Stability of gait and interlimb coordination in older adults

T. Krasovsky,1,2 M. C. Baniña,1,2 R. Hacmon,1,2 A. G. Feldman,2,3,4 A. Lamontagne,1,2 and M. F. Levin1,2
1School of Physical and Occupational Therapy, McGill University, Montreal; 2Feil & Oberfeld Research Centre, Jewish Rehabilitation Hospital (research site of the Center for Interdisciplinary Research in Rehabilitation of greater Montreal), Laval, Quebec; 3Department of Physiology, University of Montreal, Montreal; and 4Institut de réadaptation Gingras-Lindsay de Montreal, Montreal, Canada

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Krasovsky T, Baniña MC, Hacmon R, Feldman AG, Lamontagne A, Levin MF. Stability of gait and interlimb coordination in older adults. J Neurophysiol 107: 2560–2569, 2012. First published February 1, 2012; doi:10.1152/jn.00950.2011.—Most falls in older adults occur when walking, specifically following a trip. This study investigated the short- and longer term responses of young (n = 24, 27.6 ± 4.5 yr) and older adults (n = 18, 69.1 ± 4.2 yr) to a trip during gait at comfortable speed and the role of interlimb coordination in recovery from tripping. Subjects walked on a self-paced treadmill when forward movement of their dominant leg was unexpectedly arrested for 250 ms. Recovery of center of mass (COM) movements and of double-support duration following perturbation was determined. In addition, the disruption and recovery of interlimb coordination of the arms and legs was evaluated. Although young and older subjects used similar lower limb strategies in response to the trip, older adults had less stable COM movement patterns before perturbation, had longer transient destabilization (>25%) after perturbation, required more gait cycles to recover double-support duration (older, 3.48 ± 0.7 cycles; young, 2.88 ± 0.4 cycles), and had larger phase shifts that persisted after perturbation (older, −83° to −90°; young, −39° to −42°). Older adults also had larger disruptions to interlimb coordination of the arms and legs. The timing of the initial disruption in coordination was correlated with the disturbance in gait stability only in young adults. In older adults, greater initial COM instability was related to greater longer term arm incoordination. These results suggest a relationship between interlimb coordination and gait stability, which may be associated with fall risk in older adults. Reduced coordination and gait stability suggest a need for stability-related functional training even in high-functioning older adults.

FALL-RELATED INJURY in older adults places a heavy burden on the health care system with over 19 billion dollars spent in direct medical costs in the U.S. in 2000 alone (Stevens et al. 2006). Identification of mechanisms leading to falls or to recovery from falls in older adults can assist in fall prevention because it can lead to more effective interventions (Chang et al. 2004).

Most falls in older adults occur when walking (Berg et al. 1997; Nevitt et al. 1991) due to tripping (34%) or slipping (25%). The fact that young adults rarely fall during walking suggests that gait stability is affected by aging. Gait stability can be defined as the ability to maintain functional locomotion despite perturbations (Eng et al. 1991). Although the above definition of gait stability is generally accepted, quantification of stability is controversial, especially in older adults. Gait stability has been quantified using responses of the motor system to time-dependent changes in the environment and neuromuscular properties (for a recent review, see Hamacher et al. 2011). Other measures quantify the ability to maintain functional locomotion despite larger perturbations, such as path obstacles or trunk displacements. Transient and long-lasting responses to perturbations have been quantified in terms of limb strategies used (Eng et al. 1994), parameters quantifying immediate changes in and gradual return to a stable gait pattern (Bruijn et al. 2010), and by the phase resetting of gait reflecting the ability to restore body equilibrium in the environment (Feldman et al. 2011). Gait stability is a global property of the motor system, implying that all body segments are involved in the short- and longer term responses to perturbation (Marigold and Misiaszek 2009).

In young healthy adults, three typical strategies have been identified in response to a trip perturbation (Eng et al. 1994). The first is a lowering strategy, in which the perturbed leg is lowered to the ground with reduced step length and step time. The second is an elevating strategy, which consists of prolonged maintenance of the perturbed leg in the air, and then the leg arriving at the same step length or longer with a longer swing duration. The third is a delayed lowering (or combined) strategy, when an elevation strategy is attempted but eventually the leg is lowered at a shorter step length. Lowering and combined strategies were further shown to require more energy and more recovery steps (de Boer et al. 2010; Forner-Cordero et al. 2005). In older adults, some evidence suggests that lowering responses may be more prevalent than in younger subjects (Pijnappels et al. 2005; Roos et al. 2008). This may suggest that older adults use less efficient responses to perturbation.

Decreased gait stability in older adults may result from deterioration in musculoskeletal properties, reflex reactions, and central neural control. With aging, movement becomes less automatic and more cognitively challenging (Heuninckx et al. 2005). Deficits in motor performance are usually not limited to walking but also occur in other tasks, such as maintaining interlimb coordination when swinging limbs or cycling. In

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addition, older adults have lower temporal coupling between arms (Greene and Williams 1996) and between arms and legs (Serrien et al. 2000) that further decreases with increasing movement speed. The timing of gait events in the lower limbs (heel strikes) is less symmetrical (decreased temporal coupling) and less stable in older adults (Plotnik et al. 2007).

