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Original Article

Fall Risk Assessments Based on Postural and Dynamic Stability Using Inertial Measurement Unit

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Objectives: Slip and fall accidents in the workplace are one of the top causes of work related fatalities and injuries. Previous studies have indicated that fall risk was related to postural and dynamic stability. However, the usage of this theoretical relationship was limited by laboratory based measuring instruments. The current study proposed a new method for stability assessment by use of inertial measurement units (IMUs).

Methods: Accelerations at different body parts were recorded by the IMUs. Postural and local dynamic stability was assessed from these measures and compared with that computed from the traditional method.

Results: The results demonstrated: 1) significant differences between fall prone and healthy groups in IMU assessed dynamic stability; and 2) better power of discrimination with multi stability index assessed by IMUs.

Conclusion: The findings can be utilized in the design of a portable screening or monitoring tool for fall risk assessment in various industrial settings.

Key Words: Fall risk, Accelerometer, Postural stability, Local dynamic stability

Introduction

According to the statistics from the US Department of Labor, fall accidents in work places is one of the top causes for work related fatalities and injuries in recent years [1]. Focusing on the construction industrial sector specifically, in 2007, a total of 36,210 workers were injured from slips, trips, and falls, among which 447 of them passed away [2]. Even worse, statistics showed that the situation has not been improved throughout the years, regardless of the various types of workplace design guidelines and recommended work practices [3]. Therefore, reducing the occurrence of falls has become a challenge, yet, it has also become a critical mission of both employers and researchers working in the industrial safety sector.

Admitting that slips, trips, and falls are inevitable in some hazardous environments (e.g., extremely wet and slippery floors), previous studies indicated that individuals do have different levels of fall risk; i.e., some workers tend to fall more than others even in the same environment. In light of this fact, if reliable diagnostic approach could be developed to identify fall prone individuals or to track an individual's degradation of balance control, it would aid in employee screening and task assignment, and be beneficial in reducing fall accidents, just as valuable as the endeavor devoted to improve the workplace design.

Generally, an individual's level of fall risk is determined by various intrinsic factors, such as musculoskeletal and sensory functions, fatigue, training, and medication effects, as well

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as mental status such as caution or a fear of fall [4]. However, some of these factors are not easy to quantify and moreover, the dynamic combinations of them add even more difficulties to the problem. Instead of measuring these "direct and fundamental" causes, in practice, other "indirect and comprehensive" indices have been proposed and utilized, among which postural and dynamic stability, indicating the individual's mechanism and ability of posture control and locomotion [5], have been important measures in fall risk studies.

For assessing postural stability, the average velocity of center-of-pressure (COPv) during quiet upright standing has been used by many studies. COPv quantifies the intensity of postural sway and is controlled by the musculoskeletal and sensory systems. In terms of reliability, Lafond et al. [6] investigated six different measures estimated from force plate data and found that COPv was the most reliable measure for assessing postural steadiness. While assessing dynamic stability, the concept of local dynamic stability has become more and more accepted. The local dynamic stability, as characterized by the maximum Lyapunov exponent (maxLE), measures the resistance of human locomotor control system to perturbations [7]. In terms of locomotion, it quantifies how well an individual can keep steady walking patterns under perturbations in the environment or from him/herself, such as an uneven floor or different upper body movement.

The traditional ways to assess stability parameters involve laboratory-based instruments, such as force plates and motion analysis systems. These instruments perform well in terms of offering high sampling rates, taking accurate measures, and providing easy-to-interpret data such as force, moment, position, and velocity. However, even though these instruments could provide important information for employee selection and work load estimation, they often fail to work within the industrial settings simply because of their strict constraints to the environment, high cost, large size, and weight. As a result, it is natural that a miniature and cost effective device that can assess similar stability parameters would be much more accepted and welcomed by employers in reality.

