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

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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.

Keywords

Fall prevention; Proactive safety; Wearable Inertial Measurement Unit; 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 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 of 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 vision technologies but the detection of such changes may help predict the risk of fall in future.

Accordingly, this study aimed to develop a WIMU based tool to monitor the static balance of the workers for proactive fall safety management. For the said purpose, a three-stage study was conducted. Firstly, a laboratory study was conducted to validate the accuracy of WIMUs in measuring task/fatigue induced changes in the static balance with reference to a force-plate during a 20-second static balance test. Secondly, five experts were invited to determine the thresholds of static balance parameters for onsite balance classification of construction workers using the fuzzy set theory. Finally, based on those suggested thresholds, a mobile application was developed to link WIMU signals to a smartphone for onsite balance evaluation and further management perusal.

To accomplish the outlined objectives, the manuscript is organized as follows. Section 2 delineates methods employed for WIMU based detection of task/fatigue induced changes in static balance. Next, section 3 reports the results of the study. It is followed by methods and results for thresholds determination in Section 4 and 5. Section 6 demonstrates the mobile application developed for the onsite balance assessment. Finally, the discussion is made in Section 7, followed by the limitations and future works (Section 8) and conclusions (Section 9).

2. Material and methods for validation of WIMUs to detect task/fatigue induced changes in static balance

2.1 Participants

To validate the usefulness of WIMUs in detecting task/fatigue induced changes in static balance, thirteen male volunteers (university student and staff, mean age: 27.5 ± 4.4 years; mean body mass index: 22.8 ±1.5 kg/m^2) were recruited for the experiment. The volunteers were eligible for the study if they had (1) normal or corrected vision, (2) no known history of balance problems, and (3) no musculoskeletal disorders/pain in the past 12 months [23]. The current study was approved by the Human Research Ethics Committee of The Hong Kong Polytechnic University (Ref: HSEARS20160712003).

2.2 Experimental procedure

The cross-sectional study involved a randomized crossover design in a single visit (Fig. 1). On arriving at the laboratory, the participant was briefed about the experimental procedures and a written consent was obtained. To start with, a WIMU was worn on the waist using a stretchable belt. Afterwards, the participant was instructed to standstill barefooted on a force-plate for a duration of 20 seconds with his feet shoulder`s width apart, arms resting aside while looking at a target placed in front of him at the eye level [23,58]. Two familiarization trials were given prior to data collection. Further, the feet placement was traced on a piece of paper adhered to the force plate to guide subsequent static balance trials [59]. It was followed by a randomized simulation of rebar tying in one of the three postures of stooping, stool-sitting (15cm in height) and squatting. The three postures were chosen because rebar tying in these postures has shown to elicit divergent perceived discomfort levels (an indicator of whole-body fatigue) and post-task static postural stability [23,60]. Immediately after rebar tying, the participant was instructed to repeat the static balance trial in the same way as performed before the rebar tying task. Subsequently, a 20-minute relaxed sitting was provided which was followed by the repetition of aforementioned procedures for the rebar tying task in the remaining two postures.

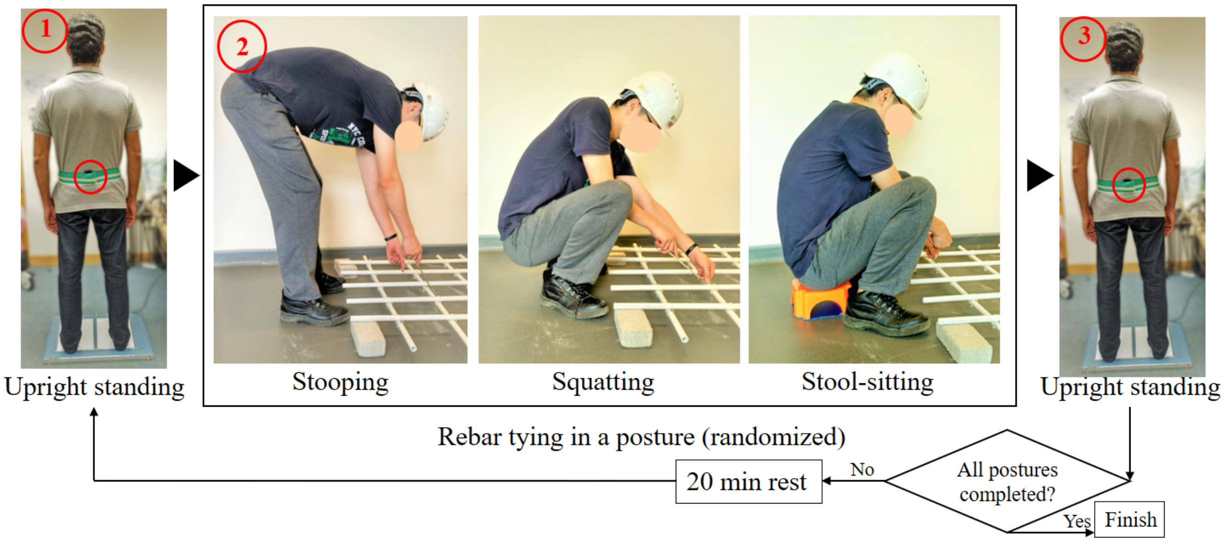


Fig. 1 Experimental Procedure

2.3 Simulated rebar tying

Rebar tying was performed using a simulation setup made of five-by-five plastic pipes [31,60]. The pipes were 1.2m in length and were separated to each other with a center-to-center distance of 0.2m. The participant was instructed to tie simulated rebar using tie-wires and a pigtail tool repeatedly in the first three rows of the setup. During the experiment, the participant was not allowed to stand or change posture in order to keep the procedure standardized for all of the participants. The duration for rebar tying in each posture was initially planned to last for 20 minutes but the pilot testing revealed that the duration was too long to hold these postures continuously because of the severe discomfort in the legs [23,60]. Noteworthy, the perceived discomfort levels during stooping posture increased at a much faster rate than the other two postures. In contrast the duration of 12.5 minutes was well tolerated by the participants during the pilot tests. Accordingly, the rebar tying duration was limited to 12.5 minutes for squatting and stool-sitting postures whereas for the stooping posture, it was reduced to 5 minutes. The specific figures of 12.5 and 5 were chosen because they were multiples of 2.5, which were the selected time interval to document perceived discomfort levels in our previous study [60].

