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Dynamic walking stability of elderly people with various BMIs

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ABSTRACT

Background: Falls are one of the major causes of injury in the elderly. Obesity may be related to the risk of falling. Understanding the dynamic stability mechanisms of obese elderly people during gait is important as it may be associated with fall protection.

Research question: Does obesity affect the dynamic walking stability of elderly people?

Methods: This is a prospective study. Fifty-three elderly participants, aged 60–82 years, were categorized into body mass index (BMI) groups. In single-limb support experiments, the center of mass velocity (COMv), center of mass acceleration (COMa), region of velocity stability (ROSv) and region of acceleration stability (ROSa) were calculated using kinematic data sampled from a motion analysis system. In addition, all participants were assessed for the dynamic balance ability test scale (DBATS). Statistical analyses were performed by one-way ANOVA, Kruskal–Wallis/Wilcoxon nonparametric tests, or bivariate Pearson/Spearman correlation analysis.

Results: During walking, peak COMv and COMa decreased with increasing BMI (Normal BMI: 1.20 ± 0.14 m/s, 1.66 ± 0.36 m/s^2; High BMI: 1.14 ± 0.11 m/s, 1.56 ± 0.30 m/s^2; Higher BMI: 1.04 ± 0.15 m/s, 1.47 ± 0.25 m/s^2). At toe-off (TO), the normalized participants' center of mass (COM) is significantly more anterior in the Higher BMI group (Normal BMI: -0.30 ± 0.09, High BMI: -0.23 ± 0.07, Higher BMI: -0.16 ± 0.10), their normalized COMv and COMa (Normal BMI: 1.40 ± 0.16, 0.53 ± 0.11; High BMI: 1.33 ± 0.13, 0.49 ± 0.11; Higher BMI: 1.21 ± 0.16, 0.46 ± 0.11) are slower. The mean DBATS score of the Higher BMI group was the highest, indicating the weakest dynamic balance ability.

Significance: The COM dynamic stability parameters indicate that obesity may worsen balance, with the peak COMv and ROSv most affected. With increasing BMI, the dynamic stability and balance of elderly people both decreased.

1. Introduction

One-quarter to one-third of elderly people fall each year [1,2]. These falls are a major cause of injury and death in the elderly worldwide [3], and falls continue to be the leading cause of accidental death in elderly people [4]. The weak balance may cause fall injury, approximately 53% of falls by the elderly are caused by weak balance [5]. Hamacher et al. [6] proposed that *gait instability is a major fall risk factor, particularly in geriatric patients*. Moreover, as *walking is one of the most frequent dynamic activities of daily living* [6], the research of dynamic walking stability among elderly people is important for fall protection.

The methods used to evaluate balance include subjective observation, balance scale testing, and objective measurement. The subjective observation lacks objective criteria, and the interpretation of such observations relies on the experience of individual clinicians or specialists. Commonly used balance scales in medical institutions include the Berg balance scale and the Tinetti scale, both of which exhibit high reliability and validity [7,8]. Nevertheless, owing to differences in region and ethnicity, the balance scale testing should be revised appropriately. The rapid development of sensor technology and signal processing has made objective measurement more feasible for researchers. Objective parameters can reflect real-time variations in human movement and have good repeatability and high sensitivity; objective measurement has therefore been widely used to reveal the physical and physiological mechanisms of balance [9].

To effectively evaluate balance ability, researchers have introduced the concept of center of mass velocity (COMv) [10], which can reflect real-time variation in momentum and has been used to characterize dynamic stability [11–13], thus producing satisfactory results in

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evaluating dynamic balance. Fujimoto et al. later proposed center of mass acceleration (COMa) and region of acceleration stability (ROSa), which directly reflect active control of the COM momentum [14]. These two parameters are not only more sensitive to age-related differences in momentum control during gait and for grading individuals with different gait balance control abilities, but also reveal the mechanisms that make elderly people more likely to fall because of the decline in the skeletal muscle control ability.