The inertial measurement units (IMUs), consisting of accelerometers, gyroscopes, magnetometers, etc., are devices which have been shown capable to take such role. Numerous motion studies have been conducted in utilizing IMUs for differentiating daily activities [8], measuring human energy expenditure [9], estimating spatio-temporal gait parameters [10], and assessing local dynamic stability [11]. To the best of our knowledge, however, most of these studies concentrated on the clinical interpretations or health care solutions, whereas the possible applications in the realm of industrial safety are still not fully explored and addressed. Therefore, the current study was designed to investigate the feasibility of utilizing IMU-assessed standing and walking stability for fall risk evaluation in industrial safety designs. Further, it explored implementations with major requirements of low cost, fast to conduct, and easy to interpret. It was hypothesized that the standing and walking stability measures would be significantly different between fall-prone groups and healthy groups.

Materials and Methods

Participants

Twelve subjects (4 young adults and 8 old adults), recruited from a large pool of community dwelling individuals, participated in this study. Old adults were categorized into two fall risk levels (healthy and fall prone) based upon their self-reported occurrence of falling in the recent 6 months (at least one fall within the past 6 months). No history of falling was reported from the young group, thus, all of the young adults were categorized as healthy. Table 1 summarizes the demographic information of the participants.

All of the participants were screened following a medical history form to make sure they were in general physical health. The informed consent was reviewed by the Institutional Review Board and was obtained from each participant prior to data collection.

Table 1. Participants' demographic information

Group	Gender		Age (years)	Weight (kg)	Height (m)
	Male	Female			
Healthy young	1	3	21.75 ± 0.96	64.07 ± 13.90	1.67 ± 0.09
Healthy old	2	2	73.25 ± 7.09	71.89 ± 23.14	1.71 ± 0.10
Fall prone old	2	2	74.50 ± 2.65	73.71 ± 12.49	1.73 ± 0.14

Values are presented as number or mean ± standard deviation.

Apparatus and procedures

One force plate (BERTEC # K80102, Type 4550-08; Bertec Corporation, Columbus, OH, USA) was used to collect kinetic data at a sampling rate of 100 Hz in the quiet standing test. One tri-axial IMU (Motion Tractor X [MTx]; Xsens Technologies BV, Netherlands) was used to collect acceleration data at a sampling rate of 50 Hz. In terms of the orientation performance, the MTx has an angular resolution of 0.05° RMS, static accuracy of < 0.5°, and dynamic accuracy of < 1.0°. The dynamic ranges for the acceleration and angular velocity outputs are ±50 m/s^2 (5 g) and ±1,200°/s, respectively [12]. For the quiet standing test, the IMU was attached at the lower back (i.e., L5/S1), as this location closely represents the whole body center of mass. For the treadmill-walking test, the IMU was attached at the right ankle. This location was selected as being sensitive to changes in dynamic stability [7].

Participants were informed about the detailed procedures prior to the experiment. Written consent was obtained. Each participant was then provided with a short sleeve shirt, shorts, and a pair of athlete shoes, in order to minimize the interference of clothing in data collection.

The first part of the experiment was the quiet upright standing test. Participants stood on a linear walkway with a force plate underneath. They were instructed to finish three standing tasks: standing with feet open as they felt comfortable for three minutes, with feet put together for one minute, and with feet open but eyes closed for 10 seconds. These postures and periods were chosen because they were the specific tasks defined in the widely used Berg's balance test [13].

The second part of the experiment was the treadmill-walking test. Participants were required to walk on a treadmill at their normal speed. A period of 2 minutes was given prior to the actual data collection for each of the participants in order to get familiar with treadmill walking. Once the data collection started, participants were instructed to walk continuously for 3 minutes.

A sufficient time of rest was provided to participants, particularly to the fall prone ones, between the two tests in order to minimize the interference of localized muscle fatigue.

Data analysis

The postural stability was characterized by two means: the average velocity of center of pressure (COPv) measured by the force plate and the resultant acceleration (Acc) at the lower back measured by the IMU. The following formulas were used.

$$X_i = -M_y/F_z,\ Y_i = M_x/F_z \qquad \text{eq. 1}$$

$$COP_v = \frac{COP_p}{T} = \frac{\sum_{i=1}^{N-1}\sqrt{(X_{i+1}-X_i)^2+(Y_{i+1}-Y_i)^2}}{T} \qquad \text{eq. 2}$$

$$Acc = \sqrt{A_x^2 + A_y^2 + A_z^2} \qquad \text{eq. 3}$$

where M and F were the moment and force measures from the force plate; A was the acceleration measure from the IMU; T was the overall measurement time; and subscripts x, y, and z represented the anterio-posterior (AP), medio-lateral, and vertical directions, respectively.