2.4 Instrumentation for data acquisition and variables of interest

For the static balance trials, a multicomponent force-plate (0.4m by 0.6m) with four load cells (Kistler 9286AA, Kistler Instrument Corp., Switzerland) was used to assess the postural stability of the participants while the rate of data collection was 1,000Hz. The load cells registered ground reaction forces once a participant stood on it. The postural stability parameters were then calculated based on the variations in load cell readings arising from subtle body movements. Smaller body movements indicated better static balance. The force-plate data acquisition was synchronized with the acceleration data collection (1500Hz) from a WIMU (MyoMotion system, Noraxon USA) worn at the level of S1 spinous process using a stretchable belt. The WIMU was placed at the specified body landmark because this location closely represents an individual`s center of mass [57,61].

The static balance of a participant using the force-plate (considered as an industry standard) was evaluated using *total path length* metric of the center of pressure (COP). COP is the vertical projection of the center of an individual`s mass and usually measured using a force-plate [62] whereas total path length is one of the widely used COP metrics for static balance assessment [63]. The raw data from the force-plate was filtered through a second-order Butterworth filter with a cut-off frequency of 3Hz prior to the calculation of the COP metric [23,64]. Afterwards, total path length was calculated as follow:

$$Total\ path\ length = \sum_{n=1}^{N-1} \left[(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2\right]^{1/2} \qquad (1)$$

In the above equation n and N refer to n^{th} and last data set value of 20-second static trial, respectively while AP and ML refer to force-plate COP coordinates in anterior-posterior and mediolateral directions, respectively.

To compare with the total path length data on the force-plate, four WIMU metrics were computed to assess the 20-second static balance of the participants; namely resultant acceleration, horizontal plane velocity and displacement in the AP and ML directions. Multiple metrics were explored to ascertain which one of them would be more suitable for the balance monitoring tool. Resultant acceleration was calculated by computing root mean square of the acceleration values in the three planes of the accelerometer [57], whereas velocity and displacement related metrics were calculated by integrating the respective acceleration data in the corresponding planes [61,65]. A smoothing window of 1.3 seconds with a step size of 1.5 milliseconds was applied to the raw data prior to calculation of WIMU based metrics. Regardless of the metric used (force-plate based or WIMU), a larger magnitude (sway) indicates poor static balance and vice versa [55]. The analyses revealed no significant difference among the various pre-task static tasks for any of the parameters. Accordingly, the three pre-task static balance values for each metric were averaged together for the subsequent analysis. Customized MATLAB programs (Version 2015a, MatchWorks, Inc., Natick, USA) were used for all static balance data processing.

2.5 Statistical analysis

To compare the performance of WIMU against the force-plate in detecting task/fatigue induced changes in the static balance, separate one-way repeated measures ANOVA were used to compare averaged pre-task and post-task static stability values for each of the aforementioned metrics. Statistically significant results were explored using post-hoc paired t-test with false detection rate (FDR) correction [66]. To further explore the suitability of each WIMU metric for the balance tool, the ability of each metric to discriminate different balance conditions (effect sizes) was compared using partial eta-squared statistic. Additionally, Pearson`s correlation coefficient was used to compare the correlation between each WIMU metric and force-plate based total path length data. The statistical significance level was set at 0.05 for all tests and SPSS (Version 19.0, IBM Corporation, USA) software was used for all statistical analyses.

3. Results for using WIMUs to detect task/fatigue induced changes in static balance

One-way repeated measures ANOVA revealed that all of the force-plate and WIMU based metrics were able to detect significant differences among pre- and various post-task static balance conditions. All of the force-plate and WIMU metrics indicated that pre-task test demonstrated least postural instability (sway) whereas rebar tying in squatting posture resulted in the worst stability except for WIMU based ML displacement, which indicated post-stooping balance to be the most unstable (Fig. 2). Additionally, paired t-tests (with FDR correction) for all of the metrics (force-plate and WIMU) indicated that using the stooping or squatting posture for rebar tying caused a significant deficiency in postural stability as compared to the respective pre-task static balance test results ($p<0.05$). Similarly, post-stooping and post-squatting sway was significantly larger than post-stool sitting sway ($p<0.05$). In contrast, stool-sitting posture did not have any significant detrimental effect on the static balance (the difference between pre-task and post-stool sitting sway was not statistically significant, $p>0.05$ for all metrics). Interestingly, while the force-plate based total path length found that the post-squatting sway was significantly larger than the post-stooping sway, none of the WIMU based metrics could statistically differentiate between these two conditions.

