Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance

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Abstract

This study was performed to investigate whether elderly patients with imbalance can be distinguished from healthy elderly subjects by comparing their whole body center of mass (COM) motion in the medio-lateral (M-L) direction during obstacle crossing. Nine healthy elderly adults and six elderly patients having complaints of ‘dizziness’ or ‘unsteadiness’ during walking (three with bilateral/unilateral vestibular weakness and three with unclear diagnosis) were recruited to perform unobstructed level walking and crossing of obstacles set to 2.5, 5, 10 and 15% of each subject’s height. Kinematics of the COM was calculated using a weighted sum average of a 13-segment biomechanical model. There were no significant group differences for the temporal-distance gait parameters during all testing conditions. However, elderly patients with balance disorders demonstrated significantly greater and faster lateral motion of the COM when crossing obstacles. These measurements distinguish elderly patients with imbalance from healthy elderly subjects. Furthermore, the increased M-L motion of the COM during obstacle crossing showed a positive correlation with an increased M-L range of motion of the swing foot trajectory. This increase in M-L motion indicates a compensatory adjustment in the swing foot trajectory to land the swing foot at an appropriate location that would establish a new base of support to counter the balance disturbance in the frontal plane.

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1. Introduction

One of the most serious problems facing elderly adults is an increased susceptibility to falls as a result of balance impairments. Approximately, one-third of the community dwelling elderly population (>65 years) experience falls more than once a year [1–3]. Additionally, falling to the side has been identified as an important risk factor for hip fracture [4]. These fractures account for a large share of the disability, death, and medical costs in this population [1,5,6]. Half of these falls were reported to occur during locomotion [7,8]. A better understanding of the biomechanical challenges imposed on whole body dynamic stability in the elderly will provide a significant opportunity to reduce the incidence of falls through early detection and intervention, thereby limiting the number of debilitating injuries suffered by this population.

Imbalance and tripping over obstacles during walking have been reported as two of the most common causes of falls in the elderly [2,9,10]. Greater and faster motion of body segments while negotiating an obstacle will result in greater and faster movement of the whole body center of mass (COM). Furthermore, a greater swing time required for the swing limb when stepping over a higher obstacle also implies a longer duration of single stance for the supporting limb [11,12]. Inappropriate body segment coordination in response to the obstacle will likely perturb balance maintenance in the frontal plane and cause falls to the side in the elderly, increasing the risk of hip or pelvis fracture [13,14].
Relatively few studies have investigated whole body dynamic balance control during locomotion and have been limited to unobstructed level walking [15–22]. Results from our recent study demonstrated that stepping over higher obstacles resulted in significantly greater ranges of motion of the COM in the anterior–posterior (A–P) and vertical directions, a greater velocity of the COM in the vertical direction, and a greater A–P distance between the COM and COP in young adults [23]. In contrast, the range of motion and peak velocity of the COM in the medio-lateral (M-L) direction was less likely to be affected when negotiating obstacles of different heights. This invariant M-L COM motion during obstacle crossing in the young adults may indicate a successful control strategy to maintain the line of progression within the base of support and to avoid imbalance in the frontal plane. However, this observation of well-confined M-L COM motion during obstacle crossing may not hold true for the elderly adults due to degeneration of the balance control system. It has been reported that elderly patients with vestibular hypofunction demonstrate excessive lateral momentum of the whole body during unobstructed gait [19]. Similar observations on increased center of gravity velocity and displacement variability in the frontal plane during a stepping test were also reported in subjects with cerebellar pathology [24]. Therefore, any increase in the M-L COM motion from unobstructed to obstructed walking may be used as functional indicators to identify persons who are at greater risk of imbalance (or falling).

In order to minimize the risk of tripping during obstacle crossing, the toe-obstacle clearance increases from an average of 3 cm (toe-ground clearance) during unobstructed walking to approximately 10–15 cm for various obstacle heights [11,12,25]. The hip, knee and ankle joints of the swing limb need to be properly coordinated to ensure an appropriate elevation of the swing foot over the obstacle. Inherently, the greatest change in the swing foot trajectory should be in the vertical direction, however increased motion in the frontal plane may be possible due to an effort to produce a compensatory movement in maintaining sideways stability. Changes in the swing limb trajectory over the obstacle are expected to be associated with alterations in motion of the whole body COM. To our knowledge, the association of the swing foot motion with whole body balance control during obstacle crossing has not been examined previously.

