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Short-term changes in protective stepping for lateral balance recovery in older adults

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Abstract

Background—Fall prevention for older adults is dependent on the ability to maintain protective balance. This study measured the short-term changes of protective stepping following waist-pull perturbations in the medio-lateral direction, to identify what, if any, properties of protective stepping are improved with repeated perturbation exposures.

Methods—Sixty waist-pulls (2 directions × 5 intensities × 6 repetitions) from a single session were analyzed separately as early, middle, and late testing periods, for a comparison over time of typical responses. Outcome measures included the number of evoked steps, type of step, incidence of interlimb collisions, and kinematic and kinetic properties of the first step in frequently used crossover-type responses.

Findings—Improvements were evident as significantly reduced number of steps and collisions. However, these improvements could not be completely accounted for by significant changes in first step kinematic or kinetic properties.

Interpretation—We infer that older individuals experiencing repeated lateral waist-pull perturbations optimize the predictive or feed-forward motor control for balance recovery through stepping.

INTRODUCTION

Falls among older adults are a considerable cause of injury and decreased quality of life, and their prevention is largely based on individuals' ability to protectively respond to perturbations of standing balance [Johnell and Kanis 2006]. Identifying those individuals at risk for falls [Brauer 2000, Johnson-Hilliard 2008, Maki 1994], and intervening to reduce this risk [see Gillespie 2009 for review], have therefore been important and ongoing topics of study.

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Despite the multifactorial nature of age-associated falls, diminished standing balance ability is among the major factors contributing to falling [Gillespie 2009, Lord 1996, Lord 1999, Tinetti 1994]. Previous work has shown that certain characteristics of stepping can be effectively used as measures of dynamic balance function and fall likelihood. For example, a tendency to respond to medio-lateral (M-L) perturbations of balance with multiple recovery steps is a sensitive indicator of prospective fall risk [Johnson-Hilliard 2008]. Step width can also indicate resilience to lateral loss of balance in gait [Bauby and Kuo 2000] and in protective stepping [Maki and McIlroy 2006].

While the properties of a stepping response are important for fall prevention, it is not clear what biomechanical and physiological factors underlie the observed behaviors. In determining the number and type of steps necessary to prevent falling, the central nervous system (CNS) likely estimates the future locations of the base of support (BOS) and the center of mass (COM) to determine whether and how the position and momentum of the body induced by a perturbation can be safely controlled. Using a forward dynamic model based on anthropometric data, Pai and Patton determined the limit of stability in the COM position-velocity plane in the antero-posterior direction, beyond which the BOS must be changed by a step response to prevent a fall [Pai and Patton 1997]. In young and elderly subjects, Patton and colleagues compared the point in the COM position-velocity plane at which steps were induced [Patton 2006]. Young adults initiated steps just prior to their calculated biomechanical stability limit. In contrast, older subjects stepped well before their limit, indicating a conservative estimate of the tolerable momentum. Additionally, subjects with high fall risk had stepping evoked at lower perturbation magnitudes than low fall risk subjects, relative to their calculated biomechanical limit [Luchies 1994, Patton 2006]. Thus, the prediction of the biomechanical stability limits may underlie the strategy choices (e.g., step timing, number and type of steps) that generate the step characteristics associated with high fall risk, and it is likely that the CNS is involved in this prediction of, and can make modifications following perturbations that test, those limits [Pai 2010b].

In previous work, behavioral observations using M-L perturbations have mainly analyzed only the first trial, citing the likelihood of adaptation [Owings 2001, Troy and Grabiner 2006, Troy 2008], or have used whole-session analyses where all trials of the same direction and magnitude of perturbation are grouped [Johnson-Hilliard 2008]. However, preliminary findings suggested the possibility of short term changes to stepping performance during repeated lateral perturbations [Hurt 2010]. However, the extent to which the elderly can undergo practice-related changes in balance performance through protective stepping is not well understood. Moreover, a previous study (Johnson-Hilliard et al., 2008) has indicated that at least some older adults may not improve their ability to recover balance in the frontal plane using a single step over repetitive trials where the persistence of multiple stepping behavior was prospectively linked with increased fall risk. Thus, further information is needed to better elucidate details of practice-related changes in dynamic balance stability with aging as a potential basis for fall prevention programs.