Previous epidemiological studies have shown that obesity can influence balance and dynamic stability, and the fall risk in obese elders has also increased considerably [15,16]. Wearing et al. [17] reported that studies *focusing on the obese have encompassed the locomotor characteristics of obese adults, plantar pressures under the feet of the obese, the influence of obesity on muscular strength and power, and the potential relationships between obesity and postural control*. For the studies of relationships between obesity and stability, Hue et al. [18] determined the independent effect of body weight, age, body height, and foot length on the balance stability by a stepwise multiple regression analysis, and reported that *an increase in body weight correlates with a greater balance instability*. In conclusion, the previous study showed that aging and obesity both increase the risk of falls through the impact on balance stability. However, how to quantitatively reflect the impact remains to be studied. Body mass index (BMI) is commonly used to describe the degree of obesity. In a longitudinal study, Okubo et al. [15] additionally found that the elderly who fall often have a higher BMI. Levine et al. [16] concluded that, compared with the normal-weight elderly, the higher BMI elderly people reported impaired quality of life, particularly worse physical functioning and well-being. Although many studies have examined obesity and falling in the elderly, the mechanisms underlying the influence of the body weight on the dynamic stability and balance ability have not yet been systematically studied.

In summary, the purpose of this study was to quantitatively evaluate the association between the BMI and dynamic stability. The hypothesis of whether obesity affects the dynamic walking stability of elderly people was verified, and recommendations for supplements and revisions to the fall risk assessment in the elderly were provided.

2. Experiment

2.1. Participants

Fifty-three elders (mean (SD) age: 69.5 (6.4) years) participated in this study. According to *Criteria of weight for adults* (WS/T 428–2013, the criteria were issued by the National Health Commission of the People's Republic of China, and is applicable to the determination of overweight and obesity among Chinese adults, 18 years and older.), the participants' BMIs were classified as: Normal ($18.5\,kg/m^2 \le BMI < 24.0\,kg/m^2$, $n = 21$), High ($24.0\,kg/m^2 \le BMI < 28.0\,kg/m^2$, $n = 18$), and Higher ($BMI \ge 28.0\,kg/m^2$, $n = 14$). The participants reported no history of neurological pathology, head trauma, vestibular dysfunction, or any disease that may be dangerous during the experiment. All the participants were 60 years of age or older; the BMI was evenly distributed within normal weight, overweight, and obesity; written informed consent was collected prior to testing. The experimental protocol was approved by the Office of Research Ethics at Beihang University, the number of registration is BM20180039.

2.2. Protocol

The elders were dressed in experimental tights and a total of 24 reflective markers were placed on bony landmarks to define a 15-segment model (Fig. 1). The COM was calculated in accordance with the Inertial Parameters of the Adult Human Body (GB/T17245-2004). All elders walked barefoot at a self-selected comfortable pace. Marker trajectories were recorded using a 15-camera motion analysis system at 60 Hz (Motion Analysis Corp., Santa Rosa, CA, USA); the data were smoothed using a fourth-order Butterworth low-pass filter with a cut-off frequency of 6 Hz.

The dynamic balance ability test scale (DBATS) (Appendix A, 2011, National Health Commission of the People's Republic of China) is a balance scale tailored for use in China; because of its high reliability and validity, the National Health Commission recommends its use for assessing the balance of urban-dwelling elderly Chinese people. Wang et al. employed this scale in their investigation of the fall history and balance ability of 1600 elderly people [19]; the scale's Cronbach's α was found to be 0.910 (generally, if Cronbach's α reaches 0.8–0.9, the scale is reliable) and the Pearson correlation coefficients of each item and the total score all ranged from 0.621 to 0.781 (a Pearson correlation coefficient of 0.6–0.8 represents strong correlation).

In the study, the data of DBATS, COMv, COMa, ROSv, ROSa, and the normalized COM position were involved. The data of DBATS did not conform to the normal distribution; therefore the Kruskal–Wallis/Wilcoxon nonparametric tests were used for the difference analysis, and the Spearman method was used for the correlation analysis. The data of COMv, COMa, ROSv, ROSa, and the normalized COM position were consistent with the normal distribution and homogeneity of variance; therefore, one-way ANOVA was used for the difference analysis, and the Pearson method was used for the correlation analysis. Statistical analyses were performed by SPSS 20.0 with a significance level of $p = 0.05$.

3. Methods

Participants' COM, COMv, COMa, ROSv and ROSa were calculated from the motion analysis data.