The purpose of this study was to test the hypothesis that increases in the M-L COM motion during obstructed walking can successfully identify persons who are at greater risk for imbalance. We hypothesized that elderly patients with balance disorders would display greater and faster COM motion in the M-L direction than healthy elderly adults while negotiating obstacles of different heights. Furthermore, the strength of association between changes in the swing foot trajectory and the M-L COM motion was evaluated. We hypothesized that increased M-L motion of the swing foot is directly associated with increased whole body M-L COM motion during obstacle crossing.

2. Methods

Nine healthy elderly adults, seven male and two female with a mean age of 72 ± 6.4 years, mean height of 172.3 ± 10.3 cm and mean body mass of 75 ± 15.7 kg were recruited for this study. Six elderly patients with complaints of imbalance during walking, one male, five female with mean age of 76 ± 3.9 years, mean height of 162.1 ± 7.8 cm and mean body mass of 70 ± 15.1 kg were also recruited. The experimental protocol was approved by the Institutional Review Boards of the Mayo Foundation and the University of Oregon. The experimental procedures were explained to all subjects prior to testing, and verbal and written consent were obtained.

Elderly patients were recruited from the Vestibular/Balance Laboratory at the Mayo Clinic, where the patients were referred for vestibular/balance evaluation due to their complaints of ‘dizziness’ or ‘unsteadiness’ during walking. Results of their clinical evaluations with the sensory organization test (SOT) on a computerized dynamic posturography (CDP) platform (EquiTest, Clackamas, OR [26]) and the bilateral/bithermal caloric irrigation procedure (ICS Medical, Schaumburg, IL, USA) are reported in Table 1. All patients were community dwelling and able to walk more than 100 m without the use of a gait aid at the time of testing.

Table 1 Summary of the vestibular/balance evaluation on recruited elderly patients with complaints of imbalance during walking

<table>
<thead>
<tr>
<th>Patient subject</th>
<th>Caloric testsa</th>
<th>Sensory organization tests (six conditions with three trials each)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not tested</td>
<td>Two falls and one abnormal on condition 5; two falls and one abnormal on condition 6</td>
</tr>
<tr>
<td>2</td>
<td>Left-unilateral weakness</td>
<td>Abnormal on conditions 4 and 5; one fall and two abnormal on condition 6</td>
</tr>
<tr>
<td>3</td>
<td>Bilateral weakness</td>
<td>All falls on conditions 5 and 6</td>
</tr>
<tr>
<td>4</td>
<td>Normal</td>
<td>All falls on conditions 5 and 6</td>
</tr>
<tr>
<td>5</td>
<td>Left-unilateral weakness</td>
<td>Abnormal on condition 5; all falls on condition 6</td>
</tr>
<tr>
<td>6</td>
<td>Normal</td>
<td>All falls on conditions 5 and 6</td>
</tr>
</tbody>
</table>

a For a caloric response to be judged a unilateral weakness, there must be at least a 20% difference between the two ears when measuring the peak slow phase eye velocity. To be a bilateral weakness, the total peak slow phase eye velocity of the four responses (right warm, left warm, left cool, and right cool) had to be less than 30/s.

b All responses, not listed for Sensory Organization Testing conditions 1–4, were normal.
Healthy elderly subjects included volunteers working in the hospital or community residents recruited by posting advertisements on the campus and in the surrounding community. To be eligible for the study, healthy elderly subjects had to be free of vertigo, lightheadedness, unsteadiness, or a history of falls. All subjects were required to have a history free of significant head trauma, neurological disease or musculoskeletal impairments and to have a mean Folstein Mini-Mental Status score of 24 or higher [27].

The experimental protocol included level unobstructed walking and crossing of obstacles set to heights equal to 2.5, 5, 10, and 15% of each individual’s body height. These normalized obstacle heights were designed to produce a similar level of challenge for individuals with different body heights. In addition, the lowest height (≈5 cm) represents that of a typical door threshold, and the greatest height (≈20 cm) is similar to that of a high curb or stair. The obstacle was made of two adjustable upright standards and a padded crossbar (≈2.5 cm in diameter) two meters in length. The crossbar rested loosely on the standards, so that any foot contact would dislodge it easily, lowering the risk to the subject. A more detailed description of the obstacle design was reported previously [23]. Subjects were instructed to walk along a 6 m walkway, stepping over the obstacle and to continue along at a self-selected pace while barefoot. Each subject was allowed to select his/her preferred limb for leading over the obstacle. Starting positions were selected for each subject to ensure that a comfortable pace was reached before encountering the obstacle. The crossing stride was defined from the heel-strike of the trailing limb before the obstacle to the heel-strike of the same limb after crossing the obstacle. Unobstructed walking trials were performed first, followed by obstacle-crossing trials. The obstacle height was randomly selected for each trial. Three trials were performed for each obstacle condition.

