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The Relation of Kinematic Synergy to Stabilize the Center of Mass During Walking With Future Falls: A 1-Year Longitudinal Study

Momoko Yamagata (myamagata@people.kobe-u.ac.jp)
Kobe University
Hiroshige Tateuchi
Kyoto University
Itsuroh Shimizu
Fukui General Clinic
Junya Saeki
Waseda University
Noriaki Ichihashi
Kyoto University

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TITLE:

The relation of kinematic synergy to stabilize the center of mass during walking with future falls: a 1-year longitudinal study

Author names and affiliations:

Momoko Yamagata[123], Hiroshige Tateuchi[2], Itsuroh Shimizu[4], Junya Saeki[2,3,5], Noriaki Ichihashi[2]

[1] Graduate School of Human Development and Environment, Kobe university, 3-11 Tsurukabuto, Nada-ku, Kobe, Hyogo 657-0011, Japan

[2] Graduate School of Medicine, Kyoto University, 53 Kawahara-cho, Shogoin, Sakyo, Kyoto 606-8507, Japan

[3] Research Fellow of the Japan Society for the Promotion of Science, 5-3-1 Kojimachi, Chiyodaku, Tokyo 102-0083, Japan

[4] Fukui General Clinic, 1-42-1 Nittazuka, Fukui-shi, Fukui 910-0067, Japan

[5] Faculty of Sport Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan

Corresponding Author:

Momoko Yamagata

Graduate School of Human Development and Environment, Kobe university, 3-11 Tsurukabuto, Nada-ku, Kobe, Hyogo 657-0011, Japan

Tel: +81-78-803-7811.

E-mail address: myamagata@ people.kobe-u.ac.jp

Abstract

Background: An incorrect transfer of center of mass (CoM) to outside the base of support is a frequent cause of falls, and segmental coordination to control CoM is crucial during walking. Uncontrolled manifold (UCM) analysis is a method of examining the relation between variances in segmental coordination and the CoM stability. However, no study has investigated through a prospective cohort study how variance in segmental configurations to stabilize CoM relates to future falls. This study explored whether variances to stabilize the CoM were related to future falls.

Methods: At the baseline visit, 30 community-dwelling older adults walked 20 times on a 6-m walkway. Using kinematic data during walking, UCM analysis was performed to

investigate how segmental configuration contributes to the CoM stability in the frontal plane. One year after the baseline visit, we evaluated whether the subjects experienced falls; 12 had experienced falls and 16 had not. Comparisons of variances between older adults with and without falls were conducted by covariate analysis.

Results: No significant differences in variances were found in the mediolateral direction, whereas in the vertical direction, older adults with fall experiences had a greater variance, reflecting unstable CoM, than those with no fall experiences.

Conclusions: We verified that the high variance in segmental configurations that destabilize CoM in the vertical direction was related to future falls. The variables of UCM analysis can be useful to evaluate fall risks.

Keyword: Falls, Aged, center of mass, segmental coordination, uncontrolled manifold

Background

Falls in older adults lead to increased medical expenses and fatal injuries [1]. There are several causes of falls (e.g., stumbling, slipping, and incorrect weight shifting); in particular, the incorrect transfer of the center of mass (CoM) to outside the base of support (BoS) accounts for 41% of falls [2]. Given the fact that falls occur with lateral body movements in many cases because of greater instability of the walking

posture in the frontal plane than in the sagittal plane, the control of CoM trajectory in the frontal plane is crucial, especially during the single support (SS) phase with a small BoS [3–5].

Segment coordination is necessary to control CoM trajectory during walking, and segment coordination in relation to the control of CoM trajectory has been investigated in earlier studies using analysis [6]. UCM hypothesis assumes that the central nervous system control elemental variable (e.g., segment angle) to stabilize an important performance variable (e.g, CoM trajectory) [7]. Using UCM analysis, the segment variance across repetational tasks is categorized into two types of variance: variance that reflects a stable performance variable (V_{UCM}) and variance that reflects an unstable performance variable (V_{ORT}). The synergy index computed from V_{UCM} and V_{ORT} is a measure to quantify kinematic synergy that contributes to the stability of the performance variable [7]. A high synergy index resulting from an increase in V_{UCM} or decrease in V_{ORT} is viewed as indicating high flexibility of the degree of freedom, and important to ensure the stability of the performance variable following perturbations [8–10].

