ORIGINAL ARTICLE

Detection of Gait Instability Using the Center of Mass and Center of Pressure Inclination Angles

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ABSTRACT. Lee H-J, Chou L-S. Detection of gait instability using the center of mass and center of pressure inclination angles. Arch Phys Med Rehabil 2006;87:569-75.

Objective: To define a parameter that quantifies balance control during gait and better identifies elderly people who are at a higher risk of falling.

Design: Controlled study.

Setting: University research laboratory.

Participants: Twelve elderly patients (mean age, 76.9±6y) with complaints of imbalance during walking, or with a history of falls, and 12 matched healthy elderly adults.

Interventions: Not applicable.

Main Outcome Measures: Temporal-distance gait parameters (gait velocity, stride length, step width); and sagittal and frontal center of mass (COM) and center of pressure (COP) inclination angles.

Results: Elderly patients demonstrated a significantly greater medial, but a significantly smaller anterior, inclination angle than their matched controls during both unobstructed and obstructed gait. The medial COM-COP inclination angle was not affected by the gait velocity in the healthy elderly. When the 2 groups were compared at a similar gait velocity (≈1m/s), the elderly patients still had a significantly greater medial COM-COP inclination angle than did the controls.

Conclusions: Instantaneous COM-COP inclination angles during walking provide information about the ability to control COM position in relation to the corresponding COP. The medial COM-COP inclination angle may be a sensitive measure of gait stability in the elderly.

Key Words: Accidental falls; Elderly; Equilibrium; Gait; Rehabilitation.

FALLS ARE THE LEADING CAUSE of injuries in elderly adults and the leading cause of accidental deaths of people over the age of 85 years.[1-3] To better reveal biomechanic mechanisms underlying age-related degeneration in gait stability, and to enhance the assessment of falls risk, an accurate quantification of a person's balance maintenance during locomotion is needed.

Many studies have used the whole body center of mass (COM) motion and its relative position to the center of pressure (COP) of the supporting foot to examine gait stability.[4,5] The maximum horizontal separation distance between COM and COP during single limb stance was reported[6,7] to sensitively quantify gait instability in patients with bilateral vestibular hypofunction or cerebellar ataxia. Dynamic stability during locomotion has been assessed using COM momentum, and an excessive lateral momentum was identified in balance-impaired elderly.[5] Recent studies[8-10] also demonstrated that linear measures of COM motion in the frontal plane during obstacle crossing could better distinguish elderly subjects with balance disorders from their age-matched healthy peers. Magnitudes of these linear measures of the COM motion and the COM-COP separation distance may, however, be affected by a subject's stature.[11] Biomechanic measures of gait stability that can provide information on instantaneous coordination between the COM and COP and exclude intersubject variability are still needed.

Instantaneous orientation of the line connecting COP and COM can characterize whole body position with respect to the supporting foot during gait. When this line is referenced to the vertical line passing through the COP, an anteroposterior (AP) and mediolateral (ML) inclination angle can be defined in the sagittal and frontal planes, respectively. The magnitudes of these angles would account for both the instantaneous COM height and horizontal distance between the COM and COP. A biomechanic relation between the COM and COP during standing has been established.[12,13] Similar angles have been used to quantify postural sway during standing and were found to be similar for people of various heights.[14-16] There are no studies, however, that quantify changes in these COM-COP inclination angles during a gait cycle and its modulation with different challenges encountered during gait, such as stepping over obstacles of different heights.

Therefore, in this study, we assessed instantaneous sagittal and frontal inclination angles defined by the line connecting COM and COP during unobstructed and obstructed walking in elderly healthy adults and in patients with complaints of imbalance during walking. We hypothesized that elderly patients would demonstrate a greater angle in the frontal plane and a smaller angle in the sagittal plane when walking than would healthy elderly adults.