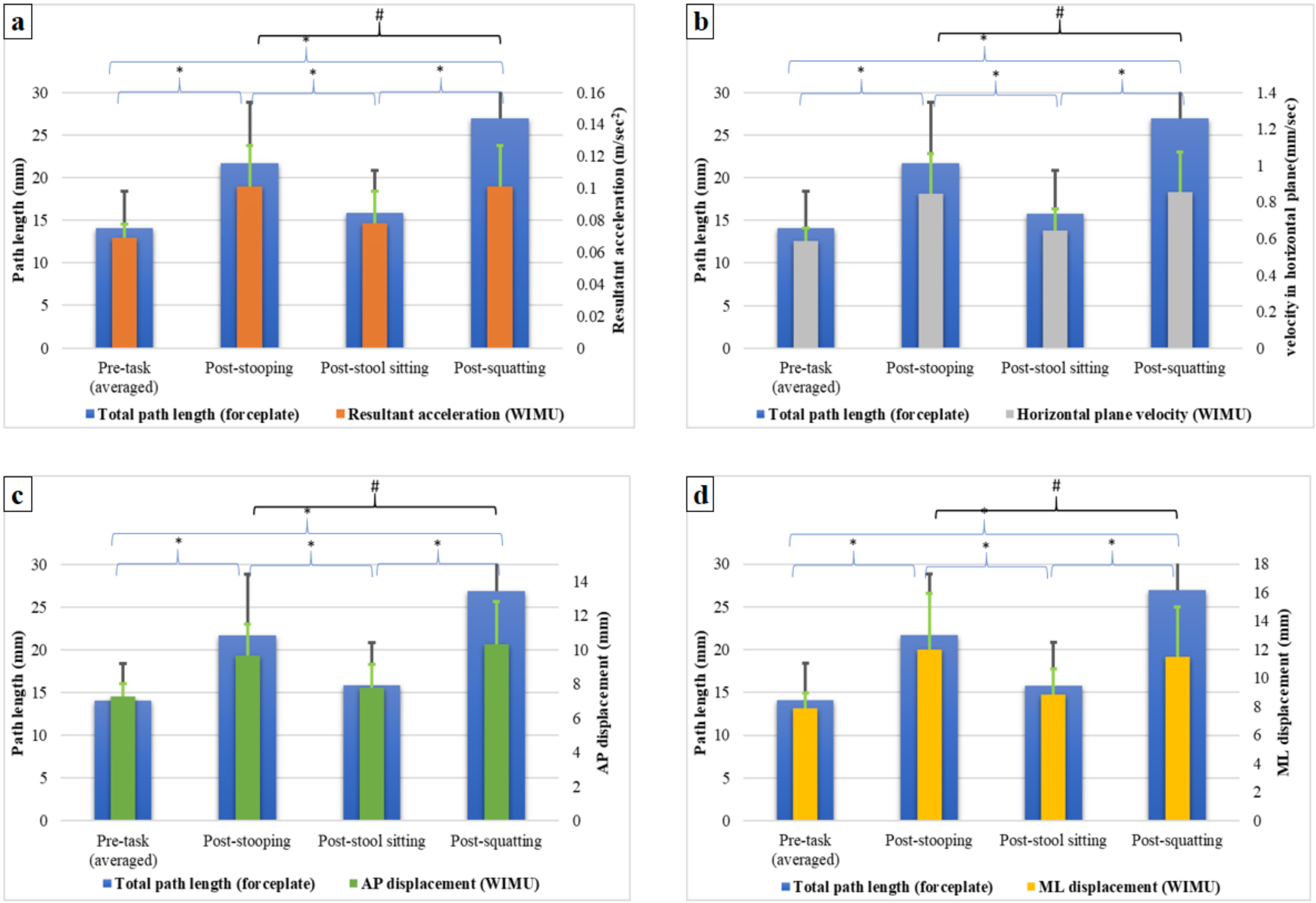


Fig. 2 Pre- and post-task static balance as measured by force-plate and WIMU metrics for various rebar-tying postures

Note: * indicates significant post-hoc paired t-test results for both force-plate and WIMU data (with FDR (false detection rate) correction; $p < 0.05$); # indicates significant difference in the force-plate data only ($p < 0.05$); Bars indicate standard deviation; AP= anterior-posterior direction; ML= mediolateral direction; WIMU= wearable inertial measurement unit

Fig. 3 depicts the effect size comparison among the various force-plate and WIMU metrics. The results showed that the force-plate based total path length was the most sensitive metric to discriminate among various stability conditions. Of all WIMU based metrics, the AP displacement had the highest discriminating power comparable to the total path length measured by the force-plate. Further, resultant acceleration and horizontal plane showed similar but relatively smaller effect size, whereas ML displacement demonstrated the least capability to discriminate various stability conditions.

