Gait Characteristics as Risk Factors for Falling
From Trips Induced in Older Adults

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Background. Falls are a significant source of morbidity and mortality in older adults, with up to 53% of these falls due to tripping. To aid in preventing trip-related falls, the factors that increase an individual’s risk of falling following a trip must be identified. This study investigated whether an older adult’s gait influences their risk of falling following a trip.

Methods. Trips were induced during gait in 79 healthy, safety-harnessed, community-dwelling older adults using a concealed, mechanical obstacle. Associations between selected gait kinematic characteristics, recorded during normal walking, and the likelihood of falling following the trip were determined using logistic regression.

Results. Older adults who walked faster, took more rapid steps, or took longer steps relative to their body height had a significantly increased likelihood of falling following the trip. Step width, average trunk flexion during gait, and the phase of gait in which the trip occurred did not affect the likelihood of falling. A multivariable logistic regression model correctly classified 89.8% of trip outcomes based on two gait characteristics: step time and step length. As predicted from their gait characteristics, the subjects, as a group, had a low likelihood of falling following a trip, but selected individuals had a high likelihood of falling.

Conclusions. The incidence of trip-related falls in healthy older adults is determined primarily by the frequency of tripping and not the ability to recover from a trip. Older adults can reduce their likelihood of falling following a trip by not hurrying while walking.

Falls are a serious health concern for older adults. Falls are a leading cause of injury and mortality (1–3) and can lead to fear and self-imposed restriction of activity (4–6). One of the most commonly reported causes of falls in older adults is tripping, responsible for up to 53% of falls in older adults (7). Therefore, there is a need to identify the factors that increase an individual’s risk of falling following a trip so that the occurrence of these trip-related falls may be reduced. Because trips occur during gait and because the characteristics of normal gait differ between individuals and are known to change with age (8,9), it is reasonable to question whether the gait characteristics of older adults influence their risk of falling following a trip.

Epidemiological studies of both community-dwelling and institutionalized older adults have found relationships between gait impairments, as measured by activity-based tests, and the incidence of falling (5,10,11). In addition, specific gait characteristics have been associated with increased falling. These include a slowed walking speed, short step length, increased step time, greater stride width, and increased percentages of the stride spent in stance and double support (5,10–16). However, the link between patterns of gait and falling is still unclear, as some studies have found no such association between these gait characteristics and falling (12,14,15,17). More important, these studies of gait and falling are not directly applicable to the prevention of trip-related falls, as they did not discriminate by the type of fall. Given this limitation, the high incidence of trip-related falls in older adults, and the possibility that gait modification could provide a relatively simple means of reducing the risk of falling, a direct study of the relationship between gait and trip-related falls is warranted.

We have previously reported on the incidence of falls resulting from trips that were induced during gait in a population of healthy older adults (18). In that study, 10 falls and 39 successful recoveries were observed, with women falling more than four times as frequently as men, and with men aged 65–69 years falling more than three times as frequently as women aged 70 years or older. The present study determined whether selected gait characteristics of these individuals, namely walking speed, step time, step length, step width, average trunk flexion angle, and the phase of gait in which the trip occurred, were related to the likelihood of falling following the induced trip.

METHODS

Subjects
Fifty women and 29 men (age: 72 ± 5 years; height: 1.6 ± 0.1 m; mass: 76 ± 14 kg), all healthy, community-dwelling, and at least 65 years of age, provided written informed consent to participate in this experiment, which was part of a larger study of falling in these older adults. Subjects volunteered in response to announcements through local older adult organizations. Each subject was screened by a geriatrician for exclusion factors that included neurological, musculoskeletal, cardiovascular, pulmonary, cognitive, and other systemic disorders, as well as a history of repeated falling. A minimum bone mineral density of the femoral neck, assessed by DXA (Hologic QDR 1000,

M583
Waltham, MA), of 0.65 g·cm−² was also required. Subjects were paid for their participation.

Experimental Protocol

The experimental session comprised a walking protocol, in which a subject’s normal gait was recorded, followed by a tripping protocol, in which the subject was tripped during gait. These previously described protocols (18) are summarized here.

Gait kinematics were recorded during each experimental trial using a six-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA). The cameras, operating at 60 Hz, recorded the motion of 18 hemispherical passive reflective markers applied over selected anatomical landmarks of the bilateral upper and lower limbs, torso, and head.

In the walking protocol, subjects walked at a self-selected, “normal” speed from a designated starting point to a final point approximately 7 m away. Kinematic data were collected over the middle three to five steps of the gait path. Average walking speed was computed from the elapsed time over the middle 4.4 m of the gait path, as measured using a pair of photoeyes trained across the gait path at chest height. Ten trials of normal walking data were collected for each subject.

