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Research Article

Center of Pressure-Center of Mass Coordination is involved in a Process of Acceleration Drive on Gait Initiation in Community Dwelling Elderly People: A Cross-Sectional Study

Masahiro Nishimura[1], Hyuna Kim[1], Takashi Hasegawa[2], Yasushi Uchiyama[1*]

[1]Department of Physical Therapy, Graduate School of Medical Sciences, Nagoya University, Nagoya, Japan; [2]Department of Physical Therapy, School of Medical Science, Nagoya Women's University, Nagoya, Japan

ABSTRACT

Background: From the perspective of dynamic postural control, the separation between the Center of Foot Pressure (COP) and the Center of Mass (COM) has been linked to COP-COM coordination. Therefore, investigating the role of COP-COM coordination during acceleration in gait initiation is important. This study investigated whether COP-COM coordination was involved in acceleration control during gait initiation in community-dwelling elderly people.

Methods: Young (n=11; age: 22.2 ± 1.4 years) and healthy elderly (n=23; age: 71.9 ± 4.3 years) subjects walked a 12 m gait 5 times at a self-selected speed. The gait velocity from the first to third step and COM were detected using 15 markers on the subject' s body *via* a motion capture system. COP was traced by a 2.4 m foot pressure distribution sensor. 'COP-COM separation' was calculated from the starting motion to the third step in Anteroposterior (AP) and Mediolateral (ML) directions. Elderly subjects were divided into two groups using the Timed-Up-and-Go-Test (TUG) time to compare sensitivity differences in balance ability.

Results: 'COP-COM separation' in the AP direction of elderly subjects with low TUG performance was significantly lower than that of other groups ($p<0.001$). Gait velocities on the second and third steps showed significant differences among groups ($p<0.001$). 'COP-COM separation' was associated with walking speed from the first to third step, regardless of age ($p<0.05$).

Conclusion: These results suggest that COP-COM coordination of healthy elderly is sensitive in the AP direction and contributes to the acceleration phase until steady-state walking.

Keywords: Gait; Center of Mass (COM); Timed Up and Go Test (TUG); Base of Support (BOS); Center of Foot Pressure (COP); Mediolateral; Anteroposterior

INTRODUCTION

Gait is a fundamental process to move the body forward by periodic lower limb movements with postural stability [1]. Gait function and balance ability are associated with walking ability, including motor, sensory, cognitive, and emotional functions [2,3]. Among the common risk factors, falls were mainly caused due to lower limb malfunction in the elderly with illness or those on medication [4]. Particularly, inadequate trunk-lower limb postural control, caused by an improper shift of the Center of Mass (COM), lower limb support, and stumbling, related to more than 70% of falls during walking [5].

Gait initiation is executed from a static stability during stationary standing to a dynamic state through voluntary postural adjustments and subsequent transitions to a periodic gait pattern. Since gait initiation requires a higher degree of control and complexity than steady-state gait, postural control during gait initiation was linked to some potential fall risks [6,7]. In this regard, many studies of gait initiation stability have been conducted from the perspective of postural stability-associated balance [8-10], which is expressed as the coordinated motion resulting from the integration of feedback elements to the process of input-postural control-motor control-output [11]. As an element of coordination, stability is defined as the cooperative control of the Center of Mass (COM)

Correspondence to: Yasushi Uchiyama, Department of Physical Therapy, Graduate School of Medicine, Nagoya University, Nagoya, Japan, E-mail: uchiyama@met.nagoya-u.ac.jp

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within a Base of Support (BOS), which is composed of the surface in contact with the plane. BOS is regulated in the plantar surface during upright walking. The mechanism that controls COM with the Center of Foot Pressure (COP) is also involved in the regulation of the floor reaction force to prevent the deviation of COM from BOS [12]. Falls during walking are also related to this postural control mechanism. The coordinated movement of the trunk and lower extremity is expressed as the positional relationship between the COP and COM. However, as an acyclic movement in which changes occur continuously over a short time period, expressing stability is difficult. As such, there are limited indices for stability evaluation.

