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# Age and height effects on the center of mass and center of pressure inclination angles during obstacle-crossing

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## Abstract

Tripping over obstacles has been reported as one of the most frequent causes of falls in the elderly. Maintenance of the body's balance and precise swing foot control is essential for successful obstacle-crossing. The aim of this study was thus to investigate the height and age effects on the center of mass (COM) and center of pressure (COP) inclination angles and angular velocities during obstacle-crossing. Ten healthy young and 15 healthy older adults were recruited to walk and cross obstacles of heights of 10%, 20% and 30% of their leg lengths. The COM and COP position data were calculated using data measured from a three-dimensional (3D) motion analysis system and forceplates. Smaller medial COM–COP inclination angles were found in the older group, suggesting that the neuromusculoskeletal system may have more room to control the swing foot with sufficient foot clearance. Decreased inclination angles with increasing obstacle height suggest that the subjects tended to keep their COM position close to the COP position to increase the body's stability. Greater anterior inclination angular velocities were found in the older group to maintain the same inclination angles as the young. Not only inclination angles, but also COM–COP angular velocity, were useful for assessing one's ability to control the body's dynamic stability.

*Keywords:* Obstructed gait; Center of mass; Center of pressure; Age; Obstacle height

## 1. Introduction

Falls are a leading cause of death in the older population in the United States [1], and 87% of fractures in adults aged 65 and older are due to falls [2]. Among the causes of falls in the elderly, tripping during obstacle-crossing was one of the most frequent [3–6]. Maintenance of the body's balance, together with precise swing foot control, is essential for successful obstacle-crossing. Inappropriate control of the locomotor system may contribute to body imbalance which may further lead to tripping over obstacles. Knowledge of the age effects on whole-body dynamic stability during obstacle-crossing may be useful for understanding the mechanisms of the increased incidence of trip-related falls in the elderly. Moreover, higher obstacles place a greater demand on the neuromusculoskeletal system [7]. Therefore, study of the effects of obstacle height is also essential.

Movement of the center of mass (COM) and its coordination with the center of pressure (COP) has been used for the study of the body's dynamic stability during activities of daily living [8–10]. Balance and posture in the frontal plane during locomotion were investigated using a whole-body inverted pendulum model [11]. Pai and Patton [10] used COM velocity-position to demonstrate the dynamic stability in the anterioposterior (A/P) direction during locomotion, and successfully predicted a feasible region of balance control in the A/P direction based on environmental (contact force), anatomical (foot geometry) and physiological (muscle strength) constraints. They suggested that forward or

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backward falls would occur when exceeding the torque and state boundaries. Extrinsic risks encountered during locomotion may further challenge the control of dynamic stability of the body. For example, encountering an obstacle during locomotion will perturb the balance of the body. In order to prevent falls, the control system needs to apply a series of reactive and feedforward corrections through the musculoskeletal system to restore the COM or COP to an optimal location on a continuous basis. It was reported that in young adults, increasing the height of the obstacle increased the challenge to the control of the stability in the vertical direction [12,13]. Increased maximum A/P, but decreased maximum mediolateral (M/L) distances between COM and COP, were also found with increasing obstacle height [12]. Since ageing may cause degradation of balance control, dynamic stability of the body in the elderly during obstacle-crossing may be affected.

Only one previous study investigated the effect of age on the body's dynamic stability during obstacle-crossing [14]. The researchers found that healthy older adults reduced their A/P COM–COP distances, indicating a conservative reduction of the mechanical load on the joints of the stance limb during obstacle-crossing. However, they were still able to maintain an M/L COM–COP distance comparable to that in young adults. Since the magnitudes of the COM motion and the COM–COP distance may be affected by a subject's stature [15], caution should be exercised when comparing results from different groups if intersubject variability cannot be excluded. The COM–COP distances have frequently been normalized by leg length (LL) or body height (BH) to exclude the influence of intersubject variability. Recently, Lee and Chou [16] proposed a method, namely COM–COP inclination angles, that removed the influence of stature differences among subjects, to describe the body's dynamic stability during locomotion. This method was applied to the investigation of dynamic stability during obstacle-crossing between fallers and non-fallers in the older population [16]. However, age effects on COM–COP inclination angles and angular velocities when crossing obstacles of different heights have not previously been reported. The purpose of this study was mainly to investigate the influence of age and obstacle height on the COM motion in terms of COM–COP inclination angles and angular velocities. Effects of normalization methods on the COM/COP relationship, including COM–COP distances normalized by LL and BH, were also studied. It was hypothesized that there would be significant age and height effects on the COM–COP inclination angles and angular velocities, and that the effects on the COM–COP inclination angles would be similar to those on COM–COP distances normalized by LL.