METHODS

Twelve elderly patients (6 men, 6 women; mean age, 76.9±5.8y; mean height, 164.5±8.2cm; mean mass, 74.9±13.7kg) and 12 healthy elderly controls (6 men, 6 women; mean age, 72.5±5.4y; mean height, 164.9±7.8cm; mean mass, 68.7±7.2kg) were recruited for this study in accord with the guidelines of our institutional review board. The 12 patients complained of imbalance during walking while participating in the study. Nine patients had experienced falls within a 2-year period prior to testing (table 1). The patient group took no medications for balance disorders.

All subjects were examined by the same physician to exclude those with significant head trauma, neurologic diseases (Parkinson's, postpolio syndrome, diabetic neuropathy), visual impairment not correctable with lenses, and musculoskeletal

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Table 1: Characteristics of Elderly Patients and History of Falls

Patients	Age (y)	Sex	History of Falls	BBS Scores
1	80	F	3 falls	48
2	85	F	2 falls	47
3	80	M	No falls	43
4	83	F	1 fall	44
5	81	M	No falls; stumbled often	52
6	71	M	1 fall	43
7	78	M	No falls	52
8	68	F	Fell frequently	48
9	74	F	2 falls	51
10	81	M	2 falls	42
11	74	F	Fell frequently	43
12	68	M	3 falls	52

Abbreviations: BBS, Berg Balance Scale; F, female; M, male.

impairments (amputation, joint replacement, joint fusions, joint deformity due to rheumatoid arthritis). The control subjects were required to have normal neurologic and musculoskeletal clinical examinations. The 12 patients had normal sensation and coordination; 2 were diagnosed with ankle muscle weakness. We used the Berg Balance Scale to assess balance in all subjects.[17] The patient group had a mean score of 47.1±4.0 (see table 1), and every healthy subject scored 54 or higher. In addition, the mental status of every subject was assessed with the Mini-Mental State Examination,[18] with a minimum score of 28 being required. The study's experimental procedures were explained to the subjects and a written informed consent form was obtained from the subject before testing.

The experimental protocol included level walking on an unobstructed surface and stepping over an obstacle set to a height equal to 2.5% or 10% of the subject's body height. Data collection for each walking trial lasted 4 seconds. Unobstructed walking trials were performed before the obstacle-crossing trials. The obstacle height was randomly selected for each trial, and at least 3 trials were collected for each height. The obstacle was made of 2 adjustable upright standards and a polyvinyl chloride crossbar (diameter, ≈2.5cm; length, 1.5m). The crossbar rested loosely on the stands so that any foot contact would easily unseat the obstacle, reducing the risk of tripping. All subjects were asked to walk at a self-selected (preferred) velocity along a 10-m walkway while barefoot. The healthy subjects were asked to perform additional unobstructed level walking trials at a self-selected pace that was distinctly faster or slower than their preferred gait velocity. Two in-series forceplates[a] were positioned in the center of the walkway, flush with the top surface of the floor. Before the data were collected, the spacing between 2 forceplates was adjusted for each subject to ensure comfortable foot placements. The obstacle was then centered between 2 forceplates. To ensure a comfortable, steady pace, the starting position was adjusted for each subject to give them at least 3 complete steps before beginning their obstacle crossing stride.

Whole body motion analysis was performed with a 6-camera motion analysis system.[b] A total of 29 reflective markers were placed on each subject's bony landmarks. A more detailed description of marker placements was reported previously.[10] Three-dimensional marker trajectory data were collected at 60Hz and low-pass filtered using a fourth-order Butterworth filter with the cutoff frequency set at 8Hz. Gait events of the heel-strike and toe-off were identified with the OrthoTrak gait analysis software,[b] using a threshold of 30N on the vertical ground reaction force. We used external markers and estimated joint centers to calculate the 3-dimensional locations of segmental COMs. Anthropometric reference data were adapted from the initial work of Dempster for both sexes.[19] Whole body COM position data were calculated as the weighted sum of all body segments, with 13 segments representing the whole body including head and neck, trunk, pelvis, 2 upper arms, 2 forearms (with hands), 2 thighs, 2 shanks, and 2 feet. The COP position was calculated using the ground reaction forces and moments measured with 2 forceplates at a sampling rate of 960Hz. The COP data were then time-synchronized with motion data. During the double-stance phase, a resultant COP was calculated for both feet using the COP and vertical ground reaction force from each foot.[20]

We defined instantaneous sagittal and frontal COM-COP inclination angles as the angle formed by the intersection of the line connecting the COP and COM with a vertical line through the COP (fig 1). The angle in each plane was calculated for each frame using the horizontal COM-COP separation distance (in AP or ML direction, respectively) and the corresponding vertical COM height, starting from the toe-off of the leading limb before crossing the obstacle to the frame immediately before the foot-floor contact of the trailing limb after crossing the obstacle.