COP-COM coordination is one indicator used to evaluate postural control ability. It indicates dynamic postural control maintained by the COP-COM interaction and could explain the stability of movements performed when the COM trajectory alternates between COP controlled by each supporting leg from the coordinated control perspective [13-15]. In previous studies, it has been used to evaluate the voluntary COM control ability during standing [16,17]. By focusing on a COP-COM interaction, the biomechanism during walking initiation and obstacle crossing-over was observed [14,18,19]. In other types of movement, COP-COM coordination was used to evaluate stability under the body-cognition dual task condition during stair climbing and descent and dynamic stability improvement during stair climbing by lower limb resistance training [20,21].

In considering postural control on gait initiation, it is important to focus on the behavior of COP-COM coordination in the process of efficiently increasing walking speed assuming daily life situations from the perspective of various kinematic performances. Therefore, this study aimed to investigate the role of COP-COM coordination in acceleration control during gait initiation among community dwelling elderly with different balance abilities. We hypothesized that: In the anteroposterior direction, COP-COM coordination is a factor that contributes to efficient acceleration on gait initiation.

MATERIALS AND METHODS

Study subjects

Eleven healthy young adults and 23 healthy elderly people participated in this study. To compare the differences in the balance ability among the elderly, we divided the subjects into two groups based on the median of Timed Up and Go Test (TUG) time in the pre-analysis phase. In general, the cut-off value for TUG time is 13.5 seconds as a clinical measure for estimating fall risk, however, TUG time of 9.0 seconds was used to distinguish community dwellers balance ability referring to two previous study [22,23], because our research targeted community-dwelling elderly people. Based on this cut-off time, the high-performance elderly group with a faster TUG time was named Elder (H), while the low-performance elderly group with a slower TUG time was named Elder (L) (Table 1). Exclusion criteria were the person who had neuromuscular, orthopedic or cognitive disorders that may have affected their daily living. This study conformed to the guidelines of the Declaration of Helsinki. All participants provided informed consent and agreed to join this study, which was approved by the Institutional Review Board of Nagoya University.

Experimental protocol

Participants performed a 12 m gait 5 times at a self-selected speed when asked to start gait by the examiner. 2.4 m long x 0.6 m wide foot pressure distribution sensor with four seats (Walkway MW-1000, Anima Inc., Tokyo, Japan) was used to trace the COP trajectory under a 100 Hz condition. The walkway was set on a flat surface. The trajectory of each trial was calculated by the device software. A motion capture system (Optitrack Trio, Acuity Inc., Tokyo, Japan) were used to detect the location and velocity of each of 12 reflective markers under a 120 Hz condition. These markers were placed on both sides of the scapular acromial tip, humeral lateral epicondyle, ulnar styloid process, posterior superior iliac spine, femoral lateral epicondyle, and fibular apex of the lateral malleolus to estimate the COM location. COM was calculated by the simplified whole body model, which was constructed with 9 segments [24]. In this study, the location of the hip joint center, which could not be detected directly, was estimated using the information of the posterior superior iliac spine with consideration of sex-specific differences [25]. Two markers were placed on both sides on the top of the calcaneus to detect the step length. One marker was located on the L3 level of the spinous process to calculate the walking speed. Acceleration data in tri-axis direction was measured by a gyro combined accelerometer (MVP-RF8, MicroStone Inc., Nagano, Japan), which placed on the level of L3-4 spinous process [26]. Both acceleration and angular velocity components were used to detect trunk acceleration, with correction for gravitational acceleration based on the Euler angle principle. Two types of synchronization, one was performed at the first heel contact for devices as a timing adjustment, the other one was matched with each location of the four corners of one sheet of foot pressure distribution sensor to the motion capture system as a coordinates adjustment, were executed.

COP-COM separation

'COP-COM separation' is considered an indicator of COP-COM coordination and used to compare dynamic postural control ability during gait initiation. This index was calculated using the formula as previously described [17], with a smaller value indicating a lower dynamic postural control ability (N: Number of samples; i:ith sample).

$$\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left\{\frac{COM(i)-COP(i)}{\max\left(COM(i)-COP(i)\right)}\right\}^2}$$

In this study, 'COP-COM separation' was calculated as the average value from the starting motion to the third heel contact in the Anteroposterior (AP) and Mediolateral (ML) directions. Considering variations in the characteristics of each subject, the actual difference between COM and COP was divided by the maximum difference between COM and COP in each trial to standardize results among all participants. In addition, since the displacement of COM and COP in the AP direction depends on the step width, this measurement was divided by the maximum difference between COM and COP in the ML direction. This process took into consideration the transferring load to the lower limbs on both sides, which defined BOS.

