Automation in Construction 94 (2018) 438–448

Contents lists available at ScienceDirect

Automation in Construction

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

Development of a tool to monitor static balance of construction workers for proactive fall safety management

Waleed Umer[a,*], Heng Li[a], Wei Lu[a], Grace Pui Yuk Szeto[b], Arnold Y.L. Wong[c]

[a] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region
[b] School of Medical & Health Sciences, Tung Wah College, 31 Wylie Road, Homantin, Kowloon, Hong Kong Special Administrative Region
[c] Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region

ARTICLE INFO

Keywords:
Fall prevention
Proactive safety
Wearable Inertial Measurement Unit
Construction industry

ABSTRACT

The construction industry around the globe is afflicted with an exorbitant rate of fatal and non-fatal falls. To lower the propensity of the falls, researchers and safety experts have recommended to supplement the traditional passive fall safety measures with some active measures (such as early identification of task/environmental hazards and personal risk factors). Unfortunately, at present, there is no readily available onsite tool which could identify workers with poor postural controls. This study aimed to develop a static balance monitoring tool for proactive tracking of construction workers on-site using a wearable inertial measurement unit (WIMU) and a smartphone. To this end, a three-phase project was conducted. Firstly, a validation study was conducted to examine the validity of using WIMUs to detect task/fatigue-induced changes in static balance during a 20-second static balance test. The results of the study revealed that WIMUs could detect the post-task subtle changes in static balance with reference to the findings of a force-plate (considered as industrial standard). Secondly, since there were no existing static balance classification methods, five experts were engaged to establish balance classification thresholds using the fuzzy set theory. Thirdly, a mobile phone application was developed for the managers/foremen for onsite balance monitoring of the construction workers using the 20-second test at different times of the day and establishing their corresponding balance performance profiles. This would assist early identification of fall prone workers, plan mitigation schemes before a fall accident happens and ultimately help reduce falls in the construction industry.

1. Introduction

1.1. Background

Around the globe, fall accidents are a substantial burden and an impediment to accomplish occupational safety in the construction industry. During the year 2015, falls accounted for 40% of the total fatal accidents in the US private construction industry [1]. In the UK, almost one-half of the all industrial fatalities every year are associated with construction fall accidents [2]. Likewise, the fatal fall accidents in the Australian construction industry accounted for more than one-third of all falls from height fatalities during 2003 to 2015 [3]. Similarly, falls constitute a major proportion of accidents in the construction industry in China, Hong Kong, South Korea, Japan and Singapore [4–6]. While statistics indicate that falls result in a considerable number of fatal injuries, non-fatal fall injuries are also severely afflicting the global construction industry by placing significant economic, emotional and medical burden on the affected workers, their families and societies [7]. In addition to the medical expenses, non-fatal falls cause losses to construction companies in forms of work absenteeism, productivity loss and compensation claims [7,8]. For example, a typical non-fatal fall accident caused an average of ten days of work absenteeism in the US construction industry from 1992 to 2000 [9]. Likewise, the highest number of compensation claims filed in the Hong Kong construction industry were related to non-fatal falls [10]. Taken together, reducing the risk of falls has become an important priority for researchers and practitioners alike in the construction industry.

1.2. Fall risk assessment in the construction industry

Various methods have been suggested in the literature for fall risk assessment in the construction industry. Traditionally, these include but

* Corresponding author.
E-mail addresses: waleed.umer@connect.polyu.hk (W. Umer), heng.li@polyu.edu.hk (H. Li), wayne.lu@polyu.edu.hk (W. Lu), graceszeto@twc.ed.hk (G.P.Y. Szeto), arnold.wong@polyu.edu.hk (A.Y.L. Wong).

https://doi.org/10.1016/j.autcon.2018.07.024
Received 23 December 2017; Received in revised form 13 July 2018; Accepted 31 July 2018
0926-5805/

are not limited to the review of fall archival data [11,12], interviews of fall affected workers [13], site inspections [14], schedule oriented site/work safety plans [15], combined use of virtual reality and 4D construction plans [16,17] and Building Information Modelling (BIM) integrated safety rules approach [18]. Although considerable fall prevention efforts have been made, falls still outweigh the other reported construction accidents [11,19,20]. One possible reason for this phenomenon may be ascribed to the shortcomings of traditional practices/techniques of fall risk identification, and passive fall protection measures [21]. For example, the use of archival data may not always reveal the actual cause of a fall incident because of probable bias, experiences and beliefs of the reporter and the subjective nature of interpretation [11,22]. Similarly, other methods (such as safety plans) cannot take into account the dynamic interactions of workers, machinery and materials, which require real-time risk identification and mitigation methods [23,24]. More importantly, these risk methods do not consider personal fall risk factors (such as physiological traits, personal health, fatigue, age and body mass index) which are considered to be a major contributor to falls [11,12].

Despite the shortcomings of existing risk identification methods, various fall protection measures have been implemented on construction sites. These include the use of personal fall arrest systems, installation of guardrails, deployment of safety nets [21,25], hole (openings) coverings [25], warning-line systems [7] and fall risks scheduling for better risk management [26]. While these passive measures may prevent workers from falls, they cannot proactively identify risk factors for loss of balance, or distinguish workers with poor balance ability [23] such that proper training or education can be given. Additionally, under certain situations, the deployment of aforementioned passive measures becomes nonpragmatic (such as working in a controlled decking zone) or these measures are not available to construction workers [21,27,28], which in turn increases the risk of falls.

