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Kinematic and behavioral analyses of protective stepping strategies and risk for falls among community living older adults

Woei-Nan Bair [a,1], Michelle G. Prettyman [a], Brock A. Beamer [b], Mark W. Rogers [a,*]

[a] Department of Physical Therapy and Rehabilitation Science, School of Medicine, University of Maryland, Baltimore, Baltimore, MD 21201, USA
[b] Division of Gerontology & Geriatric Medicine, VAMC GRECC, Baltimore, MD 21201, USA

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ABSTRACT

Background: Protective stepping evoked by externally applied lateral perturbations reveals balance deficits underlying falls. However, a lack of comprehensive information about the control of different stepping strategies in relation to the magnitude of perturbation limits understanding of balance control in relation to age and fall status. The aim of this study was to investigate different protective stepping strategies and their kinematic and behavioral control characteristics in response to different magnitudes of lateral waist-pulls between older fallers and non-fallers.

Methods: Fifty-two community-dwelling older adults (16 fallers) reacted naturally to maintain balance in response to five magnitudes of lateral waist-pulls. The balance tolerance limit (BTL, waist-pull magnitude where protective steps transitioned from single to multiple steps), first step control characteristics (stepping frequency and counts, spatial–temporal kinematic, and trunk position at landing) of four naturally selected protective step types were compared between fallers and non-fallers at- and above-BTL.

Findings: Fallers took medial-steps most frequently while non-fallers most often took crossover-back-steps. Only non-fallers varied their step count and first step control parameters by step type at the instants of step initiation (onset time) and termination (trunk position), while both groups modulated step execution parameters (single stance duration and step length) by step type. Group differences were generally better demonstrated above-BTL.

Interpretation: Fallers primarily used a biomechanically less effective medial-stepping strategy that may be partially explained by reduced somato-sensation. Fallers did not modulate their step parameters by step type at first step initiation and termination, instances particularly vulnerable to instability, reflecting their limitations in balance control during protective stepping.

1. Introduction

Falls among older adults are a multi-factorial problem (Tinetti et al., 1988) where neuromuscular (Tinetti et al., 1988; Guralnik et al., 1994; Hilliard et al., 2008) and sensorimotor impairments (DeMott et al., 2007; Lord et al., 2010; Inacio et al., 2014) underlying balance and gait deficits represent significant risk factors. These balance and mobility impairments underlying falls may be better understood in a dynamic and complex context by examining older adults' responses to externally applied, unpredictable postural perturbations that simulate the loss of balance leading to naturally occurring falls (Hilliard et al., 2008; Mansfield and Maki, 2009; Mille et al., 2005; Maki et al., 1996, 2000). Understanding protective stepping response to laterally oriented perturbations is of clinical importance because lateral balance is particularly challenging (Mansfield and Maki, 2009; Mille et al., 2013) for older adults who have greater fall risk (Hilliard et al., 2008) or a history of falls (Mille et al., 2005, 2013). Moreover, video surveillance of naturally occurring falls in older adults detected particular problems in controlling lateral balance during sideway falls (Holliday et al., 1990), and hip fractures occur most frequently in association with lateral falls (Greenspan et al., 1998).

Lateral challenges to standing balance involve unique biomechanical features wherein the body's center-of-mass (CoM) is initially moved passively relative to the base-of-support (BoS) such that the leg opposite to the direction of imposed CoM movement is passively unloaded (Mille et al., 2005; Maki et al., 1996, 2000). When protective stepping is used to maintain balance, this passive unloading assists with active weight transfer and permits a faster foot-lift-off with the unloaded leg (Mille et al., 2005; Maki et al., 1996, 2000; Yungher et al., 2012). It has been hypothesized that individuals with poorer balance will use unloaded-leg-stepping more frequently than loaded-leg-stepping, however, this hypothesis has not been consistently supported (Mille et al., 2005, 2013). While fallers commonly use multiple steps for balance recovery rather than a single step (Hilliard et al., 2008; Mansfield and Maki, 2009; Maki et al., 2000; Mille et al., 2013), there

* Corresponding author.
E-mail address: MRogers@som.umaryland.edu (M.W. Rogers).
[1] Present address: Baltimore Longitudinal Study of Aging, Intramural Research Program, National Institute on Aging, Baltimore, MD 21225, USA.

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are conflicting reports detailing the different stepping strategies taken after lateral perturbations. This issue is important to resolve because the form of stepping used reflects the complex neuromotor control involved in responding to lateral perturbations leading to more or less effective solutions for stabilizing balance (Mille et al., 2005, 2013; Yungher et al., 2012).

In addition to loaded limb lateral steps, unloaded-leg-stepping may involve different sub-types including crossover-steps (Mille et al., 2005; Maki et al., 1996, 2000; Hurt et al., 2011) (either frontward or backward (Yungher et al., 2012)), and medial-first steps taken either alone (Yungher et al., 2012) or as a part of an inter-limb medial–lateral side-step-sequence (Mille et al., 2005; Maki et al., 1996, 2000; Yungher et al., 2012; Hurt et al., 2011). Furthermore, reports on the different sub-types have been limited for various reasons including analysis of only steps where the BoS was extended beneath the falling CoM (Maki et al., 2000), not reporting medial-steps because of their low frequency (Mille et al., 2005), or reporting only crossover-steps because of their more common occurrence (Hilliard et al., 2008; Yungher et al., 2012). Such restricted information comparing the different types of stepping limits fuller understanding of the neuromotor control strategies for maintaining balance stability and preventing falls with aging.

