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Can stability really predict an impending slip-related fall among older adults?

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ABSTRACT

The primary purpose of this study was to systematically evaluate and compare the predictive power of falls for a battery of stability indices, obtained during normal walking among community-dwelling older adults. One hundred and eighty seven community-dwelling older adults participated in the study. After walking regularly for 20 strides on a walkway, participants were subjected to an unannounced slip during gait under the protection of a safety harness. Full body kinematics and kinetics were monitored during walking using a motion capture system synchronized with force plates. Stability variables, including feasible-stability-region measurement, margin of stability, the maximum Floquet multiplier, the Lyapunov exponents (short- and long-term), and the variability of gait parameters (including the step length, step width, and step time), were calculated for each subject. Sensitivity of predicting slip outcome (fall vs. recovery) was examined for each stability variable using logistic regression. Results showed that the feasible-stability-region measurement predicted fall incidence among these subjects with the highest sensitivity (68.4%). Except for the step width (with an sensitivity of 60.2%), no other stability variables could differentiate fallers from those who did not fall for the sample included in this study. The findings from the present study could provide guidance to identify individuals at increased risk of falling using the feasible-stability-region measurement or variability of the step width.

1. Introduction

Falls can result in injury, institutionalization, and even death in older adults (Bieryla et al., 2007). Slips during walking comprise 40% of outdoor falls among older adults (Luukinen et al., 2000). It is important to identify individuals at an elevated risk of falling before implementing effective fall prevention strategies. While it is logical to postulate that a person's gait stability should yield useful clues as to the likelihood of falls (Hamacher et al., 2011), there is little consensus on how gait stability should be defined or measured. Though there are many measurements quantifying human gait stability, little evidences support their capability of actually predicting an impending fall.

The definition of a person's stability can be based on the kinematic relationship between this person's center of mass (COM) and its base of support (BOS) (Borelli, 1680), as it reflects a person's ability to restore or maintain COM balance in upright posture without resorting to altering the existing BOS. Beyond the classical quantification of the margin of stability (i.e. within the confine of the BOS) which deals only with the relative position of COM to BOS, its *extended* conceptual framework measures the dynamic stability in terms of the relative motion state (i.e. the position and velocity) between COM and its BOS (Pai and Patton, 1997). Such conceptual framework has been used to estimate the feasible-stability-region (FSR) in the COM-BOS-state space in walking (Fig. 1). Two different methods: the 7-link model optimization (Yang et al., 2007) and a single-link pendulum model with a linear approximation of the equation of motion (Hof et al., 2005), have been used and different FSRs were established. The predictive measures characterized by these two methods will be named in the present study as *FSR measurement* and *margin of stability*, correspondingly.

Alternatively, gait variability has also been applied to quantify its stability. Based on the nonlinear dynamics theory for cyclical movement, variability in kinematics is indicative of stability (Dingwell et al., 2001; England and Granata, 2007; Hausdorff et al., 2001). Indices, such as the maximum *Floquet multipliers* (Dingwell et al., 2007) and *Lyapunov exponents* (Dingwell and Cusumano, 2000), have been employed to continuous joint or trunk kinematics (Bruijn et al., 2010; Dingwell and Kang, 2007) to respectively evaluate body orbital and local stability. During gait, perturbations can arise from internal (e.g. neuromuscular) and external sources (e.g. slip). Thus the likelihood of falls is dependent not only on the individual's neuro-musculoskeletal capacity, but also on external factors like type and intensity of perturbations encountered in daily life. Indeed,

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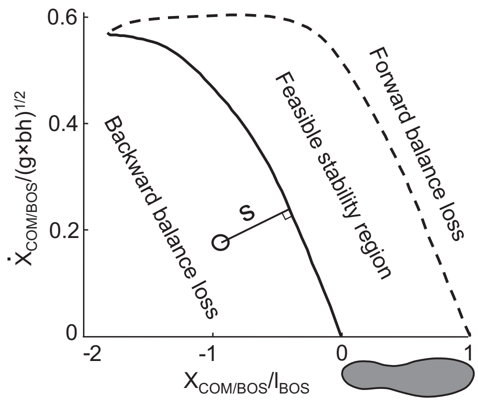

Fig. 1. Schematic illustration of the feasible-stability-region (FSR) measurements . The thin solid line indicates the magnitude of the FSR measurement against backward balance loss, which is defined as the shortest distance from the given center of mass (COM) motion state (i.e., the combination of the COM anteroposterior position and forward velocity) to the limits against backward balance loss (the thick solid line). When the COM motion state is below/above the limits, the FSR measurement value is negative/positive, respectively. Also shown is the computer predicted FSR in the COM motion state space. The FSR is enclosed by two boundaries: the limits against backward balance loss and the one against forward balance loss (the thick dashed line). Position ($X_{COM/BOS}$) and velocity ($\dot{X}_{COM/BOS}$) of the COM relative to the base of support (BOS) are dimensionless variables expressed as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} depicts the foot length, g is gravitational acceleration, and bh the body height.

some studies have proposed that the local stability (Lockhart and Liu, 2008) and the orbital stability (Grabiner et al., 2008; Hamacher et al., 2011) are able to differentiate fall-prone individuals from their healthy counterparts.