Root mean square of acceleration data

Acceleration data in each direction was calculated as Root Mean

Square (RMS) of a period from starting motion to 3rd step, which is defined as RMSacc-ML, RMSacc-V, RMSacc-AP, respectively.

Physical, mental and cognitive factors

The gait velocity was recorded at the time of the first, second, and third heel contact. To analyze the performance level of the participants, we utilized a 10-M Walking Test (10MWT) under the conditions of comfortable (10MWT com) and maximum speeds (10MWT max) as an indicator of walking ability, the Mini Mental State Examination (MMSE) as an indicator of cognitive function among elderly subjects, and the Falling Efficacy Scale (FES) as a screening test for the subjective fear of fall (Table 2).

Data processing

Before analysis, COP and COM data were processed with a low-pass filter (4 dim, cut-off frequency: 6.0 Hz). The Acceleration data were processed with Butterworth low-pass filter (4^{th} order, cutoff frequency 12.5 Hz) [27]. Through those processes, we used MATLAB 2021 (Mathworks Inc., Natick, USA).

Statistical analysis

Statistical analyses were carried out with the EZR software (ver: 1.55). The Kolmogorov-Smirnov test was used to examine the normality of the data distribution in all groups. To compare 'COP-COM separation' and acceleration RMS among the groups, the Bartlett test was first used to examine the variability of each indicator. One-way ANOVA was then used for group comparisons with the level of significance set at p<0.05. The Bonferroni method was used for post-hoc comparisons with the adjusted level of significance set at p<0.05 (original p<0.0167). Correlation analysis was performed each time series data for 'COP-COM separation' and gait velocity from the moment of starting motion to 3^{rd} step and the level of significance was set at p<0.05.

RESULTS

Subject characteristics

There were no significant differences in fundamental characteristics among all subjects and in age between the elderly groups (Table 1).

Physical, mental and cognitive performance

In physical, mental, and cognitive factors in the older adults, 10MWT com, TUG max, and FES showed significant differences (p<0.05), while MMSE did not (Table 2). No significant differences were found between Young and Elder (H) for all items (Table 2).

'COP-COM separation' and acceleration RMS in each direction

'COP-COM separation' in the AP direction showed significant difference between Elder (L) and any other groups, while that in the ML direction did not (Table 3). In terms of acceleration data, RMSacc-V was significantly higher value for Young compared to any other groups (p<0.05) and RMSacc-AP was significantly higher in order of Young, Elder (H), and Elder (L) (p<0.01), while RMSacc-ML was not (Table 3).

Table 1: Fundamental characteristics of subject's.

	Young (n=11)	Elder (H) (n=12)	Elder (L) (n=11)	p-value
Age (year)	22.2 ± 1.4	70.9 ± 3.9**	73.0 ± 4.6**	<0.01
Sex Male/Female	7/4	6/6	7/4	-
Height (cm)	167.8 ± 8.6	163.1 ± 6.9	162.3 ± 7.2	n.s.
Weight (kg)	57.3 ± 10.2	61.3 ± 9.2	60.2 ± 14.4	n.s.
BMI (kg/m^2)	20.2 ± 1.7	23.0 ± 2.3	23.2 ± 4.6	n.s.
TUG time(s)	-	8.14 ± 0.48	9.97 ± 0.70**	<0.01

Note: Young: Young adults; Elder (H): Elderly people with high balance ability; Elder (L): Elderly people with low balance ability; BMI: Body of Mass Index; TUG time: Timed-Up-and-Go-Test under the conditions of comfortable speed. Subject's characteristics, statistical significance is indicated as follows: *refers to p<0.05, **refers to p<0.01, and refers to Young *vs.* any other groups. One-way ANOVA was then used for group comparisons, the Bonferroni method was used for post-hoc comparisons with the adjusted level of significance and a result without an asterisk is not statistically significant. Each category is shown in the form mean ± standard deviation.