Six of the healthy elderly adults and all of the patients were tested at the Biomechanics Laboratory of the Mayo Clinic, Rochester, Minnesota. Three of the healthy elderly subjects were tested at the Biomechanics Laboratory of the University of Oregon, Eugene, Oregon. All subjects were tested with the same experimental protocol using identical motion analysis systems, a six-camera ExpertVision system (Motion Analysis Corp., Santa Rosa, CA). Data collections and analysis on both sites were supervised and processed by the same investigator (LSC). Twenty-seven reflective markers were placed on bony landmarks of each subject. The three-dimensional marker trajectory data were collected at 60 Hz and low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 8 Hz.

Swing trajectories of both feet were measured with markers placed on the lateral malleolus (ankle marker) and on the dorsum of foot (toe marker, between 2nd and 3rd metatarsal heads) during the swing period, and described as the M-L foot excursion and vertical foot elevation, respectively. The M-L foot excursion was defined as the M-L range of motion of the ankle marker during the swing period. The vertical foot elevation was defined as the vertical distance between the toe marker and the floor at the instant when the toe marker was directly above the obstacle. Additionally, toe-obstacle clearance was calculated as the vertical distance between the toe marker and the midpoint between the extreme ends of the obstacle at the point of crossing. Measurements of the M-L foot excursion and vertical foot elevation were calculated with respect to the global coordinate system.

The location of the whole body COM was computed as the weighted sum of each body segment’s COM from a 13-link biomechanical model [15,23,28]. The range of the M-L COM motion (the maximum minus minimum value achieved during the crossing stride) was then computed. The linear velocities of the whole body COM were calculated using the generalized cross-validation spline (GCVSPL) algorithm [29].

The dependent variables consisted of the gait temporal-distance parameters, range of motion of the COM in the M-L direction (sway), peak M-L velocity of the COM, the range of M-L foot excursion during swing and the foot elevation over the obstacle of both feet. Independent variables of the study were subject group and obstacle height. Effects of subject group and the obstacle height condition (including level, unobstructed gait) on the dependent variables were assessed using a two-way ANOVA with repeated measures of obstacle height. For those dependent variables showing significant differences for obstacle height, a polynomial test was performed to determine the trend (linear, quadratic, or cubic). Additionally, a Pearson correlation analysis was performed to assess the strength of the associations between M-L excursion of the swing foot and motion of the whole body COM (M-L displacement and peak M-L velocity). All statistical analyses were conducted with SYSTAT (Version 9, SPSS Inc., Chicago, IL).

3. Results

No incidents of tripping occurred for any of the obstacle height conditions in either subject group. The temporal-distance data are presented in Table 2. There were no significant differences between subject groups for any of the four temporal-distance parameters, although, group differences in the gait velocity and step width approached significance (P = 0.078 and 0.066, respectively). Gait velocity decreased linearly as the obstacle height increased (P < 0.001). Step width and stride time were also found to increase linearly with obstacle height (P ≤ 0.004).
Table 2
Gait temporal-distance measurements for both groups during the crossing stride.

