Center of mass and base of support interaction during gait

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ABSTRACT

During gait the body is in a continuous state of imbalance, with each subsequent step preventing a fall. Gait balance is maintained by regulating the interactions between the center of mass (CoM) and base of support (BoS). The purpose of this study was to investigate the interaction of the CoM position and velocity (CoMv) in relation to the dynamically changing BoS throughout gait. This was quantified using: (1) The shortest distance from the CoM to the boundary of the BoS; (2) The distance from the CoM to the centroid of the BoS; and (3) The distance from the CoM to the BoS along the direction of the CoMv. These interactions were investigated in healthy young adults, healthy older adults, and elderly fallers, who performed level walking at a self-selected speed. Elderly fallers demonstrated a conservative CoM–BoS separation at toe off and reduced balance control ability, specifically a decreased time to contact, when compared to healthy young adults at heel strike. Decreased time available in responding to perturbations might result in a greater number of falls. Understanding foot position and CoM trajectories might allow for appropriate rehabilitation practices.

1. Introduction

Most falls occur during locomotion [1–3], with age-related gait dysfunction being a common risk factor [4,5]. During ambulation, the body is in a continuous state of imbalance, with each subsequent foot strike preventing a fall [6]. Ability to place the foot properly in order to control the center of mass (CoM) motion and regulate the body's momentum might decline in individuals with gait imbalance [6,7]. To better understand the underlying mechanisms of gait imbalance and assess the risk of falls in the elderly, a precise analysis of foot placement and CoM movement during locomotion is required.

Stable gait is achieved as a function of the CoM position and velocity at the moment of foot placement [8,9]. The feasible stability region, defined by the allowable ranges of the CoM position and velocity in relation to the base of support (BoS), was proposed to examine whether a fall might occur [10]. This work was extended by deriving the extrapolated center of mass (XcoM) to quantify gait stability. The condition for stability is described as when the XcoM is confined within the BoS [11]. These model-based studies demonstrated the importance of the CoM velocity to assess balance control during gait.

The stability margin, defined as the shortest distance from the center of gravity to the support polygon, was used as a measure of balance [11,12]. While such studies have investigated the CoM and CoM velocity in relation to the center of pressure or BoS during quiet stance, no studies have investigated this relationship throughout a gait cycle. The instantaneous location of the CoM and CoM velocity vector in relation to the BoS could provide further insights on how static and dynamic balance is maintained during gait. This analysis might elucidate the underlying mechanisms of balance impairment and proper foot placement in order to recover from perturbations and prevent falls.

The purpose of this study was to examine the trajectory of the CoM in relation to the dynamically changing BoS during gait in healthy young adults, healthy elderly adults and elderly patients who reported gait imbalance. In addition to the XcoM and center of pressure (CoP) relationship [13,14], the CoM–BoS interaction was quantified in three ways: (1) The shortest distance from the CoM to the boundary of the BoS; (2) The distance from the CoM to the centroid of the BoS polygon; and (3) The distance from the CoM to the BoS boundary along the direction of the CoM velocity.

2. Methods

2.1. Subjects

This study included 20 healthy young adults (HY; mean age (SD): 23.6 (3.7) years, mean BMI (SD): 23.2 (2.8) kg/m^2), 10 healthy elderly adults (HE; mean age (SD): 75.4 (7.0) years, mean BMI (SD): 24.3 (2.5) kg/m^2), and 10 elderly fallers (EF; mean age (SD): 78.9 (4.9) years, mean BMI (SD): 24.5 (2.7) kg/m^2) recruited from the surrounding community. Subjects reported no history of head trauma,

neurological or heart diseases, muscle, joint, or orthopedic disorder, visual impairment that was uncorrected by glasses, persistent vertigo, or lightheadedness. Subjects were evaluated using the Berg balance scale (BBS) and questioned about their history of falls. The EF scored 52 or less on the BBS and reported one or more falls in the year previous to the testing date [15]. The study was approved by the university's institutional review board. Subjects were instructed about the procedures and written consent was obtained prior to testing.