Response of the body to perturbation involves several factors, including context-dependent coordinated responses of the arms (Eng et al. 1994; Schillings et al. 1996) and reactions of the arms (Pijnappels et al. 2010; Bruijn et al. 2010), in the short-term (1–2 steps after perturbation). Coordinated initial arm and leg responses may deteriorate in older adults, which may contribute to a decrease in gait stability in this population. Roos et al. (2008) identified differences in initial arm movements following a trip between young and older adults. They suggested that arm movement served to elevate the center of mass (COM), thus assisting recovery in young but not older adults. Pijnappels et al. (2005) showed that improper placement of the leg during recovery was related to falling in older adults. These studies only examined immediate and short-term responses to a trip perturbation. There may also be longer term changes in gait stability after a perturbation (Forner-Cordero et al. 2003), but the role of interlimb coordination of arms and legs in such recovery remains unclear. We evaluated both immediate and longer term effects of perturbation on gait stability and interlimb coordination in young and older adults. We hypothesized that older adults would be less stable and would have less coordinated whole body and limb responses to a perturbation during gait compared with younger adults. We further hypothesized that interlimb coordination in the arms and legs may play an important role in the recovery of stable walking following perturbation and that this relationship decreases with age.

METHODS

Participants

Twenty-four young adults (12 male; mean age 27.6 ± 4 yr) and 18 older adults (9 male; mean age 69.1 ± 4 yr) volunteered for the study. All subjects signed informed consent forms approved by the institutional ethics committee. All subjects except two young and three older adults were right-handed (Edinburgh Handedness Scale > 25) (Oldfield 1971). Leg dominance was evaluated by asking the subject to identify the leg preferred for kicking a ball and was identical to hand dominance in all but one subject. Subjects were excluded if they had any orthopedic, vestibular, or neurological disorders affecting gait.

Experimental Procedure

Testing protocol. Subjects walked on a self-paced treadmill (Stephenson et al. 2009) and wore a safety harness attached to the ceiling to prevent falling (Fig. 1A). For safety purposes, two switches could be pressed to stop the treadmill movement in case of an emergency. Subjects could rest for up to 2 min between trials and wore a heart rate monitor to ensure that heart rate did not exceed 70% of maximum (220 beats/min minus subject age).

Subjects were allowed to habituate to treadmill walking at their comfortable pace. Once comfortable gait speed stabilized, i.e., did not vary by more than 10%, the pace was set for each subject with a metronome. Subsequent data collection consisted of 2 blocks of six 40-s trials (n = 12 trials total). Subjects were not required to follow the metronome beat following perturbation. Trip perturbations were introduced using a custom-built device arresting forward movement of the dominant leg during swing. Two 110-cm light wooden rods were attached to ankle cuffs (Fig. 1A) and inserted into cylindrical electromagnets fastened to posts 50 cm behind the subject. Rod movement occurred with minimal friction. The device had a potentiometer that monitored forward and backward movement of the wooden rods, and baseline range of movement (swing length) was calculated. In pseudorandomly selected steps (1–2 perturbations per 40-s trial), the device transiently blocked forward leg motion of the dominant leg for 250 ms at 20–30° swing length. Early swing perturbations were chosen because they allow for a wider range of possible responses (Schillings et al. 1996) compared with perturbations in late swing, when only a leg lowering strategy is typically used. A force transducer embedded in the rod measured perturbation force. Perturbation duration was determined in a pilot study (n = 3) where a 250-ms arrest generated a consistent perturbation with no forces in the opposite direction (“backlash”). One to two trials in which no perturbation occurred were randomly included in each block to prevent anticipation. Because the response to the first perturbation may differ from those to subsequent perturbations (c.f. Marigold and Patla 2001), the first three perturbations of each subject were omitted from the analysis. Reflective markers (36 in total) were placed on body landmarks according to the Vicon Plug-in-Gait model (Vicon, Oxford, UK). Specifically, heel markers were placed on the calcanei, and finger markers were placed on the dorsums of the second metacarpals. Movement kinematics were recorded at 120 samples/s using a 12-camera Vicon motion analysis system and filtered using a sixth-order low-pass Butterworth filter (dual-pass, cutoff 10 Hz). A sixth-order Butterworth filter was chosen because, compared with the more often used fourth-order filter, it better suppressed noise above the cutoff frequency.

Clinical tests. Performance of gait-related activities was assessed in older adults by a physical therapist using the valid and reliable Functional Gait Assessment (FGA) (Walker et al. 2007; Wrisley et al. 2004; Wrisley and Kumar 2010). The FGA evaluates functional ambulation in community-dwelling older adults on a 30-point scale in which ≤ 22 indicates fall risk (Wrisley and Kumar 2010). The subject’s self-confidence (self-efficacy) when performing daily activities including walking was assessed with the valid and reliable Activities-Specific Balance Confidence questionnaire (ABC) (Myers et al. 1998; Powell and Myers 1995), a self-report questionnaire measured on a 100-point scale.