Table 2: Performance test of subject's.

	Young (n=11)	Elder (H) (n = 12)	Elder (L) (n=11)	p-value
10MWT com(s)	7.00 ± 0.80	6.57 ± 0.61	7.51 ± 0.40**a	<0.01
10MWT max(s)	4.90 ± 0.60	5.17 ± 0.41	5.47 ± 0.35**b	0.033
MMSE	-	28.3 ± 2.1	28.2 ± 1.3	n.s.
FES	-	57.5 ± 5.8	50.2 ± 7.5*a	0.038

Note: 10MWT com: 10-M Walking Test under the conditions of comfortable speed; 10MWT max: 10-M Walking Test under the conditions of maximum speed; MMSE: Mini Mental State Examination; FES: Falling Efficacy Scale. Subject's performance test statistical significance is indicated as follows: * refers to p<0.05, ** refers to p<0.01, a refers to Elder (H) *vs.* Elder (L), b refers to Young *vs.* Elder (L). One-way ANOVA was then used for group comparisons, the Bonferroni method was used for post-hoc comparisons with the adjusted level of significance and a result without an asterisk is not statistically significant. Each category is shown in the form mean ± standard deviation.

Table 3: 'COP-COM separation' and acceleration RMS in each direction.

	Young	Elder (H)	Elder (L)	p-value
COP-COM separation (ML)	0.54 ± 0.06	0.55 ± 0.07	0.53 ± 0.06	n.s.
COP-COM separation (AP)	1.22 ± 0.21	1.15 ± 0.30	0.92 ± 0.28**a	<0.01
RMSacc-ML (m/s^2)	1.07 ± 0.13	1.02 ± 0.19	1.03 ± 0.28	n.s.
RMSacc-V (m/s^2)	1.86 ± 0.17	1.67 ± 0.38*b	1.55 ± 0.40***c	<0.001
RMSacc-AP (m/s^2)	1.59 ± 0.38	1.40 ± 0.19**b	1.27 ± 0.21***c,d	<0.001

Note: RMSacc: Root Mean Square of acceleration data; ML: Mediolateral; AP: Anteroposterior; V: Vertical. 'COP-COM separation' and Acceleration RMS in each direction, the statistical significance is indicated as follows: * refers to p<0.05, ** refers to p<0.01, ***refers to p<0.001. a refers to Elder (L) *vs.* any other groups, b refers to Young *vs.* Elder (H), c refers to Young *vs.* Elder (L), d refers to Elder (H) *vs.* Elder (L). One-way ANOVA was then used for group comparisons, the Bonferroni method was used for post-hoc comparisons with the adjusted level of significance and a result without an asterisk is not statistically significant. Each category is shown in the form mean ± standard deviation.

Correlation analysis for time-series data of 'COP-COM separation' and gait velocity

In both the ML and AP direction, there was a significant correlation of time series data between 'COP-COM separation' and of gait velocity in each group. Correlation analysis for time series data of COP-COM separation and gait velocity in a period from starting motion to 3rd step. There were significant correlations in each direction among all groups (Table 4).

Time series data of COP-COM separation and gait velocity in a period from starting motion to 3rd step. Increasing COP-COM separation value effects to change of gait velocity for each group (Figure 1).

DISCUSSION

This study revealed that COP-COM coordination in the AP direction during gait initiation could sensitively estimate the dynamic postural control ability, which contributes to acceleration control before steady-state gait. Regarding COP-COM coordination, the value in the AP direction of the Elder (L) group was significantly lower those of other groups, while no significance differences in the ML direction were detected among the groups. These findings were consistent with those from a previous study of healthy elderly performing obstacle crossing-over [14]. Furthermore, during continuous voluntary movement in standing, the value in the AP direction of young adults was higher than that of the elderly, while the value in the ML direction of the elderly with a high fall risk was lower than that of the elderly with a low fall risk [16]. Interestingly, COP-COM coordination in the ML direction for subjects with a lower fall risk was approximately 0.6 [14], which is a similar level to that of participants in our study. In our study, the absence of 'COP-COM separation' difference in the ML direction, where the fall risk is more easily detected in patients or those with a severe balance disfunction, might be related to the faster TUG time of all elderly subjects, as compared to those in the aforementioned study.