2.2. Experimental protocol

All subjects walked barefoot at a self-selected comfortable pace along a 10-m unobstructed walkway. In addition, 10 healthy young adults were asked to walk at a self-selected slower walking speed. Walking trials were recorded after each subject had become familiar with the laboratory setting by performing a few practice trials. Whole body motion was recorded using an 8-camera motion analysis system (Santa Rosa, CA) at 60 Hz and low-pass filtered using a fourth-order Butterworth filter with cutoff frequency set at 8 Hz. A total of 29 reflective markers were placed on subjects' bony landmarks to define a 13-segment model [16].

2.3. Data processing

Whole body CoM position was calculated as the weighted sum of the 13-segment model [16]. Linear CoM velocity was calculated using Woltring's cross validated spline algorithm from the CoM positions [17]. The CoP was calculated from the ground reaction forces and moments of two force plates (Advanced Mechanical Technologies Inc., Watertown, MA) placed in series along the walkway. The two-dimensional BoS area was instantaneously defined based on the configurations of both feet; whether at heel strike, foot flat, heel off, or toe off (Fig. 1). During single limb support, the boundaries of the BoS were defined by the supporting limb's foot width, ankle width and foot length. The heel marker (taking into account the radius of the marker, marker wand and base) was the demarcation for the posterior boundary. The anterior boundary was defined as the distal end of the toes using the measured foot length along the vector defined by the metatarsal–phalangeal and heel markers. The medial and lateral boundaries were defined using the measured ankle and foot widths at the location of the ankle marker and metatarsal–phalangeal joint marker, respectively.

During double limb support, the BoS was defined similarly to single limb support, while including portions of each foot in contact with the ground as well as the area between the feet (Fig. 1). At heel strike, only the posterior boundary of the contacting limb was included in the BoS. At foot flat the entire foot was part of the BoS. During heel off, the metatarsal–phalangeal joint became the posterior boundary. At toe off, the swing limb no longer was included in the BoS and the contralateral limb was in single limb support. The BoS area was calculated throughout the gait cycle.

Toe off and heel strike were detected based on the vertical velocity of the midfoot (Fig. 1B) [18]. Foot flat was determined based on the anterior velocity of the toe marker dropping below 100 mm/s [19]. Heel off was determined at the point at which the heel marker exceeded the threshold of 40 mm above its position during foot flat [20].

The shortest distance from the CoM to the boundary of the BoS was identified and calculated throughout gait (Fig. 2). When the CoM is within the BoS, the distance is referred to as the stability margin. A smaller stability margin could indicate a less stable configuration. When the CoM is located outside the BoS, the distance is referred to as the CoM separation. This CoM separation is used as an indicator to evaluate the individual's ability in dynamic balance maintenance, with a greater distance indicating a better capability to displace and recapture the CoM outside the BoS. Alternatively, it is possible that individuals with poor balance might extend their CoM a greater distance outside the BoS due to an inability to control movement. The centroid of the BoS polygon was calculated based on an equal density distribution across the entire BoS surface. A smaller distance from the CoM to the centroid demonstrates close proximity to the center of the BoS and greater static balance control.

Dynamic balance was determined utilizing the instantaneous direction of the CoM velocity vector. The displacement of the CoM to the boundary of the BoS along the direction of the velocity vector is referred to as the dynamic distance to the border of the BoS, regardless of whether the CoM is inside or outside the BoS. The time to contact was determined by dividing the CoMv distance by the CoM velocity. This variable described the amount of time needed for the CoM to cross the border of the BoS. In addition, the XcoM was calculated as $XcoM_x = p_x + v_x/\omega_o$, where $\omega_o = \sqrt{gravity/vertical\ CoM\ position}$, p_x is the CoM position and v_x is the CoM velocity [11]. Lateral and anterior separations between the XcoM and CoP were calculated at heel strike [13].