Data Analysis

Immediate and longer term responses: stability. Following the definition above (Introduction), we quantified gait stability by parameters characterizing immediate and longer term effects on the steady-state gait pattern. Immediate effects of the leg perturbation were classified into three typical response strategies, as described in the Introduction (Fig. 1B). Characteristics of the immediate and longer term effects of perturbation were analyzed using the recovery of COM movements and the double-support times and long-lasting phase shifts in the gait pattern. COM position was calculated using Vicon’s Plug-in-Gait model. For each trial, each step was time-normalized to 100 points, and during a preperturbation period of 8 steps, the position and velocity of the COM were calculated in 3 axes (mediolateral, anteroposterior, and vertical). COM velocity was calculated using a 2-point central difference algorithm filtered with a 25-Hz cutoff low-pass second-order Butterworth filter (Post et al. 2000). For each axis, COM trajectory during unperturbed walking was described as a stable-state attractor by mean (+ SD) velocity vs. position phase plots. The Euclidean distance of COM from the steady state after a perturbation was calculated following the method of Bruijn et al. (2010) as...
Fig. 1. Experimental setup: 3 strategies of responses to perturbation (A) and basic descriptors of gait stability (B and C). A: experimental setup. Subjects walked on a self-paced treadmill where treadmill speed was determined via a custom-built microcontroller and changed according to the anteroposterior position of a string attached to the subject’s back. Subjects wore a harness connected to a metal bar attached to the ceiling, with no constraint to motion on the treadmill. Velcro leg cuffs were attached to both legs to equate sensation, and an electromagnet automatically clamped the rod attached to the cuff on the dominant leg for a period of 250 ms at -20% of swing length. B: phase plots of 3 types of postperturbation leg strategies (lowering, combined, elevation). Plots describe the anteroposterior position (abscissa) and velocity (ordinate) of the heel marker on the perturbed leg. Thin solid black lines indicate 3 preperturbation cycles; thick gray line indicates perturbation (vertical dotted line). The x-axis is normalized time, where 100% is the time from heel strike to the consecutive heel strike of the contralateral leg. The y-axis is the Euclidean distance from a mean phase plot (attractor), normalized by standard deviations of the mean and summed over 3 movement axes. Gray line represents the fitted exponential function (see text). Immediate measures of stability include time to peak distance (τ) and value of peak distance (B), whereas longer term recovery is described by the slope of the initial recovery function (β) and mean distance from the attractor at the 5th step after perturbation (A).

\[
\text{DIST}_{100s+1} = \sqrt{\sum_{j=1}^{3} \left( \left[ \frac{N_{ij} - P_{ij,100s+1}}{S_{ij,100s+1}} \right]^2 + \left[ \frac{DN_{ij} - DP_{ij,100s+1}}{DS_{ij,100s+1}} \right]^2 \right)}
\]

where \( j \) is the movement axis, \( N \) and \( DN \) are the mean nonperturbed position and velocity respectively, \( P \) and \( DP \) are the instantaneous position and velocity after perturbation, \( S \) and \( DS \) are the instantaneous SDs of the mean position and velocity, respectively, \( s \) is the step index following the perturbation, and \( i \) is the index within the step [1–100] (Fig. 1C).

Because the distance at each time point depends on the SD of the stable state, and to verify that differences did not depend on baseline variability, the mean SD of the stable state was defined as

\[
\text{SD} = \frac{1}{100} \sum_{i=1}^{100} \sqrt{\sum_{j=1}^{3} S_{ij,100s+1}^2 + DS_{ij,100s+1}^2}
\]

To identify variables related to postperturbation recovery of stable-state walking, we fit an exponential function to the distance curve from the peak onwards (Post et al. 2000; Bruijn et al. 2010):

\[
F_i = A_{\text{COM}} + (B_{\text{COM}} - A_{\text{COM}}) \times e^{-\beta_{\text{COM}}(i - \tau_{\text{COM}})}
\]

This analysis yielded variables that defined the immediate \( (B_{\text{COM}}, \tau_{\text{COM}}) \) and longer term \( (\beta_{\text{COM}}, A_{\text{COM}}) \) responses of the COM to perturbation (Fig. 1C). \( B_{\text{COM}} \) is the peak of the distance curve, which indicates the degree of COM disruption, and \( \tau_{\text{COM}} \) is the time to \( B_{\text{COM}} \), which indicates the duration of the initial destabilizing response. \( \beta_{\text{COM}} \), the slope of the exponential function, describes the rate of return of the function to baseline following the initial response, and \( A_{\text{COM}} \) is the mean value of the distance of the function from the attractor at the fifth postperturbed step, indicating the recovery of a stable gait pattern at a time when full recovery was expected. Trials in which \( A_{\text{COM}} \) was higher than twice the baseline SD were discarded to ensure reliable decay of the distance function following perturbation (Post et al. 2000). On the basis of this criterion, 6% of trials were removed in young adults and 9% of trials in older adults.