Data were analyzed during the obstacle crossing stride, which was defined as the heel-strike of the trailing limb (the limb crosses the obstacle last) to the heel-strike of the same limb after stepping over the obstacle. A 2-factor analysis of variance with repeated measures was performed to detect the effects of subject group and obstacle height on dependent variables, including temporal-distance gait parameters (gait velocity, stride length, step width), peak anterior COM-COP

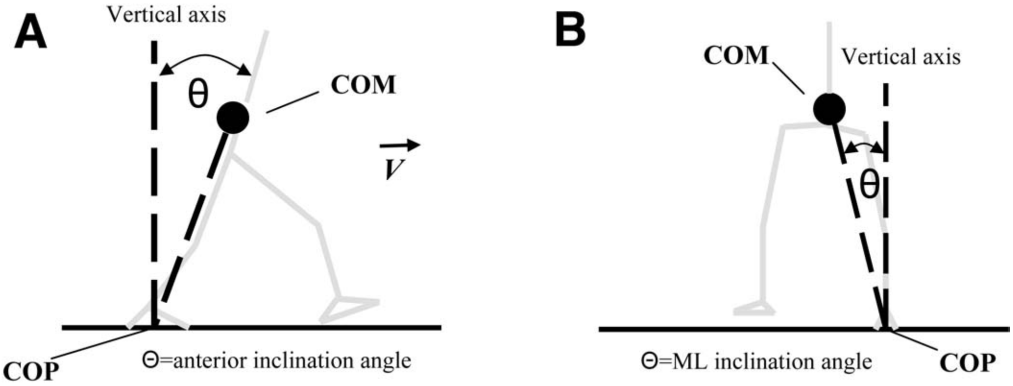

Fig 1. Diagrammatic illustration of COM-COP inclination angles in the (A) sagittal and (B) frontal planes.

Table 2: Gait Temporal-Distance Measurements for Both Subject Groups During the Crossing Stride

	None		2.5%		10%		
Obstacle Height	Controls	Patients	Controls	Patients	Controls	Patients	*P**
Preferred gait velocity (m/s)	1.16±0.18	1.01±0.16	1.02±0.14	0.91±0.18	0.99±0.18	0.80±0.16	<.001* .047†
Stride length (cm)	123.31±9.70	109.21±12.27	122.70±7.68	113.18±14.85	124.33±8.01	110.74±12.20	.482* .006†
Step width (cm)	11.32±1.86	13.67±4.36	11.64±1.85	12.45±4.68	11.31±1.61	14.43±5.13	.122* .119†

NOTE. Values are group mean ± standard deviation (SD).
*Represents obstacle height effects.
†Represents group effects.

inclination angles, peak posterior COM-COP inclination angles, and peak COM-COP inclination angles. In addition, the inclination angles were identified when the toe-marker of the swing foot was directly above the obstacle (obstacle clearance). The significance level was set at *P* equal to .05 for all statistical tests. All statistical analyses were performed with SPSS.[c]

RESULTS

All subjects completed all trials without tripping the obstacle. No significant group differences were found in anthropometric measures (age, $P=.066$; body height, $P=.896$; body mass, $P=.177$).

There were significant group differences in gait velocity ($P=.047$) and stride length ($P=.006$), but not in step width (table 2). Gait velocities in both groups decreased significantly ($P<.001$) as obstacle height was increased. No significant obstacle height effects were found for either the stride length or step width.