## 2. Materials and methods

Ten young adults (age: 26.1 ± 2.5 years, height: 174.3 ± 6.8 cm, mass: 68.7 ± 8.6 kg, leg length: 88.9 ± 3.6 cm) and 15 older adults (age: 72 ± 6 years, height: 160 ± 5.7 cm, mass: 58 ± 10.4 kg, leg length: 79.8 ± 5.1 cm) participated in the current study with informed consent. They were all free of neuromusculoskeletal dysfunction and with normal or corrected vision. Clearance to conduct the study was provided by the Institutional Human Research Ethics Committee. In a gait laboratory, each subject walked at a self-selected pace and crossed a height-adjustable obstacle made of an aluminum tube placed across a metal frame. Twenty-two infrared-retroreflective markers were placed on the superior aspects of the scapular acromion process, the medial and lateral humeral epicondyles, the ulnar styloid, the greater trochanter, the medial and lateral femoral epicondyles, the medial and lateral malleoli, the navicular tuberosity and the fifth metatarsal base. Three-dimensional marker trajectory data were measured using a seven-camera motion analysis system (Vicon 512, Oxford Metrics Group, UK) at a sampling rate of 120 Hz and were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 5 Hz. Two forceplates (Advanced Mechanical Technology Inc., USA) were placed on either side of the obstacle to measure the ground reaction forces (GRF) at a sampling rate of 1080 Hz. Two additional markers were placed on each end of the tube to define the position of the obstacle. Test conditions included crossing obstacles of three different heights (10%, 20% and 30% LL) for both limbs, in which LL is defined as the distance between the ipsilateral ASIS and the medial malleolus. Six trials, three for each side, for each condition were recorded for each subject.

A 12-body-segment model of the whole body with the trunk-head-neck, upper arms, forearm-hands, pelvis, thighs, shanks and feet modeled as rigid bodies was used for COM motion analysis. The position of the COM of the whole body ($\vec{\boldsymbol{C}}$) was calculated as

$$\vec{\boldsymbol{C}} = \frac{\sum_{i=1}^{12} m_i \vec{\boldsymbol{c}}_i}{\mathrm{BM}}, \tag{1}$$

where $m_i$ and $\vec{\boldsymbol{c}}_i$ were the mass and position of the COM of the $i$th body segment calculated using marker data and Dempster's coefficients [17]. BM was the total body mass of the subject. The COP position was calculated using forces and moments measured by the two forceplates. The difference between the sampling frequencies for kinematics and GRF was dealt with by time-synchronizing both signals. During double stance phase, a resultant COP was calculated from the COP and GRF of each foot. The A/P position of the COM and COP were described relative to the obstacle, a zero value being directly above the obstacle and a positive value being anterior to the obstacle (Fig. 1). The medial-lateral (M/L) positions of the COM and COP were described relative to the line of progression that bisected the M/L range of motion (ROM) of the COM during a stride cycle, a positive value being to the side of the leading limb (Fig. 1). The vertical positions of the COM and COP were described relative to the ground (Fig. 1). The COM–COP inclination angles in the

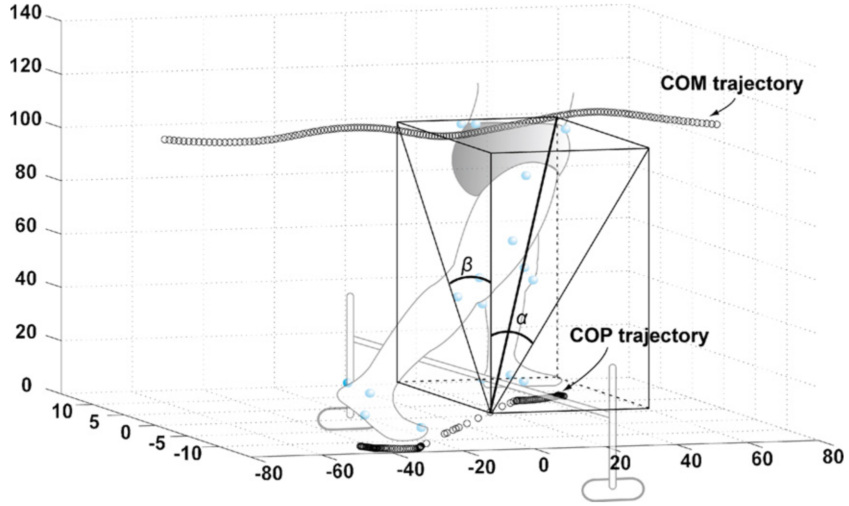

Fig. 1. A typical three-dimensional trajectory of the COM and COP motion during a crossing cycle. The COM–COP line and its A/P inclination angle ($\alpha$) and M/L inclination angle ($\beta$) is also represented in the figure.