To further investigate this issue, the aim of this study was to measure the changes over time of protective stepping within a single session of repeated lateral perturbations to standing balance in community-dwelling older adults. We hypothesized that if changes in performance are primarily due to biomechanical enhancement of the step response, then first-step kinematic properties in later trials would be earlier, faster, and/or longer than in early trials. Alternately, if practice effects improved the CNS predictive contribution to protective stepping, then behavioral changes should be less directly related to changes in biomechanical measures.

METHODS

Participants

Twenty community-dwelling older adults with a mean age of 72.8 years (range, 65.4–83.9y, 6 male) participated in this study. Subjects, aged 65 years and older, were recruited by the Geriatric Assessment Clinic (GAC) of the Gerontology Research, Education and Clinical Center (GRECC) of the Baltimore Veteran's Administration Medical Center. A phone screen and medical examination by a geriatrician were conducted to determine eligibility. Exclusion criteria were: 1) cognitive impairment (Folstein Mini Mental Score Exam < 24); 2) sedative use; 3) non-ambulatory; 4) any clinically significant functional impairment related to musculoskeletal, neurological, cardiopulmonary, metabolic, or other general medical problem that could limit functional activities; and 5) Centers for Epidemiological Studies Depression Survey score greater than 16. Subjects gave written, informed consent in accordance with the Institutional Review Board of University of Maryland, Baltimore and the Baltimore Veteran's Administration Medical Center prior to participation.

Postural Perturbation

We applied postural perturbations by position-controlled, motor-driven waist-pulls at five different intensities (Levels 1–5) in the right lateral and left lateral directions. The details of the perturbation method, illustrated in Fig 1A, have been presented previously [Johnson-Hilliard 2008, Mille 2005, Pidcoe and Rogers 1998]. Briefly, perturbations ranged in magnitude from Level 1, being 4.5 cm at 8.6 cm/s with an initial 180 cm/s² acceleration, through Level 5, which was 22.5 cm at 50.0 cm/s at an initial acceleration of 900 cm/s². Testing included a total of sixty perturbations (5 pull intensities × 2 directions × 6 repetitions). Trials were pseudorandomly arranged in intensity and direction for each subject, such that no more than two consecutive trials were in one direction.

For each trial, subjects stood in a comfortable position, placing each foot on a separate force platform that recorded the ground reaction forces at a sampling frequency of 600Hz (Advanced Mechanical Technology Inc., 176 Waltham St., Watertown, MA 02472). Foot tracings were taken to ensure that foot placement was consistent between trials. Subjects wore a safety harness that prevented hip or knee contact with the floor but did not otherwise restrict movement. An adjustable belt, snugly secured around the waist, was aligned such that pulling cables were in line with the greater trochanters. Subjects were instructed to hold a light cylindrical object with both hands at approximately waist height prior to each trial. Throughout testing, subjects were monitored for safety and instructed to react naturally to prevent themselves from falling.

Data Collection and Analysis

Reflective markers on the lateral malleoli were recorded for seven seconds per trial at a sampling rate of 120Hz, using a 6-camera Vicon motion analysis system (Vicon, 7388 S. Revere Parkway Suite 901, Centennial, CO 80112). The numbers of protective steps were documented by observation and kinematic recordings. Stepping strategies were categorized based on the first step response of each trial. Four main stepping strategies, illustrated in Figure 1B–E, were identified, expanded from the two that have been previously observed [Johnson-Hilliard 2008, Mille 2005]: 1) a lateral side step (LSS) with the passively loaded leg (near side to pull); 2) an unloaded crossover step with the passively unloaded leg (far side to pull), in front of the body (CSF); 3) an unloaded crossover step behind the body (CSB); and 4) an unloaded step with the passively unloaded leg that moves medially towards, but not past, the passively loaded leg (MS). For all trials that evoked one or more steps, the type of step strategy that was used by the subject was tallied. For each subject, the percentage of such trials for the predominant step type was used as a metric of step strategy.

variability. Additionally, the number of inter-limb collisions was determined. For analysis, the sixty trials per testing session were divided evenly into three epochs: early, middle, and late testing periods such that there were approximately four trials of each perturbation intensity in each period. Results from the early period were used as a baseline and compared with the middle and late periods.