The typical pattern of COM-COP inclination angles from leading limb toe-off to heel-strike during 10% of body height obstacle crossing is illustrated in figure 2. Immediately after the leading limb toe-off, the COM is located behind the COP and results in a maximum posterior inclination angle in the sagittal plane. As the subject traverses forward, the COM moves anteriorly and passes over the COP, which changes the COM-COP alignment from a posterior to an anterior inclination angle and reaches its peak magnitude immediately before the heel-strike of the leading limb. During the double-stance period, the COP shifts quickly from the trailing foot to the leading foot and returns the COM-COP alignment from an anterior to a posterior inclination angle until the toe-off of the trailing limb. This pattern of sagittal COM-COP alignment repeats as gait progresses. In the frontal plane, the COM moves along on the medial side of the COP and forms a medial inclination angle for the inverted pendulum during a single-support period (see fig 2). This angle decreases when the COP shifts from the trailing to the leading foot during the double-stance period. The line then forms a similar medial inclination angle with respect to the COP of the supporting foot. The medial inclination angle reached its maximum value at the beginning of the single-support period.

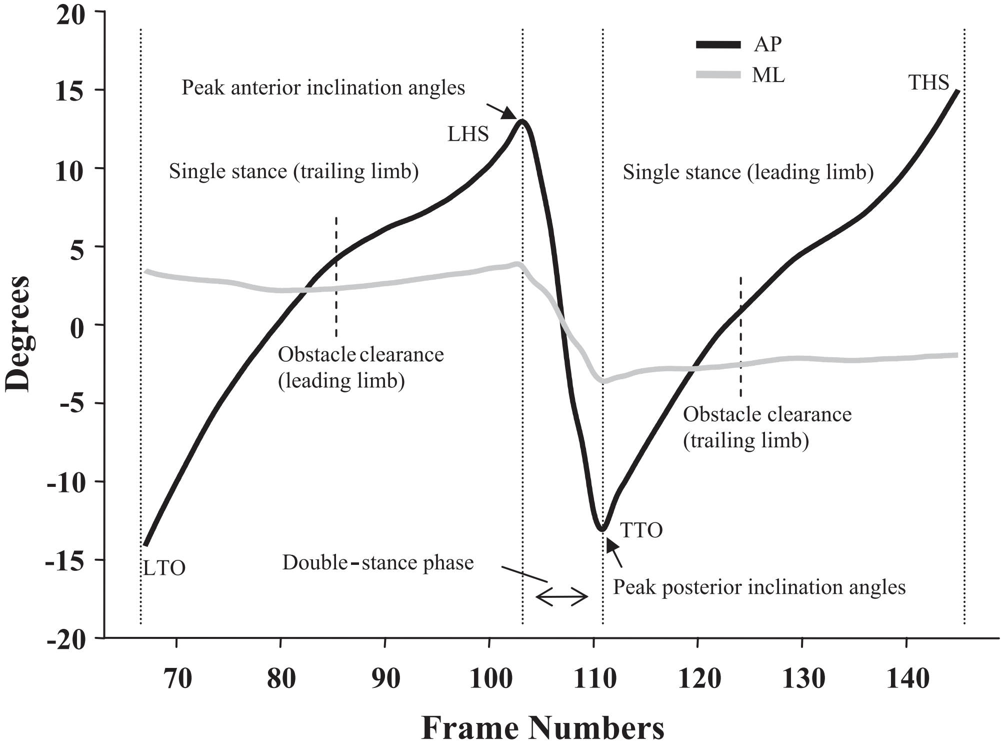

Fig 2. Patterns of COM-COP inclination angles between the leading limb toe-off (LTO) and trailing limb heel-strike (THS) when stepping over an obstacle of 10% of body height. LHS, leading limb heel-strike; TTO, trailing limb toe-off.