sagittal and frontal planes (Fig. 1) were then calculated as follows [16],

$$\theta = \sin^{-1}\left(\frac{\vec{\boldsymbol{P}}_{\text{COP–COM}} \times \vec{\boldsymbol{P}}_{\text{vertical}}}{|\vec{\boldsymbol{P}}_{\text{COP–COM}}|}\right), \tag{2}$$

where $\vec{\boldsymbol{P}}_{\text{COP–COM}}$ was the vector pointing from the COP to the COM in the given plane, and $\vec{\boldsymbol{P}}_{\text{vertical}}$ was the unit vector of the vertical. The crossing cycle was defined as the heel-strike of the trailing limb before crossing the obstacle to the next heel-strike of the same foot after crossing the obstacle. Since only two forceplates were used in the study, the COP, and thus the angle $\theta$ in each plane, was calculated from toe-off of the leading limb to the next heel-strike of the trailing limb. Angular velocities of $\theta$ in each plane were then calculated by smoothing and differentiation of the $\theta$-trajectories using the generalized cross-validatory spline method [18].

During the complete crossing cycle, the instances when the swing toe was above the obstacle and at the transition between single and double stance (i.e., heel-strike and toe-off) were critical points at which maintaining body stability should be more difficult. Therefore, values of the curves of the COM–COP inclination angles and the corresponding angular velocities at these instances for both limbs, including leading toe-off (T1), leading heel-strike (T3), trailing toe-off (T4) and the instance when the swing toe was above the obstacle (T2 and T5), were extracted for subsequent statistical analysis. Apart from inclination angles, crossing velocities, stride lengths and COM–COP distances for all conditions were also calculated. COM–COP distances were then normalized by LL and BH, and stride lengths by LL.

Table 1
Between-method comparisons for the position of the COM and COP

| Method | IA | | Non-normalized | | LL-normalized | | BH-normalized | |
|---|---|---|---|---|---|---|---|---|
| | Height | Group | Height | Group | Height | Group | Height | Group |
| A/P direction | | | | | | | | |
| T1 | ↑ | – | ↑ | O < Y | ↑ | – | ↑ | – |
| T2 | ↓ | O > Y | ↓ | O > Y | ↓ | O > Y | ↓ | – |
| T3 | – | – | – | O < Y | – | – | – | – |
| T4 | ↓ | – | ↓ | O < Y | ↓ | – | ↓ | – |
| T5 | ↓ | – | ↓ | – | ↓ | – | ↓ | – |
| M/L direction | | | | | | | | |
| T1 | – | – | – | – | – | – | – | – |
| T2 | ↓ | O < Y | ↓ | O < Y | ↓ | O < Y | ↓ | O < Y |
| T3 | – | – | – | – | – | – | – | – |
| T4 | ↑ | – | ↑ | – | ↑ | – | ↑ | – |
| T5 | – | – | – | – | – | – | – | – |

IA: inclination angle; non-normalized: COM–COP distance without normalization; LL-normalized: COM–COP distance normalization by leg length (LL); BH-normalized: COM–COP distance normalization by body height (BH); T1: leading toe-off; T2: leading toe above the obstacle; T3: leading heel-strike; T4: trailing toe-off; T5: trailing toe above the obstacle; ↑ significantly increase with increasing obstacle height ($p < 0.05$); ↓ significantly decrease with increasing obstacle height ($p < 0.05$); –: no effect ($p > 0.05$); O: older group; Y: young group.

Table 2
Means (S.D.) of the stride length and crossing speed in older and young groups when crossing obstacles of different heights

| Group | Obstacle height | | | Age effects |
|---|---|---|---|---|
| | 10% | 20% | 30% | |
| Stride length (% LL) | | | | |
| O | 143.60 (13.09) | 141.07 (10.71) | 138.85 (11.72) | $p = 0.24$ |
| Y | 136.67 (6.60) | 135.92 (6.11) | 137.65 (9.38) | |
| Crossing speed (m/s) | | | | |
| O | 0.84 (0.12) | 0.73 (0.09) | 0.66 (0.08) | $p = 0.08$ |
| Y | 0.89 (0.05) | 0.81 (0.05) | 0.76 (0.09) | |

For all calculated variables, a mixed analysis of variance (ANOVA) with one between-subject factor (age group) and one within-subject factor (obstacle height) was used. If a height effect was found, a polynomial test was performed to determine the trend (linear or quadratic). All significance levels were set at $\alpha = 0.05$. SPSS version 11.0 (SPSS Inc., Chicago, USA) was used for all statistical analyses.

## 3. Results

Differences in between-method comparisons were found in the A/P but not in the M/L direction (Table 1). In the A/P direction, inclination angles (IA) and COM–COP distances normalized by LL (LL-normalized) were found to have the same height and age effects. However, results normalized by BH (BH-normalized) were different from the other two methods. Age effects were not found in the stride length and crossing speed (Table 2).