The perturbation intensity at which protective stepping responses became riskier multistep balance recovery patterns was defined as the Balance Tolerance Limit (BTL). Thus, for each subject, the minimum intensity where multiple steps (mean number of steps greater than 1) occurred during the early testing period was identified as the BTL. Use of multiple recovery steps has been a consistent finding that distinguishes older adults from younger adults and older fallers from non-fallers [Johnson-Hilliard 2008, Luchies 1994, Maki 2006, Mille 2005, Patton 2006]. The identification of a BTL for each subject allowed the definition of pull intensities relative to BTL, specifically Below, At, and Above. Although this limited the range of analysis to only three intensities per subject, it effectively normalizes pull intensity according to the transition to multistep balance recovery. One subject's BTL was identified as Level 5, thus preventing analysis at the Above BTL level. That subject's data were omitted from subsequent analyses.

Since crossover stepping is a commonly used strategy employed by older adults to recover lateral balance and collisions are most likely to occur during crossover steps (CSF and CSB) [Maki 2006, Mille 2005], the kinematic properties of the first step for CSF and CSB responses were compared between test periods. Stepping motion characteristics were determined using customized analysis programs. The onset and cessation of the first step were identified with a threshold of the vertical position of the step side lateral malleolus marker at 103% of baseline. Temporal and spatial characteristics were extracted, including M-L distance, onset time, and mean velocity [Johnson-Hilliard 2008, Mille 2005]. Spatial characteristics were then expressed as a fraction of subjects' leg length, calculated as the distance between the greater trochanter and lateral malleolus during quiet stance. Additionally, the kinetic properties of the first step for crossover stepping responses were determined from the force platform recordings. The horizontal force oriented in the direction of the pull, thereby opposing the perturbation-induced COM momentum, was identified during single limb support. The shear impulse was then calculated as the area under the resultant force-time curve from step onset to landing via numerical integration.

The Wilcoxon Signed Rank test was used to determine the significance of change between testing periods for kinematic, kinetic, number of steps, and collision data. For all variables except the predominant step type variability, pull direction was not used as a factor for analysis. A value of $p < 0.05$ was considered significant.

RESULTS

A representative example of a crossover stepping trial for one subject showing the vertical loading force beneath the stepping limb, first step medio-lateral foot displacement, medio-lateral horizontal force beneath the single support limb, and pulling perturbation displacement is presented in Figure 2. Overall, the mean number of recovery steps is shown in Figure 3 for each pulling magnitude during early, middle, and late testing periods. The mean number of steps decreased over time for each of the five intensity levels except Level 3, with significant decreases between the early and late periods ($p < 0.05$). The number of steps and occurrence of each step strategy and subjects' BTL values are listed in Table 1.

The normalized comparisons across time for pull intensities below, at, and above BTL are shown in Figure 4. The number of steps decreased significantly at and above the BTL

intensity, with significant decreases occurring between the early and middle testing periods and between the early and late periods ($p < 0.01$). The effect size at and above the BTL was approximately one step. Below the BTL, there was no significant change from the early to middle testing periods, although there was a decrease by the late period ($p < 0.05$).

Observations of the step type frequencies indicated a decrease in the variability of stepping strategy over time. Seventy-five percent of subjects (15 of 20, $p < 0.01$) increased the frequency of the most common step type between the early and middle testing periods, with 55% (8 of 15, $p > 0.05$) further decreasing the variability in late testing. The incidence of the most common step choice increased significantly from early to middle testing ($p < 0.01$), but there was no further change in the late period ($p > 0.3$).

Thirteen of the twenty participants experienced interlimb collisions (Table 1); of those thirteen, seven had one collision throughout their test session and six had multiple trials with collisions. All collisions occurred during crossover or medial steps. In the early, middle, and late testing periods, 13, 5, and 1 interlimb collisions were observed, respectively. The reduction in collision frequency between early and middle testing was 60.2%, approaching significance ($p = 0.083$), with a large but non-significant further 80.0% reduction ($p = 0.16$) between the middle and late periods. Between the early and late test periods, there was a 92.2% reduction that was statistically significant ($p < 0.004$).