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Given that in unperturbed walking, an increase in the duration of double leg support correlates with impaired balance (Winter et al. 1990), the time required to recover steady-state walking was also described by the number of gait cycles required for the return of the double-support duration to preperturbation values (double-support recovery index). Because the SD of double-support time in nonperturbed walking did not exceed 10% of the mean, we defined recovery of double-support duration as the first gait cycle when double-support duration was within 10% of baseline values.

The long-term (residual) effect of the perturbation on whole body stability was quantified by computing long-lasting phase shifts of all four limbs (Feldman et al. 2011; Yamazaki et al. 2003). This measure is complementary to the COM analysis, because the COM stability analysis quantifies the return of the COM to the preperturbed stable state, whereas phase resetting describes the residual change in the movement pattern, i.e., changes that persist after the perturbation. A long-lasting phase shift was defined as a shift in the locomotor rhythm that persisted for at least three cycles after perturbation. Phase shifts were computed by comparing the timing of gait events: the foot contact for the legs and the front-to-back movement direction reversal for the arms. These events were identified on the basis of movements of heel and finger markers, respectively, in the sagittal plane before and after perturbation. The anteroposterior position of each limb in the three cycles before perturbation was projected forward, and the minimal time between the actual and projected foot contact/direction reversal was divided by the preperturbed cycle period. In the case of more than one event occurring within the duration of one preperturbed cycle, the first event was used (Ford et al. 2007). The obtained value was multiplied by 360°, resulting in a range of possible phase shifts from −180° to +180°. A negative value denoted a phase advance, and a positive value denoted a phase delay.

Immediate and longer term responses: interlimb coordination. The immediate effect of the perturbation on interlimb coordination of arms and legs was described using the same approach outlined above for the COM. The difference in the angular position of limb pairs, arms (shoulder flexion angle) or legs (hip flexion angle), was used. The angular difference rather than the continuous relative phase (c.f. Scholz et al. 1987) was used, because the latter is indicated only for sinusoidal signals (Peters 2003). Shoulder and hip angles were computed using the Plug-in-Gait model. Shoulder angles in three movement planes (flexion/extension, abduction/adduction, and rotation) were calculated relative to thorax movement, and hip angles (flexion/extension, abduction/adduction, and rotation) were calculated relative to pelvic movement. The baseline interlimb coordination was quantified by calculating the difference between the angular position signals of the two limbs in each plane for each time point. The angular position of the limb on the perturbed side was subtracted from that of the nonperturbed side, and the phase plot was produced as above. The parameters of initial and longer term recovery derived were , , and A for arms and B, and A for legs. These parameters were used as explanatory variables for COM stability. In addition, the baseline SD of the difference signal was calculated for arm and leg trajectories to verify that baseline conditions were similar between groups.

**Statistical Analyses**

A one-way ANOVA was used to test the effect of group on response strategy. Because response strategy selection was assumed to affect recovery (de Boer et al. 2010), it was entered as an independent factor in further analyses. Generalized estimation equations (GEE; Wald statistic) (Zeger and Liang 1986, 1988) were used to test the effect of group and response strategy on gait stability and interlimb coordination. GEE was selected because of its ability to accommodate correlated and missing data. To prevent variations due to different walking speed in individual trials, walking speed was set as a covariate in the model. For phase shifts of all four limbs (circular variables), Harrison-Kanji tests were performed (circular 2-way ANOVAs with response pattern and group as independent variables; Harrison and Kanji 1988). A repeated-measures ANOVA was used to test for group differences in the duration of coordination disruption for arm, leg, and COM movements. Spearman correlations were used to correlate gait stability with interlimb coordination and the clinical scores (for older adults). All analyses were carried out in SPSS (version 17.0) except for circular data analyses, which were computed in Matlab 6.5 (The MathWorks, Natick, MA) using the circular statistics toolbox (Berens 2009). Significance was set at for all tests. For the correlations, Bonferroni corrections were used to adjust for the number of planned comparisons ( < 0.006).

**RESULTS**

Anthropometric data for all subjects are detailed in Table 1. Walking speed was similar for both groups. The perturbation generated a consistent mean force of 38.1 ± 8.3 N that did not vary by response strategy or group. All subjects easily adapted to treadmill walking and produced rhythmical locomotor patterns in the arms and legs (Fig. 2A). Perturbation disrupted the rhythmical patterns in all four limbs. Gait speed in the first three postperturbed steps decreased by a small but significant percentage in both groups (by 2.6% in young subjects and by 5.1% in older adults, < 0.05 for group). This change was not correlated with any of the analyzed variables related to recovery of steady-state walking.