Patterns of the ensemble-averaged curves of the COM–COP inclination angles in the A/P and M/L directions during the crossing showed that rapid changes of the COM–COP inclination angle were found between the leading heel-strike and trailing toe-off (T3 and T4, Figs. 2 and 3).

Significant height effects on the A/P COM–COP inclination angles were found at all critical times, except for those at T3 ($p < 0.004$, Table 3). However, an age effect on the A/P COM–COP inclination angles was found only at T2 ($p = 0.04$). For the A/P COM–COP angular velocity, height effects were found at T2 and T5 ($p < 0.0001$), while age effects were found at all critical times, except for those at T1 and T5 ($p < 0.035$).

Significant height effects on the M/L COM–COP inclination angles were found at T2 and T4 ($p < 0.03$, Table 4).

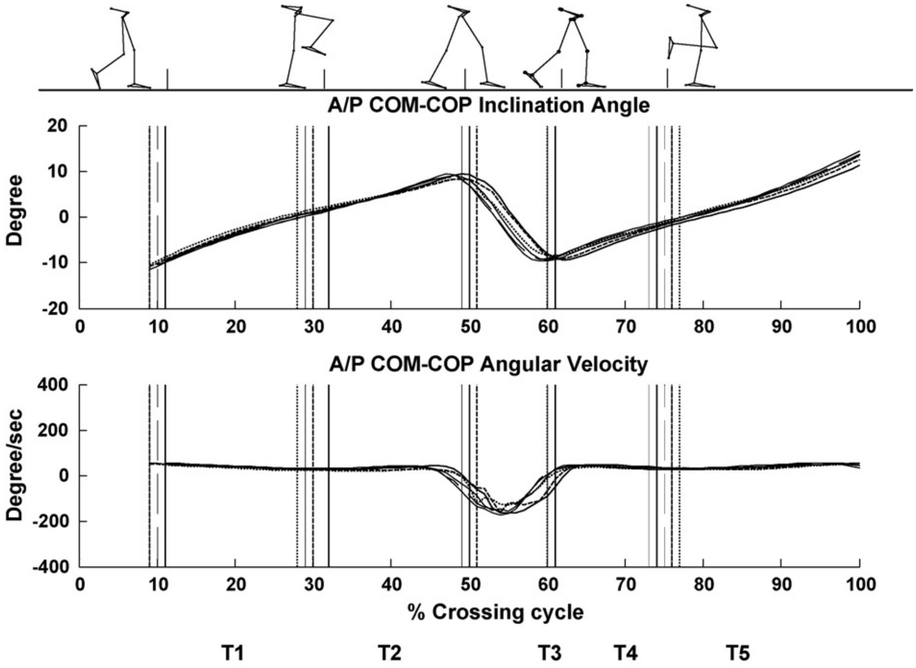

Fig. 2. Ensemble-averaged A/P COM–COP inclination angle and angular velocity in older (thick curves) and young group (thin curves) when crossing obstacles of 10% LL (solid), 20% LL (dashed) and 30% LL (dotted). Vertical lines indicate the critical times (T1: leading toe-off; T2: leading toe above the obstacle; T3: leading heel-strike; T4: trailing toe-off; T5: trailing toe above the obstacle). Stick figures above the curves demonstrate the motions of the locomotor system at critical times during obstacle-crossing.