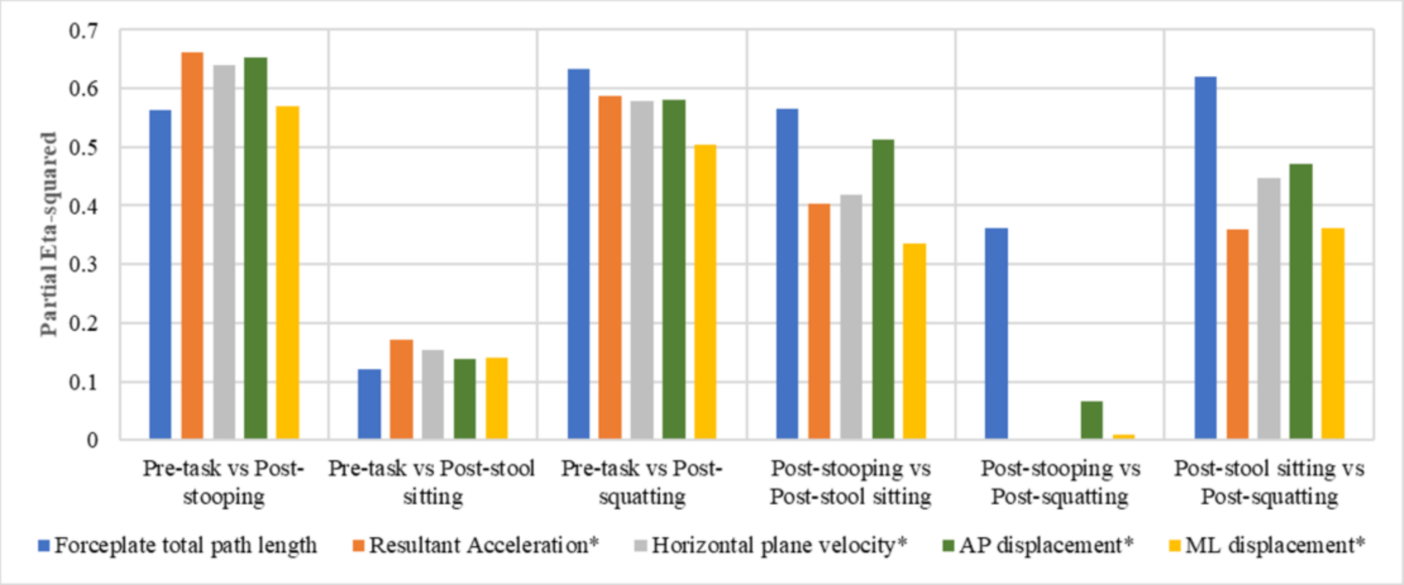


Fig. 3 Effect size comparisons among various force-plate and WIMU metrics in discriminating various post-task static balance

Note: AP= anterior-posterior direction; ML= mediolateral direction; * indicates measured using a wearable inertial measurement unit (WIMU)

Separate Pearson`s correlation coefficient calculation for the force-plate based total path length data and each of the WIMU metrics revealed significant correlation for all of the WIMU based metrics ($p<0.05$, Fig.4). Specifically, the correlation was the strongest between total path length and AP displacement ($r = 0.69$), moderate between total path length and each of resultant acceleration and horizontal plane velocity ($r = 0.53$ for each) and weak between total path length and ML displacement ($r = 0.38$). Taken together, our results (Fig. 2, 3 and 4) suggested that WIMU based AP displacement was the best parameter to detect the task/fatigue induced differences in static balance for future onsite balance assessment.

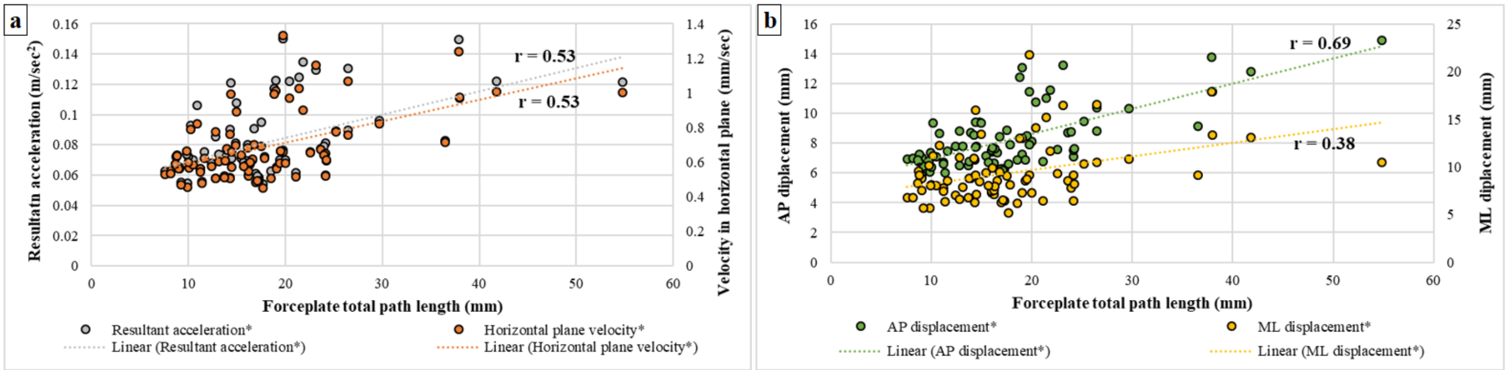


Fig. 4 Pearson`s correlation coefficient comparisons among various WIMU metrics against force-plate data

Note: AP= anterior-posterior direction; ML= mediolateral direction; r= Pearson`s correlation coefficient; * indicates measured using a wearable inertial measurement unit (WIMU)

4. Material and methods for determining the threshold for static balance conditions

While an increased postural sway may indicate a higher risk of falls [32,33], there are no established objective methods/standards/cutoff values that can categorize the balance performance of a worker as “very good”, “good”, “poor” and “very poor”. Given the subjective and vague boundaries in separating various balance categories, it was a big challenge to classify people into different levels of balance performance. Unlike quantitative information with randomness which could be explained by a probability distribution, the uncertainty in the current scenario was more related to vagueness and ambiguity of information for which the probabilistic approach and associated methods are not recommended [67,68]. To bridge this gap, this study adopted the fuzzy set theory, which allows decision making (characterization in this study) by applying mathematical operators and programming to the fuzzy information [69]. The theory has been widely adopted in the domain of construction management for decision making in dealing with the prevalent vagueness and fuzziness in human concept formation and reasoning [69–72].

