]. In our previous studies, we used a smartphone attached to participants' waists to detect fall portents, and the threshold algorithm used exhibited an acceptable accuracy of 88.5% in a working scenario [22,53]. Schall et al. employed inertial sensors to measure thoracolumbar trunk motion and evaluated the potential risk of work-related musculoskeletal disorders (e.g., low back pain) when workers performed manual material-handling activities [54]. Alwasel et al. also used inertial sensors to monitor the kinematics of workers' shoulder movements and further prevent construction work–related musculoskeletal disorders [55].

Safety monitoring must not only monitor workers' physiological status (e.g., fatigue, illness, or inebriation), but also detect any dangerous motions caused by adverse physiological status before an actual accident occurs. Several researchers have successfully employed motion monitoring, respiratory monitoring, and heart-rate monitoring to assess the physiological status of construction workers [56–59]. Presently, numerous construction sites have alcohol-free-workplace policies to ensure workers are sober and physiologically able to perform their duties. Such policies are implemented using breathalyzers at the gates of construction sites (e.g., the breathalyzer detects whether a worker has consumed any alcohol and monitors whether a worker is being exhausted by detecting their oxygen consumption and respiratory rate) [56–59].

To prevent construction accidents, the safety monitoring of construction workers requires constant but interference-free monitoring of their dangerous motions before actual accidents occur. The continuous