The dynamic stability was characterized by the one-gait-step maxLE. The AP acceleration at the right ankle measured by the IMU was used to compute maxLE following the published method [14]. Briefly, a time-delayed coordinate method was adopted to reconstruct a state space using AP acceleration data. Rosenstein's algorithm was applied to calculate maxLE during the time period corresponding to the initial 100% gait cycle. Computations were performed in MATLAB R2007a (MathWorks Inc., Natick, MA, USA).

Analysis of variance (ANOVA) was performed on COPv, Acc, and maxLE in order to investigate if there was any significant difference between the two groups. A significance level of α = 0.05 was selected. Each pair of group means was compared using the Student's t test.

Discriminant analysis was performed on COPv, Acc, maxLE as well as their combinations to select the parameters needed in the fall risk estimation. Linear discriminant model was used and the power of discrimination was characterized as the actual number of participants being correctly classified. All of the statistical analyses were conducted in JMP 7.0 (SAS Institute, Cary, NC, USA).

Results

Data profiles

The stabilograms, which were composed by average velocities of COPv and accelerations at lower back (Acc) during standing, as well as the AP acceleration at the right ankle during walking, were demonstrated in Fig. 1.

Parameter differences between groups

Significant differences existed between the fall prone group and the healthy group in maxLE value, whereas all of the other parameters (COPv and Acc in feet open, feet closed, and eyes closed tasks) did not show any significant difference between the groups. Fig. 2 and Table 2 summarize the results of the ANOVA test.