For the said purpose, five experts (including three registered physiotherapists, an occupational therapist and a biomedical engineer, each with at least five years of experience in conducting static balance assessments in their daily job or for research projects) were contacted to provide opinions on the cutoff thresholds for characterizing good and poor static balance. Five experts were deemed to be sufficient because a study conducted to assess the effect of number of assessors (5, 10, 15 and 22) found that five assessors could be sufficient to obtain a reasonable response using fuzzy set theory [73]. Upon their consent, the study was explained and the data collected during the abovementioned experiment was shared with them. The experts were asked to assist in forming two sets of triangular fuzzy membership functions using the interval estimation method [74], which could be used for classifying static balance of the workers. Interval estimation method was chosen among other methods (e.g. point estimation, membership function exemplification and pairwise comparison) because it better suited the requirements of this study. Chameau and Santamarina [73] found that the interval estimation method was simpler, easier and more capable to handle vagueness when compared to other methods.

The first set of fuzzy membership function characterized pre-work shift static balance of the workers as; “very good”, ‘good”, “poor” and “very poor” based on the AP displacement data of WIMU. Similarly, the second set of fuzzy membership function characterized the relative increase in post-task/post-work-shift sway (percentage change in WIMU AP displacement) as “small”, “medium”, “large” or “very large”. Specifically, triangular membership functions were chosen for this work because they are easier to understand, use and process in a fuzzy environment [75,76]. A triangular fuzzy membership function was represented using three real numbers such that $\tilde{A} = (L,M,U)$ where L,M, U are lower limit, modal (the strongest grade of membership) and upper limit values, respectively for a particular membership function [72]. These limits are an expansion of the idea of confidence interval with varying degree of membership for a given WIMU-based AP displacement value. For a given x (AP displacement), there is a corresponding real number $\mu\tilde{A}(x) \in [0,1]$, where $\mu\tilde{A}(x)$ is the degree of membership of x for $\tilde{A}$, 1 refers to the full membership while 0 refers to the null membership. For the intermediate values, $\mu\tilde{A}(x)$ is determined as follow:

$$\mu\tilde{A}(x) = \begin{cases} (x - L)/(M - L), & L \le x \le M \\ (U - x)/(U - M), & M \le x \le U \end{cases} \quad (2)$$

Accordingly, each of the contacted experts was asked to provide three defining values for each stability condition of the two fuzzy membership functions. Additionally, no specific overlapping limit was imposed on the experts for the membership functions in order to capture the most suitable values for each stability condition as per their experience and knowledge.

5. Results for the determination of thresholds for static balance conditions

The fuzzy membership functions related response gathered from the experts was averaged for the final membership functions which could readily be used for the balance monitoring tool. Table 1 and 2 depict the subjective opinion of each of the experts for the two fuzzy membership functions. Based on their response, the final fuzzy membership functions are illustrated in Fig. 5.

Table 1

Suggested values by the experts for pre-task/unfatigued characterization of static balance

Expert	**Pre-task/unfatigued static balance AP displacement values (mm)**			
	Very good	**good**	**poor**	**Very poor**
1	(0,0,7)	(4,7,10.3)	(8,11,15.5)	(14,17,40)
2	(0,6.5,8)	(7,18,29)	(28,35,41)	(40,42,50)
3	(0,1,6)	(6.5,16,21.5)	(15,26,29.5)	(28,35,49)
4	(0,3,8)	(7,13,19.5)	(16,20.5,25.5)	(23,30,51)
5	(0,5,10)	(7,17,20)	(18,25,42.5)	(32.5,42,55)
Final membership functions	(0,3.1,7.8)	(6.3,14.2,20.1)	(17,23.5,30.8)	(27.5,33.2,49)

Note: AP refers to anterior-posterior direction; each triplet represents the lower bound, strongest grade of membership and upper bound AP displacement values for each stability condition

Table 2

Suggested values by the experts for post-task/post-work-shift characterization of static balance

Expert	Post-task/post-work-shift increase in sway (%)			
	Small	**Medium**	**Large**	**Very large**
1	(0,5,10)	(7,14.5,20)	(18,45,70)	(60,100,150)
2	(0,5,10)	(9,20,55)	(50,70,110)	(100,120,200)
3	(-10,0,15)	(10,35,55)	(30,60,90)	(85,150,200)
4	(0,1,15)	(10,20,55)	(50,70,100)	(90,108,115)
5	(-5,5,20)	(10,25,60)	(45,80,150)	(100,190,250)
Final membership functions	(-3,3.2,14)	(9.2,22.9,49)	(38.6,65,104)	(87,133.6,183)

Note: AP refers to anterior-posterior direction; each triplet represents the lower bound, strongest grade of membership and upper bound AP displacement values for each stability condition