Custom MATLAB (Mathworks, Natick, MA, USA) programs were used to calculate the BoS, XcoM and the corresponding CoM–BoS and XcoM–CoP interactions. Statistical analyses were performed with SPSS 14.0 (SPSS Inc., Chicago, IL, USA) using a one-way analysis of variance to detect differences among groups for CoM–BoS distances, time to contact and XcoM–CoP distances. Between-group analysis was performed at the transition phases of gait, specifically heel strike and toe off. A Bonferroni correction was used to adjust the alpha level to $P = .0167$. A Student T-test with alpha level set at $P = .05$ was used when comparing young adults walking at a slow speed and elderly fallers. Pearson correlations were performed between BBS scores and CoM–BoS interactions for all elderly adults, with alpha level set at $P = .05$.
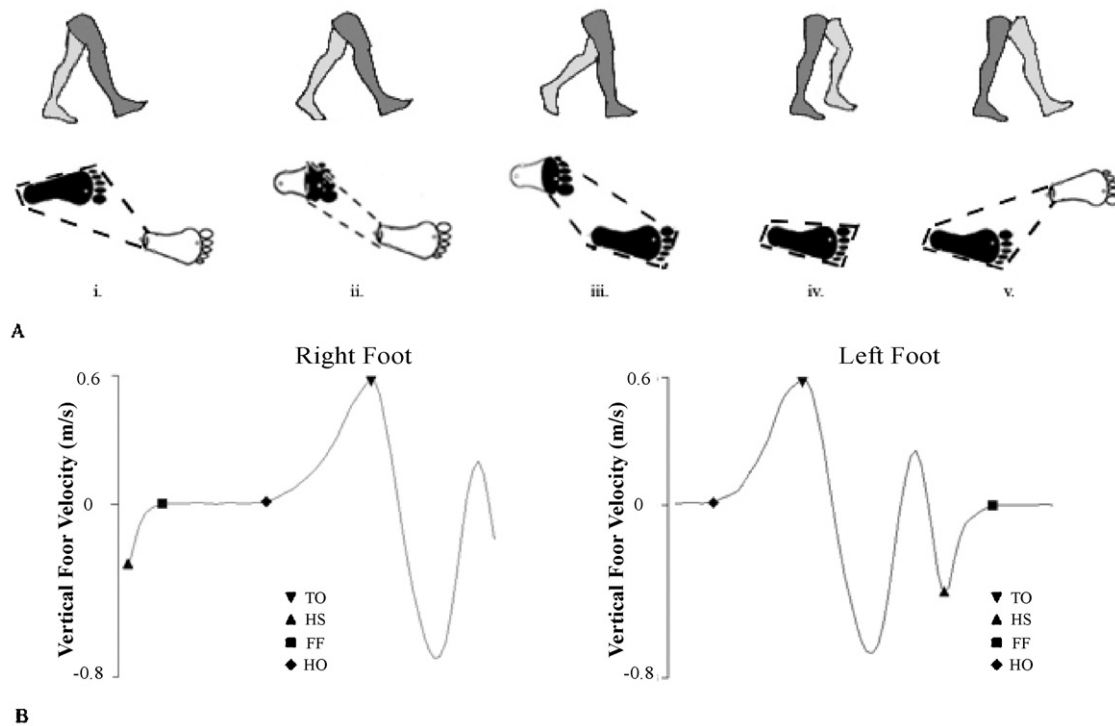