For the tripping protocol, subjects wore a full-body safety harness that was attached by a pair of dynamic ropes to a bearing on a ceiling-mounted track. Rope lengths were adjusted such that the wrists and knees could not touch the floor. A calibrated load cell (Omega Engineering Inc., Stamford, CT), connected in series with the dynamic ropes, measured the force exerted on the ropes by the subject. The load cell force signal was sampled at 1000 Hz in synchrony with the kinematic data.

Before attempting to induce a trip, data were collected from one trial of normal walking in the safety harness. This trial was identical to those of the walking protocol and performed after the subject had become accustomed to walking in the harness. Data from this trial confirmed that the presence of the safety harness did not introduce any meaningful changes to the gait of the subjects (18).

Trips were induced using a concealed, pneumatically driven, metal, mechanical obstacle. This obstacle would rise 5.1 cm from the floor in approximately 170 ms when manually triggered by the investigator, inducing a trip by obstructing the toe of the swing foot during mid-to-late swing. For the trip, a decoy “tripping rope” was also laid across the gait path, 1.5 m before the mechanical obstacle. The rope provided a visible hazard, the implicit purpose of which was to mislead the subject as to the time, location, and mechanism of the trip.

Subjects were informed that a trip would take place during one of the upcoming trials. Instructions were to walk as in the preceding walking protocol, looking straight ahead, and, if tripped, to recover and continue walking. On a subsequent trial, when the stance foot was judged to be appropriately placed, the obstacle was triggered and a trip induced. Only one attempt was made to trip each subject.

Data Analysis

Each trip outcome was classified as either a recovery, fall, rope-assist, or miss. Falls were identified visually and corresponded to the subject being fully and continuously supported in a prone position by the safety harness. Recoveries and rope-assists were differentiated based on the force exerted on the safety harness ropes. The load cell force signal was low-pass–filtered recursively at 16 Hz and integrated for 1 second following the triggering of the obstacle. Based on the distribution of these integrated forces, trip outcomes with less than 5% body weight·second exerted on the ropes were classified as recoveries. Outcomes with larger integrated forces were considered rope-assists. Misses resulted when impact with the obstacle was not with the most anterior portion of the shoe during mid-to-late swing or if reliable load cell data was unavailable. The former misses were due entirely to inappropriate timing of the triggering of the obstacle.

Four gait variables were computed for each step recorded in the kinematic data: step time, step length, step width, and average trunk flexion angle. To compute these variables, the times of heelstrike, the locations of the toe and heel of each shoe, and the spatial orientations of the trunk and pelvis were determined from the three-dimensional paths of the reflective markers. These determinations were made using transformations derived from anthropometric measurements and kinematic data collected during an initial trial of quiet standing in a specified body position.

Step time was measured between consecutive heel strikes. Step length was measured in the direction of gait between contralateral static locations of the heel during stance. Step lengths were normalized to body height, as justified by an allometric scaling analysis (19). Step width was measured normal to the direction of gait between contralateral static locations of the heel-toe midpoint during stance. Trunk flexion was computed as the rotation, from the vertical, of the trunk about an axis located at the level of L3-L4 and oriented parallel to the mediolateral axis of the pelvis. The trunk was defined as being vertical when the shoulder joint centers were 6.8 cm posterior to the hip joint centers during quiet standing, based on the mode of the observed distribution in our subjects. The trunk flexion angle was averaged between consecutive heel strikes. Average values of each gait variable were computed for each subject across all recorded steps from the normal walking trials, including that while in the safety harness. Walking speed was averaged across the 10 walking trials.

The phase of gait in which each trip occurred was determined as the perpendicular distance between the obstacle and the static location of the toe of the obstructed foot during the preceding stance phase. This distance was expressed as a percentage of the length of the contralateral stride preceding the trip. The stride length was computed as the distance between ipsilateral static stance-phase heel locations.

Statistics

Subjects were grouped by their trip outcome. Independent t tests were used to determine whether the computed gait variables differed between the recovery and fall groups. A chi-square test was used to evaluate whether the probability of falling following a trip could be considered uniform across all phases of gait in which trips occurred. For this test, the uniform probability of falling was estimated from the total numbers of falls and recoveries, the range of the phase of gait in which the trip occurred was divided into intervals of one percent of stride length, and the expected number of falls within each interval was predicted from the number of trips that occurred therein, neglecting those whose outcome was a rope-assist.