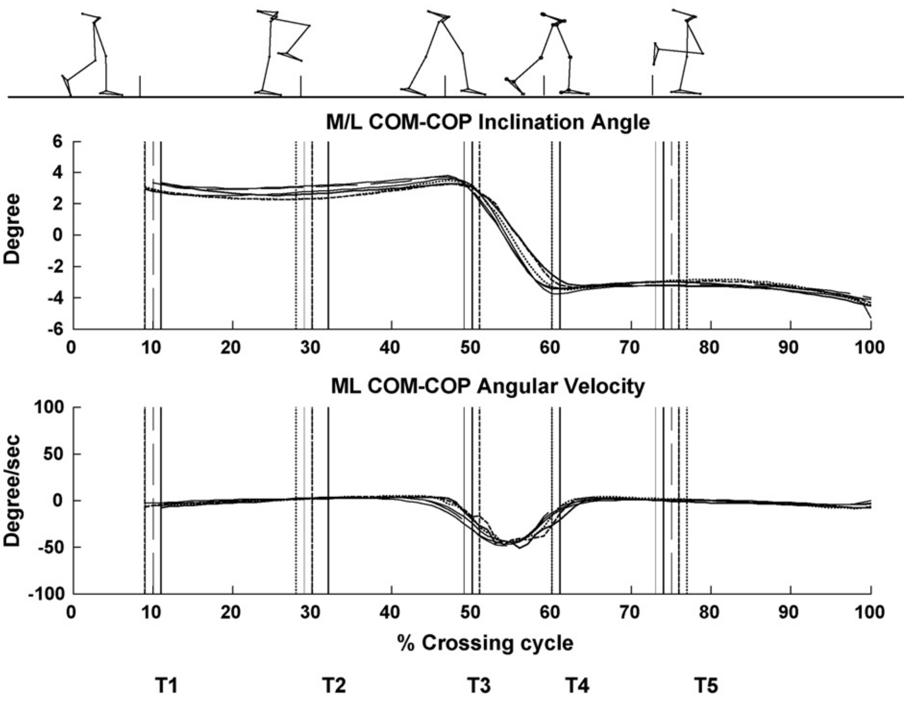

Fig. 3. Ensemble-averaged M/L COM–COP inclination angle and angular velocity in older (thick curves) and young group (thin curves) when crossing obstacles of 10% LL (solid), 20% LL (dashed) and 30% LL (dotted). Vertical lines indicate the critical times (T1: leading toe-off; T2: leading toe above the obstacle; T3: leading heel-strike; T4: trailing toe-off; T5: trailing toe above the obstacle). Stick figures above the curves demonstrate the motions of the locomotor system at critical times during obstacle-crossing.

An age effect on this variable was found at T2 ($p = 0.012$). For the M/L COM–COP angular velocity, height effects were found at T2 and T3 ($p < 0.039$), while age effects occurred at T3 ($p < 0.0001$).

## 4. Discussion

Among all methods of investigating COM–COP distance and inclination angles, differences of age and obstacle height effects were found in the A/P, but not in the M/L direction, suggesting that intersubject variability affects mainly the COM–COP distances in the A/P direction (Table 1). Since BH in the young group was significantly higher than that in the older group, results of the A/P COM–COP distance without normalization may have had a significantly different age effect when compared to the results of the other method. This may lead to incorrect interpretation of the data. Age and height effects on the A/P COM–COP distance normalized by LL were the same as those for the A/P inclination angles (Table 1). Therefore, normalization by LL may be an alternative method to remove the influence of a subject's stature on the COM–COP distances.

When the leading toe was above the obstacle, the older group used greater anterior, but smaller medial COM–COP inclination angles than did the young group (Figs. 2 and 3 and Tables 2 and 3). The older subjects tried to minimize medial inclination angles to maintain dynamic stability in the frontal plane. Falling to the side is one of the risk factors of hip fracture, occurring mostly in the elderly [19]. Moreover, the M/L COM stability has been reported as an important parameter to distinguish older people with imbalance, namely that fallers have greater M/L inclination angles [16,20]. Therefore, reduced medial COM–COP inclination angles in older people may be helpful for them to cross an obstacle successfully without falling sideways. Anterior COM–COP inclination angles for both groups were small when the leading toe was above the obstacle for all heights, suggesting that the position of the body's COM was nearly above the position of the COP. It may be a useful strategy to maintain sufficient A/P stability with minimized control effort when the leading toe is above the obstacle, such that the neuromusculoskeletal system may have more room to control the swing foot with sufficient foot clearance. Greater anterior COM–COP inclination angles in the older group indicate that the older group needed to exert more control effort to maintain A/P stability. Greater foot clearance found in older people [7] would also require extra control effort. The observed strategies for the control of the COM motion in relation to the COP in the older subjects may be related to age-related degradations of the neuromusculoskeletal system, such as reduced muscle strength and degraded coordination. This information may be helpful for the design of fall-prevention devices and for the planning of programs for preventing trip-related falls in the elderly.

With increasing obstacle height, A/P COM–COP inclination angles were decreased at trailing toe-off (T4) and when

Table 3
Means (S.D.) of the A/P COM–COP inclination angles and angular velocities at five critical times