**Role of Response Strategy in Recovery of Steady-State Walking**

We identified three strategies in response to perturbation. In 48% of cases in young adults (percentage of cases was determined for each subject and averaged across group) and 64% of cases in older adults, a lowering strategy was used. A combined strategy was used in 44% and 31% of cases in young and older subjects, respectively, and an elevation strategy was used in 8% and 5% of cases, respectively. There were no group differences in strategy selection (Fig. 3A).

Response strategy was related both to the immediate and longer term characteristics of COM trajectories following the perturbation. In both groups, the immediate COM responses were related to the strategy used (Fig. 3A2, TCOM: = 56.69, < 0.001; Fig. 3A3, TCOM: = 8.98, < 0.01). A lowering strategy generated the largest disruption in COM trajectory (BCOM, < 0.01) and the longest duration of the initial response (τCOM, < 0.001). In contrast, an elevation response generated the smallest disruption to COM trajectory. In the

**Table 1. Anthropometric and kinematic data for young and older adults**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Young Adults</th>
<th>Older Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height, cm</td>
<td>172.1 ± 7.7</td>
<td>167.5 ± 10.5</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>71.6 ± 10.8</td>
<td>69.2 ± 13.3</td>
</tr>
<tr>
<td>Age, yr</td>
<td>27.6 ± 4.5</td>
<td>69.1 ± 4.2</td>
</tr>
<tr>
<td>FGA</td>
<td>27.8 ± 2.3</td>
<td>93.5 ± 6.6</td>
</tr>
<tr>
<td>ABC</td>
<td>10.22 ± 0.33</td>
<td>13.3 ± 1.1</td>
</tr>
<tr>
<td>Comfortable gait speed, m/s</td>
<td>1.07 ± 0.09</td>
<td>1.06 ± 0.17</td>
</tr>
<tr>
<td>Swing length, mm</td>
<td>661.1 ± 39</td>
<td>645.1 ± 68</td>
</tr>
<tr>
<td>Swing time, s</td>
<td>0.44 ± 0.02</td>
<td>0.43 ± 0.03</td>
</tr>
</tbody>
</table>

Data are means ± SD for young (n = 24) and older adults (n = 18). FGA, Functional Gait Assessment (30-point scale); ABC, Activities-Specific Balance Confidence questionnaire (100-point scale).
longer term, response strategy was related to COM stability at the fifth step after perturbation (Fig. 3B1, $A_{\text{COM}}$: $\chi^2 = 24.51$, $P < 0.001$) and consequently, also to the rate of return to steady-state walking (Fig. 3B2, $B_{\text{COM}}$: $\chi^2 = 7.01$, $P < 0.04$). In addition, a lowering strategy was associated with longer double-support recovery time (Fig. 3B3, $\chi^2 = 38.68$, $P < 0.001$) and larger long-term phase shifts for all limbs ($\chi^2 > 300.3$, $P < 0.001$).

**Effect of Age on Recovery of Steady-State Walking**

Older adults had larger baseline SDs of COM trajectory during nonperturbed walking ($\chi^2 = 16.80$, $P < 0.001$). However, by the fifth step after perturbation, COM trajectories ($A_{\text{COM}}$) returned to baseline in both groups.

Characteristics of both the short- and longer term responses were different in older compared with young adults. In older adults, the duration of the initial response was longer (95% CI $\chi^2 = 102.8$% $P < 0.001$) and the contralateral and ipsilateral arms ($\chi^2 > 300.3$, $P < 0.001$). Older adults had lower rates of recovery from perturbation ($B_{\text{COM}}$: $\chi^2 = 4.24$, $P < 0.04$), took more steps to recover double-support duration ($\chi^2 = 8.68$, $P < 0.004$), and had larger phase shifts ($-83^\circ$ to $-90^\circ$) compared with young adults ($-39^\circ$ to $-42^\circ$; $\chi^2 > 22.0$, $P < 0.001$).

**Interlimb Coordination and Recovery of Steady-State Walking**

Baseline SDs of arm and leg interlimb coordination were similar between groups. In both groups, the initial disruption in arm coordination ($\tau_{\text{arms}}$) occurred later than that of the COM and the legs ($F_{1.30} = 45.68$, $P < 0.001$), whereas the durations of the coordination disruptions in COM and legs did not differ in either group. In both groups, response strategies were related to the amount of disruption in arm and leg interlimb coordination at the fifth step after perturbation ($A_{\text{arms}}$: $\chi^2 = 28.87$, $P < 0.001$; $A_{\text{legs}}$: $\chi^2 = 12.14$, $P < 0.003$) such that the coordination between the two arms and the two legs was more disrupted at the fifth step if a lowering strategy was used.