For each of the gait variables, logistic regression was used to
determine, from the combined data of the recovery and fall groups, the relationship between the gait variable and the likelihood of falling following a trip. Odds ratios for falling were computed for a change in each gait variable equal to one standard deviation of the mean values observed across all subjects tested. A backwards, stepwise, multivariable, logistic regression of the computed gait variables against the trip outcome was performed for the data of the recovery and fall groups, and the post hoc predictive accuracy of the resulting model was evaluated. In this analysis, the initial model included subject age and all gait variables possessing significant univariate relationships to the trip outcome. The likelihood-ratio test with a cutoff probability of .1 was used in variable elimination, and the threshold probability for classification into the fall group that provided the greatest predictive accuracy was employed. A significance level of .05 was used in all analyses.

RESULTS

As previously reported (18), of the attempted trips of 79 subjects, 39 outcomes were classified as recoveries, 10 as falls, 12 as rope-assists, and 18 as misses. The fall-to-recovery ratio was 9/25 in the women and 1/14 in the men. Within the women, the fall-to-recovery ratio was 7/12 for those aged 65–69 and 2/13 for those 70 or older.

Three of the six gait variables differed significantly \((p < .05)\) between the subjects who successfully recovered following the trip and those who fell (Table 1). As compared to those who recovered, fallers walked faster, took more rapid steps, and took longer steps relative to their body height. There were no significant differences \((p > .05)\) in step width, average trunk flexion during gait, or phase of gait in which the trip occurred between those who recovered and those who fell. The distribution of falls across the phases of gait in which the trips occurred did not differ significantly \((p > .9)\) from a uniform distribution (Figure 1).

Table 1. The Mean ± SD of the Recovery Group \((n = 39)\) and the Fall Group \((n = 10)\) for the Gait Parameters and Phase of Gait in Which the Trip Occurred

<table>
<thead>
<tr>
<th>Gait Parameter</th>
<th>Recovery</th>
<th>Fall</th>
<th>(p) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking speed (m/s)</td>
<td>1.18 ± 0.16</td>
<td>1.31 ± 0.16</td>
<td>.018</td>
</tr>
<tr>
<td>Step time (s)</td>
<td>0.54 ± 0.04</td>
<td>0.50 ± 0.05</td>
<td>.010</td>
</tr>
<tr>
<td>Step length (% body height)</td>
<td>39.9 ± 3.4</td>
<td>43.1 ± 3.7</td>
<td>.011</td>
</tr>
<tr>
<td>Step width (cm)</td>
<td>9.2 ± 3.0</td>
<td>8.9 ± 3.2</td>
<td>.747</td>
</tr>
<tr>
<td>Trunk flexion (deg from neutral)</td>
<td>9.0 ± 5.5</td>
<td>11.1 ± 6.7</td>
<td>.317</td>
</tr>
<tr>
<td>Gait phase of trip (% stride length)</td>
<td>58.3 ± 4.4</td>
<td>59.1 ± 4.5*</td>
<td>.714</td>
</tr>
</tbody>
</table>

\(n = 9\) due to missing data for one subject.
indicating that, across the range of phases tested, the probability of falling from the trip was unaffected by the phase of gait at which the trip occurred.

The logistic regressions indicated that walking speed, step time, and step length relative to body height were each significantly ($p < .05$) related to the likelihood of falling following a trip (Table 2). An increase of one standard deviation in walking speed or step length, or a decrease of one standard deviation in step time, increased the odds of falling following a trip by a factor of between 2.5 and 3.5. Step width, average trunk flexion during gait, and the phase of gait in which the trip occurred were unrelated to the likelihood of falling following a trip ($p > .05$).

The multivariable logistic regression model determined through a backward, stepwise procedure included step time and step length as the final predictor variables. Use of a threshold probability of falling of .36 to predict who would fall provided the greatest accuracy of classification for the model. With this threshold, the multivariable logistic regression model was able to correctly classify 37 of the 39 subjects that recovered and 7 of the 10 subjects that fell, for an overall success rate of 89.8% (Figures 2 and 3).