Further, simpler yet, variables in descriptive spatiotemporal *gait parameters* such as the standard deviation of step length, step width or step/stride time can also yield useful information reflecting a person's control of gait stability (Hausdorff et al., 2001; Owings and Grabiner, 2004; Woledge et al., 2005). It is unclear how well these methods can predict an impending slip-related fall in walking among community-dwelling older adults, and how well these approaches will agree with each other.

The purpose of this study was to evaluate the degree to which these stability measurements could predict an impending slip-related fall among community-dwelling older adults. We have been able to successfully induce inadvertent falls by initiating slips unknown to the walking older adults in a protective laboratory environment (Pai et al., 2014). The outcome from the gait-slip among older adults (fall vs. recovery) would be used to evaluate the capability of predicting slip-related falls for each one of these stability measurements.

2. Methods

2.1. Subjects

One hundred and eighty seven community-dwelling older adults (age 71.9 ± 5.1 years) participated in the gait-slip experiment (Table 1). All participants signed an informed consent form approved by the Institutional Research Board prior to participating in this study. They were free of any known neurological, musculoskeletal, or other systemic disorders that would have affected their postural control.

2.2. Experimental setup

An unannounced slip was induced as subjects walked along a 7 m instrumented pathway in which a sliding device was embedded. The device consisted of a side-by-side pair of movable platforms, firmly locked in place when subjects walked along the walkway during regular walking (Fig. 2) (Yang and Pai, 2007). They had a low profile approximately 6 mm above the walkway, and were mounted on top of two low-friction metal frames embedded in the walkway. The locks were electronically released, unknown to the person who stepped on the platform, to initiate a forward slip. The platforms were free to slide ≥ 0.75 m forward after release. During walking, all subjects wore a full-body safety harness which was connected to a bearing by shock-absorbing ropes at the shoulders and waist. This low-friction linear bearing moved smoothly along a ceiling-mounted track. The harness system protected subjects from any potential injuries during falling while imposing negligible resistance or constraint to their walking movement (Fig. 2).

Subjects were instructed to walk in their preferred speed. Although they were informed that a slip might occur later, they were not aware when, where, and how it would happen. They were also instructed to try to recover their balance after slipping and continue walking forward. After approximately 20 normal walking strides, the right platform was released immediately after the right (slipping) foot contacted it. The left platform would then be released once the subjects' left (recovery) foot landed on it during the slip trial. The detection of foot contact was based on the measurement from four force plates (AMTI, Newton, MA) installed beneath the metal frames.

2.3. Data reduction

Full body kinematics data from 28 retro-reflective markers placed on the subjects' body and platforms were gathered using an 8-camera motion capture system (MAC, Santa Rosa, CA) at 120 Hz synchronized with the force plates and load cell at 600 Hz. Locations of joint centers, heels, and toes were computed from the filtered marker positions. The body COM kinematics (including its position and velocity) was computed using gender-dependent segmental inertial parameters (de Leva, 1996) based on a distributed-mass human model. The trunk segment's position and orientation were calculated from the joint centers of shoulders, hips and neck marker (C7) as well as sacrum marker (Online Supplement). The vertical component of the ground reaction force was used to identify the instants of touchdown in gait.

Table 1
The demographics in mean ± SD and history of fall for both groups (fall vs. recovery).

Groups	Fall (n=98)	Recovery (n=89)	p value	Pooled (n=187)
Age (years)	71.8 ± 5.5	71.9 ± 4.8	0.969	71.9 ± 5.1
Gender (female)	77 (78.6%)	52 (58.4%)	0.003*	129 (69.0%)
Height (cm)	164.1 ± 7.5	168.8 ± 9.2	0.001	166.2 ± 8.6
Mass (kg)	75.8 ± 13.7	77.1 ± 14.0	0.515	76.4 ± 13.8
Fall history (%)	36.1	38.8	0.749*	37.4

* The χ^2 test was used.

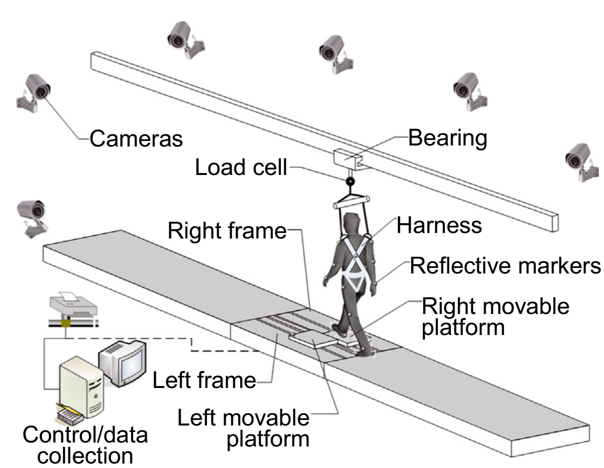

Fig. 2. Diagrammatic representation of the experimental setup for inducing slip in gait. A slip is induced by releasing two low-friction movable platforms. Each of the two platforms is mounted on a frame with four linear bearings, and the frame was bolted to two force plates to measure the ground reaction force. The movable platforms were embedded in a 7 m walkway and made less noticeable to the subject by surrounding stationary decoy platforms. A set of 28 light-reflective markers were placed on bilateral upper and lower extremities, torso, and platforms. Their spatial positions were captured by an 8-camera motion capture system. The subjects were required to wear a safety harness which was individually adjusted to prevent a fall to the ground. A load cell was used to measure the force exerted on the harness.