Interlimb coordination in both arms and legs at the fifth step after perturbation ($A_{\text{arms}}$, $A_{\text{legs}}$) was more disrupted in older compared with young adults. Although by the fifth step after perturbation, the COM trajectory ($A_{\text{COM}}$) returned to baseline in both groups, arm and leg coordination remained relatively
more disrupted in the older group ($A_{\text{arms}}$: $\chi^2 = 8.90, P < 0.004$; $A_{\text{legs}}$: $\chi^2 = 10.74, P < 0.002$).

In both groups, the larger initial destabilization of COM ($B_{\text{COM}}$) led to a larger disruption in arm coordination ($B_{\text{arms}}$): young: $r = 0.63, P < 0.006$, older: $r = 0.72, P < 0.007$). However, only in young adults was the duration of the initial disruption of COM trajectory ($\tau_{\text{COM}}$) related to the duration of the initial disruption in arm and leg coordination ($\tau_{\text{arms}}$: $r = 0.56, P < 0.005$; $\tau_{\text{legs}}$: $r = 0.65, P < 0.005$). In young adults, in addition, the duration of the initial disruption of leg coordination ($\tau_{\text{legs}}$) was also related to double-support recovery time ($r = 0.59, P < 0.02$).

These relationships were absent in older adults. However, in the older group, a larger initial destabilization ($B_{\text{COM}}$) affected the disruption in arm coordination after five steps ($A_{\text{arms}}$: $r = 0.62, P < 0.007$) such that the arms remained less coordinated after five steps when the initial destabilization was larger. Recovery of gait stability or interlimb coordination in the older adults was not related to clinical tests of walking performance (FGA) or balance self-confidence (ABC).

**DISCUSSION**

We investigated gait stability and interlimb coordination in young and older adults following a perturbation to the dominant leg during walking at comfortable speed. Perturbation resulted in a disruption to the steady-state walking pattern in all subjects followed by a return to baseline walking pattern and a long-lasting phase shift in all four limbs. Gait stability was related to the pattern of leg movement used in response to the perturbation such that when a lowering strategy was used, a longer lasting and stronger disruption of stability occurred. Older adults had more variable COM patterns at baseline, an initially longer COM destabilization following perturbation, slower COM recovery, and a larger residual phase shift in movements of the arm and legs. In addition, arm and leg coordination of older adults remained more disrupted for up to five steps following perturbation. In young adults only, the temporal evolution of arm and leg coordination was correlated with COM stability. In older adults, however, a stronger initial destabilization led to a larger and longer term disruption in arm coordination.

The older participants were all able to recover from the trip perturbation and regain their baseline walking pattern. They used the same strategies as young adults when reacting to the perturbation (Pavol et al. 2001). In young adults, use of a lowering strategy is typical for mid- and late-swing perturbations (Schillings et al. 1996) and is considered less energy efficient than an elevation strategy (de Boer et al. 2010). We showed that use of this strategy was related to a longer lasting, more unstable postperturbation state compared with the use of...
combined or elevation strategies. Previous studies have anec-
dotally suggested that strategy selection might differ between
young and older adults (Pijnappels et al. 2005; Roos et al.
2008). Although we did not find evidence to support a different
distribution of response strategies in young and older adults,
older adults differed from young adults in immediate effects
and longer term responses to perturbation. Specifically, older
adults had a 25% longer initial destabilization, took longer to
recover COM stability and double-support duration, and had
larger whole body long-lasting phase shifts. These differences
were observed in a group of high-functioning, physically active
older adults with FGA scores of 27.8 ± 2.3 out of 30, compared
with a reported average of 27.1 ± 2.3 for people aged 60–69 yr
and 24.9 ± 3.9 for people aged 70–79 yr (Walker et al. 2007).
None of the older adults in this study was at risk of falling (FGA ≤ 22),
and yet we observed that the period of decreased stability following perturbation was longer
in this group. Thus the clinical tests may be less sensitive
to minor changes in the ability to recover from perturbation, as
also implied by the lack of relationship between clinical me-
asures of balance (FGA) and balance self-confidence (ABC) and
the recovery of steady-state walking. This is consistent with
preliminary results of Marone et al. (2011), who suggested that
balance self-confidence (ABC scores) had no influence on the
kinematic response to an induced trip in older adults. However,
it is possible that more differences would be observed in a
group of older adults with more functional heterogeneity.

Age-related differences in gait stability such as those de-
dscribed here could result from several factors, including de-
clines in muscle strength and/or central and reflex reactions. In
healthy, physically active older adults, peak isometric strength
decreases by one-third by the age of 65 yr. Although neuro-
logical factors such as reaction times also change with age
(Thelen et al. 1996), the magnitude of these differences is small
(10–25 ms) and unlikely to explain age differences in tripping
responses (Schultz 1995; Schultz et al. 1997). In this study, age
differences in gait stability were not specific to the first step,
indicating a prolonged period of instability following a forward
loss of balance (Forner-Cordero et al. 2003). Furthermore, the
finding that the response observed in both young and older
adults involved the whole body may indicate the involvement
of a central mechanism. It is well known that in cats, the motor
cortex and specifically the corticospinal tract are involved in
obstacle avoidance during gait by modifying forelimb eleva-
tion according to obstacle characteristics (Drew 1988, 1993;
Lajoie et al. 2010). Microstimulation of pyramidal tract neu-
rons generated a phase shift in the locomotor patterns in the cat
hindlimb (Orlovsky 1972) similar to phase shifts observed in
this study. In humans, both the corticospinal tract and other
supraspinal locomotor centers (mesencephalic locomotor re-