(1) *COM*

The COM along the anteroposterior (AP) direction was calculated as the weighted sum of 15 body segments (Fig. 2a), as follows:

$$COM = \sum p_s * [(1 - l_s) * a_u + l_s * a_l]/\varepsilon \tag{1}$$

where p_s is the percentage of segment weight relative to the total body weight; l_s is the percentage calculated as the length of the part above the segment's centroid divided by the length of the whole segment multiplied by 100%; and a_u and a_l are the coordinate positions of the segment's upper and lower reflective markers, respectively. The values of these parameters are listed in Table 1, where ε denotes the correction factor ($\varepsilon_m = 0.9999$ for males and $\varepsilon_f = 1.0001$ for females).

(2) COMv and COMa

The COMv and COMa were calculated using Woltring's generalized cross-validated spline algorithm from the COM positions [20–22]. Peak COMv and COMa values are shown in Fig. 2b.

(3) ROSv and ROSa

A single-link-plus-foot inverted pendulum model was used to calculate ROSv and ROSa [14], TO instants was detected based on the vertical velocity of the midfoot [23], and the right-foot length was used to standardize each parameter [24].

$$-\widetilde{X}_{TO} \le \widetilde{\dot{X}}_{TO} \le 1 - \widetilde{X}_{TO} \tag{2}$$

where $\widetilde{X}_{TO} = \frac{X_{To} - X_h}{L_f}$ is the normalized COM position at TO, and $\widetilde{\dot{X}}_{TO}$ is the normalized COMv at TO, defined as $\widetilde{\dot{X}}_{TO} = \frac{\dot{X}_{TO}}{w_0 L_f}$ (where $w_0 = \sqrt{\frac{g}{l}}$, l is the pendulum length (distance from the ankle to the COM), g is the gravitational acceleration, and $L_f = X_t - X_h$ is the foot length.

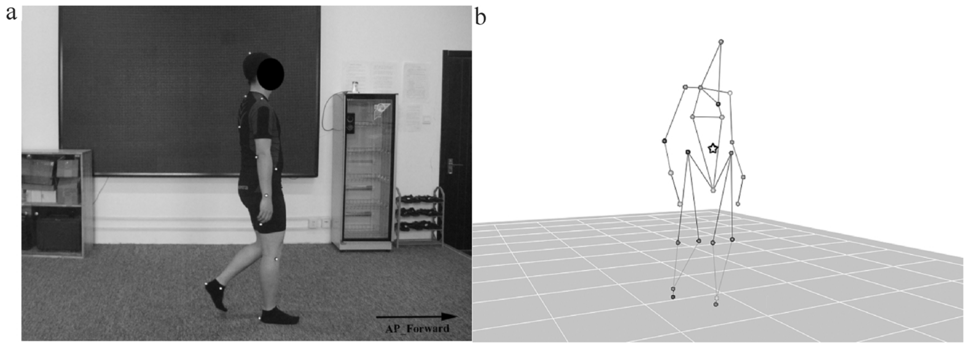

Fig. 1. (a) Experimental environment (AP view) and (b) a schematic indicating the reflective markers and COM position (indicated by a star).

$$\ddot{\widetilde{X}}_p \le \frac{\left(1-\widetilde{X}_{TO}+\frac{\dot{X}i}{w_0 L_f}\right)\left(1-\widetilde{X}_{TO}-\frac{\dot{X}i}{w_0 L_f}\right)}{\widetilde{X}_{TO}-\widetilde{X}_i} \qquad (3)$$

where $\ddot{\widetilde{X}}_p$ is the normalized COMa prior to TO, $\dot{X}_i$ is the normalized initial COMv, and $\widetilde{X}_i$ is the normalized initial COM position, defined as $\ddot{\widetilde{X}}_p = \frac{\ddot{X}_p}{{w_0}^2 L_f}$, $\widetilde{X}_i = \frac{X_i - X_h}{L_f}$.

4. Results

As shown in Fig. 3, the DBATS score significantly increased with the increasing BMIs of the participants (Normal BMI: 1.3 ± 0.6, High BMI: 3.8 ± 1.6, Higher BMI: 4.9 ± 1.9, $p < 0.05$). The moderate positive correlation was also significant ($r = 0.759$, $p < 0.001$).

Fig. 4 indicates the peak COMv (Fig. 4a) and COMa (Fig. 4b) values for the three groups. The Higher BMI group demonstrated a significantly smaller peak COMv than the Normal BMI group (Higher BMI: 1.04 ± 0.15 m/s, Normal BMI: 1.20 ± 0.14 m/s, $p < 0.05$). No significant differences were found in peak COMa across groups.