COP-COM coordination was significantly associated with the gait velocity during gait initiation. COM acceleration for COM transfer during gait initiation was limited by lower coordination [28,29], which might result from a decrease in functional BOS due to an age-related decline in postural control [30]. Alternatively, this phenomenon might result from a decline in control within the "feasible stability region", which consisted of both BOS and COM velocity [31]. Several studies have suggested that hereditary spastic paraplegia patients might compensatively reduce COP-COM coordination with pelvic immobilization by trunk lateral bending [32], while stroke patients with paraplegia attempt to maintain as much walking speed and COP-COM coordination as possible by shortening the stance phase on the affected side [33].

Our findings also imply that the reduction of the maximal capacity of coordination could lead to a compensatory reduction of the actual COP-COM coordination [14,34], which might be influenced by factors closely related to the control of COP and COM, such as inactivity of hip abductor and adductor muscles, a decreased ability to control plantar/dorsal flexion of the ankle joint, or decreased lateral sway strategy [35,36]. Based on these findings, the elderly with reduced balance ability may have adjusted their walking speed to maintain stability by compensatory reduction of coordination, which may be an estimator of dynamic postural control ability on gait initiation.

Our study had some limitations. First, detailed analysis of discrete time-series data points during gait initiation was difficult to obtain. One study reported that COP-COM distance on heel ground contact was shorter in non-fallers than in fallers [37], indicating that COP and COM might be stabilized by having them to be closer during large changes of COM acceleration. This report might overlook modalities of postural control, which cannot be demonstrated by uniformly averaging them. Unlike our findings, non-fallers had lower COP-COM coordination than those of fallers (both of slipped and tripped groups) on heel contact. Second, analysis with changing walking speed was not conducted. Of note, at the walking speed of stroke patients, the 'COP-COM separation' value of healthy elderly was smaller than that of stroke patients [33]. Excessive forward positioning of COM relative to COP causes stumbling, while it's backward positioning causes slipping on the heel strike. Therefore, a smaller value of 'COP-COM separation' may be more desirable at certain periods. A new method, in which differences in time-series were observed by normalizing the entire gait initiation, was recently reported [38].

Table 4: Correlation analysis for time series data of COP-COM separation and gait velocity.

	ML direction		
	Coefficient	95% CI	p-value
Young	0.39	0.211-0.544	<0.01
Elder (H)	0.451	0.280-0.594	<0.01
Elder (L)	0.419	0.243-0.568	<0.01
	AP direction		
	Coefficient	95% CI	p-value
Young	0.658	0.531-0.756	<0.01
Elder (H)	0.518	0.359-0.648	<0.01
Elder (L)	0.64	0.508-0.742	<0.01

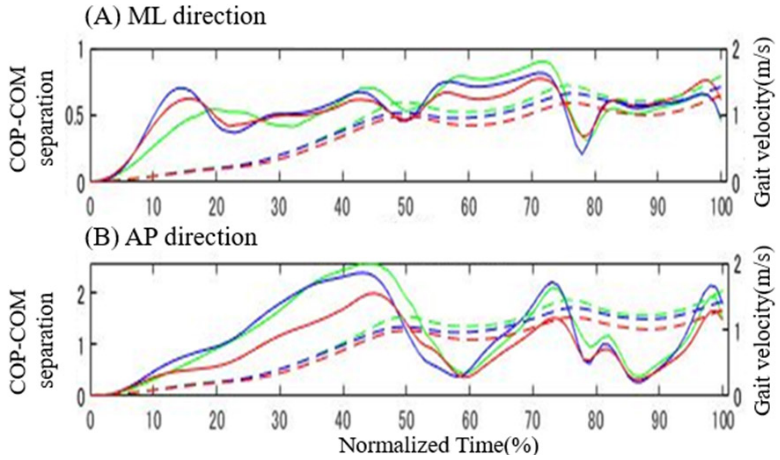

Figure 1: Trend of COP-COM separation and gait velocity. A) ML Direction; B) AP Direction. **Note:** ( ): Young COP-COM separation; ( ) :Young gait velocity; ( ): Elder (H) COP-COM separation; ( ): Elder (H) gait velocity; ( ): Elder (L) COP-COM separation; ( ): Elder (L) gait velocity; Young: Young adults; Elder (H): Elderly people with high balance ability; Elder (L): Elderly people with low balance ability; ML: Mediolateral; AP: Anteroposterior.

