Journal of Biomechanics 46 (2013) 2463–2468

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

# Alteration in community-dwelling older adults' level walking following perturbation training

Feng Yang, Clive (Yi-Chung) Pai *

*Department of Physical Therapy University of Illinois at Chicago Chicago, IL 60612, USA*

ARTICLE INFO

*Article history:*
Accepted 10 July 2013

*Keywords:*
Stability
Fall prevention
Adaptation
Slip
Postural disturbance

ABSTRACT

While perturbation training is promising in reducing fall-risk among older adults, its impact on altering their spontaneous gait pattern has not been investigated. The purpose of this study was to determine to what extent older adults' gait pattern would be affected by exposure to repeated slips. Seventy-three community-dwelling older adults (age: 72.6 ± 5.4 years) underwent 24 repeated-slip exposure induced by unannounced unlocking and relocking of low-friction sections of a 7-m pathway upon which they walked. Full body kinematics and kinetics were recorded during the training. The gait parameters and the center of mass (COM) stability against backward balance loss were compared before and after the training. The results revealed that the training reduced fall incidence from 43.8% upon the novel slip to 0 at the end of training. After the training, subjects significantly improved gait stability by forward positioning of their COM relative to the base of support without altering gait speed. This forward COM shift resulted from a shortened step at the end of single stance and forward trunk leaning during double stance. They also adopted flat foot landing with knee flexed at touchdown (with an average change of 6.9 and 4.1 degrees, respectively). The perturbation training did alter community-dwelling older adults' spontaneous gait pattern. These changes enabled them to improve their volitional control of stability and their resistance to unpredictable and unpreventable slip-related postural disturbance.



## 1. Introduction

Falls pose a significant health threat to elderly and a serious economic burden to the society (Baker and Harvey, 1985; Tinetti, 2003). Falls initiated by slipping account for about 25% of all falls among older people (Holbrook et al., 1984). Backward falls from a slip frequently cause hip fracture that can have devastating consequences (Kannus et al., 1999). Extensive efforts have been directed towards designing and implementing fall prevention programs (Hu and Woollacott, 1994; Rubenstein and Josephson, 2006; Wolf et al., 2003; York et al., 2011).

A newly-emerged paradigm relies on perturbation training to reduce fall-risk (Bhatt et al., 2012; Parijat and Lockhart, 2012; Shimada et al., 2004; Yang et al., 2013). This paradigm focuses on adaptation to perturbation rather than on self-motivated improvements of one's volitional performance. Such perturbation training can reduce fall incidence among older adults from 44% upon the first encounter of a novel slip to 0 upon the final slip during walking (Pai et al., 2010). It has been demonstrated that perturbation training has the potential to produce fall-reduction effects that are not only retainable but also generalizable outside of the training context (Bhatt and Pai, 2009; Parijat and Lockhart, 2012).

While the results from perturbation training are promising (Bhatt et al., 2006b; Parijat and Lockhart, 2012; Shimada et al., 2004; Yang et al., 2013; Yungher et al., 2012), the impact of the slip perturbation training on the temporal and spatial kinematics of regular gait has not been investigated. This is not a trivial issue. Perturbation training may not only improve older adults' reactive control of stability after perturbation onset during recovery, it can also affect the control of stability during volition movement, such as their gait pattern, in a proactive or feed-forward mode (Bhatt et al., 2006b; Marigold and Patla, 2002; Parijat and Lockhart, 2012; Yang et al., 2013). For instance, it was found that after the slip perturbation training, subjects would be able to proactively and reactively adjust their dynamic stability to enhance their resistance to slip-related falls by landing foot flat (Bhatt et al., 2006b; Cham and Redfern, 2002; Marigold and Patla, 2002), flexing knee (Cham and Redfern, 2002), and shortening step length (Bhatt et al., 2006b; Cham and Redfern, 2002) at touchdown upon repeated slips to improve their dynamic stability and hence reduce the incidences of falls. As the first line of defense, effective proactive adjustments in gait can reduce later need for and reliance on reactive correction during an unpredictable and unpreventable event of a slip in everyday living.