Fig. 1. The base of support throughout one gait cycle (A) for heel strike (i), heel off (ii), foot flat (iii), toe off (iv) and heel strike (v). The shaded regions of the foot and the dashed lines represent the foot contact area and the boundary of the base of support, respectively. The base of support is determined based on foot positions (B) of heel strike (HS), toe off (TO), foot flat (FF) and heel off (HO) for both limbs.
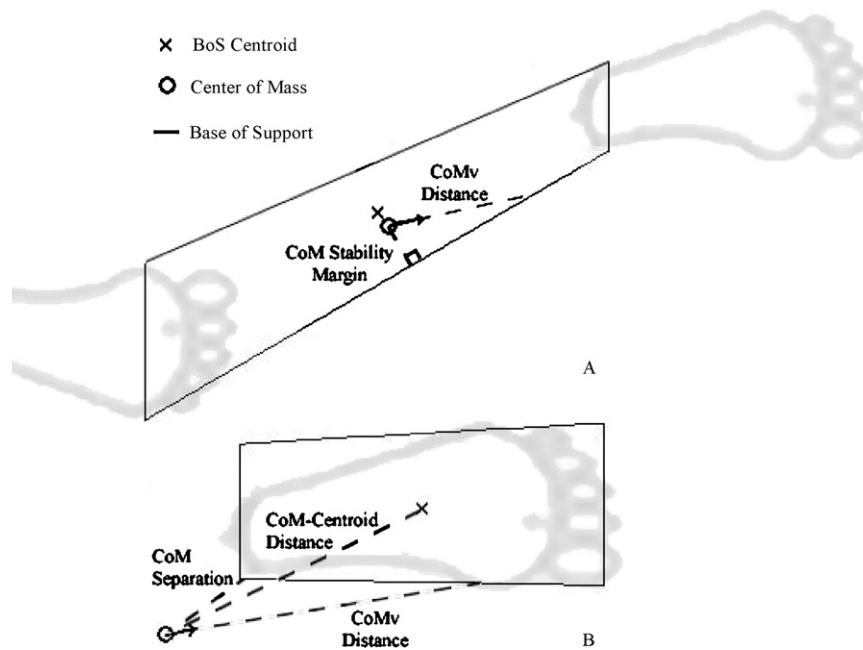
Fig. 2. Center of mass and base of support interaction during double limb (A) and single limb (B) support phases.

3. Results

The CoM–BoS interaction is indicative of both static and dynamic balance control ability (Fig. 3). During double limb support, the CoM and CoP remains within the boundary of the BoS for all subjects. In contrast, during single limb support, while the CoP remains within the boundary of the BoS, the CoM travels outside of the BoS, with the CoMv vector initially directed towards the medial border of the foot at contralateral toe off and directed away from the boundary from midstance till the subsequent heel strike. When the CoMv vector is directed away from the BoS, the CoMv distance to the border is not calculated. Greatest separation between all CoM variables and the BoS is found at the instant of toe off and prior to heel strike.

EF walked at a slower self-selected gait velocity than both HY ($P < .001$) and HE ($P = .048$; Table 1). At heel strike, while the stability margin and distance to centroid was similar for all groups, HY demonstrated a greater CoMv distance to the border than both HE and EF (Table 1; Fig. 3). At toe off, a greater CoM separation and distance to the BoS centroid was demonstrated by HY when compared to both HE and EF (Table 1; Fig. 3). In addition, a larger CoMv distance to the border was shown by HY compared to EF. Throughout gait, HE showed a similar pattern to that seen among HY, while EF maintained their CoM closer to the BoS when compared to the other two groups (Fig. 3). The CoM was contained within the BoS for all groups when both feet were on the ground.

Young adults who were asked to walk at a slower than comfortable speed demonstrated a similar gait velocity to elderly fallers (Table 2) ($P = .754$). While no differences were seen in the BoS area, the elderly fallers demonstrated a 5 cm smaller distance to the BoS along the CoM velocity vector ($P = .007$) and 45 ms shorter time to contact with the border ($P = .003$) at heel strike, when compared to HY. No differences were seen among the static CoM–BoS measures at heel strike or during toe off.

No significant group differences were detected for the XcoM–CoP distance in the lateral direction ($P = .764$; Table 3). In the anterior direction, the XcoM–CoP distance at heel strike was approximately 11 cm greater in HE than EF ($P = .049$) and 20 cm greater in HY than EF ($P < .001$).

Across all elderly subjects, no significant correlations were found between the BBS and any of the CoM–BoS interactions at either heel strike or toe off ($P > .05$).

4. Discussion

The purpose of this study was to propose a method for identifying the dynamically changing BoS during gait, as well as provide static and dynamic balance measures for the interaction of the CoM and BoS. When applied to our subjects, elderly fallers demonstrated a reduced ability to control their CoM in relation to the BoS due to poor balance and possible fear of falling.