| A/P COM–COP | Group | Obstacle height | | | Effects |
|---|---|---|---|---|---|
| | | 10% | 20% | 30% | |
| Inclination angle (°) | | | | | |
| T1 | O | −10.64 (1.52) | −11.64 (1.30) | −11.34 (1.33) | $p_{\mathrm{h}} < 0.0001$* |
| | Y | −10.12 (1.13) | −11.15 (0.93) | −11.77 (1.68) | $p_{\mathrm{a}} = 0.75$ |
| T2 | O | 1.75 (0.71) | 0.94 (0.76) | 0.71 (0.73) | $p_{\mathrm{h}} < 0.0001$* |
| | Y | 0.92 (0.52) | 0.59 (0.45) | 0.08 (0.64) | $p_{\mathrm{a}} = 0.04$+ |
| T3 | O | 10.60 (1.56) | 9.71 (0.98) | 9.35 (1.60) | $p_{\mathrm{h}} = 0.05$ |
| | Y | 9.80 (0.60) | 9.78 (0.59) | 9.99 (0.65) | $p_{\mathrm{a}} = 0.96$ |
| T4 | O | −10.90 (1.12) | −10.19 (0.85) | −9.64 (0.93) | $p_{\mathrm{h}} = 0.004$* |
| | Y | −10.64 (1.15) | −10.80 (0.86) | −10.64 (1.21) | $p_{\mathrm{a}} = 0.31$ |
| T5 | O | −2.88 (0.92) | −1.75 (1.05) | −0.97 (1.66) | $p_{\mathrm{h}} < 0.0001$* |
| | Y | −3.21 (0.48) | −2.23 (0.80) | −0.95 (0.53) | $p_{\mathrm{a}} = 0.53$ |
| Angular velocity (°/s) | | | | | |
| T1 | O | 54.32 (8.60) | 46.37 (5.53) | 47.61 (7.51) | $p_{\mathrm{h}} = 0.79$ |
| | Y | 45.56 (8.63) | 52.13 (8.02) | 52.71 (11.77) | $p_{\mathrm{a}} = 0.84$ |
| T2 | O | 25.78 (4.18) | 24.57 (5.66) | 21.15 (4.80) | $p_{\mathrm{h}} < 0.0001$* |
| | Y | 31.24 (1.81) | 26.66 (3.20) | 25.84 (3.67) | $p_{\mathrm{a}} = 0.019$+ |
| T3 | O | 32.23 (20.39) | 32.48 (10.69) | 31.69 (12.14) | $p_{\mathrm{h}} = 0.56$ |
| | Y | 8.43 (14.53) | 18.40 (12.09) | 12.04 (14.13) | $p_{\mathrm{a}} < 0.0001$+ |
| T4 | O | −45.10 (21.62) | −60.28 (44.47) | −72.84 (36.05) | $p_{\mathrm{h}} = 0.23$ |
| | Y | −28.60 (26.71) | −39.99 (33.01) | −27.07 (27.08) | $p_{\mathrm{a}} = 0.035$+ |
| T5 | O | 37.11 (5.95) | 32.58 (5.34) | 29.13 (6.14) | $p_{\mathrm{h}} < 0.0001$* |
| | Y | 35.71 (1.28) | 27.71 (2.46) | 25.85 (4.40) | $p_{\mathrm{a}} = 0.15$ |

T1: leading toe-off; T2: leading toe above the obstacle; T3: leading heel-strike; T4: trailing toe-off; T5: trailing toe above the obstacle; O: older group; Y: young group.

* A significant height effect with linear trend ($p_{\mathrm{h}} < 0.05$).

\+ A significant age effect ($p_{\mathrm{a}} < 0.05$).

the swing toe was above the obstacle (T2 and T5) (Table 2). Similar results were also found in the M/L COM–COP inclination angles, except for the data at T5 which showed no height effect. The decreased inclination angles suggest that when the extrinsic challenge increased as indicated by increasing the obstacle height, all the subjects tended to keep their COM position close to the COP position in order to increase the body's stability. Significant height effects on A/P COM–COP inclination angles at T4 were also reported by Lee and Chou [16], but the inclination angles increased with increasing obstacle height. These differences may be associated with the selection of the subject population. The older subjects in the current study walked slower with shorter stride lengths than those in Lee and Chou's study [16]. Walking speed has been shown to affect gait variables and the COM motion [21–23].

At leading heel-strike (T3) and trailing toe-off (T4), older people maintained the same COM–COP inclination angles in the sagittal plane compared to the young. However, greater angular velocities of these inclination angles were found in the older group (Fig. 2 and Table 2). The A/P inclination angles at T3 and T4 occurred around the peaks of the A/P inclination angle curve during a crossing cycle, suggesting that control of the body's dynamic stability at these times may be critical for fall-prevention. It has been noted that not only the position of the COM with respect to the base of support, but also the magnitude and direction of its corresponding velocity may provide critical information about one's ability to control stability [10,24]. Greater angular velocity presented by older adults in the current study may suggest that different control strategies for dynamic stability of the body may be used between groups to achieve the same COM–COP inclination angles during obstacle-crossing. It seems that an assessment of one's ability to control the body's dynamic stability should consider both the position and the velocity of the COM and COP. Methods that combined the position and velocity data of the COM have been proposed to establish the feasible region/margin of stability [10,25,26] but instantaneous stability of motions within the margin cannot be evaluated using these methods. Further study is needed to develop methods for the evaluation of the instantaneous stability during obstacle-crossing between older and younger groups, considering both displacement and velocity of the COM and COP.