The ROSv and ROSa results are illustrated in Fig. 5(a) and (b), respectively. The horizontal axes in both the figures are the normalized COM positions and the vertical axes are the normalized COMv and COMa in Fig. 5(a) and (b), respectively. The ROSv and ROSa boundaries are represented by lines and the scattered points show the data from each participant, with different shapes denoting the three BMI groups.

As shown in Fig. 5(a), the normalized COM position of the Higher BMI group was found to be significantly anterior to that of the other groups (Higher BMI: -0.16 ± 0.10, High BMI: -0.23 ± 0.07, Normal BMI: -0.30 ± 0.09, $p < 0.05$). In addition, the normalized COMv of the Higher BMI group was significantly slower than that of the other groups (Higher BMI: 1.21 ± 0.16, High BMI: 1.33 ± 0.13, Normal BMI: 1.40 ± 0.16, $p < 0.05$). In the Higher, High, and Normal BMI groups, respectively, 64.3% (9 out of 14), 77.8% (14 out of 18), and 71.4% (15 out of 21) of the scattered points were located outside the forward

Table 1
Anthropometric data.

Segment	Marker_a_u	Marker_a_l	Gender	p_s	l_s
Head and neck	1	2-3	M	8.62	46.9
			F	8.20	47.3
Upper trunk	2-3	4-5	M	16.82	53.6
			F	16.35	49.3
Lower trunk	4-5	6	M	27.23	40.3
			F	27.48	44.6
Thigh	7/8	11/12	M	14.19	45.3
			F	14.10	44.2
Shank	9/10	13/14	M	3.67	39.3
			F	4.43	42.5
Upper arm	15/16	17/18	M	2.43	47.8
			F	2.66	46.7
Forearm	17/18	19/20	M	1.25	42.4
			F	1.14	45.3
Hand	19/20	21/22	M	0.64	36.6
			F	0.42	34.9
Foot	13/14	23/24	M	1.48	48.6
			F	1.24	45.1

*M: male, F: female. Data in the table are derived from the Inertial Parameters of the Adult Human Body (GB/T17245-2004).

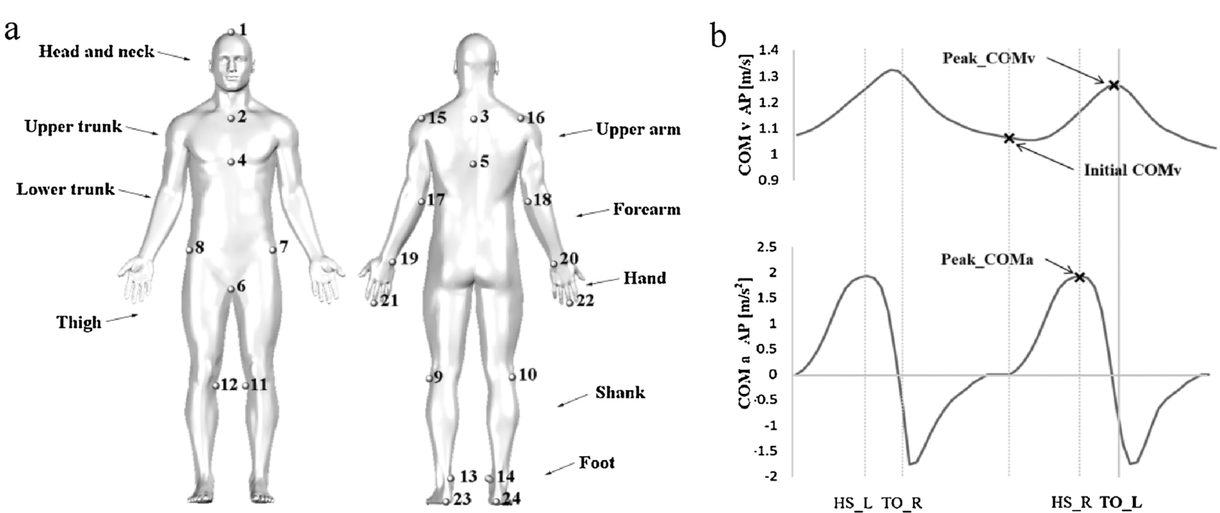

Fig. 2. (a) A total of 24 reflective markers were placed on participants' bony landmarks to define a 15-segment model, using a Solid 3D Male Muscular System (Zygote, USA) human model; (b) representative time–history plot of the COMv and COMa. HS_L/HS_R and TO_L/TO_R represent left/right heel strike and left/right TO, respectively. The initial COMv occurs when the COMa is zero, which is used to construct the ROSa.