gion, subthalamic locomotor region) have been implicated in
the control of swing length modulation during gait (Shik and
Orlovsky 1976) with possible differences between step short-
ening and lengthening reactions (Varraine et al. 2000). The
long-term whole body responses observed in this study may be
mediated by the superposition of a supraspinal signal on a
spinal locomotor command. A change in this control sequence
or a slowing of transmission in locomotor pathways in older
adults could be responsible, in part, for the difference in the
resulting locomotor patterns following perturbation.

Results from this study also suggest that arm and leg
coordination following perturbation are linked to recovery of
COM stability. In the short term following a perturbation to the
torso, early-onset muscle activity occurred in shoulder and arm
muscles (Misiaszek 2003). Brujin et al. (2010) compared short-
and long-term gait stability of young adults following a per-
turbation to the torso with and without arm swing. They
showed that walking without arm swinging increased the time
to peak distance from the attractor (τ) and decreased the slope
of the return to baseline (β) for the trunk. Despite differences
in the methodology used in our study (analysis of COM instead
of a trunk rigid body), we found similar results when compar-
ing responses between different strategies at similar speeds: a
lowering response was related to longer initial destabilization
and a longer recovery phase (Fig. 2). We further found, using
the same technique for evaluating changes in interlimb coor-
dination, that timing of the disruption in arm and leg interlimb
coordination was coupled with COM stability only in young
adults. In older adults, however, the timing of the initial
interlimb coordination response was not related to COM sta-

tility. This suggests that older adults were less able to adapt the
arm and leg responses to the changes in COM stability result-
ing from perturbation. This finding is consistent with those of
Roos et al. (2008), who investigated the role of arm movements
in the sagittal plane immediately following a trip in young and
older adults. These authors found a positive correlation be-
tween vertical arm movement and COM displacement in young
but not older adults. It was suggested that older adults did not
use the arms to assist COM elevation following a trip. We
investigated movement in three dimensions and showed that
the larger disruptions in interlimb coordination persisted in
older adults in the longer term. In older but not young adults,
the disruption in the arm interlimb coordination after five steps
was still related to the perturbation, suggesting a longer term
global effect.

A mechanism by which the arms may initially assist recov-
er in the case of a trip has been suggested by Pijnappels et al.
(2010). They showed that during the leg elevation response
elicited by a trip, the arm swing amplitude increased and was
associated with a large body rotation in the transverse plane,
supporting the increased step length required to prevent a fall.
These authors focused on elevation responses during over-
ground walking. In our study, however, trip perturbations led
to a majority of lowering or combined responses that involve
premature lowering of the perturbed leg. In this type of re-

dose, a transition from swing to stance occurs in one leg and
and from stance to swing in the other (phase shift; Feldman et al.
2011). To completely regain the preperturbed whole body
coordination pattern and regardless of the initial response to
perturbation, the arms have to switch movement direction
(from forward to backward or vice versa) such that the anti-
phase pattern between the arms and legs is restored and a
similar phase shift is observed in upper and lower limbs (Fig.
2). We have shown that in both young and older adults, the
initial response of the arms occurred after that of the legs and
COM. However, in older adults, the arms and legs remained
less coordinated for up to five steps after the perturbation,
whereas COM stability was restored in both groups.

Gait can be considered as resulting from translation of body
equilibrium in the environment (Feldman et al. 2011). To
prevent falling, subjects can transiently slow down or speed up
the translation in response to perturbation, which can be detected as a long-lasting phase shift in gait. Thus this shift may be involved in fall prevention by allowing subjects to regain gait stability following a perturbation, as also follows from the analysis of reactions to perturbations in a simple biomechanical model of gait (Yamasaki et al. 2003). Therefore, the ability to perform the coordinated phase shift in all four limbs required to successfully recover from perturbation may be decreased in older adults, and interlimb coordination, especially for the arms, may be less stable.