As pointed out by Saunders et al. [27], the movement of the COM during locomotion is the result of all forces and motions acting on the body segments. There have been several studies investigating the joint kinematics and kinetics

Table 4
Means (standard deviations) of the M/L COM–COP inclination angles and angular velocities at five critical times

| M/L COM–COP | Group | Obstacle height | | | Effects |
|---|---|---|---|---|---|
| | | 10% | 20% | 30% | |
| Inclination angle (°) | | | | | |
| T1 | O | 3.45 (0.74) | 3.01 (0.53) | 3.15 (0.68) | $p_h = 0.08$ |
| | Y | 3.20 (0.74) | 3.30 (0.64) | 2.94 (0.59) | $p_a = 0.84$ |
| T2 | O | 2.62 (0.80) | 2.23 (0.62) | 2.21 (0.56) | $p_h = 0.01^*$ |
| | Y | 3.11 (0.54) | 2.95 (0.48) | 2.69 (0.58) | $p_a = 0.012^+$ |
| T3 | O | 3.47 (0.90) | 3.54 (0.98) | 3.81 (0.91) | $p_h = 0.67$ |
| | Y | 3.79 (0.98) | 3.82 (0.59) | 3.68 (0.71) | $p_a = 0.68$ |
| T4 | O | −3.37 (0.81) | −3.28 (0.68) | −3.49 (0.53) | $p_h = 0.03^*$ |
| | Y | −3.49 (0.82) | −3.45 (0.94) | −3.87 (0.90) | $p_a = 0.51$ |
| T5 | O | −2.97 (0.75) | −3.04 (0.69) | −2.85 (0.54) | $p_h = 0.38$ |
| | Y | −3.18 (0.67) | −3.04 (0.69) | −3.04 (0.70) | $p_a = 0.33$ |
| Angular velocity (°/s) | | | | | |
| T1 | O | −8.22 (3.68) | −4.53 (3.29) | −5.61 (3.71) | $p_h = 0.72$ |
| | Y | −1.89 (5.57) | −4.06 (3.96) | −3.55 (4.12) | $p_a = 0.06$ |
| T2 | O | 2.91 (3.23) | 1.01 (1.76) | 0.66 (2.65) | $p_h = 0.039^*$ |
| | Y | 2.51 (1.64) | 1.58 (1.88) | 1.55 (1.45) | $p_a = 0.66$ |
| T3 | O | −1.38 (4.55) | −0.39 (5.46) | 0.46 (5.43) | $p_h = 0.017^*$ |
| | Y | −13.27 (5.98) | −8.18 (6.51) | −9.92 (5.04) | $p_a < 0.0001^+$ |
| T4 | O | −21.96 (10.35) | −28.28 (11.38) | −35.58 (14.08) | $p_h = 0.12$ |
| | Y | −22.12 (8.85) | −24.49 (9.14) | −21.60 (7.71) | $p_a = 0.15$ |
| T5 | O | −0.36 (1.81) | 0.99 (1.72) | 1.68 (1.40) | $p_h = 0.023^*$ |
| | Y | −0.69 (3.04) | −0.19 (1.79) | −0.45 (1.77) | $p_a = 0.12$ |

T1: leading toe-off; T2: leading toe above the obstacle; T3: leading heel-strike; T4: trailing toe-off; T5: trailing toe above the obstacle; O: older group; Y: young group.

* A significant height effect with linear trend ($p_h < 0.05$).

\+ A significant age effect ($p_a < 0.05$).

of the locomotor system during obstacle-crossing [7,28–32] to understand the muscular contribution towards controlling joints. However, the motion of the COM and its coordination with the COP were not considered in these studies. Therefore, further studies should investigate joint mechanics together with COM and COP motion data, which may be helpful for understanding how the joint mechanics contribute towards the stability control of the body during obstacle-crossing.

## 5. Conclusions

A successful and safe obstacle-crossing requires not only sufficient foot clearance of the swing limb, but also the stability of the body provided by the stance limb, especially when the swing toe is above the obstacle. At this critical time the older group used smaller medial COM–COP inclination angles to cross the obstacle successfully without falling sideways, suggesting that the neuromusculoskeletal system may have more room to control the swing foot with sufficient foot clearance. Decreased inclination angles with increasing obstacle height suggest that the subjects tended to keep their COM position close to the COP position to increase the body's stability. Not only inclination angles, but also COM–COP angular velocities were useful for assessing one's ability to control the body's dynamic stability. Results of this study may be helpful for the design of fall-prevention devices and for the planning of programs for preventing trip-related falls in the elderly.

## Conflict of interest

None.

## References

[1] Hoyert DL, Arias E, Smith BL, Murphy SL, Kochanek KD. Deaths: final data for 1999. Natl Vital Stat Rep 2001;49:1–113.

