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Semi-supervised near-miss fall detection for ironworkers with a wearable inertial measurement unit

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ABSTRACT

Accidental falls (slips, trips, and falls from height) are the leading cause of occupational death and injury in construction. As a proactive accident prevention measure, near miss can provide valuable data about the causes of accidents, but collecting near-miss information is challenging because current data collection systems can largely be affected by retrospective and qualitative decisions of individual workers. In this context, this study aims to develop a method that can automatically detect and document near-miss falls based upon a worker's kinematic data captured from wearable inertial measurement units (WIMUs). A semi-supervised learning algorithm (i.e., one-class support vector machine) was implemented for detecting the near-miss falls in this study. Two experiments were conducted for collecting the near-miss falls of ironworkers, and these data were used to test developed near-miss fall detection approach. This WIMU-based approach will help identify ironworker near-miss falls without disrupting jobsite work and can help prevent fall accidents.

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1. Introduction

The construction industry is considered one of the most dangerous industries in the United States. Among construction-related accidents, fall accidents are one of the leading causes of fatalities and account for more than 30% of fatal accidents during recent decades [1]. Ironworkers are exceptionally susceptible to fall accidents and face the highest lifetime risk of fatal injuries among construction trades [2]. According to Beavers [3], between 2000 and 2005, more than 75% of fatal ironwork accidents were caused by fall accidents. Such high fatality rates among ironworkers are rooted in various factors: (1) most of the time, ironworkers are working on narrow surfaces of structural steel beams installed at high elevations and are thereby exposed to numerous open edges, and (2) ironwork construction consists of physically demanding tasks such as handling heavy steel materials (e.g., beams, columns, and steel plate) and equipment for steel erection. These work characteristics contribute to the risks that ironworkers face in their daily tasks.

Due to the high risk of fall accidents among ironwork erection projects in general construction, the Occupational Safety and Health Organization (OSHA) requires the use of fall protection measures such as guardrails, safety nets, and personal protective equipment to protect workers when working at elevation. The current safety measures for fall accidents are classified as active/primary protection measures (e.g., guardrails and covers), which physically prevent the occurrence of falls, and passive/secondary protection measures (e.g., personal fall arrest systems, safety nets), which help to prevent or minimize injury from falls [4,5]. While passive/secondary protection measures are generally employed for ironworkers, the use of active/primary fall protection measures is limited due to the constraints of ironworkers' working environments. This shortcoming faces particular criticism since current fall protection measures emphasize reducing the severity of an injury rather than proactively preventing a fall accident [6]. As an example, the use of a personal fall arrest system (PFAS) does not prevent the occurrence of fall itself during ironwork. Although the proper use of PFAS can save the life of workers who fall after losing their balance, being suspended in a harness may result in a suspension trauma, orthostatic intolerance, or other, more severe injuries [7]. Moreover, many workers still get injured due to using incomplete or inadequate fall protection devices [8].

In pursuit of a proactive approach for preventing accidents (including falls), researchers have turned their attention to collecting and utilizing accident leading indicators [9,10]. Leading indicators are conditions, events, or measures that are valuable in predicting the future occurrence of undesirable events, including accidents, incidents, or near misses [9]. Leading indicators are designed to monitor the safety process by identifying gaps between the current environment and the recommended settings [9,11]. The knowledge identified through this monitoring is then used to decrease the possibility of injury occurrence [11]. Thus, such indicators are associated with proactive approaches seeking to identify, assess, and eliminate a related risk [10]. A near

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miss is one such accident leading indicator [11,12] and is defined as an event that causes no damage or loss at the time of occurrence but could have materialized into an actual accident in a slightly different environment [13]. Near misses have been widely used to reduce the likelihood of future accidents in diverse industries (e.g., chemical, airline, nuclear, railroad, medicine, and construction) by detecting systemic flaws and managing such flaws by removing risk factors before accidents occur [14–17]. Thus, having knowledge about near misses (e.g., cause, worker, and location) can help identify hazardous elements and vulnerable workers. This knowledge can also provide opportunities to eliminate such hazardous conditions at the job site or to alert possible victims that they need to change their behavior before an accident. For this reason, identifying and collecting near misses is an important step in implementing proactive accident prevention measures.

Previous studies of utilizing near misses for occupational safety have emphasized the importance of near misses and introduced different applications of near-miss data [12,14,18–20]. In such cases, the collection of near-miss data mainly depends on a self-reporting system of workers. However, collecting near-miss data using a reporting system is not an easy task since such an approach is easily influenced by qualitative and retrospective decisions based upon the perceived attitudes of individual workers, such as, fear of discipline, acceptance of risk, and inconsistent perception of near-miss falls [18]. One of the available methods for collecting quantitative near-miss data is using a technology solution—such as Ultrasound or RFID—to acquire real-time information about workers' exposure to known jobsite hazards [21]. However, such a proximity-based approach is not sufficient to capture near misses that are caused by unknown hazards or not triggered by physical hazards. Alternatively, one promising technology is WIMUs, which can document subtle body movements (i.e., acceleration, angular velocity) with a 3-axis accelerometer, gyroscope, and magnetometer. In previous studies, WIMUs were widely used in fall detection [22–26], activity recognition [27–33] and gait analysis [34–36]. Due to its small size, a WIMU can be easily attached to the body of a subject and can transmit kinematic data through wireless communication. Thus, WIMUs have the potential to be widely deployed as a wearable tool on construction sites. To this end, this study utilizes WIMUs to document ironworkers' near-miss falls and developed a near-miss falls detection approach.

