Automation in Construction 96 (2018) 189–199

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Automated detection and classification of construction workers' loss of balance events using wearable insole pressure sensors

Maxwell Fordjour Antwi-Afari[a], Heng Li[a], JoonOh Seo[a,*], Arnold Yu Lok Wong[b]

[a] Dept. of Building and Real Estate, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region
[d] Dept. of Rehabilitation Sciences, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region

ARTICLE INFO

Keywords:
Construction workers
Falls on the same level
Insole pressure sensors
Loss of balance
Supervised machine learning

ABSTRACT

Fall on the same level is the leading cause of non-fatal injuries in construction workers; however, identifying loss of balance events associated with specific unsafe surface conditions in a timely manner remain challenging. The objective of the current study was to develop a novel method to detect and classify loss of balance events that could lead to falls on the same level by using foot plantar pressure distributions data captured from wearable insole pressure sensors. Ten healthy volunteers participated in experimental trials, simulating four major loss of balance events (e.g., slip, trip, unexpected step-down, and twisted ankle) to collect foot plantar pressure distributions data. Supervised machine learning algorithms were used to learn the unique foot plantar pressure patterns, and then to automatically detect loss of balance events. We compared classification performance by varying window sizes, feature groups and types of classifiers, and the best classification accuracy (97.1%) was achieved when using the Random Forest classifier with all feature groups and a window size of 0.32 s. This study is important to researchers and site managers because it uses foot plantar pressure distribution data to objectively distinguish various potential loss of balance events associated with specific unsafe surface conditions. The proposed approach can allow practitioners to proactively conduct automated fall risk monitoring to minimize the risk of falls on the same level on sites.

1. Introduction

Falls are the primary cause of construction workers' injuries [1]. In Hong Kong, statistics show that workers' injuries associated with falls accounted for almost half of the construction injuries [2], and about HK $ 40 million of total compensation in 2008 [3]. Especially, falls on the same level are one of the most significant causes of construction workers' injuries in Hong Kong, accounting for about 20% of construction accidents [4]. Compared with falls from height, the severity of injuries from falls on the same level is relatively low (generally leading to non-fatal injuries), but they are the most frequent types of injuries in construction, accounting for 40% of non-fatal fall injuries [5,6]. Given that these fall injuries can cause a delay in construction schedule, decrease productivity, and increase economic burden [7], the prevention of falls on the same level is an important priority in the construction industry [8].

Previous studies have shown that falls on the same level occur when workers suddenly lose their balance because of loss of balance events such as slips, trips, unexpected step-downs and twisted ankles [9–11]. Numerous intrinsic and extrinsic risk factors can lead to loss of balance events on construction sites [12]. While some intrinsic risk factors are non-modifiable (e.g., cerebellar problems) and modifiable (e.g., physical fitness, agility, fatigue, and attention etc.) [12], most of the extrinsic risk factors for falls on the same level on construction sites are related to unsafe environmental surface conditions such as uneven work surfaces, the presence of an obstacle or contaminant, and slippery surfaces [12,13]. For safety officers and managers at construction sites, identifying and detecting loss of balance events associated with unsafe environmental surface conditions are crucial to prevent same-level fall accidents. However, previous studies usually relied on experts' judgments and retrospective data (e.g., accident reports) for injury analysis and identifying loss of balance events associated with fall risk factors [14,15]. Despite the value these prior studies, their approaches not only might involve a subjective bias or missing data [16], but also might unable to prevent continuous monitoring of fall risk factors due retrospective nature of these studies [11].

To address these issues, we propose real-time detection and classification of loss of balance events by using wearable pressure insole

* Corresponding author.
E-mail addresses: maxwell.antwiafari@connect.polyu.hk (M.F. Antwi-Afari), heng.li@polyu.edu.hk (H. Li), joonoh.seo@polyu.edu.hk (J. Seo), arnold.wong@polyu.edu.hk (A.Y.L. Wong).

https://doi.org/10.1016/j.autcon.2018.09.010
Received 21 March 2018; Received in revised form 24 July 2018; Accepted 19 September 2018

sensors that measure foot plantar pressure distributions. Each loss of balance event (e.g., slips, trips, unexpected step-downs and twisted ankles) is associated with specific unsafe environmental surface conditions (e.g., slippery floors, uneven surfaces or obstacles on the path etc.), creating unique foot plantar pressure distribution patterns measured by using wearable insole pressure sensors. Supervised machine learning algorithms were developed to classify types of loss of balance events by using spatial and temporal features that reflect the unique plantar pressure data patterns. Detecting workers' loss of balance events provide useful information for (1) diagnosing potential causes (i.e., types of unsafe environmental surface conditions) of falls on the same level and (2) implementing appropriate interventions for construction workers who are more vulnerable to a loss of balance under given conditions. To test the detection performance, we conducted laboratory experiments to collect foot plantar pressure distribution data from simulated loss of balance events, and applied developed supervised machine learning algorithms. Based on the testing results, the feasibility of the proposed approach and its potential application areas were discussed.