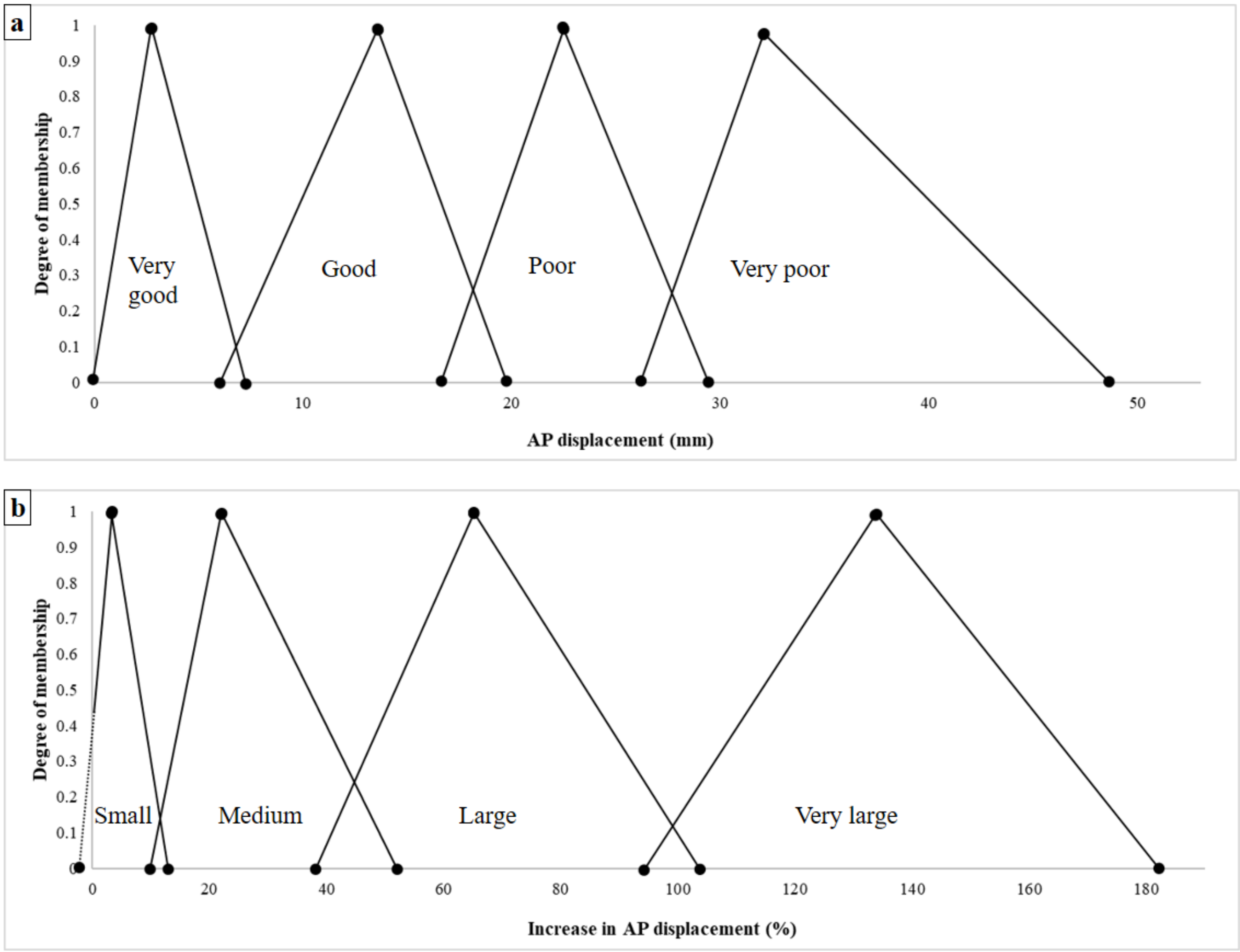
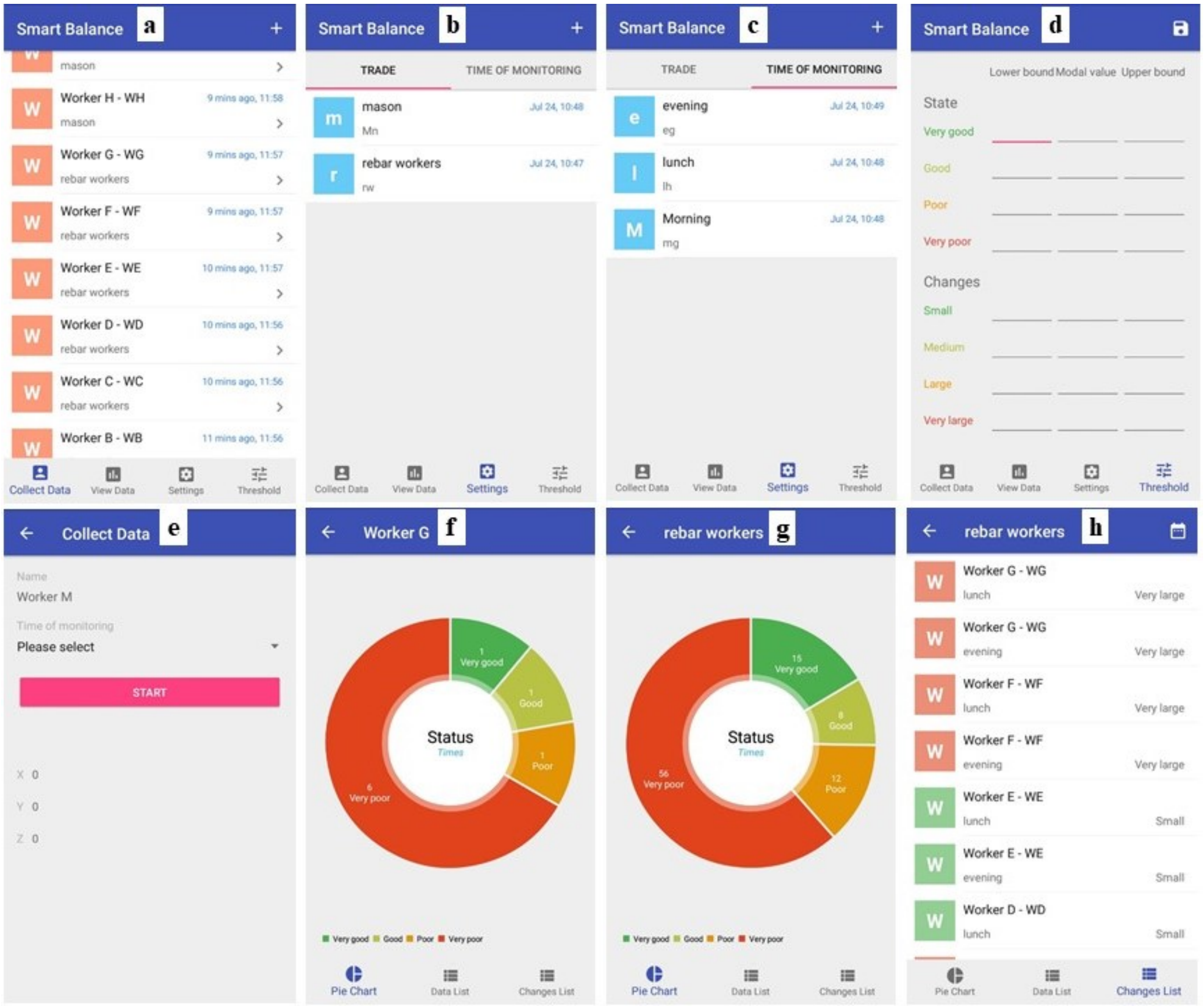