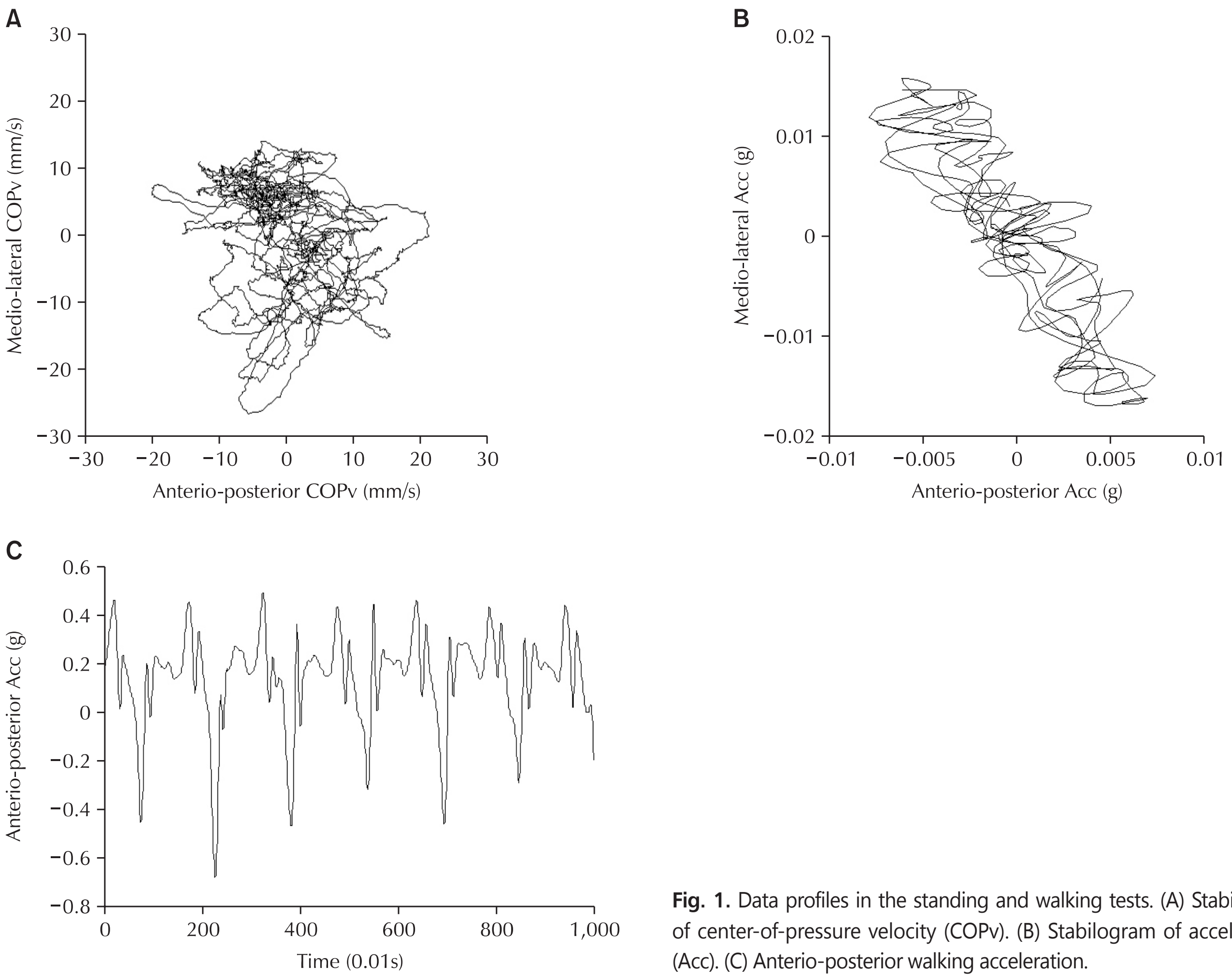

Fig. 1. Data profiles in the standing and walking tests. (A) Stabilogram of center-of-pressure velocity (COPv). (B) Stabilogram of acceleration (Acc). (C) Anterio-posterior walking acceleration.

Power of differentiation with uni-parameter versus multi-parameters

The maxLE perfectly measures the discriminated fall prone old group from the healthy group, yet, it misclassified half of the healthy old and healthy young individuals. The overall percent of misclassification was 33.33%. With a secondary parameter, such as feet closed Acc (fcAcc), only one healthy old and one healthy young was misclassified. The overall percentage of misclassification decreased to 16.67%. The combination of more than two parameters did not generate better discrimination performance. Fig. 3 shows the receiver operating characteristic (ROC) curves of the suggested parameters used in the discriminant analysis.

Discussion

The exploration of fall risk assessment measures has been an important objective in locomotion study for many decades; yet, no assessment tools have been fully satisfactory [4]. As suggested by some recent studies, however, local dynamic stability characterized by maxLE appeared to be a promising index in differentiating fall prone and healthy adults [7,14]. In addition, the current study demonstrated its capability and feasibility. The maxLE at the right ankle, computed in the current study, had an average value of 1.5545 and a standard deviation of 0.0930, which fell in between the values of the similar measures obtained by Dingwell et al. [15] and Liu et al. [7]. Despite the slightly different absolute values, which may be caused by measuring devices and computation options, the general trend was the same and agreed with the theoretical model; individuals with higher fall risk tend to have higher maxLE.

Both the COPv and the Acc parameters during the standing test were not significantly different among groups. This was consistent with the findings of Kang and Dingwell [5], which suggested that mechanisms governing standing and walking stability were different. However, it was found in the current study that the group with lower walking stability also presented lower standing stability. Therefore, the involvement of standing