To better strategize against falls, it is essential to develop proactive strategies to identify task and environment related fall risks and to discern construction workers with poor balance controls [7,11,23]. Given that many construction trades are labor intensive and physically demanding, these work tasks may leave the workers susceptible to fatigue, muscle pain and distraction which could afflict the balance of construction workers [23,29–31]. For instance, it is not uncommon for construction workers to be involved in heavy manual material handling and working on sloped surfaces that can disturb their postural stability [23,32–34]. If such fall risks can be identified proactively, remedial measures could be taken. For example, Umer et al. found that commonly adopted rebar tying postures in squatting or stooping may lead to the subsequent suboptimal control of standing balance [23]. Accordingly, they developed an ergonomic intervention using stool-sitting to significantly improve the standing balance after rebar tying tasks [23]. Furthermore, it is essential to identify fall risks in construction jobsites because multiple factors (personal, task-related and environmental risks) may present and interact concurrently. While each individual risk factor might have a minimal effect on balance control [35], these factors may interact with one another to compromise the balance of workers [36,37]. In fact, since loss of balance is known to be a major cause of falls on construction sites [21,38–42], it is paramount to proactively monitor the balance of the construction workers at different times of the day and plan appropriate mitigation strategies.

1.3. Recent related fall prevention studies in the construction industry

Traditionally, the fall prevention research in the construction industry was focused on optimum utilization of personal safety equipment and other allied fall protections. Lately, with recent technological advancement, efforts are underway to detect and mitigate fall risk factors before any accident occurs. Fall risk assessments have been used in health research for a long time. For example, balance assessments in community-dwelling elderly can provide information about the necessity of using walking aids and help caretakers taking care of seniors [29]. Likewise, there is a pressing need to proactively identify fall risk factors in construction workers because fall incidents in the construction industry could cause serious injuries or fatality [21,41]. Dzeng et al. [29] studied the feasibility of detecting falls and fall portents (unsteady stepping, swaying or loss of balance) using mobile phone gyroscope and accelerometer. They reported that the accelerometer data was suitable for future fall and fall portent detection on actual jobsites. Recently, Fang and Dzeng extended their work by attaching multiple accelerometers to various body parts and utilized a hierarchical threshold-based algorithm to successfully curtail the false alarm rate for detecting fall portents for tile-fixing [43]. Jebelli et al. [41,44] demonstrated that wearable inertial measurement units (WIMUs) are sensitive to differentiate between different static work postures. They recommended the development of a tool to monitor fall risk in future. Besides exploring fall portents and static postures, studies have also explored the feasibility of WIMUs to detect fall risks during walking. Jebelli et al. [45,46] experimented with different walking tasks of varying difficulty levels to assess the capability of a WIMU in distinguishing them. They found that it was able to significantly differentiate difficult walking tasks from the easier ones. Similarly, Yang et al. [47] successfully employed a semi-supervised learning algorithm to identity non-stable gait sections during simulated walking on iron beams using WIMUs. Likewise, Kim et al. [48] and Yang et al. [49] showed that collective acceleration responses (acquired using WIMUs) from workers could be advantageous in identifying unsafe locations on a construction site. Building on this concept, they successfully experimented augmentation of the gait data with spatial (location) information to identify fall hazards on a worksite [50]. Recently Kim et al. [51] illustrated the use of WIMUs to quantify and differentiate the risk of slipping caused by various coatings of steel beams. Collectively, these studies have advanced our understanding pertinent to pro-active monitoring of fall hazards and abnormal gait patterns.

1.4. Research gap

Despite aforementioned advances, to date, there is no readily available tool that can be deployed by site managers or foremen to evaluate the static or dynamic balance of the construction workers on site [41]. Static balance ability is known to be a predictor of: falls in the elderly community [52], ankle sprains in teenagers [53,54] and prospective falls among construction workers [23]. Generally, the static balance test requires a person to stand as stable as possible to keep the movement of his center of gravity at a minimum, usually for a minimum duration of 20-second [55,56]. Traditionally, force-plates are considered as an industrial standard for static balance assessment. However, given their excessive weight and size, higher cost, and requirement of additional electronic and power components, it is not feasible to use them at construction sites [57].

Recent WIMU related fall prevention studies can be broadly classified into two categories: (1) static and (2) dynamic. Static studies primarily investigated the capability of using WIMU signals to differentiate different static work postures in a laboratory setting and to detect the risk of falls during stationary work tasks [29,41,43,44]. On the other hand, dynamic studies explored the feasibility of using WIMUs to characterize gait patterns under different situations (e.g. normal walking, obstacle passing, walking on slippery surfaces, walking with a load) based on data collected from an individual [46,47] or a group of participants [27,45,49–51]. Importantly, no previous studies have developed tools to evaluate static or dynamic balance of construction workers as to help identify individuals with poor balance skills and to plan appropriate preventive measures. Additionally, with respect to static balance, despite the ability of WIMUs to classify postures [41], it remains unclear whether WIMU can detect temporal changes in static standing balance induced by construction tasks tested in the same posture. In many instances, these changes may be unobservable by