Table 3: Peak COM-COP Inclination Angles

Obstacle Height	None		2.5%		10%		
	Controls	Patients	Controls	Patients	Controls	Patients	*P**
Peak anterior inclination angles (deg)	13.18±1.76	10.31±2.02	13.93±1.70	11.89±2.48	15.12±2.04	12.04±2.30	<.001* .004†
Peak posterior inclination angles (deg)	11.69±1.39	10.07±4.24	12.25±1.70	11.82±4.40	13.14±1.93	12.51±3.82	<.001* .486†
Peak medial inclination angles (deg)	4.06±0.69	5.89±1.52	4.23±0.84	5.22±1.35	4.09±0.89	5.62±1.41	.684* .001†

NOTE. Values are group mean ± SD.
*Represents obstacle height effects.
†Represents group effects.

Patterns of COM-COP inclination angles during unobstructed level walking and obstacle crossing were similar for all subjects.

When subjects walked at preferred gait velocities, there were significant group differences in the peak anterior ($P=.004$) and medial ($P=.001$) COM-COP inclination angles (table 3). No significant group differences were found, however, in the peak posterior inclination angles ($P=.486$). Elderly subjects with balance disorders had a significantly greater peak medial, but a significantly smaller peak anterior, COM-COP inclination angle across all conditions than did healthy controls. Stepping over a higher obstacle during gait resulted in a significantly larger ($P<.001$) COM-COP inclination angle in both anterior and posterior directions for both groups. There were no significant obstacle height effects for the medial inclination angle ($P=.684$).

When the toe of the leading or trailing foot was directly above the obstacle, both controls and patients maintained a similar AP inclination angle (table 4). The patients, however, demonstrated a significantly greater medial inclination angle ($P=.038$) than the controls when the toe of the leading foot was directly above the obstacle. Neither the AP or medial inclination angles during obstacle clearance were significantly affected by the obstacle height (table 4).

Among the healthy subjects, we found significant differences in walking speeds when they performed at their preferred (1.2±0.2m/s), faster (1.3±0.2m/s), and slower (0.9±0.1m/s) unobstructed level walking ($P<.001$). Their slower walking speed was similar ($P=.086$) to the preferred walking speed adopted by elderly fallers (1.0m/s). Significant walking speed effects among the controls were found in the peak anterior COM-COP inclination angle ($P<.001$; fig 3), but not in the peak posterior COM-COP inclination angles ($P=.641$). Furthermore, no significant walking speed effects were found in the peak medial COM-COP inclination angle ($P=.543$; fig 4).

When walking at a similar gait velocity, elderly patients with balance problems still demonstrated a significantly greater medial COM-COP inclination angle ($P=.008$; see fig 4) than did the control subjects. No significant group differences were found in the peak anterior ($P=.242$) and posterior ($P=.222$) COM-COP inclination angles.

DISCUSSION

Our results demonstrate that elderly patients with balance disorders display significantly greater COM-COP inclination angles in the ML direction than do healthy elderly during unobstructed walking and when negotiating obstacles of different heights. It has been reported that the most frail elderly are at higher risk to fall sideways during daily activities.[21] This may indicate that elderly fallers have more difficulties controlling sideways COM motion during gait and have a larger inclination COM-COP angle in the frontal plane. Our findings on the obstructed gait are consistent with a previous study[8] that reported linear measures of COM motion. We further detected a significant group difference, however, in the frontal plane peak COM-COP inclination angle during unobstructed level walking. This may indicate that frontal plane COM-COP inclination angles can sensitively detect elderly fallers during unobstructed walking.

Berger et al[11] reported that linear COM excursions may be affected by a person's stature. A higher COM position is expected for a taller subject, which may produce a greater COM excursion in the AP and ML directions and result in a larger COM-COP separation distance than that found in a shorter person, although they have the same COM-COP inclination angles (fig 5A). A taller subject, however, may show the

Table 4: COM-COP Inclination Angles When the Toe Marker Was Directly Above the Obstacle

Obstacle Height	2.5%		10%		
	Controls	Patients	Controls	Patients	*P**
AP inclination angles during obstacle clearance of the leading limb (deg)	4.12±3.96	4.29±2.99	3.74±3.43	2.44±2.01	.226* .137†
AP inclination angles during obstacle clearance of the trailing limb (deg)	2.45±1.53	2.96±1.71	2.67±1.64	2.25±1.27	.182* .533†
Medial inclination angles during obstacle clearance of the leading limb (deg)	3.18±0.63	3.38±0.93	2.99±0.51	3.14±1.03	.426* .038†
Medial inclination angles during obstacle clearance of the trailing limb (deg)	3.35±0.44	3.25±1.36	2.79±0.32	3.50±1.13	.344* .085†

NOTE. Values are group mean ± SD.
*Represents obstacle height effects.
†Represents group effects.