Fig. 5 Fuzzy membership functions developed for the WIMU based balance monitoring tool

Note: AP refers to anterior-posterior direction; WIMU= wearable inertial measurement unit

6. Mobile application developed for the balance monitoring tool

Based on the fuzzy membership functions, a mobile application (Android) was developed to link a WIMU to a smartphone using Bluetooth and onsite deployment of the WIMU based balance monitoring tool. The interface of the mobile application is shown in Fig. 6. Fig 6 (a) indicates a list of construction workers registered in the application (the data used in the illustrations is fictitious). The time mentioned in front of each worker refers to the point in time of his registration in the application. Fig. 6(b) illustrates the two construction trades (mason and rebar tying) as an example to which the registered workers belonged to whereas Fig. 6(c) refers to the suggested times of the day for balance monitoring. Both the trades and the time of monitoring could be edited or added as per onsite requirements using the application interface. The established thresholds for the stability conditions obtained using the fuzzy set theory could be plugged-in/edited using an interface as shown in Fig. 6(d). The interface for taking new static balance reading is shown in Fig. 6(e). Prior to data collection, it is necessary to specify the worker and the time of monitoring. Additionally, Fig. 6(f) and Fig. 6(g) show two pie charts depicting the stability records of an individual worker and workers from a specific trade, respectively. Fig. 6(h) shows the recorded changes in static stability of various workers of a specific trade after a particular work task/ post-work-shift. Once the stability related data is collected using the developed tool, it could be used in a number of ways for proactive fall prevention as explained in the next section (i.e. Discussion).



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Worker H - WH 9 mins ago, 11:58
mason

Worker G - WG 9 mins ago, 11:57
rebar workers

Worker F - WF 9 mins ago, 11:57
rebar workers

Worker E - WE 10 mins ago, 11:57
rebar workers

Worker D - WD 10 mins ago, 11:56
rebar workers

Worker C - WC 10 mins ago, 11:56
rebar workers

Worker B - WB 11 mins ago, 11:56

mason Jul 24, 10:48
Mn

rebar workers Jul 24, 10:47
rw

evening Jul 24, 10:49
eg

lunch Jul 24, 10:48
lh

Morning Jul 24, 10:48
mg

Name
Worker M

Time of monitoring
Please select

X 0
Y 0
Z 0

Worker G - WG
lunch Very large

Worker G - WG
evening Very large

Worker F - WF
lunch Very large

Worker F - WF
evening Very large

Worker E - WE
lunch Small

Worker E - WE
evening Small

Worker D - WD
lunch Small

Fig. 6 Mobile application developed for the balance monitoring tool

Note: All shown data is fictitious

7. Discussion

This study, for the first time, developed a proactive WIMU based static balance assessment tool tailored for construction site workers. The tool utilized a small and lightweight WIMU along with a mobile application, which is expected to enhance its acceptance for onsite fall prevention by the construction industry [57]. This will allow foremen/site managers to monitor the static balance of the construction workers using the 20-second static balance tests at different times of the day in order to keep a balance profile of the workers longitudinally. Ultimately, the tool would enable them to identify the workers with consistent balance deficits that require relevant balance trainings.

7.1 Use of WIMUs to detect changes in static balance

The results of this study indicate that the WIMU based metrics are sensitive to differentiate distinct changes in balance conditions induced by rebar tying task in different work postures. Specifically, WIMU-based AP displacement was highly correlated to the total path length as measured by a force-plate in detecting task/fatigue induced changes in static balance (Fig. 2(c), Fig. 3 and Fig. 4). It is noteworthy that although WIMU-based AP displacement indicated a greater post-squatting static sway than post-stooping sway, the AP displacement metric could not differentiate between the two balance conditions, which could be distinguished by the force-plate-based total path length (Fig. 2(c) and 3). This finding might be attributed to the fact that tasks inducing severe static instability (such as rebar tying in squatting and stooping postures in this experiment) may also require hip strategy to regain the balance in addition to ankle strategy (Fig. 7) [61]. Under such circumstances, there could be movements at the hip (sacrum) level without corresponding changes in COP parameters [61], that results in a reduction of association between the force-plate and WIMU parameters which might explain the aforementioned disparity.