<table>
<thead>
<tr>
<th>Obstacle height</th>
<th>None</th>
<th>2.5%</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>Controls</th>
<th>Patients</th>
<th>Controls</th>
<th>Patients</th>
<th>Controls</th>
<th>Patients</th>
<th>Controls</th>
<th>Patients</th>
<th>Controls</th>
<th>Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait velocity (m/s)</td>
<td>1.179 (0.145)</td>
<td>1.018 (0.131)</td>
<td>1.114 (0.178)</td>
<td>1.009 (0.194)</td>
<td>0.911 (0.153)</td>
<td>0.865 (0.157)</td>
<td>0.974 (0.147)</td>
<td>0.810 (0.169)</td>
<td>$P_h &lt; 0.001$, $P_g = 0.078$</td>
<td></td>
<td></td>
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<tr>
<td>Stride time (s)</td>
<td>1.092 (0.090)</td>
<td>1.123 (0.093)</td>
<td>1.170 (0.171)</td>
<td>1.219 (0.213)</td>
<td>1.306 (0.222)</td>
<td>1.368 (0.125)</td>
<td>1.327 (0.212)</td>
<td>1.454 (0.145)</td>
<td>$P_h &lt; 0.001$, $P_g = 0.343$</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Stride length/body height</td>
<td>0.744 (0.063)</td>
<td>0.700 (0.056)</td>
<td>0.745 (0.065)</td>
<td>0.726 (0.077)</td>
<td>0.746 (0.064)</td>
<td>0.722 (0.089)</td>
<td>0.737 (0.069)</td>
<td>0.717 (0.100)</td>
<td>$P_h = 0.062$, $P_g = 0.495$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step width/inter-ASIS distance</td>
<td>0.363 (0.086)</td>
<td>0.371 (0.093)</td>
<td>0.386 (0.100)</td>
<td>0.532 (0.210)</td>
<td>0.492 (0.164)</td>
<td>0.414 (0.052)</td>
<td>0.526 (0.178)</td>
<td>0.434 (0.053)</td>
<td>0.600 (0.275)</td>
<td>$P_h = 0.004$, $P_g = 0.066$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$P_h$, represents height effect; $P_g$, represents group effect.

Mean value, with standard deviation in parentheses.
The typical patterns of the M-L COM position and velocity during a crossing stride from representative trials of both subject groups when stepping over the obstacle of 15% body height are shown in Fig. 1. The profiles of the M-L position and velocity of the whole body COM during unobstructed level walking and when negotiating obstacles were similar. Elderly patients with balance disorders demonstrated significantly greater range of motion in M-L COM displacement (P \(< 0.039) across all obstacle conditions when compared to healthy elderly (Fig. 2). The M-L displacement of the COM did not increase significantly as obstacle height increased for either subject group. The peak M-L velocity occurred during double stance periods (weight-shifting periods). The patient group also displayed significantly greater peak M-L COM velocity (P \(< 0.036) across all obstacle heights (Fig. 3). However, no significant obstacle height effect on the peak M-L velocity of the COM was identified. In addition, a further analysis revealed that the average M-L COM displacement and peak velocity across all obstacle height conditions were significantly greater than that during unobstructed walking (P \(< 0.015 and 0.004, respectively).

In general the M-L swing foot motion increased with obstacle height, with varied crossing patterns (Fig. 4). The range of M-L excursion of the swing foot trajectory in both the leading and trailing limbs increased significantly with obstacle height (P \(< 0.010 and 0.003, respectively) (Fig. 5). These trends were found to be linear for both limbs (leading, P \(< 0.05; trailing, P \(< 0.017). There were no significant group differences for either limb. The vertical foot elevation (toe marker relative to the floor) at the time of obstacle crossing increased with obstacle height, for both limbs (P \(< 0.001) (Fig. 6). Polynomial tests revealed a linear trend for each limb (P \(< 0.001). No significant group differences were found for either limb during obstacle crossing.

Toe-obstacle clearance did not show significant differences for either group or obstacle effect. Group mean values for the toe-obstacle clearance of the leading and trailing limbs are presented in Fig. 7.

Correlation analyses revealed a significant positive association between M-L foot excursion of both limbs and COM M-L displacement (r \(= 0.536, P \(< 0.001 for leading limb; r \(= 0.404, P \(< 0.002 for trailing limb). Similarly, M-L foot excursion of both limbs and the peak M-L velocity of the COM demonstrated significant positive association (r \(= 0.627, P \(< 0.001 for leading limb; r \(= 0.401, P \(< 0.002 for trailing limb). However, no significant associations between the foot elevation and either M-L displacement or peak velocity of the COM were identified.
4. Discussion

Inability to adequately control the motion of the COM in the frontal plane may lead to a loss of balance resulting in a sideways fall, which has been reported as one of the important risk factors for hip fractures among frail elderly nursing home fallers [4]. Therefore, the resultant M-L motion of the COM during locomotion can be used as a functional indicator to identify persons who are at greater risk of falling. Results of this study demonstrated that elderly adults with complaints of ‘dizziness’ or ‘unsteadiness’ displayed a significantly greater and faster COM motion in the M-L direction than the healthy elderly while negotiating obstacles of different heights. Furthermore, the increased M-L motion of the COM during obstacle crossing showed positive correlation with the increased M-L range of motion of the swing foot trajectory.