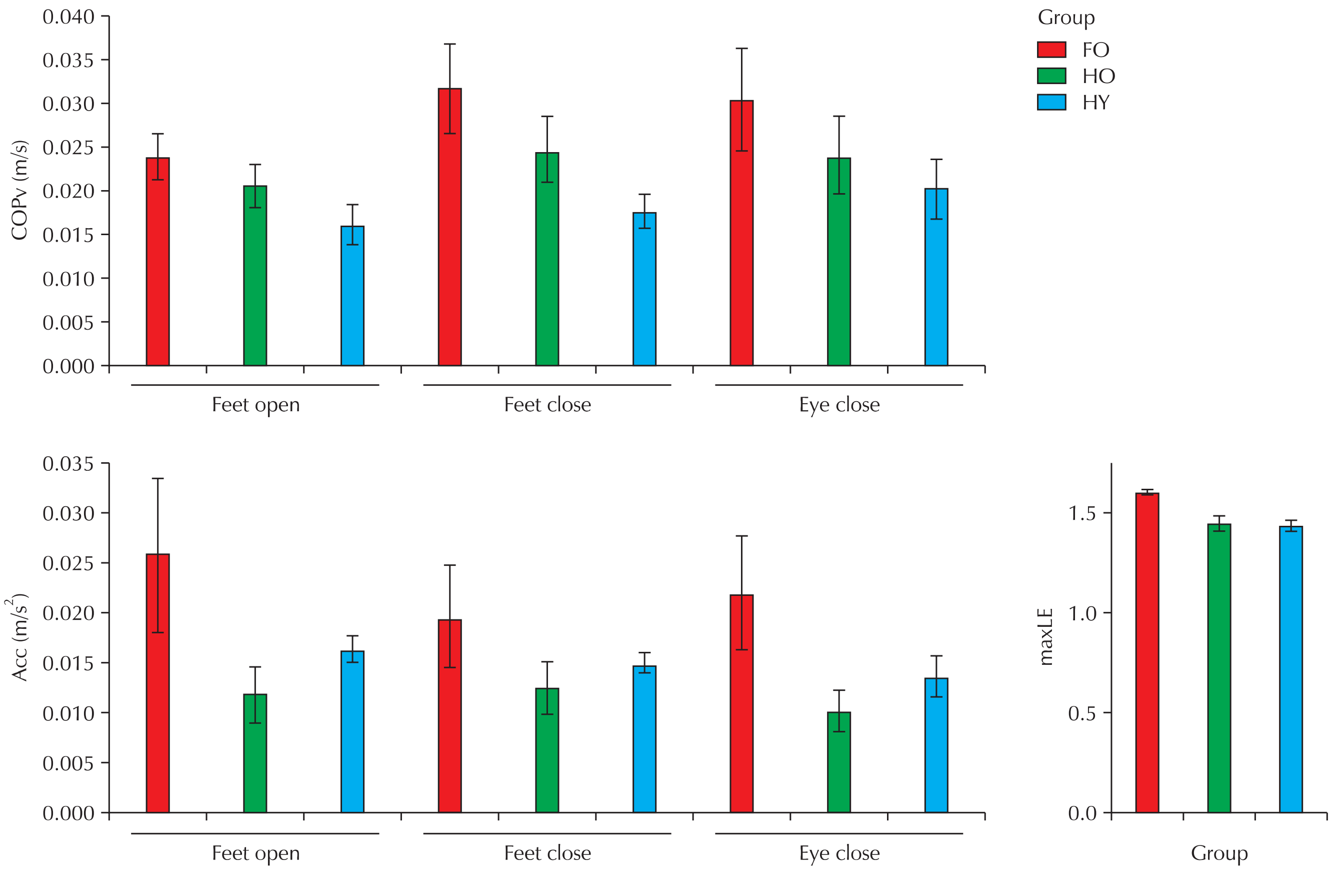

Fig. 2. Group means and standard deviations of the stability parameters. COPv: center-of-pressure velocity, Acc: acceleration, maxLE: maximum Lyapunov exponent, FO: fall-prone old, HO: healthy old, HY: healthy young.

Table 2. p-values of ANOVA test

Parameter	p-value	Parameter	p-value
COPv feet open	0.1425	Acc feet open	0.1714
COPv feet close	0.0841	Acc feet close	0.3586
COPv eyes close	0.3575	Acc eyes close	0.1179
maxLE	0.0044*		

ANOVA: analysis of variance, COPv: center-of-pressure velocity, Acc: acceleration, maxLE: maximum Lyapunov exponent.
*Significant difference.

stability measures in the discriminant model did improve the performance of the discrimination.