Kinematic and kinetic analyses of the first crossover-type step (Figure 2) was limited to the 15 subjects who used a crossover strategy (CSF or CSB) in at least half of the trials at the intensity one level above BTL. Thus, subjects 5, 7, 9, 12, and 15 were excluded (see Table 1). Only trials at the intensity above BTL were used because it was the most challenging perturbation experienced by, and comparable for, the majority of the subjects. The distances of the subjects' first steps did not change significantly between testing periods (Figure 5A). Similarly, the mean velocities of the steps were not significantly different from period to period (Figure 5B). However, the durations of the steps increased significantly ($p < 0.01$) between the early and late testing periods (Figure 5C). Concurrently, there was a significant increase ($p < 0.03$) in shear impulse during testing (Figure 6). To further explore the potential relationship between step duration and stance limb shear impulse, we calculated their Pearson's product-moment correlation. Although there was a moderately strong correlation between shear impulse and step duration during the early period of testing ($\rho = 0.728$, $p = 0.002$), this relationship weakened in the middle ($\rho = 0.560$, $p = 0.03$) and late ($\rho = 0.261$, $p > 0.3$) periods.

DISCUSSION

The main findings of the study were decreases in the number of protective steps, the number of interlimb collisions, and the variability of step type over repeated waist-pull perturbations to standing balance. Significant changes in the biomechanical properties of the stepping response were limited to an increase in first step duration and in the stance foot shear impulse, with non-significant effects in step length and velocity.

Number of Steps and Collisions

The number of protective steps was reduced by repeated exposures to lateral waist pulls. Across most perturbation intensities, there were significant decreases in the number of evoked steps between the early and middle testing periods. The non-significance of change at Level 3 may be caused by the disparity between responses above and below BTL, as is evident in Figure 4. Since the pulling perturbation is position controlled, the waist pulls were consistent in their mechanical effects [Johnson-Hilliard 2008, Pidcoe and Rogers 1998, Rogers 2003]. Using the Balance Tolerance Limit (BTL) to define a functionally relevant

performance level, the waist pull intensities can be designated as “Below”, “At”, and “Above” the BTL. Normalizing responses in this way permits analysis of the protective stepping behaviors common to the BTL across all subjects. We defined the BTL in the early testing period, when the waist pull was a relatively more novel postural perturbation, so that the changing properties of the protective steps could be expressed in terms of a defined functional baseline.

The use of multiple steps for a balance recovery in response to lateral perturbation is especially important in the context of fall likelihood. As a diagnostic tool, protective responses with multiple steps have been shown to be a sensitive predictor of fall risk [Johnson-Hilliard 2008]. One component of this relationship is the incidence of interlimb collisions. As fewer protective steps are taken, there are correspondingly fewer opportunities for the limbs to collide. Our results support this observation, as the frequency of observed collisions decreased over testing in parallel with a reduction in the percentage of multiple stepping trials. This functional improvement in performance suggests that subjects may have better optimized their protective responses.

Step Type

In addition to multiple stepping behavior, the type of step that subjects use to regain their balance stability contributes to the likelihood of interlimb collisions. Lateral steps (LSS) that widen the base of support preclude collisions. On the other hand, crossover and medially directed steps (CSF, CSB, MS) that apparently take advantage of the mechanical effects of the perturbation that passively unload the stepping leg, counterproductively increase the risk of interlimb contact and often require additional steps to regain stability that could generate further opportunities for collisions [Mille 2005]. This is reflected in our results, where collisions were only observed in CSF, CSB, and MS steps. All but one of the subjects predominantly used CSF, CSB, and MS strategies.

Repeated exposures to the lateral waist pulls affected stepping strategy, as subjects' most common step types during the early period of testing became more frequent in the middle and late periods for 75% (15 of 20) of subjects. This sustained stepping strategy suggested a decrease in motor variability, which has been observed in other work that directly studied adaptation [Shadmehr and Mussa-Ivaldi 1994, Yang 2007]. Even though subjects decreased their average number of protective steps, they typically did not modify their step type selection in favor of using a more mechanically stable lateral side step that would result in fewer steps [Patton 2006].