By maintaining a shorter separation of the CoM outside the BoS, elderly fallers demonstrated a conservative gait pattern. At toe off, the CoM is medial and posterior to the BoS, with the CoM velocity directed towards the medial border of the supporting limb. At heel strike, EF had a significantly smaller anterior XoM–CoP separation than both HE and HY. These results support prior studies, which demonstrated reduced CoM–CoP separation and CoM anterior velocity among the elderly during level walking [21]. Smaller distances to the border among elderly fallers could be indicative of a fear of a sideways or backwards fall, as well as reduced muscle strength. Adaptations to fear of sideways falls, which are a factor for hip fractures [22], could be accomplished by maintaining the CoM closer to the medial boundary before toe off of the swing foot.

Differences in gait velocities between subjects might be a limitation of this study, as velocity affects foot placement and CoM movement in the sagittal and frontal planes. Elderly fallers, who walked slower, demonstrated a larger BoS in the frontal plane, with a reduced BoS in the sagittal plane. Therefore, the effect of speed was tested among young adults. When HY were asked to walk at slower speeds, they demonstrated larger balance control capacities than EF. At heel strike, young adults had a similar BoS area as the elderly fallers, yet controlled their CoM such that the distance to the BoS along the direction of the CoM velocity vector and time to contact with the border was significantly greater than EF. This might be indicative of an elderly faller's inability to properly control the CoM momentum while landing the swing foot. Smaller time to contact will result in a reduced ability to compensate for
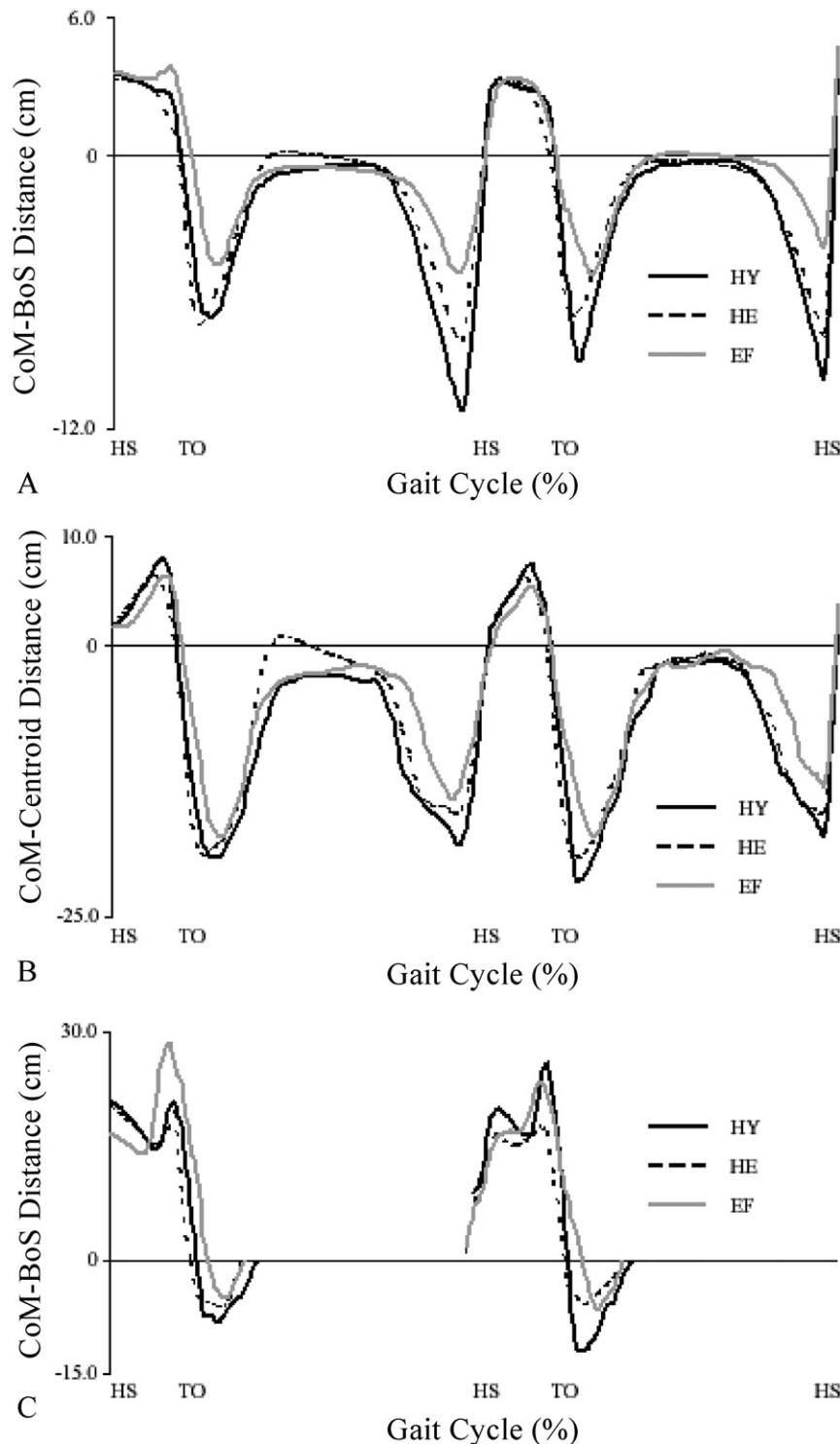
Fig. 3. Ensemble average of gait cycles for HY, HE, and EF. Positive values occur when the CoM is inside the base of support, and negative values are found when the CoM is outside the base of support. The instant of heel strike and toe off are represented with HS and TO, respectively. The empty sections of (C) represents points when the CoM is outside the BoS and the CoM velocity is directed away from the BoS.