CONCLUSION

In future studies, combining meaningful data points from a kinematic aspect to analyze the postural control process in further detail is necessary. Additionally, the extent by which changes in acceleration might affect dynamic postural control at different walking velocities also remains to be investigated. Our study provided a valid quantification of dynamic postural control ability during gait initiation. COP-COM coordination during gait initiation of community dwelling elderly might be sensitive in the AP direction and contribute to acceleration control until steady-state gait.

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DECLARATIONS OF INTEREST

All authors have no financial relationships to disclose involved in this research.

REFERENCES

1. Perry J, Burnfield JM. Gait analysis: Normal and pathological function 2nd ed. California: Slack. 2010.
2. Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: A 1-year prospective study. Arch Phys Med Rehabil. 2001;82(8):1050-1056.
3. Deandrea S, Lucenteforte E, Bravi F, Foschi R, La Vecchia C, Negri E. Risk factors for falls in community-dwelling older people: A systematic review and meta-analysis. Epidemiology. 2010;21(5):658-668.
4. Neville C, Nguyen H, Ross K, Wingood M, Peterson EW, Dewitt JE, et al. Lower-limb factors associated with balance and falls in older adults: A systematic review and clinical synthesis. Journal of the American Podiatric Medical Association. 2020;110(5).
5. Robinovitch SN, Feldman F, Yang Y, Schonnop R, Leung PM, Sarraf T, et al. Video capture of the circumstances of falls in elderly people residing in long-term care: An observational study. The lancet. 2013;381(9860):47-54.

6. van Andel S, Cole MH, Pepping GJ. Influence of age and falls incidence on tau guidance of centre of pressure movement during gait initiation. Gait Posture. 2019;70:104-108.

7. Callisaya ML, Blizzard L, Martin K, Srikanth VK. Gait initiation time is associated with the risk of multiple falls-a population-based study. Gait Posture. 2016;49:19-24.

8. Crenna P, Frigo C. A motor programme for the initiation of forward-oriented movements in humans. J Physiol. 1991;437(1):635-653.

9. Caderby T, Yiou E, Peyrot N, Begon M, Dalleau G. Influence of gait speed on the control of mediolateral dynamic stability during gait initiation. J Biomech. 2014;47(2):417-423.

10. Maslivec A, Bampouras TM, Dewhurst S, Vannozzi G, Macaluso A, Laudani L. Mechanisms of head stability during gait initiation in young and older women: A neuro-mechanical analysis. J Electromyogr Kinesiol. 2018;38:103-110.

11. Massion J. Postural control systems in developmental perspective. Neurosci Biobehav Rev. 1998;22(4):465-472.

12. Lugade V, Lin V, Chou LS. Center of mass and base of support interaction during gait. Gait Posture. 2011;33(3):406-411.

13. MacKinnon CD, Winter DA. Control of whole body balance in the frontal plane during human walking. J Biomech. 1993;26(6):633-644.

14. Hahn ME, Chou LS. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. J Biomech. 2004;37(6):837-844.

15. Parker TM, Osternig LR, van Donkelaar PA, Chou L. Gait stability following concussion. Med Sci Sports Exerc. 2006;38(6):1032.

16. Tucker MG, Kavanagh JJ, Morrison S, Barrett RS. Voluntary sway and rapid orthogonal transitions of voluntary sway in young adults, and low and high fall-risk older adults. Clin Biomech (Bristol, Avon). 2009;24(8):597-605.

17. Tucker MG, Kavanagh JJ, Morrison S, Barrett RS. Differences in rapid initiation and termination of voluntary postural sway associated with ageing and falls-risk. J Mot Behav. 2010;42(5):277-287.