Kinematic and Kinetic Changes

We observed that the first steps of CSF and CSB responses at the “Above BTL” intensity had longer step durations in the late period than in the early period but did not result in significantly greater step lengths. While the shear impulse was positively and significantly correlated with step duration during the early period, this relationship progressively faded by the middle and late periods. The mechanical contributions of shear impulse during single leg stance to the control of the swing were evident early in testing, and although they were less consistent by late testing, they could have contributed to prolonging step duration and to lowering the incidence of collisions, as shear force could regulate COM motion to enhance balance recovery. It is possible that the non-significant changes in step length and velocity and/or the significant increase in step duration may have contributed to the decreases in the number of protective steps and frequency of interlimb collisions. Similarly, the increase in the shear impulse under the stance foot, which acts to decelerate the momentum of the COM during single limb support, may have been caused by more torque about the hips and obviated multiple steps [Mathiyakom and McNitt-Gray 2008]. However, the weakening

relationship between shear impulse and step durations and the rapid changes observed in the number of protective steps suggest that the kinetic changes are unlikely to be the primary causes of the decreased step count.

The step length and velocity in the M-L direction could be expected to account for decreasing the number of protective steps, as both account for the spatiotemporal properties of the BOS following a perturbation. Longer and faster first steps could reduce the need for second or third steps, by moving the lateral limits of the BOS to a position where torque about the waist can be generated to arrest the momentum of the COM following step landing. However, neither of these properties changed significantly over testing. It is not clear whether the length and mean velocity of the step were already near the subjects' maximum capacities in the early period, or if these properties did not need to be altered to enhance the protective response.

Predictive Motor Control

While the number of predominantly crossover protective steps decreased with repeated trials at pull intensities at or above the BTL, the kinematic and kinetic properties of the first crossover step do not appear to account for the observed changes in stepping behavior. Alternately, it is possible that the number of steps are, at least in part, determined predictively and enacted in a feed-forward mode of CNS control. This type of control scheme has been shown to underlie many motor behaviors [Goodman 2006, Johansson 1993, Muller 2010], including protective stepping [Pai and Patton 1997, Pai 2010a, Pai 2010b].

The sensory information reflecting the evolving instability during lateral waist pulls is likely to be weakly mapped in the sensorimotor system during early testing. In experiencing the repeated perturbation and their biomechanical effects, subjects appeared able to improve this sensorimotor mapping. If CNS predictions of the BTL and the sufficient responses to perturbations at and beyond the limit are improved between the early, middle, and late periods, then the number of steps can decrease without necessitating modifications to the kinetic and kinematic properties of the first step. This is compatible with older adults' use of a margin of safety in antero-posterior protective stepping [Pai and Patton 1997]. The practice effects observed in elderly study participants, resulting in improved responses to lateral waist pull perturbations, are likely based on optimizing predictive aspects of motor control over repeated exposures.

Clinical Implications

The experimental design of the present study was observational, and subjects were instructed only to "React naturally" and "Prevent a fall". Thus, the short term increases in preferred step type frequency that we observed were not the result of any external suggestions about optimizing performance. It may be possible to encourage the use of direct side-stepping by expressly instructing the patient to favor that strategy. Hence, reducing fall likelihood in a clinical intervention may be most effective when promoting the safer, if more difficult, lateral step, as well as in improving crossover stepping performance for situations where it may be necessary due to biomechanical constraints.

The present findings corroborate suggestions that protective balance responses and fall prevention may be enhanced with clinical interventions that emphasize the medio-lateral direction [Johnson-Hilliard 2008]. The role of short term changes of motor behavior in antero-posterior fall prevention has been demonstrated previously [Pai 2010a], and here we have shown that challenging perturbations in the medio-lateral direction yield significant improvements in a number of important dimensions. It remains to be seen whether the short-

term changes observed here can generalize to everyday activities and can be retained in the healthy, community-dwelling elderly population to prevent falls. Nevertheless, the current findings yield promising potential for balance improvement fall interventions in the clinical setting, which will be investigated in planned future work.