One influential factor affecting laterally-evoked stepping is the magnitude of perturbation (Maki et al., 1996; Meyer et al., 2004). Prior studies either used a single perturbation magnitude that always induced stepping (Hilliard et al., 2008; Mille et al., 2005, 2013), or included a systematic range of perturbation magnitudes that rarely, usually, or frequently evoked stepping without detailed characterization of the spatio-temporal parameters of each stepping type in relation to magnitude (Maki et al., 1996; Yungher et al., 2012; Meyer et al., 2004). Therefore, it is not clear how perturbation magnitude may influence the use of different stepping strategies and the identification of performance differences among fallers and non-fallers.

To further address the foregoing issues, we applied lateral waist-pull perturbations of standing balance at different magnitudes to older adults with and without a history of falls. The aims of the study were to: 1) Compare between groups the waist-pull magnitude where protective stepping transitions from single to multiple balance recovery steps (this waist-pull magnitude is defined as the Balance Tolerance Limit, BTL); 2) investigate if stepping frequency and number of steps taken differ in relation to group, step type and BTL; and 3) examine if first step spatio-temporal kinematic parameters differ in relation to group, step type and BTL. We hypothesized that the BTL would occur at a lower perturbation magnitude for the fallers compared with non-fallers, and that the stepping types used and their associated control characteristics would differ in relation to the perturbation magnitude and fall status.

2. Method

2.1. Participants

Community dwelling adults over 65-years-old were recruited from the greater Baltimore area, and from the GRECC of the Baltimore VA Medical Center. Volunteers were first screened by phone and then if qualified were medically examined by a geriatrician. Exclusion criteria were: 1) Mini Mental State Examination ≤24; 2) centers for Epidemiological Studies Survey ≥16; 3) sedative use; 4) any clinically significant functional impairment related to musculoskeletal, neurological, cardiopulmonary, metabolic, or other general medical problems that limit functional activities; 5) non-ambulatory or use of walking device at home; 6) participating in vigorous exercises or muscle strengthening exercises; 7) advised not to exercise by primary care physician; and 8) received surgery in the past year. Participants gave written informed consent according to procedures approved by the IRB of University of Maryland, and Baltimore and VA Medical Center. Subjects visited the testing laboratory once for about 3 h. Participants were divided into faller and non-faller groups based on their self-reported fall history in the past year. Testers were blinded to participants' fall history during testing. A total of 52 participants were reported with 16 fallers (mean 73.4 (standard deviation 4.6) years-old, 10 females) and 36 non-fallers (74.6 (7.6) years-old, 17 females).

2.2. Testing procedures, instructions and protocol

Participants were given verbal explanations but no physical demonstration of the waist-pulls. They were instructed to respond naturally and prevent themselves from falling. Participants wore their normal walking shoes and stood quietly using an individually standardized stance-width based on their anthropometrics (i.e., shoulder width). This standardization method is similar to that used in previous studies (i.e., 11% (Maki et al., 2000) or 20% (Mille et al., 2005) height) to minimize potential impact of stance variation on recovery step recovery responses. Participants stood with each foot on a separate force platform (AMTI, Newton, MA, USA) as the starting position before the onset of each waist-pull. The foot locations were traced onto the platform surface to ensure consistent initial foot placement across trials for each participant. The ground reaction forces were recorded at 600 Hz. Reflective markers were placed according to Eames et al. (1999) and kinematics were recorded by a six-camera Vicon motion analysis system (Vicon 460, Oxford, UK) at 120 Hz for 7 s for each trial. Participants wore a safety harness that rescued them if they fell but did not otherwise restrict their movement. The harness system is designed to move with the participants in the frontal plane as they took recovery steps. Most participants regained balance by taking steps before the harness reached its travel limit. Only a few participants (1 faller and 3 non-fallers, each with 1 trial at the beginning of testing) were caught by the harness before they regained balance. These caught-by-harness trials were excluded from analysis. An inelastic adjustable belt, snugly secured around the waist, was aligned in participants' frontal plane at pelvis level so that the waist-pulls were applied in the medio-lateral directions. Subjects held a light cylinder in front of their body at waist level to prevent blocking the hip markers before the onset of waist-pulls. They were allowed to do anything with the rod after waist-pull onset.

Lateral waist-pulls were applied by a position-controlled motor-driven system (Pidcoe and Rogers, 1998) at five different magnitudes (from smallest magnitude-1 to largest magnitude-5; displacement: 4.5–22.5 cm, velocity: 8.6–50.0 cm/s, acceleration: 180–900 cm/s^2) in both the right and left directions.

Selection of the waist-pull magnitude values was based on our previous studies of stepping responses in older and younger adults where we identified a parametric range of displacement–velocity–acceleration combinations that produced perturbations where steps were reliably less likely to occur (levels 1–2), likely to occur (level 3) and always occurred (levels 4–5) with or without multiple steps. This waist-pull magnitude range has been used to identify the threshold differences in taking protective steps between young and older adults (Mille et al., 2003) and to demonstrate short-term adaptive changes in stepping behavior, including multiple-steps, commonly observed in fallers (Hilliard et al., 2008; Mansfield and Maki, 2009; Maki et al., 2000; Mille et al., 2013; Yungher et al., 2012). Six trials were administered for each magnitude and for each direction with a total of 60 waist-pulls. Trials were pseudo-randomly arranged by block (5 magnitudes × 2 directions in each block).

2.3. Data analysis

Step count was first determined for each balance recovery trial. Then, for each participant, stepping frequency (number of trials with stepping response), mean step count (total step count divided by the number of waist-pulls) and the Balance Tolerance Limit (BTL, the lowest waist-pull magnitude at which the mean step count was greater than one) were determined. Perturbation magnitude effects on stepping