2. Research background

2.1. Fall risk factors and preventive measures of falls on the same level

Understanding the underlying mechanisms of fall risk factors that may lead to falls on the same level is essential to identify and detect loss of balance events, and this could eventually help safety managers to implement effective preventive measures [17]. Fig. 1 presents the role of intrinsic and extrinsic risk factors that may lead to falls on the same level. As shown in Fig. 1, intrinsic risk factors are related to either an individual's perceptual ability to identify any existing unsafe conditions or motor control ability to recover from imbalance. Besides, extrinsic risk factors are associated with occupational environments and work organization [12]. Among the extrinsic risk factors (see Fig. 1) that may lead to falls on the same level, unsafe environmental surface conditions such as the presence of obstacles, uneven work surfaces, and slippery surfaces have been reported to be the most prevalent risk factors [18,19]. By analyzing more than 20,000 recorded falls in the United Kingdom, Manning [20] found that there are four major types of loss of balance events that could lead to falls on the same level: 1) slips; 2) trips; 3) unexpected step-downs; and 4) twisted ankles. These four events account for more than 90% of unsafe environmental surface conditions that resulted in falls on the same level [20]. They are directly associated with specific unsafe environmental surface conditions (i.e., extrinsic risk factors), such as a slippery surface (a slip), an obstacle on a walkway (a trip when striking it and a twisted ankle when stepping on it) and an uneven surface (unexpected step-down) [21]. As a result, identifying loss of balance events associated with specific unsafe environmental surface conditions are of importance to safety managers to propose appropriate interventions to prevent falls on the same level injuries.

Kaskutas et al. [22] reported that the two most effective preventive measures used to minimize the risk of falls on the same level are: (1) safety training programs [23,24], and (2) behavior-based management techniques such as goal-setting, motivational technique etc. [25,26]. However, current methods such as observations, surveys and retrospective reports that are used to assess the aforementioned preventive measures may encounter some inherent challenges on construction sites for identifying loss of balance events [16]. These challenges include but not limited to the: (1) dynamic and continuous changing of construction working environment; (2) differences in individuals' intuition, background, experiences and knowledge in reviewing these methods; (3) increase in resources and supply components at various stages of construction; and (4) inability of safety managers to assess the severity and frequency of occurrences of multiple risk factors in real time [27,28]. Taken together, there is a crucial need to introduce an efficient approach and a novel method for automated detection and classification of loss of balance events associated with specific unsafe environmental conditions that could help address such limitations and enhance the implementation of effective fall preventive measures.

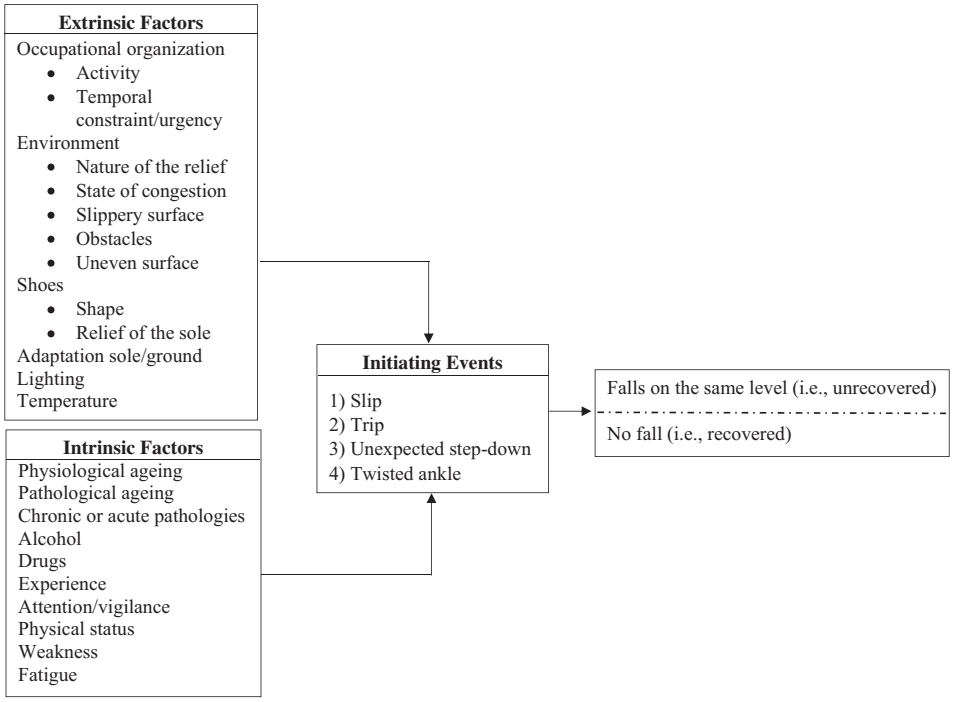

Fig. 1. Mechanisms of falls on the same level.
(Adopted from Gauchard et al. [12])