The results of this study indicate that M-L motion of the COM could be a more sensitive measure to demonstrate patients complaints of instability during walking when compared to the temporal-distance parameters. Our results demonstrated that significant group differences in both the gait velocity and normalized step width could potentially be detected. The lack of significant group differences for temporal-distance parameters in this study may be due to a small sample size or relatively high variability within a subject group, which might be related to the severity of the balance impairment as well as selections of movement strategies in response to a perturbed balance during locomotion. Furthermore, both the healthy elderly and elderly

Fig. 4. Typical patterns of the swing foot trajectories for both the leading and trailing limbs while crossing an obstacle (indicated with a bold line) set to 15% body height from the top view.

![Control vs Patient](image)

![Diagram](image)

Fig. 5. Means and standard deviations of the M-L: (a) leading; and (b) trailing foot excursion during the swing phase. The M-L swing foot excursion in both limbs increased linearly with obstacle height. There was no significant group effect.
patients maintained a similar magnitude of M-L COM motion during unobstructed walking. However, while negotiating obstacles, the elderly patients demonstrated significantly greater and faster M-L motion of the COM than the healthy elderly adults. The increased M-L COM motion in the elderly patients demonstrated their difficulty in maintaining dynamic stability in the frontal plane. It appears that body motion in the frontal plane may be a functional indicator of balance maintenance during walking, and with the addition of the obstacle it could be a sensitive measurement of dynamic stability.

Interestingly, the greatest group difference in M-L COM motion occurred in the 2.5% obstacle height condition, suggesting this height as the best condition for monitoring dynamic stability. It has been previously demonstrated that properties of obstacles, such as how fragile the obstacle is, can influence the movement of the swing limb [30]. Similarly, the level of difficulty (i.e. obstacle height) may influence the alertness of the subject in executing the task; i.e. more caution will be taken when stepping over a higher obstacle. This may also explain why the M-L COM displacement and peak velocity in the frontal plane did not change linearly with increasing obstacle height. Therefore, the greatest M-L perturbation to the COM motion while stepping over the lowest obstacle in the elderly patients may be the result of their faulty judgment of threat to their impaired balance control system.

To our knowledge, the effect of balance deficits on the swing foot motion during obstacle crossing has not been examined previously. The goal of the swing foot during obstacle crossing is not only to successfully clear the obstacle but also to establish a new base of support that can appropriately maintain stability for gait progression. Significantly positive correlations between the increased M-L COM motion and increased M-L swing foot excursion could be explained as a compensatory adjustment to the swing foot trajectory in response to the perturbed COM motion in the frontal plane. Once an unstable M-L COM motion is detected, the trajectory of the swing foot is adjusted accordingly so that the foot lands at an appropriate location to establish a base of support and to counter the disturbance. Therefore, increases in the swing foot M-L excursion during obstacle crossing could have become a result of their dynamic instability. However, the swing foot M-L excursion alone was not able to distinguish people with imbalance. Similar to the gait temporal-distance parameters, the M-L excursion of swing foot could vary greatly depending on an individual’s selection of compensatory adjustment in the swing foot trajectory. This might be the reason for the relatively low correlation coefficients with the M-L COM motion.
One major limitation of this study is sample size. As the patient group consisted of only six subjects, the large variation seen in most of the temporal-distance parameters may have resulted in the insignificant trends found in the group comparisons. A sample size analysis, based on the largest group difference (15% obstacle height condition) in the normalized step width, showed that approximately 20 subjects are necessary in each group for detecting a statistically significant group difference ($\alpha = 0.05$) with a power of 0.75. However, the small sample size did not restrict the findings of significant group difference in M-L COM displacement and peak velocity, or the significant correlations between leading limb M-L foot excursion and COM motion. Another limitation is the gender difference between the two groups tested. The majority of patients with imbalance in this study were female, compared to a primarily male control group. Significant gender differences in both the crossing speed and step length during obstacle crossing were reported previously [25]. However, no meaningful gender difference was found for the step width, which is more related to the COM motion in the frontal plane. Nevertheless, further investigations are needed to address any gender-related differences in the COM motion.

In conclusion, the findings of this study supported our hypothesis that increased M-L COM motion during obstructed walking could be a better parameter to identify persons at greater risk of imbalance. This suggests that examining the motion of the whole body COM might be a valuable tool in clinical evaluations of patients with balance disorders. Information about an individual’s ability to control their COM trajectory during obstacle crossing allows us to identify individuals at risk for imbalance and falls, which may provide early detection, allowing preventative intervention before falls actually occur.

Acknowledgements

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References