[2] Fife D, Barancik JI. Northeastern Ohio Trauma Study III: incidence of fractures. Ann Emerg Med 1985;14:244–8.

[3] Overstall PW, Exton-Smith AN, Imms FJ, Johnson AL. Falls in the elderly related to postural imbalance. BMJ 1977;1:261–4.

[4] Blake AJ, Morgan K, Bendall MJ, Dallosso H, Ebrahim SB, Arie TH, et al. Falls by elderly people at home: prevalence and associated factors. Age Ageing 1988;17:365–72.

[5] Tinetti ME, Speechley M. Prevention of falls among the elderly. N Engl J Med 1989;320:1055–9.

[6] Campbell AJ, Borrie MJ, Spears GF, Jackson SL, Brown JS, Fitzgerald JL. Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study. Age Ageing 1990;19:136–41.

[7] Lu TW, Chen HL, Chen SC. Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. Gait Posture 2006;23:471–9.

[8] Goldie PA, Bach TM, Evans OM. Force platform measures for evaluating postural control: reliability and validity. Arch Phys Med Rehabil 1989;70:510–7.

[9] Collins JJ, Luca CJD. Open-loop and close-loop control of posture: a random-walk analysis of center-of-pressure trajectories. Exp Brain Res 1993;95:308–18.

[10] Pai YC, Patton J. Center of mass velocity-position predictions for balance control. J Biomech 1997;30:347–54.

[11] Mackinnon CD, Winter DA. Control of whole body balance in the frontal plane during human walking. J Biomech 1993;26:633–44.

[12] Chou LS, Kaufman KR, Brey RH, Draganich LF. Motion of the whole body's of mass when stepping over obstacles of different heights. Gait Posture 2001;13:17–26.

[13] Wang TM, Chen HC, Lu TW. Effects of obstacle height on the control of the body center of mass motion during obstructed gait. JCIE 2007;30:471–9.

[14] Hahn ME, Chou LS. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. J Biomech 2004;37:837–44.

[15] Berger W, Trippel M, Discher M, Dietz V. Influence of subjects' height on the stabilization of posture. Acta Otolaryngol 1992;112:22–30.

[16] Lee HJ, Chou LS. Detection of gait instability using the center of mass and center of pressure inclination angles. Arch Phys Med Rehabil 2006;87:569–75.

[17] Winter DA. Biomechanics and motor control of human movement, New York; 1990.

[18] Woltring HJ. A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. Adv Eng Software 1986;8:104–13.

[19] Wei TS, Hu CH, Wang SH, Hwang KL. Fall characteristics, functional mobility and bone mineral density as risk factors of hip fracture in the community-dwelling ambulatory elderly. Osteopor Int 2001;12:1050–5.

[20] Chou LS, Kaufman KR, Hahn ME, Brey RH. Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait Posture 2003;18:125–33.

[21] Kirtley C, Whittle MW, Jefferson RJ. Influence of walking speed on gait parameters. J Biomed Eng 1985;7:282–8.

[22] Brach JS, Berthold R, Craik R, VanSwearingen JM, Newman AB. Gait variability in community-dwelling older adults. J Am Geriatr Soc 2001;49:1646–50.

[23] Orendurff MS, Segal AD, Klute GK, Berge JS, Rohr ES. The effect of walking speed on center of mass displacement. J Rehabil Res Dev 2004;41:829–34.

[24] Pai YC, Naughton BJ, Chang RW, Rogers MW. Control of body center mass momentum during sit-to-stand among young and elderly adults. Gait Posture 1994;2:109–16.

[25] Patton J, Pai YC, Lee WA. Evaluation of a model that determines the stability limits of dynamic balance. Gait Posture 1999;9:38–49.

[26] Hof AL, Gazendam MGJ, Sinke WE. The condition for dynamic stability. J Biomech 2005;38:1–8.

[27] Saunders JB, Inman VT, EBerhart HD. The major determinants in normal and pathological gait. J Bone Joint Surg 1953;35A:543–5.

[28] McFadyen BJ. Anticipatory locomotor adjustment during obstructed human walking. Neurosci Res Commun 1991;9:37–44.

[29] Patla AE, Prentice SD. The role of active forces and intersegmental dynamics in the control of limb trajectory over obstacles during locomotion in humans. Exp Brain Res 1995;106:499–504.

[30] Chou LS, Draganich LF. Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. J Biomech 1997;30:331–7.

[31] Begg RK, Sparrow WA, Lythgo ND. Time-domain analysis of foot-ground reaction forces in negotiating obstacles. Gait Posture 1998;7:99–109.

[32] Chen HL, Lu TW. Comparisons of the joint moments between leading and trailing limb in young adults when stepping over obstacles. Gait Posture 2006;23:69–77.