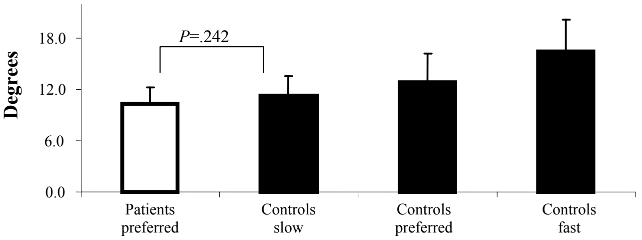

Fig 3. Peak anterior COM-COP inclination angles of elderly patients (white bar) while walking with a preferred velocity and of healthy elderly controls (black bars) while walking with a slower, preferred, or faster velocity. NOTE. Values are mean ± standard deviation (SD).

same amount of COM linear excursion or COM-COP separation distance as the shorter subject, but show a smaller COM-COP inclination angle (fig 5B). Therefore, compared with COM-COP separation distances, the COM-COP inclination angle not only illustrates relative positioning control between COM and COP during gait, but also excludes any effects of body height, which is more suitable for intersubject comparison.

As the obstacle height increased, all subjects walked slower to accommodate a greater COM-COP inclination angle in the sagittal plane. Because there were no significant obstacle height effects on the stride length, increases in the anterior COM-COP inclination angle when stepping over a higher obstacle could be due to a larger trunk forward sway, which displaces the COM to a more anterior position.[10] This indicates that the foot placement as well as postural alignment could affect the COM-COP inclination angle. The peak COM-COP inclination angle in the frontal plane, however, was not affected by the obstacle height in both groups. This finding may be justifiable given that no significant obstacle height effects were found on the step width, and it is reasonable to expect very little postural adjustment in the frontal plane when stepping over an obstacle. At the time of obstacle clearance, both groups demonstrated relatively smaller inclination angles in both sagittal and frontal planes regardless of obstacle heights. This result suggests that the COM is well positioned above the COP to avoid any imbalance and to ensure a safe crossing. Elderly patients, however, showed significantly greater medial angles than the healthy subjects when the leading foot was above the obstacle. MacKinnon and Winter[4] found that a precisely controlled interaction between active muscle torques and passive inertial and gravitational moments about the hip joint is achieved to minimize the upper-body motion in the frontal plane. Our findings reflect that the medial COM-COP inclination angle may be an activity level (eg, obstacle height) that is an independent indicator of gait stability.

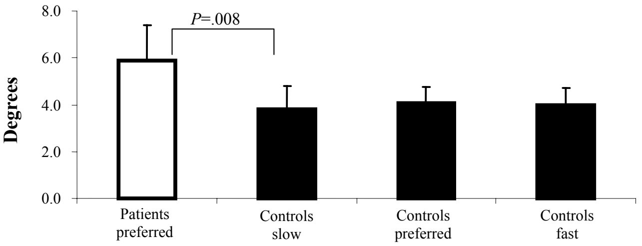

Fig 4. Peak medial COM-COP inclination angles of elderly patients (white bar) while walking with a preferred velocity and of healthy elderly controls (black bars) while walking with a slower, preferred, or faster velocity. NOTE. Values are mean ± SD.