Previously, we explored the relationship between falls and UCM indices using the swing foot position as a performance variable [11]. We found older adults with fall

histories exhibited a higher synergy index compared to older adults with no fall history, implying that older adults with fall history use high segment coordination to maintain the stability of the swing foot trajectories. Similar results were observed for stroke patients [12]. Such a person, however, is not a "good walker" and is quite unlikely to have higher walking stability than a healthy person. The increased segmental configurations stabilizing swing foot during walking might lead to the failure of CoM control instead, that is, a decrease in synergy index stabilizing CoM [13]. However, no study has investigated the relationship between fall experiences and UCM indices to control CoM trajectory.

The purpose of this study was to examine through a prospective cohort study whether UCM indices stabilizing CoM trajectory in the frontal plane is related to falls in the future. Our hypothesis was that the low segment flexibility pattern, that is, high V_{ORT}, low V_{UCM}, and low synergy index, at baseline visit is related to future falls.

Methods

Subjects

Community-dwelling older adults from 60 years of age were recruited in this study. Thirty volunteers participated, and they gave written informed consent according

to the procedure approved by the Research Ethics Committee of Kyoto University. The following inclusion criteria were evaluated by the interview: a person without neurological disorders or musculoskeletal injuries, and a person who can walk without assistance. In this prospective study, we used the same cohort as in our previous study.

Experiment at baseline visit

At baseline visit, the subjects walked on a 6-m walkway at their comfortable speed, repeated 20 times. A physical therapist with 6 years of experience placed reflective markers on the 7^{th} cervical vertebra (C7) and 10^{th} thoracic vertebra (T10), and on both sides of each subject at the following locations: anterior to external auditory, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial and lateral femoral condyles, medial tibia condyle, head of fibula, medial condyle of tibia, medial and lateral malleolus. The kinematics data were collected with eight infrared cameras (VICON MX; Vicon Motion Systems, Oxford) at 100Hz. We defined the mediolateral direction relative to the global laboratory coordinate system and the frontal plane perpendicular to the global anterior-posterior axis.

The data of the SS phase from toe off until initial contact in the dominant foot was normalized by time (0–100%). After excluding the first four steps, a total of 40

steps were used for further analysis. Each joint center was calculated from marker data, and CoM was defined as the position of the center of mass of the whole body calculated from the sum of each segmental center of mass [11, 14, 15]. The segments were defined with each joint center as shown in Figure 1 (shank: ankle to knee joint; thigh: knee to hip joint; pelvis: left hip to right hip joint; lower trunk: middle point of both hip joints to T10; upper trunk: T10 to C7; neck: C7 to middle point of both external auditory). We calculated the average and variabilities of CoM position across 40 steps. The variability was calculated as the standard deviation. The fall efficacy scale (EFS) was evaluated as physical information at the baseline visit [16].

Future falls

One year after the baseline visit, we sent a questionnaire to all subjects asking, “Have you experience falls within a year?” [17, 18]. In cases where the subjects had experienced falls, we also asked whether they were injured when falling. The subjects were divided into two groups (older adults with fall experiences: Faller; older adults without fall experiences: Non-faller). Further data analysis was conducted on the subjects who answered all questions.