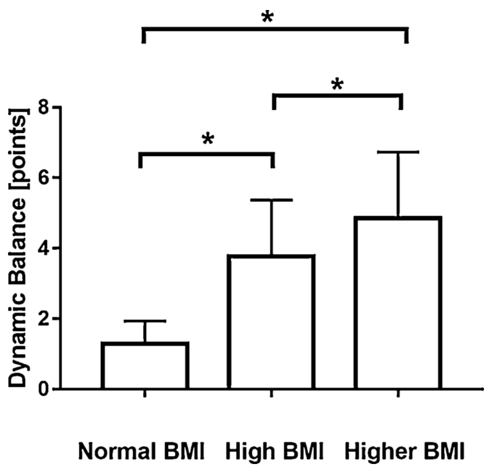

Fig. 3. DBATS scores for the Normal, High, and Higher BMI groups (* $p < 0.05$).

boundary.

The ROSa results (Fig. 5b) demonstrated that the normalized COMa decreased as the BMI increased (Higher BMI: 0.46 ± 0.11, High BMI: 0.49 ± 0.11, Normal BMI: 0.53 ± 0.11). The ROSa boundaries of each group exhibited the same decreasing trend, where the Higher BMI group demonstrated the largest ROSa boundary, followed by the High and Normal BMI groups. Like the ROSv results, 64.3% (9 out of 14), 88.9% (16 out of 18), and 95.2% (20 out of 21) of the scattered points were located outside the forward boundary in the Higher, High, and Normal BMI groups, respectively.

5. Discussion

This study quantitatively evaluates dynamic stability during walking among elderly people with different BMIs using the COMv, COMa, ROSv, and ROSa metrics. First, all the participants were assessed on the DBATS. Second, the dynamic stability parameters of COMv, COMa, ROSv and ROSa were used to quantitatively evaluate the dynamic walking stability of the elderly people with various BMIs. In summary, the results showed that the dynamic stability and balance of elderly people both decrease with increasing BMI.

The DBATS results showed that, with increase in the BMI, the elderly people's balance and dynamic stability gradually worsen. This finding indicates that obesity could lead to deteriorating balance and increase the risk of falls, a conclusion that is consistent with earlier epidemiological studies [15,16]. One possible reason for this result is that obese elderly people who had poorer body function [16] tended to adopt a more sluggish, incomplete, and disjointed gait, which affected the scores.

The peak COMv results in this study showed that, compared with the Normal BMI group, the elders in the Higher BMI group tended to adopt a more comfortable, slow pace. COMv is widely used as an indicator of gait stability [10–13]. With aging, the elderly people's leg muscle strength and momentum control weaken, which subsequently causes them to walk more slowly [25]. Compared with the normal-weight elders, the obese elders bear a larger burden when walking, which leads to a slower pace and lower peak COMv.

Fujimoto et al. presented the COMa parameter to better reflect the changes in muscle strength [26]. In another study, the group reported that, although no significant difference in the peak COMv was detected between healthy young and elderly people, their peak COMa values differed significantly [14]. In this study, all the peak COMa values were consistent with those of healthy older adults in Fujimoto et al.'s study. Moreover, there were no significant differences observed among the three BMI groups, perhaps because the elderly people's reduced momentum control may primarily be caused by muscle and bone deterioration, which indirectly affect the dynamic stability [27]. The effect of body weight may only be a secondary influencing factor.

ROSv is the velocity-related dynamic stability region during walking, which could reflect the participants' COM control over their bodies. In this regard, the results showed that normalized COM position differed significantly across the three groups. The normalized COM position of the Higher BMI group was found to be significantly anterior compared to that of the other groups, which may be because the obese elderly people tend to choose a more conservative gait balance strategy by placing their COM closer to the supporting point. Fischer et al. [28] put forward that extra weight on the human body affects joint torque and load, which in turn affects the gait. The results in this work are consistent with that conclusion. Additionally, the normalized COMv of the Normal and High BMI groups were significantly higher than that of the Higher BMI group, suggesting that the obese elderly people are more likely to rely on a relatively static support control mode for balance, whereas others tend to rely on dynamic inertial control to achieve balance.