any perturbations or obstacles that are encountered at foot strike, including slips. Slips have been highly associated with falls in the elderly, with greater hamstring activation and greater ability to reduce heel contact velocity found among young adults when compared to older adults [23]. Such velocity modifications and muscle activation might not be present in our elderly fallers, which might predispose them to greater risk of falling. According to the dynamic walking model, the step-to-step transition may require

60–70% of the overall metabolic energy spent during ambulation, and is responsible for re-directing the CoM velocity [24]. It is possible that weaker musculature and a poorer strategy among elder has resulted in a walking strategy that is redirecting the CoM velocity in a less efficient manner than healthy adults.

Based on the XcoM concept, a perturbation which causes a change in the CoM velocity will induce a change in foot placement of the subsequent step (or CoP) by $\Delta v/\omega_o$ [14]. This "offset-plus-

Table 1

Group averages (SD) for the CoM and the BoS interaction at heel strike and toe off.

Gait variable	HY	HE	EF
Gait velocity (m/s)	1.38 (0.14)	1.26 (0.20)	1.02[*,†] (0.10)
At heel strike (CoM inside BoS)			
CoM stability margin (cm)	3.5 (0.4)	3.5 (0.6)	3.9 (0.8)
Distance to centroid (cm)	2.2 (0.7)	2.2 (0.4)	2.5 (0.4)
CoMv distance to border (cm)	23.0 (4.1)	18.7[*] (4.0)	17.5[*] (2.6)
Time to contact (ms)	157.4 (30.9)	146.0 (39.4)	165.3 (25.9)
BoS area (cm²)	475.0 (59.8)	435.4 (57.2)	401.9[*] (71.7)
At toe off (CoM outside BoS)			
CoM separation (cm)	12.4 (2.5)	10.4 (2.4)	8.3[*] (2.4)
Distance to centroid (cm)	25.5 (2.6)	23.4 (3.0)	21.4[*] (2.4)
CoMv distance to border (cm)	17.2 (3.7)	15.3 (6.7)	11.3[*] (4.0)
Time to contact (ms)	117.2 (25.3)	111.0 (39.9)	114.9 (38.9)
BoS area (cm²)	218.0 (34.2)	219.8 (35.7)	227.7 (40.0)

[*] Significant difference from HY ($P < .0167$).
[†] Significant difference from HE ($P < .0167$).

proportional control" of balance was not seen in this study, with similar XcoM–CoP distances observed in the lateral direction among all subjects, while a reduced XcoM–CoP distance was demonstrated in the anterior direction at heel strike among EF. Greater differences in foot placement and the lateral stability margin might be witnessed among the EF if a perturbation is placed during gait [14].