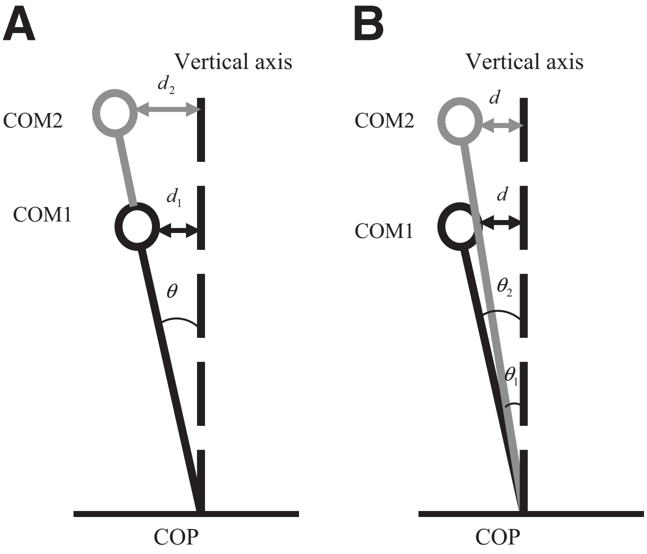

Fig 5. Diagrammatic illustration of the effect of stature on the COM-COP inclination angles and linear COM excursions. (A) A taller subject is expected to have a larger COM-COP separation distance than a shorter subject with the same COM-COP inclination angles. (B) A shorter subject exhibits a greater COM-COP inclination angle than a taller subject with the same COM-COP separation distances.

Gait velocity significantly affects many gait kinematic and kinetic measurements.[22-27] Results from our study and others[28,29] demonstrate that elderly people with balance problems walk significantly slower than their healthy peers. To enhance our ability to identify a potential faller through gait analysis, a quantitative measure that can sensitively demonstrate the difference from healthy subjects and is independent of walking speed, is needed. It is, therefore, important to examine the effects of walking speeds on the COM-COP inclination angles. Our findings indicate that in healthy elderly adults, gait velocity affects the anterior, but not the posterior and medial, COM-COP inclination angles. Furthermore, when the 2 subject groups with similar gait velocities (elderly patients walked with a preferred speed, 1.0m/s; healthy elderly walked with a self-selected slow speed, 0.9m/s), were compared, elderly patients still demonstrated a significantly greater medial COM-COP inclination angle than the healthy elderly. This indicates that the greater medial COM-COP inclination angles of elderly fallers were not a result of their slower gait speeds. Therefore, the larger medial COM-COP inclination angle may result from pathologies in their balance control systems.

Excessive frontal plane COM-COP inclination angles during gait may lead to a loss of balance. Results of a bipedal walking model study[30] indicated that an active control from the central nervous system is necessary to maintain frontal plane gait stability. Consequently, coordination between the COM motion and foot position most significantly relies on visual, vestibular, and proprioceptor inputs.[31] These integrated inputs provide an important feedback for the brainstem and cerebellum to activate necessary lower-extremity muscle excitations to properly maintain gait stability in the ML direction. Studies[32-34] have also shown, however, that elderly fallers were diagnosed with less sensitive sensory functions than healthy elderly adults. This degraded sensory feedback may affect their ability to control COM motion and result in a greater medial COM-COP inclination angle. It is also possible, however, that weaker muscle strength of elderly fallers is a contributing factor to