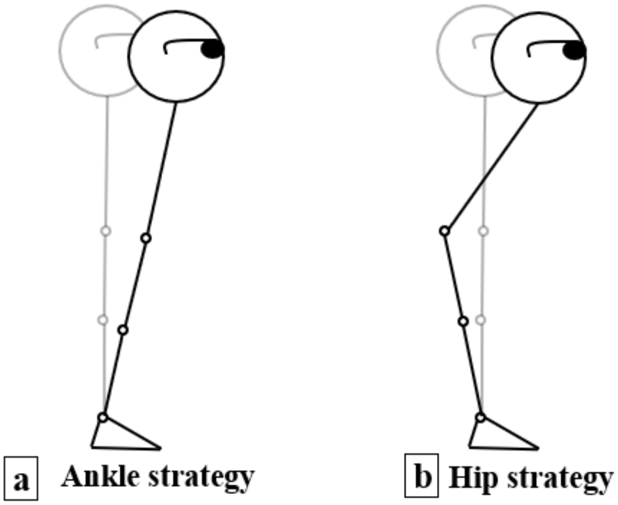

Fig. 7 Strategies for regaining balance

7.2 Implications

Generally, most of the construction trades are physically demanding (e.g., prolonged and repetitive awkward postures, manual material handling, and operating heavy tools) [77–79]. As such, the daily tasks of different trades may predispose the workers to peripheral or whole-body fatigue. It is known that fatigue of individual body parts (such as ankle [80], lower back [33], shoulder [81], neck [82]) or whole-body [83,84] could lead to loss of balance. Therefore, the developed tool will provide an opportunity to quantify the postural instability induced by any of these construction tasks, such as bricklaying, floor laying, carpentry or concrete laying.

Given that loss of balance is one of the major causes of fall incidents on the construction sites [21,38,47], the use of our tool may enable proactive balance monitoring for high fall risk workers/activities. For instance, previous studies have indicated that fall accidents happen more often in the afternoon [5,12], which could be attributed to highly demanding construction tasks leading to fatigue and associated poor balance control [23,33,47]. As such, there is an increased need for monitoring of the workers in that time [5]. Similarly, ageing workforce has been a serious challenge for the construction industry in a number of countries. Since, ageing is linked with a decline in work capacity, cognitive and proprioceptive skills and muscle strength [85,86], aged workers more commonly suffer from fall accidents than their younger counterparts [87]. The developed tool in this study provides an innovative and pragmatic way to increase the fall risk surveillance in these situations.

Combined with the developed tool, Prevention through Design (PtD) [28,88] could be a more effective avenue to lower the risk of falls in the construction industry. For instance, by employing the tool, various task and environment related fall risks (e.g. height, equipment and gear, work-technique, visual stimuli) could be analyzed and their effect on the balance of the workers could be better understood. Subsequently, appropriate risk alleviation strategies could be adopted. Similarly, while three-quarters of all fall accidents involve specialty trades workers [27,89], PtD approach could be used to target the individual trade workers with a higher fall risk (such as roofers and structural steel erectors). In different trades, the balance monitoring tool could be effectively used to redesign work-rest cycles to minimize fatigue and associated fall risk [57].

While many workers may have poor balance, those with poor postural controls can undergo balance training programs to enhance their static and dynamic balance skills [90]. These training programs may include muscle strengthening, agility and plyometric exercises, single and double leg stance on unstable surfaces such as wobble boards and biofeedback based balance improvement schemes systems [90–92]. During or by the end of the balance training program, our tool can be used to quantify improvements attained by the workers. Moreover, the tool can be used to assess the efficacy of any newly designed balance training program.

Although the use of our developed balance monitoring tool could be beneficial, the importance of other fall safety measures cannot be overlooked. Other mitigation measures (such as the use of fall protections, enforcement of safety provisions and compliance to protection plans [28], educational trainings, workshops and seminars) are regarded as useful in preventing falls, enhancing fall hazard awareness and imparting safe behaviors among the construction workers [11,93]. Importantly, using a holistic systems approach is highly recommended to reduce the risk of fall and other accidents on construction sites [94].

8. Limitations and future works

Despite numerous advantages, the current study has a few limitations. First, it is important to evaluate both the static and dynamic balance of workers in order to assess the fall risk [23]. Accordingly, future studies should develop pragmatic dynamic balance assessment tools for construction workers. Second, the current study validated the use of WIMUs to detect task/fatigue induced changes in static balance using inexperienced workers in a laboratory setting and entailing a single work task (i.e. rebar tying). Future studies should validate the usefulness of WIMUs using experienced construction workers, on actual worksites and incorporating various construction trade tasks. Third, this study explored a single duration of work task for inducing changes in static balance. Future studies should evaluate the relation between fatigue development in the three postures and the corresponding induced static imbalance as a function of rebar tying duration. Additionally, it will be worthwhile to explore the effect of prolonged rebar tying in various postures against intermittent rebar tying in identical postures (with frequent work-breaks) on fatigue development and induced static imbalance. Finally, the current study established the thresholds for balance classification based on the laboratory data from a relatively small sample size and the opinions from a few experts using a questionnaire. Accordingly, future studies should gather the data from a large number of construction workers, and should involve a methodology (e.g., a Delphi method) that can obtain consensus from experts for establishing more reliable thresholds.

9. Conclusions

The current study adopted a three-step approach to develop a tool for onsite balance monitoring of the construction workers. First, a validation study was conducted to investigate the suitability of the WIMUs to detect task/fatigue induced faint changes in the static balance by validating various WIMU metrics against the metric from a force-plate. The study found that WIMU based AP displacement metric was an adequate alternative for the force-plate based static balance assessment. Second, five experts were contacted to help determine AP displacement based thresholds for categorizing static balance performance of individuals. Last, a mobile application was developed to link data collected by WIMU during 20-second balance trials to the mobile phone application. The developed tool will have a great potential to enhance proactive identification of the workers with a higher risk of falls so that proper balance training can be provided. It can also be used to assess the effect of various tasks and environmental risk factors on the ensuing balance. Collectively, the tool can contribute to informed decision making to alleviate the risk of falls in the construction industry.

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