What is gait stability and how is it measured? It is defined here as the ability to restore or maintain a person's center of mass

* Correspondence to: Department of Physical Therapy, University of Illinois at Chicago, 1919 West Taylor St., Room 426 (M/C 898), Chicago, IL 60612, USA. Tel.: +1 312 1996 507; fax: +1 312 996 4583.
*E-mail address:* cpai@uic.edu (C.-C. Pai).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.07.025

(COM) balance in upright posture without resorting to the alteration of the existing base of support (BOS). A step taken by this person is the most common form of such alteration. Unlike the classic definition of the stability (Borelli, 1680), which is only applicable in quiet (quasi-static) standing, the *generalized* conceptual framework characterizes the stability in terms of the motion state (i.e. the position and velocity) that relates the body COM to its BOS (Pai et al., 1994). Mathematical modeling and simulations have been applied to estimate the feasible stability region (FSR) in this COM-BOS-state space (Fig. 1) (Pai and Patton, 1997; Yang et al., 2007), and the results can be distinctively different from those of the static concept (Pai et al., 1998).

Based on this generalized concept, the regular walking consists of alteration of stability recovery (i.e., the state trajectory is either moving towards or staying inside the FSR as the thin dotted line depicted in Fig. 1) followed by an instable period (i.e., it is moving outside and away from the FSR as depicted by the thin dashed line). While the latter is essential to achieve the desired forward mobility, without the former action a person would have fallen onto the ground (Pai, 2003). In forward progression, however, such motion trajectory is clearly *not* intended to ever become backward instability (as allowing one's own motion trajectory to fall inside backward balance loss region in Fig. 1).

The stability is hence measured by the shortest distance from the COM motion state to the boundary of the FSR (Yang et al., 2008a; Yang et al., 2008b), which has two: The limits of stability (LOS) against backward balance loss (the thick solid line in Fig. 1) and those against forward balance loss (the thick dashed line). From this perspective, when a COM motion state lies within the FSR, this person is *not obligated* to alter the existing BOS (Pai, 2003). Nonetheless, a motion state falling outside the posterior LOS (i.e., it would be a negative measurement in Fig. 1) brings instability that a backward step becomes a *necessity* due to insufficient forward momentum to carry the COM forward to the BOS. Conversely, as the motion state is more forward than the anterior LOS (i.e. a more positive measurement greater than 1 in Fig. 1), a forward step becomes *inevitable* due to the excessive forward momentum (Pai, 2003), even when the COM is still within the BOS (as during the midstance, $x=0.5$ in Fig. 1). Based on this generalized conceptual framework (Pai et al., 1994), it is still unclear how slip perturbation training would alter older adults' (unperturbed) step behavior and motion state, more specifically, their control of stability.