It was previously found that even during unperturbed gait, older adults have a less stable bilateral leg coordination (Plontik et al. 2007), as manifested by a more variable relative phase between strides. The temporal stability of interlimb coordination between arms or between arms and legs was also lower in older adults in tasks unrelated to gait, such as bimanual cycling (Greene and Williams 1996) or arm-leg swinging during sitting (Fujiyama et al. 2009; Serrien et al. 2000). These deficits were more pronounced during anti-phase movements as in walking. Our leg perturbation caused a disruption in arm and leg coordination in both young and older adults. However, older adults had more difficulty recovering coordination following the perturbation. The performance of anti-phase limb swinging (even without walking) is considered to be an “effortful” process, compared with in-phase movement, which is considered to be more “automatic” (Greene and Williams 1996). An effortful process typically requires increased attention. The reduced stability of anti-phase movements in older adults’ performance may be related to a reduction in cognitive resources (Sparrow et al. 2005; Wishart et al. 2000). A perturbation places additional load on cognitive resources of older adults (for review, see Maki and McIlroy 2007) and increases the disruption to interlimb coordination (Heuninckx et al. 2004). Although attention was not directly measured in this study, it is possible that the perturbation placed an increased load on the system and generated a larger disruption to interlimb coordination.

In our study, early-to-mid swing perturbations generated relatively more lowering responses compared with previous studies involving treadmill walking with perturbations (c.f. Schillings et al. 2000). The difference may partly be explained by the type of perturbations used in different studies. In our study, the perturbation consisted of a posterior force applied to the ankle (pulling from behind), whereas in previous studies, perturbations consisted of the placement of an obstacle in the walking path. Two studies (Forner-Cordero et al. 2003; Kobayashi et al. 2000) investigated a similar type of posterior pull perturbation in young healthy subjects. In the single-subject study of Kobayashi et al. (2000), early-to-mid swing perturbations resulted in a lowering strategy and a phase advance similar to results reported here. In the report of Forner-Cordero et al. (2003), different strategies were observed for early-swing perturbations, and the authors hypothesized that strategy selection may be optimized in terms of safety or energy consumption. In contrast to our study, both of these previous studies used a motor-driven treadmill, which may have led to different responses because subjects had to “keep up” with the treadmill speed.

To quantify gait stability and interlimb coordination, we used the method described by Bruijn et al. (2010), which enables a fine-grained comparison of differences in recovery of steady-state walking between different conditions. Bruijn et al. (2010) suggested that the initial response to a destabilizing perturbation (quantified by $\tau$ and $B$) is indicative of the steady-state walking pattern, whereas $\beta$ and $A$ quantify the recovery of steady-state walking. The authors suggest that lower values of $\tau$ indicate less stability in the initial response to perturbation. Results from our study suggest an additional interpretation. We found that $\tau_{\text{COM}}$ was related to response strategy. For example, a lowering strategy, known to be less energy efficient and require longer recovery, was associated with higher values of $\tau_{\text{COM}}$. Combined and elevation strategies, which are less destabilizing (de Boer et al. 2010), were associated with lower values of $\tau_{\text{COM}}$. A higher value of $\tau$ implies that the least stable point occurs later in the recovery process. This means that the initial destabilization of the COM caused by the perturbation was longer in duration. These results coincide with higher values of $A$ and lower values of $\beta$, indicating that both stages of the recovery were less efficient when a lowering strategy was used compared with combined or elevation strategies.

The method of Bruijn et al. (2010) relies on the similarity of baseline standard deviations to enable comparisons. In our case, older adults had larger baseline variability of COM trajectories. However, by the fifth step after perturbation, COM stability returned to similar values with respect to baseline SD in both groups. The higher baseline SD in older adults did not affect the temporal evolution of the response ($\tau_{\text{COM}}$) but may have resulted in lower values of initial COM disruption ($B_{\text{COM}}$) in this group. On the other hand, the higher variability in COM movement in older adults is important given the link between gait variability and falls (c.f. Hausdorff et al. 2001). Our data suggest that group differences were not due to baseline differences, since other measures of gait stability, namely, phase shifts and double-support recovery, were also disrupted in older subjects.

This study has several limitations. Our sample of older adults was relatively high functioning, and more group differences between young and older adults could possibly be found in a sample of older adults with a wider range of FGA scores. The use of a self-paced treadmill limited the ability to control gait speed (cadence control only), but it did enable a more functional examination of responses to perturbation than use of a motorized treadmill. It also allowed us to produce multiple perturbations in each subject. Finally, the use of a metronome to pace walking may have unnaturally stabilized gait patterns or introduced an increased cognitive load by adding a distractor. However, we did not insist that subjects follow the metronome pacing after perturbations, and perturbations were initiated only after walking patterns stabilized during each trial.

In conclusion, results from this study indicate that in older adults, gait stability and stability of interlimb coordination were more disrupted following perturbation in both the immediate and longer term. The longer period of destabilization in older adults following a perturbation suggests that older adults would be more vulnerable to additional perturbations during this period, for example, when walking on unstable terrain (rocks, ice, etc.). This finding in a group of high-functioning older adults with no fall risk could indicate a possible need for functional training of stability using a perturbation approach (Marigold and Misiaszek 2009). In young adults but not in older adults, COM stability was related to the timing of the disruption in arm and leg interlimb coordination, but only in
older adults did the disruption to gait affect longer term arm interlimb coordination. This suggests a relationship between interlimb coordination and recovery of gait stability in older adults.

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AUTHOR CONTRIBUTIONS


REFERENCES