### Table 2: Changes in the Odds Ratio for Falling Associated With Changes of One Standard Deviation for the Tested Population in Each of the Measured Gait Parameters

<table>
<thead>
<tr>
<th>Gait Parameter</th>
<th>Change Employed for Odds Ratio</th>
<th>Odds Ratio for Falling* (95% Confidence Interval)</th>
<th>$p$ value†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking speed</td>
<td>+0.161 m/s</td>
<td>2.56 (1.11–5.86)</td>
<td>.027</td>
</tr>
<tr>
<td>Step time</td>
<td>-0.041 s</td>
<td>3.49 (1.24–9.88)</td>
<td>.018</td>
</tr>
<tr>
<td>Step length</td>
<td>+3.72% body height</td>
<td>3.46 (1.23–9.76)</td>
<td>.019</td>
</tr>
<tr>
<td>Step width</td>
<td>-3.10 cm</td>
<td>1.13 (0.55–2.34)</td>
<td>.741</td>
</tr>
<tr>
<td>Trunk flexion</td>
<td>+5.94°</td>
<td>1.43 (0.71–2.89)</td>
<td>.314</td>
</tr>
<tr>
<td>Gait phase of trip</td>
<td>+4.42% stride length</td>
<td>1.15 (0.55–2.42)</td>
<td>.707</td>
</tr>
</tbody>
</table>

*The odds ratio equals the factor by which the odds of falling (i.e., probability of falling divided by probability of recovering) increase if the associated gait parameter changes by the given amount.

†$p$ value was determined based on Wald’s chi-square test.

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### DISCUSSION

This study used a direct, prospective, experimental approach to determine that the manner in which a healthy older adult walks is related to his or her likelihood of falling following a trip. Characteristics of the normal, self-selected gait of a sample population of healthy older adults were measured, then a concealed mechanical obstacle was used to induce a trip during normal gait. The likelihood of falling following a trip was found to be related to selected individual gait characteristics and most
of the older adults who fell when tripped were found to exhibit a specific, distinctive pattern of gait.

A faster walking speed, a shorter step time, and a longer step length during normal gait were each found to increase the likelihood of falling following a trip. However, it is likely that these three individual relationships reflect the influence of a single, common factor related to walking speed. This is because a decreased step time and increased step length accompany an increase in walking speed (20), and, in the 49 subjects of the combined recovery and fall groups, walking speed was significantly correlated to both step time ($r = -0.64; p < .001$) and normalized step length ($r = 0.80; p < .001$). A general implication of the results, therefore, is that walking with a hurried or purposeful gait increases the likelihood that an older adult will fall if they trip. Such a direct relationship is reasonable. Walking faster increases the mechanical energy of the body at the time of the trip and decreases the time available in which to respond and recover, both of which would be expected to increase the likelihood of falling. This contention is consistent with the findings of a study of community-dwelling older adults in which tripping was the most common cause of falls and “hurrying too much” was the most often cited reason for falling (21).

Our findings seem to contrast with those of all epidemiological studies of gait and falling in older adults to date, however. In these studies, if any relationship between gait and falling has been found, it has been a slowed walking speed, shorter step length, and increased step time that increased the risk of falling (5,10–14,16). The discrepancy between our results and the others is not an artifact of the experimental conditions. As argued previously (18), the induced trips closely simulated ordinary, unexpected, trips over an unseen object, the trips were induced during normal gait, and the reactions to the trips were natural. The gait characteristics obtained should also reliably reflect the normal gait of the subjects, as these were compiled over multiple steps and trials. Therefore, there must be factors contributing to a true discrepancy between the present results and those of previously published epidemiological studies.

One possible contributor to the discrepancy is that we considered only falls that result from trips, whereas the epidemiological studies have not discriminated by the type of fall. As falls in varying directions from varying causes inherently differ from one another, the associated risk factors also likely differ. Indeed, significant reductions in activity-based gait and balance scores have been associated with some types of falls but not
of these characteristics. A truer picture of the relationship between gait and the likelihood of falling following a trip is, therefore, obtained through a multivariate approach. Results of the single-variable logistic regression analyses cannot be used for this purpose because of significant correlations between gait characteristics. A multivariable logistic regression model was required.

The multivariable logistic model obtained indicated that most of the older adults tested had a low likelihood of falling following a trip during normal walking based on their pattern of gait. The median predicted likelihood of falling across all subjects was only 13.2%. However, the model also indicated that a small number of subjects, primarily those who fell following the induced trip, had a specific, distinctive pattern of gait that was associated with much higher likelihoods of falling. The distinctiveness of this high-risk pattern of gait is evidenced by the fact that the multivariable logistic model was able to correctly classify 89.8% of the trip outcomes based solely on two gait variables.

The pattern of gait associated with an increased likelihood of falling following a trip is directly determinable from the coefficients of the multivariable logistic model, as the gait variables in the model were not significantly correlated ($r = -0.27; p = .064$). According to the model, the pattern of gait associated with an increased likelihood of falling involved taking longer (relative to body height) and more rapid steps. As discussed earlier, such a pattern of gait is most consistent with walking with a hurried or purposeful gait. In retrospect, this appropriately describes most who fell. Such individuals constitute a group that is at risk of falling from a trip because of a reduced ability to recover. These individuals likely represent an exception to the earlier statement that implicated the frequency of tripping as the dominant cause of trip-related falls.