The change of task difficulty (i.e., change of postures or distortion of sensory system) during the quiet upright standing test generated neither consistent effect on standing stability nor advantage in terms of differentiation. One possible reason was that the effect of difficulty confounded with participant's concentration on the tasks during the test, i.e., some participants tend to be more cautious and concentrated during more demanding tasks (i.e., feet closed or eyes closed standing), and as a result, their performance did not degrade significantly. In order to investigate the effect of task difficulty in the future, an improved experimental design with repeated measures should be adopted.

Several limitations existed in the current study. First, the result should be interpreted with caution due to the small sample size. Second, the performance of treadmill walking may be different from the performance of the over ground walking in terms of dynamic stability [15], whereas the latter case was the one of our real interest. Future studies should recruit more individuals, specifically employees, such as construction workers, for the actual over ground walking test, and also use multi IMUs (e.g., two IMUs attached at both ankles) to compare the assessments at different body land markers during the same task, which may provide a better understanding of the whole body stability and coordination.

In conclusion, the current study investigated the feasibility of assessing postural and dynamic stability for fall risk estima-

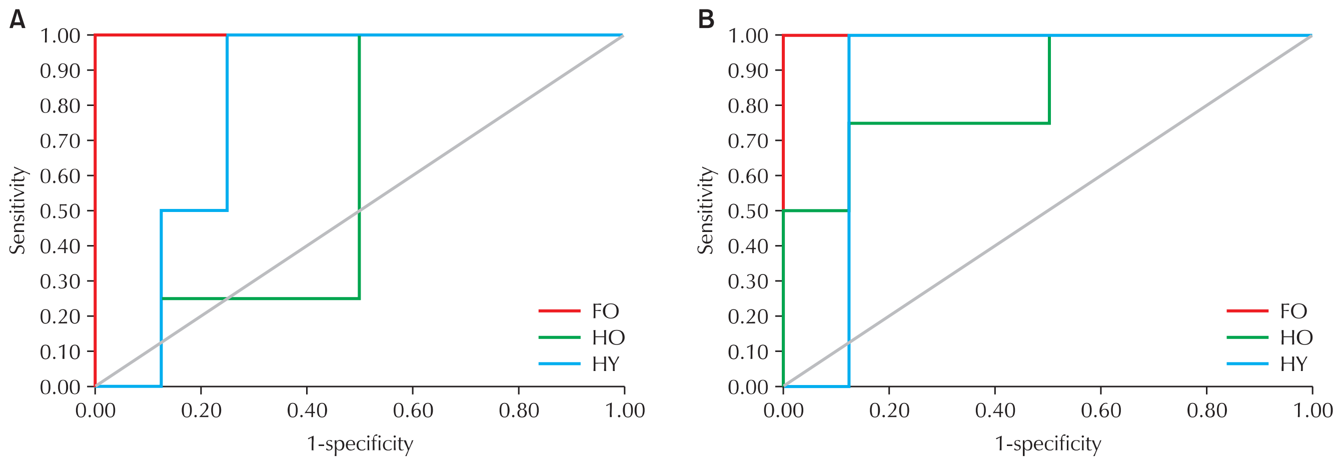

Fig. 3. Receiver operating characteristic (ROC) curves of the discriminant analysis. (A) Discriminant analysis with maxLE. (B) Discriminant analysis with maxLE and fcAcc. maxLE: maximum Lyapunov exponent, fcAcc: resultant acceleration under the condition of feet closed, FO: fall-prone old, HO: healthy old, HY: healthy young.

tion by use of the IMUs. The results indicated that: 1) significant differences existed between fall prone and healthy groups in the right ankle dynamic stability during walking; 2) it was not sufficient to differentiate healthy and fall prone individuals with only postural stability assessed by either lower back Acc or COPv method; and 3) the combination of postural and dynamic stability measures assessed by the IMU had better performance in discriminating fall risk levels than any of the other individual measures.

Three major applications may stem from the results. First, a non-intrusive and portable fall risk assessment tool can be developed for employee screening or evaluation, particularly for older employees. Second, flexible assignment, shift, or rest policy can be established based on the monitored stability decline due to fatigue. Lastly, stability assessed by IMU can be used as a validation measure to confirm the effectiveness of mobility training programs designed and provided to employees for improving their balance control.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgments

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