Conclusion

The protective stepping responses of community-dwelling elderly subjects were studied using lateral waist-pull perturbations of standing balance. Over the course of testing, performance improved by using fewer recovery steps and yielding fewer interlimb collisions. Most kinematic and kinetic characteristics of crossover-type steps did not improve in a mechanically meaningful way, suggesting that practice effects were manifested in the predictive control of stepping.

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Figure 1.

Illustration of Experimental Setup and Step Strategy Types. Pull direction indicated by arrows at waist-level. A: Position-controlled motor pulls waist belt in one of two lateral directions at one of five magnitudes. Subjects are instructed to hold a lightweight object at approximately waist height and to react naturally to prevent a fall. B: Lateral Step Strategy (LSS). C: Crossover Step to the Front (CSF). D: Crossover Step to the Back (CSF). E: Medial Step (MS).

Figure 2.

Representative trial data from one subject at perturbation intensity one level above BTL, resulting in a single CSF step to the right. From top to bottom: Vertical ground reaction force under stepping (left) foot; Shear ground reaction force under stance (right) foot (impulse during stepping in shaded area); M-L location of the stepping (left) foot; waist-pull perturbation displacement. Vertical lines indicate, from left to right: Pull onset, Step Onset, and Step Cessation.

Figure 3.

Mean Number of Steps during Early, Middle, and Late testing periods, mean of subject means $\pm$ S.E. Significant decreases in the number of steps evoked by a waist-pull were observed between early and late periods at all intensity values except at the Level 3 intensity ($p < 0.01$).

Figure 4.

Mean Number of Steps at Normalized Pull Intensity, mean of subject means $\pm$ S.E. Pull intensities aligned according to minimum value at which subjects used multiple steps during early testing. Significant decreases across all testing periods ($p < 0.01$) were observed at and above the BTL, but only at late testing at the intensity below the BTL ($p < 0.05$).

Figure 5. First Step Kinematics in Crossover type responses (mean $\pm$ S.E.). A: Step Distance in M-L direction, as a percentage of leg length. B: Mean Step Velocity in M-L direction, normalized to leg length. C: Step Duration (sec). Significant differences were only found in step durations between early and late testing.

Figure 6.

Shear Impulse (Force $\times$ time) in M-L direction under Stance Leg during Crossover stepping, (mean $\pm$ S.E.). Results shown as a fraction of shear impulse during Early testing. Forces were oriented such that positive impulses acted as a braking force, towards the direction of the pull. Middle testing had significantly greater shear impulse than the early period, with minimal change between middle and late testing.

Table 1

Inter-subject variation in pattern of response to lateral perturbations.

Subject	Number of trials ^a							Col ^c	BTL ^d
	Number of steps			Stepping Strategies ^b					
	None	One	Multiple	LSS	CSF	CSB	MS		
1	30	14	16	0	0	17	13	0	4
2	38	16	6	0	11	11	0	0	5
3	34	14	12	4	8	13	1	1	4
4	33	12	8	0	1	18	1	0	4
5	21	11	26	19	0	0	18	1	3
6	32	5	23	0	3	22	3	0	4
7	22	2	36	1	2	0	35	2	3
8	19	14	27	0	11	20	10	1	3
9	21	24	15	17	17	2	3	0	3
10	22	7	31	9	0	15	14	2	2
11	23	13	24	5	14	16	0	1	3
12	10	1	49	12	0	1	37	2	3
13	22	20	15	0	30	0	5	1	3
14	17	17	25	0	14	24	4	2	2
15	17	24	19	19	20	0	4	0	3
16	15	12	25	9	1	20	7	2	3
17	21	25	14	1	19	18	1	0	3
18	17	10	33	0	39	0	4	1	3
19	17	16	27	2	0	36	5	2	3
20	21	12	27	3	16	0	20	1	3
Total	452	269	458	101	206	233	185	19	

^aTotal of 60 per subject, with exceptions for mechanical limitations of pulling system.

^bSee Figure 1 for step types.

^cColl. = Collisions.

^dBTL = Balance Tolerance Limit.