In addition to the larger stability margin, the normalized COMa values of the elderly people in the Higher BMI group were more within the boundaries of the ROSa. According to Fujimoto et al. [14], the stability margin is the largest for fallers who have the worst dynamic stability. Based on their conclusion, the dynamic stability of the elderly participants in the Higher BMI group was weaker than that of the participants in the other BMI groups. The subjective evaluation results using the DBATS also validated this conclusion. Moreover, the calculation of the ROSa was related to initial the COMv and COM positions. The large stability margins in the obese elderly people may be caused by their lower initial COMv and anterior initial COM position. According to Pai et al. [29], the peak momentum of the COM depends on two factors: walking velocity and the positional relationship between the COM and base of the support. They further posit that the momentum control ability is closely related to balance control. People with a weaker balance control tend to choose conservative gait strategies. Given the results of this study, the obese elderly people may have

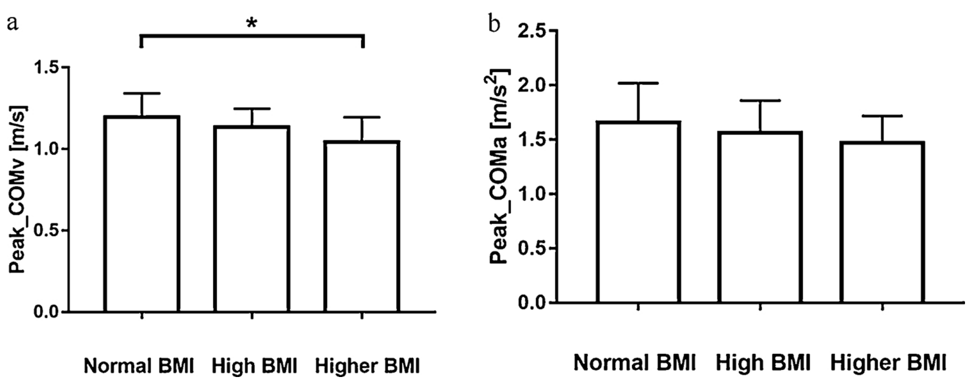

Fig. 4. (a) Peak COMv and (b) peak COMa for the Normal, High, and Higher BMI groups (* $p < 0.05$).