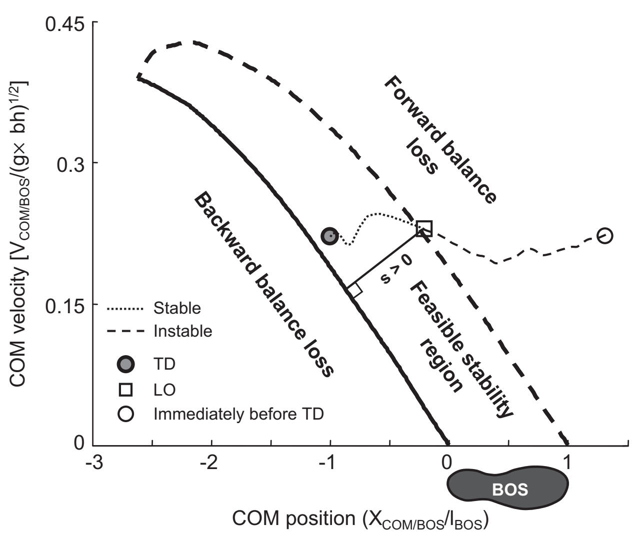


**Fig. 1.** Schematic illustration of the feasible stability region (FSR), which is enclosed by two boundaries: the limits of stability (LOS) against backward balance loss (the thick solid line) and those against forward balance loss (the thick dashed line). The stability measurement (*s*, the length of the thin solid line) indicates the magnitude of the instantaneous stability of the center of mass (COM) against backward balance loss, and is defined as the shortest distance from the instantaneous COM motion state (i.e., the *x*-coordinates represent the COM anteroposterior position and the positive *y*-coordinates indicate its forward velocity) to the corresponding LOS. The regular walking consists of alteration of stability recovery (i.e., the motion state trajectory is either moving towards or staying inside the FSR as the thin dotted line) followed by an instable period (i.e., it is moving outside and away from the FSR as depicted by the thin dashed line) progressing from the touchdown (TD, thick filled circle), through the *contralateral* foot liftoff (LO, thin square), and immediately prior to the *contralateral* foot TD (thin circle). Position and velocity of the COM relative to the base of support (BOS) are dimensionless as a fraction of $l_{BOS}$ and $\sqrt{g \times bh}$, respectively, where $l_{BOS}$ represents the foot length, $g$ is gravitational acceleration, and $bh$ the body height. Please note, a single foot was used as the BOS in the stability calculation for the illustration purpose of keeping the COM motion state trajectory continuous during each step cycle.

The purpose of this study was therefore to determine to what extent older adults' gait pattern would be affected by exposure to 24 repeated slips. We hypothesized that repeated slips would reduce older adults' step length and increase their cadence without altering their gait speed after the training that would improve their stability against any future threats of such postural disturbance.

## 2. Methods

### 2.1. Subjects

One-hundred-thirty-three community-dwelling older adults (≥65 years) were initially recruited. After giving their written informed consent, they were screened for selected drug usage that may alter one's control of stability (e.g. tranquilizers). As safety precautions, older adults who may be at a great risk of fracture during training (based on calcaneal ultrasound body mineral density scan *T* score $< -1.5$ (Thompson et al., 1998)), who may have difficulty to follow instructions (the Folstein Mini Mental Status Exam score $<25$ (Folstein et al., 1975)), or who may not be able to complete the protocol due to poor mobility ($>13.5$ s on the Timed-Up-and-Go test (Podsiadlo and Richardson, 1991)) were excluded from the study. Finally, a total of 73 community-dwelling older adults (46 female) were paid to participate in the institutionally approved study. The mean ± SD age, body mass, and body height were 72.6 ± 5.4 years (range: 65–90), 75.3 ± 12.9 kg, and 1.67 ± 0.09 m.

### 2.2. Experimental setup and protocol

The details of the perturbation training could be found somewhere else (Bhatt et al., 2006b). Briefly, the perturbation training consisted of 24 repeated slips mixed with 13 nonslip trials in a block-and-random design. The unannounced slips were induced through electronic-mechanical unlocking of a sliding device embedded in a 7-m pathway. The device consisted of two low-friction, movable platforms capable of sliding for 90 cm on the right and 75 cm on the left. Each platform was mounted on a frame supported by two force plates (AMTI, Watertown, MA) to record the ground reaction force in order to trigger the release of the moveable platform and to identify the touchdown or liftoff in analysis (Yang and Pai, 2007). A harness connected with a load cell was employed to protect the subjects while imposing negligible constraint to their movements (Yang and Pai, 2011). The force recorded from the load cell was used to determine whether a fall occurs (Yang and Pai, 2011).

Subjects were informed that they would be performing normal walking initially and would experience simulated slip later without knowing when, where, and how that would happen. They were only told to walk in any manner and at any speed they preferred, and to recover their balance on any slip incidence and then to continue walking. Each subject first underwent approximately 10 walking trials (unperturbed) before the perturbation training protocol as well as four post-training trials. The trial immediately prior to the first slip and the third trial after the last slip trial of the training were selected to represent the pre- and post-training spontaneous walk in order to examine the effect of the perturbation training on a person's gait pattern. 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) synchronized with the force plates and load cell.

### 2.3. Data reduction

The timing for two events in each gait cycle, touchdown (TD) and liftoff (LO), was identified from the vertical component of ground reaction force. Temporal measures included the double (from TD to following LO at the contralateral limb) and single (from LO to the following TD at the ipsilateral foot) stance phase times. The cadence was determined as the reciprocal of the duration from TD to the following TD at the contralateral limb and expressed over 1 min.