18. Hass CJ, Waddell de, Fleming RP, Juncos JL, Gregor RJ. Gait initiation and dynamic balance control in Parkinson's disease. Arch Phys Med Rehabil. 2005;86(11):2172-2176.

19. Rathore R, Tucker CA, Jeka JJ, Wright WG, Hurt CP. Effect of increasing obstacle distances task on postural stability variables during gait initiation in older nonfallers and fallers. Arch Phys Med Rehabil. 2022;103(12):2303-2310.

20. Song Q, Li L, Zhang C, Sun W, Mao D. Long-term Tai Chi practitioners have superior body stability under dual task condition during stair ascent. Gait Posture. 2018;66:124-129.

21. Gavin JP, Reeves ND, Jones DA, Roys M, Buckley JG, Baltzopoulos V, et al. Combined resistance and stretching exercise training benefits stair descent biomechanics in older adults. Front Physiol. 2019;10:442317.

22. Batko-Szwaczka A, Wilczynski K, Hornik B, Janusz-Jenczen M, Wlodarczyk I, Wnuk B, et al. Predicting adverse outcomes in healthy aging community-dwelling early-old adults with the timed up and go test. Clin Interv Aging. 2020:1263-1270.

23. Vargas RF. Timed up and go values in older people with and without a history of falls. Rev Med Chil. 2021;149(9):1302-1310.

24. Tisserand R, Robert T, Dumas R, Cheze L. A simplified marker set to define the center of mass for stability analysis in dynamic situations. Gait Posture. 2016;48:64-67.

25. Dumas R, Cheze L, Verriest JP. Adjustments to McConville et al. and Young et al. body segment inertial parameters. J Biomech. 2007;40(3):543-553.

26. Moe-Nilssen R. Test-retest reliability of trunk accelerometry during standing and walking. Arch Phys Med Rehabil. 1998;79(11):1377-1385.

27. Howcroft J, Kofman J, Lemaire ED, McIlroy WE. Analysis of dual-task elderly gait in fallers and non-fallers using wearable sensors. J Biomech. 2016;49(7):992-1001.

28. Masani K, Vette AH, Kouzaki M, Kanehisa H, Fukunaga T, Popovic MR. Larger center of pressure minus center of gravity in the elderly induces larger body acceleration during quiet standing. Neurosci Lett. 2007;422(3):202-206.

29. Yu E, Abe M, Masani K, Kawashima N, Eto F, Haga N, et al. Evaluation of postural control in quiet standing using center of mass acceleration: Comparison among the young, the elderly, and people with stroke. Arch Phys Med Rehabil. 2008;89(6):1133-1139.

30. King MB, Judge JO, Wolfson L. Functional base of support decreases with age. J Gerontol. 1994;49(6):M258-M263.

31. Pai YC, Patton J. Center of mass velocity-position predictions for balance control. J Biomech. 1997;30(4):347-354.

32. van Vugt Y, Stinear J, Davies TC, Zhang Y. Postural stability during gait for adults with hereditary spastic paraparesis. J Biomech. 2019;88:12-17.

33. Said CM, Goldie PA, Patla AE, Culham E, Sparrow WA, Morris ME. Balance during obstacle crossing following stroke. Gait Posture. 2008;27(1):23-30.

34. Martin M, Shinberg M, Kuchibhatla M, Ray L, Carollo JJ, Schenkman ML. Gait initiation in community-dwelling adults with Parkinson disease: Comparison with older and younger adults without the disease. Phys Ther. 2002;82(6):566-577.

35. Winter DA, Prince FR, Frank JS, Powell CO, Zabjek KF. Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol. 1996;75(6):2334-2343.

36. Rogers MW, Mille ML. Lateral stability and falls in older people. Exerc Sport Sci Rev. 2003;31(4):182-187.

37. Wright RL, Peters DM, Robinson PD, Watt TN, Hollands MA. Older adults who have previously fallen due to a trip walk differently than those who have fallen due to a slip. Gait Posture. 2015;41(1):164-169.

38. Moudy SC, Patterson RM, Bugnariu N. A sensitive data analysis approach for detecting changes in dynamic postural stability. J Biomech. 2020;108:109899.