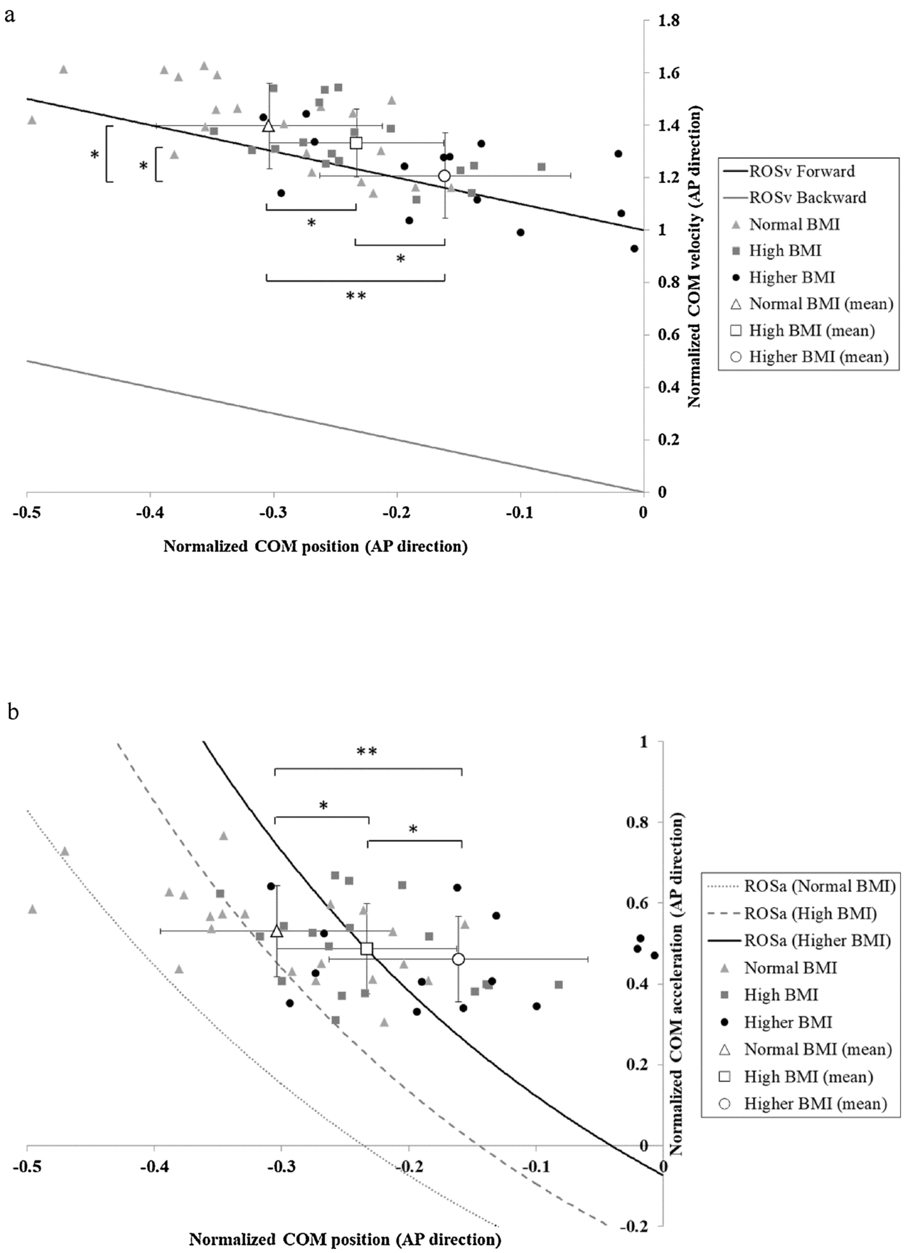

Fig. 5. Normalized COMv (a) and COMa (b) with respect to the normalized COM position for the Normal, High, and Higher BMI groups. The mean ± SD COMv and COMa for each group are also indicated. The top and bottom lines in (a) indicate the forward and backward ROSv boundaries, respectively (*$p < 0.05$, **$p < 0.001$). The three plots in (b) indicate the forward ROSa boundaries for each BMI group (*$p < 0.05$, **$p < 0.001$).

adopted the same strategies.

In conclusion, dynamic stability COM parameters could be used to quantitatively describe the dynamic balance ability of elderly people in different BMI groups during walking; the velocity-related peak COMv and ROSv were the most sensitive of these parameters. Furthermore, the results of the research showed that obesity might affect the dynamic stability of the elderly, which in turn would increase the risk of falls. In order to reduce the risk of falls during hospitalization, medical institutions commonly perform the fall risk assessment for patients when the patients are hospitalized [30]; however, the routine clinical assessment for fall risk does not include obesity. Based on the results of this study, the BMI should be added to the fall risk assessment to better guide the caring of patients and reduce the risk of falls during hospitalization.

However, a part of an invalid sample was excluded based on the exclusion criteria of the study. The 53 participants included were not evenly distributed in the three BMI groups (Normal, 21; High, 18; Higher 14), which may have an impact on the results. In addition, limited by the sample size, the research did not analyze the differences between genders, which also require further research. Furthermore, only dynamic stability parameters in the AP direction in the sagittal plane were analyzed. For more comprehensive results, future work should supplement these data with parameters measured along different directions in the transverse and frontal planes.

Conflict of interest

There are no conflicts of interest to declare.

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Appendix A

Dynamic Balance Ability Test Scale

Item	Interpret	Score
Initiation of Stride	① Is able to move immediately without hesitation	= 0
	② Needs to try several times to take a step	= 1
Stride height	① Lifts foot off the ground efficiently	= 0
	② Foot does not clear the ground	= 1
Stride length	① The stride length is longer than the foot length	= 0
	② Dares not take a big step	= 1
Proportionality of footsteps	① Uniformity: length, and height of each step are the same	= 0
	② Uneven steps, hobbling	= 1
Continuity of walking	① Continuous step without a pause	= 0
	② Incoherent, sometimes needs to pause	= 1
Straightness of walking	① Can walk along a straight line	= 0
	② Cannot move straight, tends to move to one side	= 1
Trunk stability	① Smooth and steady, not swaying	= 0
	② Sways or needs to stretch out hands to maintain balance	= 1
Turn around	① Trunk is stable, turn and walking are continuous	= 0
	② Sways, needs to pause before or during turn	= 1

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