2. Research background

Many previous studies have focused on identifying fall accident risk factors to increase worker safety in construction. Chi [4] investigated accident patterns of previous fatal fall accidents and proposed accident prevention measures for each type of accidental scenario. Huang [8] identified factors related to fall accidents (i.e., cause of accident, fall height, and accident-related elements) based on accident records from OSHA, and Cattledge [37] studied injury records of nonfatal falls and identified problems with current fall accident prevention measures. As a proactive approach to accident prevention, Wu [12] developed a systematic model for identifying near-miss information from ongoing project using knowledge from historical accident database. Wu deduced knowledge from previous accidents and applied this knowledge to an ongoing construction project with a real-time near-miss tracking and reporting system that used RFID technology. Cambraia [19] provided near-miss guidelines utilizing near-miss information for accident prevention. Cambraia collected near-miss data from construction projects, analyzed the risks of identified near misses and suggested recommendations for implementing a near-miss system. Finally, Navon [38] introduced an automated fall-hazard monitoring system for construction sites. This study identified the risks of fall accidents in activities included in project schedules and proposed a guardrail installation measures to prevent fall accidents. Also, this study monitored the status of guardrail installation (e.g., missing or incomplete) through wireless communication to enhance worksite safety.

However, previous studies have only focused on investigating previous accidents to derive general recommendations [4,8,37] or on identifying potential accidents using previously known hazards and locations [12,19,38]. Moreover, previous techniques have failed to consider individual workers, who are actually at risk of accidents while working on construction sites. In particular, proximity-based systems [12,38] require substantial resources to prevent ironworker fall accidents since this population almost always works near open edges on narrow-surface steel beams. This exposure problem is compounded by the fact that ironworkers have only a small surface space to recover from even a small degree of balance loss, and current proximity-based systems do not address this issue in real time. These shortcomings of proximity-based systems emphasize the current challenge in implementing fall-prevention for ironworkers and highlight the reasons this population is still at the high risk of fall accidents in construction.

Information technology-based construction site data (e.g., about workers, work environment) collection measures assist in increasing the ability to store, retrieve, and manipulate data during the construction process [39]. As a possible alternative to capturing near-miss data, a WIMU, which includes an accelerometer, a gyroscope, and a magnetometer, can robustly document and wirelessly communicate human movement data. This advantage has led to the use of WIMUs for fall detection to increase the safety of patients and workers [22–26]. In biomedical studies, attaching accelerometers to the body is a widely used approach for detecting fall accidents, especially for the elderly [22,24]. Automated detection of fall accidents using wearable sensors has been considered a promising method for protecting the elderly or people with a disability from an unidentified fall risk. In previous biomedical studies [22–24], the key research objective focused on detecting fall accident situations or accident-related conditions such as accident location, severity of injury, or injured body parts. These previous studies approached fall accident detection by detecting strong accelerometer signals from when a subject actually fell to the ground rather than by identifying or monitoring dangerous movements (e.g., loss of balance) that reveal informative data about future or potential fall accidents. This limited focus is problematic for translating biomedical research to ironworkers since according to Beavers [3], loss of balance (LOB) is one of the major proximal causes of fall accidents for ironworkers, and LOB is cited as contributing to most unintentional falls even in spite of the lack of a quantitative definition [40].

There are a few studies that attempt to detect near-miss falls—sometimes called “near-falls”— automatically using body-attached sensors. In one such study, Weiss et al. [41] investigated subjects walking on treadmills to detect near-falls in normal activities. To generate near-fall data, different types of obstacles were placed in the walking path at random. In his study, he defined near-falls similarly with trip accidents. Many accelerometer-related features (e.g., signal vector magnitude, normalized signal magnitude area, and other derived features) were tested in his study with an 85% sensitivity and 88% specificity with one feature (i.e., vertical maximum peak to peak acceleration amplitude derivative). The study also showed an 85% sensitivity and 90% specificity with the combination of two features (i.e., vertical maximum peak to peak acceleration amplitude derivative and vertical maximum acceleration). This study reveals the possibility of near-miss fall detection using body-attached accelerometers in a controlled laboratory environment. In the construction domain, Dzeng et al. [42] used a smartphone accelerometer and gyroscope to detect fall portents (e.g., swaying, unsteady footsteps, and loss of balance), which are referenced by self-reporting and video observation. To detect fall portents, Dzeng et al. measured the signal magnitude vector using accelerometer or gyroscope and detected the fall portents using a threshold-based detection approach. As a result of this approach, Dzeng et al. acquired 88.5% accuracy for detecting fall portents from construction tiling workers on a scaffold.

Although previous near-miss fall detection methods demonstrate their feasibility for detecting fall-related near misses, they predominantly

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