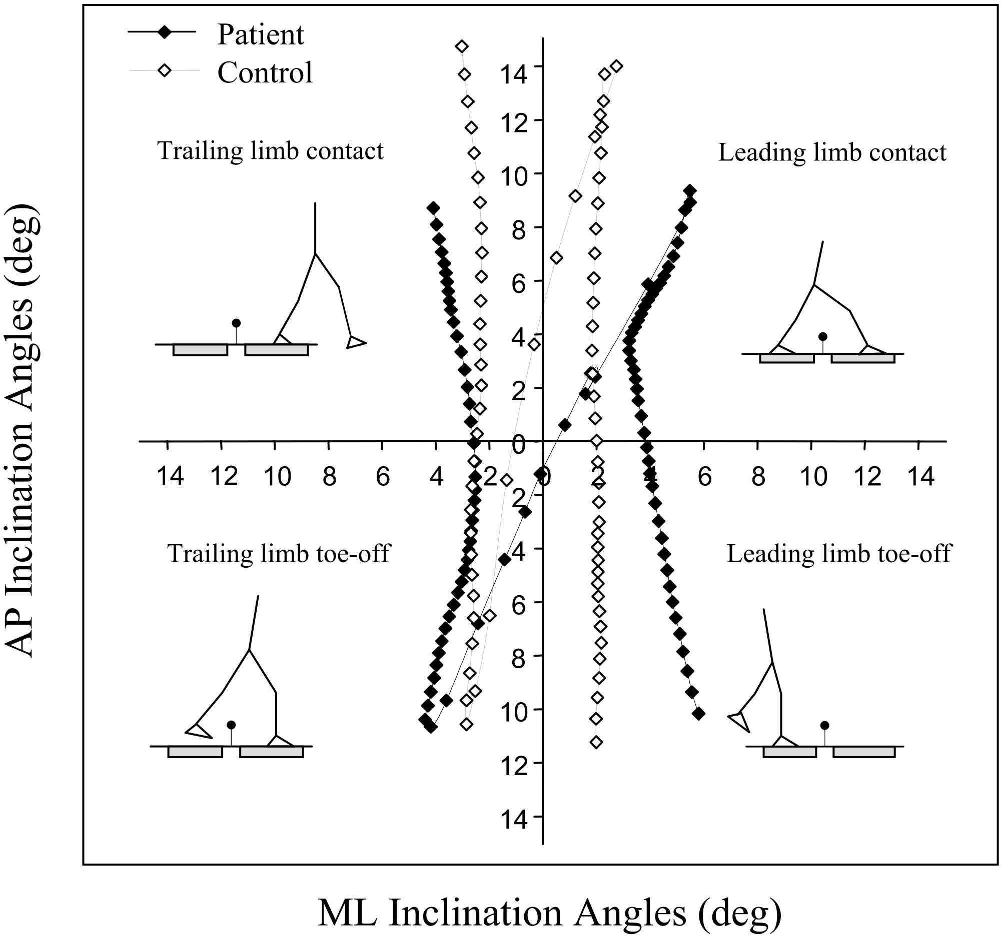

Fig 6. Typical patterns of the AP versus medial COM-COP inclination angles plots during the time between the leading limb toe-off and the trailing limb foot-floor contact in a representative healthy elderly and elderly patient, respectively, when stepping over an obstacle of 10% of body height during gait.

their inability to minimize the excessive ML COM motion following a proper active control.

To quantify dynamic stability or postural perturbation requires an understanding of how the COM and COP motion is generated and controlled continuously during locomotion.[5,7] Because we examined each of the instantaneous COM-COP inclination angles discretely for each time instant, only a quasistatic assessment on gait stability was determined. When plotting the sagittal inclination angle against the medial inclination angle, however, a continuous trace of angular alignment between the COM and COP, similar to body sway angles during quiet standing, could be generated for each subject during gait. Deviations of an individual trace from the normative curve might provide an alternative tool to quantify falls risk in the elderly. Representative plots from a healthy elderly adult and an elderly patient when they stepped over the obstacle of 10% of body height are illustrated in figure 6. Another limitation of this study is that the body segment mass proportion data we used were not specifically reflective of the elderly who have decreased muscle mass and increased adipose tissue. This general limitation may have affected our calculation for the whole body COM. The magnitude and pattern of COM trajectories reported in our study are, however, in agreement with values reported previously.[4,13,20]

CONCLUSIONS

Instantaneous COM-COP inclination angles in both sagittal and frontal planes identified elderly people with imbalance. In addition, we found the frontal plane COM-COP inclination angle to be a walking speed and activity level (eg, obstacle height) independent variable. These measures may allow us to better identify elderly people who are at risk for imbalance or falls.

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Suppliers

a. Advanced Mechanical Technologies Inc, 176 Waltham St, Watertown, MA 02472.

b. Motion Analysis Corp, 3617 Westwind Blvd, Santa Rosa, CA 95403.

c. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.