Defining the base of support during gait further demonstrates foot placement strategies used to capture the dynamically changing center of mass during locomotion, where 50% of all falls occur [25]. A quantitative definition of the BoS was determined previously [26], however, only double-limb support of a lifting exercise was investigated and dynamic changes to the BoS and its interaction to the CoM during gait were not investigated. Past work has also shown that the CoM–BoS stability margin may be a useful measure during dynamic situations [11], with the projection of the CoM to the supporting boundary being used as a measure of stability among walking machines [12,27]. Utilizing the technique presented, it is possible to determine the relative position of the CoM to the border and centroid of the base of support as well as the CoM's distance to the boundary along the direction of velocity. These variables might provide a greater understanding of a person's static and dynamic balance control.

No correlations were found between CoM and BoS measures and the BBS. While most HE scored a maximum of 56 on the BBS, some demonstrated similar CoM–BoS interactions as the EF. Conversely, HY who scored a 56 did not demonstrate similar gait measures to the EF. The BBS, which has a ceiling effect and is a static test of balance, might not detect an individual's deficiency in dynamic balance control [28,29]. The CoM–BoS interactions,

Table 2

Group averages (SD) for the CoM and the BoS interaction at heel strike and toe off when HY are controlled for speed.

Gait variable	HY – slow	EF	P-value
Gait velocity (m/s)	1.00 (0.13)	1.02 (0.10)	.754
At heel strike (CoM inside BoS)			
CoM stability margin (cm)	3.7 (0.7)	3.9 (0.8)	.590
Distance to centroid (cm)	2.6 (1.1)	2.5 (0.4)	.750
CoMv distance to border (cm)	22.5 (4.5)	17.5 (2.6)	.007[*]
Time to contact (ms)	210.0 (31.9)	165.3 (25.9)	.003[*]
BoS area (cm²)	434.7 (97.7)	401.9 (71.7)	.404
At toe off (CoM outside BoS)			
CoM separation (cm)	8.9 (2.9)	8.3 (2.4)	.638
Distance to centroid (cm)	21.8 (2.5)	21.4 (2.4)	.727
CoMv distance to border (cm)	12.0 (3.6)	11.3 (4.0)	.683
Time to contact (ms)	112.9 (36.5)	114.9 (38.9)	.909
BoS area (cm²)	212.9 (27.1)	227.7 (40.0)	.346

[*] Significant difference between EF and HY slow speed ($P < .05$).

Table 3

Group averages (SD) of the XcoM–CoP interaction in the anterior and lateral directions at heel strike.

Variable	HY	HE	EF
Anterior separation (cm)	60.9 (7.6)	52.4 (8.6)	41.6 (6.6)[*,†]
Lateral separation (cm)	6.4 (2.3)	7.3 (2.3)	6.6 (3.3)

[*] Significant difference from HY ($P < .0167$).
[†] Significant difference from HE ($P < .0167$).

CoMv–BoS in particular, could be more sensitive in distinguishing deviations in balance control and gait adaptations in the elderly.

In conclusion, we have proposed a method for calculating the base of support and its interaction with the CoM throughout gait. Elderly fallers positioned their CoM and controlled their CoM velocity in a different manner than healthy adults at toe off and heel strike. When young adults walked at a similar gait velocity, they demonstrated greater dynamic stability than the elderly fallers. Knowledge of foot placement and the CoM trajectory could help identify rehabilitation practices for patients with balance disorders [30]. Proper foot placement and BoS changes might elucidate a safer and more efficient gait pattern among elderly fallers.

Conflict of interest statement

None of the authors had any conflict of interest during this study.

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