Age is often implicated as a risk factor for falling (5,6,25). However, age played a lesser role than gait characteristics in determining the likelihood of falling following a trip, as age was not included in the final multivariable logistic model. In fact, the changes in gait generally associated with aging, namely a slowed gait speed, longer step time, and shorter step length (8.9), were all associated with a reduced likelihood of falling following a trip, illustrating a possible benefit of this adaptation. Implications on fall epidemiology of such an age-related reduction in the likelihood of falling following a trip have been discussed previously (18). Evidence of this beneficial adaptation in gait with age was not seen in the healthy older adults tested, however. Considering age-groups of women as in our previous report (18), the proportion of women classified by the multivariable logistic model as likely (i.e., probability greater than .36) to fall did not differ significantly between women aged 65-69 and those aged 70 or older (6/27 and 3/23, respectively; $p = .64$ by the Pearson chi-square test of association). This constant proportion across age groups could indicate that the healthy older adults with a high-risk pattern of gait do not adapt, and remain at a high risk of falling following a trip, as they age further. If so, early interventions should be targeted at these individuals.

There were no between-sex differences in the prevalence of the identified high-risk pattern of gait; in those who were successfully tripped, the proportion of men and women classified as likely to fall did not differ (2/20 and 9/41, respectively; $p = .43$ by the Pearson chi-square test of association). Thus, gait characteristics alone could not explain the fourfold greater fre-
quency of falling observed in the women. However, these same results, and the fact that seven of the nine women who fell were classified as likely to fall, also imply that the increased frequency of falling in the women is not attributable to sex, as such, but to specific high-risk women.

Whether the relationship between gait and the likelihood of falling following a trip differs between sexes could not be determined, as only one man fell. Rather than exclude this man or any others from the analysis a priori, it was assumed that the influence of gait on trip outcome would be independent of sex. This assumption seems reasonable, as similar gait patterns should lead to similar tripping dynamics for a given obstacle, hence similar recovery requirements. Nevertheless, the man who fell and one woman who fell were identified as outliers in the multivariable relationship found between gait and falling. These outliers most likely indicate that factors other than the gait characteristics considered also contribute to the outcome of a trip. Excluding the two outliers from the analyses did not alter the results, except to amplify the significant odds ratios and increase the classification ability of the multivariable model to 94%.

There are several practical implications to the results of the present study. The most important is that older adults can reduce their likelihood of falling following a trip by not walking quickly. There is a select group of individuals to whom this is particularly applicable, as they are at a high risk of falling if they trip during normal gait. Such individuals may be identified using the computed multivariable logistic regression model, although the degree to which the model represents a general relationship is not known. Also, because most healthy older adults appear to have a low likelihood of falling following a trip, interventions that improve the ability to recover from a trip will probably be of little benefit in preventing trip-related falls in this population. Instead, the prevention of trip-related falls should concentrate on factors that will reduce the incidence of trips. These conclusions illustrate the practical importance of separating the risk factors for a postural disturbance from those for the ability to recover from that disturbance. The results also support the notion that prevention of falls in older adults should not be addressed as a single, homogeneous problem. Different subpopulations may be at risk for different types of falls for different reasons and the most effective intervention for fall prevention may differ among these subpopulations.

Despite the associations found between gait and falling, the results do not necessarily imply that gait modification, in itself, will affect the likelihood of falling. The characteristics of normal gait reflect a number of physical and psychological factors (14,26), and it is the factors responsible for the high-risk pattern of gait that may need addressing. In addition, the results of the present study may not be generalizable to the entire population of older adults. The results were determined from a sample of healthy, active, community-dwelling, older adults. Only five subjects were aged 80 years or older and few, if any, subjects exhibited any gait abnormalities. Other limitations were the small number of falls and the fact that, because only one attempt could be made to trip each subject, subjects who fell were not necessarily those at the greatest risk of falling and vice versa.

Nevertheless, the present study has found that the likelihood of falling following a trip is related to selected individual gait characteristics and that those healthy older adults who are most likely to fall when tripped exhibit a specific, distinctive, pattern of normal gait that is most consistent with hurried or purposeful walking. The outcome provides a simple and easily implemented means of reducing the incidence of trip-related falls in older adults. In order for older adults to reduce their chances of falling following a trip, they should take their time while walking.

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