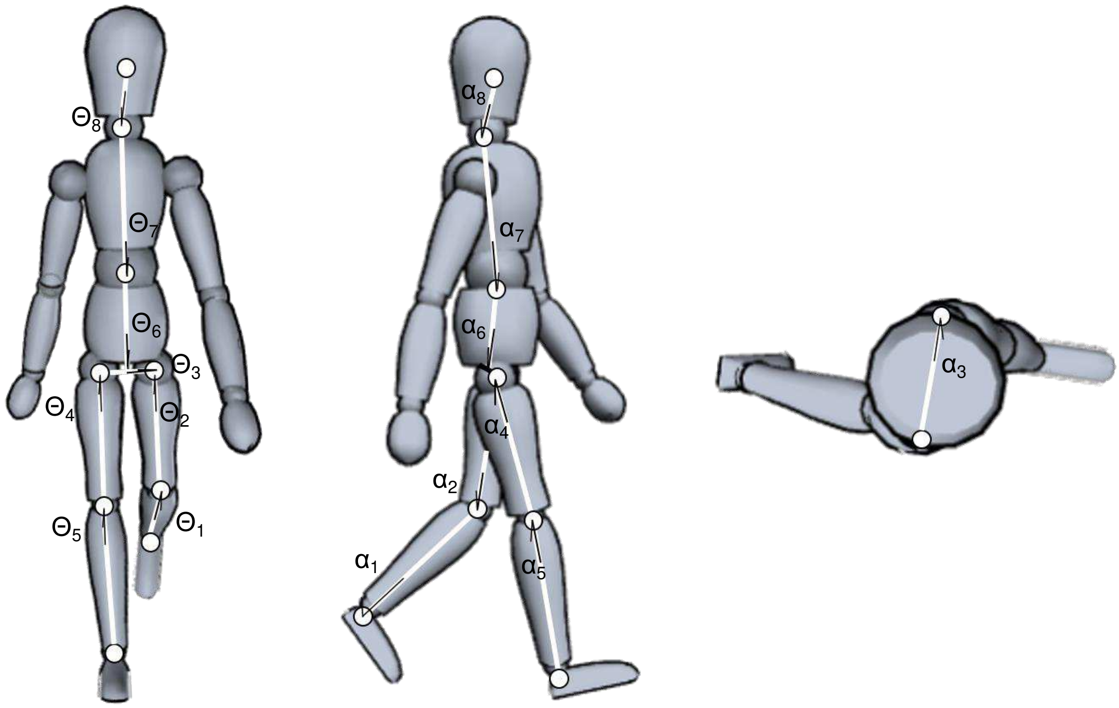

Figure 1. Illustrations of the segmental angles for the geometric model.

Eight segments and 16 degrees of freedom are used for the analysis; 8 degrees of freedom in the frontal plane (Θ1: left shank, Θ2: left thigh, Θ3: pelvis, Θ4: right thigh, Θ5: right shank, Θ6: lower trunk, Θ7: upper trunk, Θ8: head) and 8 degrees of freedom in sagittal and transverse plane (α1: left shank, α2: left thigh, α3: pelvis, α4: right thigh, α5: right shank, α6: lower trunk, α7: upper trunk, α7: head).

UCM analysis

CoM trajectories in the mediolateral (CoM_{ML}) and vertical (CoM_V) directions

were used as performance variables as below [7, 14]:

$$CoM = x_0 + \sum_{i=1}^{8} M_i x_i$$

where:

$$x_i = \sum_{j=1}^{i} C_j L_i \cos\alpha_j \sin\theta_j \quad \text{for} \quad CoM_{ML}$$

$$x_i = \sum_{j=1}^{i} C_j L_i \cos\alpha_j \cos\theta_j \quad \text{for} \quad CoM_{V}$$

and:

$$C_j = 1 \quad \text{for} \quad j < i$$

where x_0 and z_0 are the segmental positions of the absolute coordinate system in ML and V directions, $\Theta_1, \ldots, \Theta_8$ are the defined segmental angles in the frontal plane, $\alpha_1, \ldots, \alpha_8$ are the defined segmental angles in the sagittal and transverse planes, $C_1, \ldots, C_8$ are

the estimated locations of segmental center of mass, M_1 ,..., M_8 are segmental masses normalized by total body mass, and L_1 ,..., L_8 are the lengths of the segments [14, 15].

A Jacobian system (J) was used to link between the changes in elemental variable (segmental angles in 16 DoFs) and changes in the performance variable (CoM trajectory). J is the matrix of partial derivatives of changes in the CoM trajectory with respect to segmental angles, and the null space (ε) is the ($n-d$) vector represented by the dimensions in the segmental configuration space (n = 16) and CoM trajectory (d = 1). At every portion of the SS phase, the differences between the segmental configurations and their mean $(\theta - \overline{\theta})$ were projected onto the null space:

$$\theta_{UCM} = \sum_{i=1}^{n-d} (\theta - \bar{\theta}) * \varepsilon_i$$

and the space orthogonal to the null space:

$$\theta_{ORT} = (\theta - \bar{\theta}) - \theta_{UCM}$$

The variance in the segment configuration that does not affect the CoM_{ML} or CoM_V (V_{UCM}) was calculated as the average of the squared length of θ_{UCM} across 40 steps, and normalized by the DoFs within the UCM subspace:

$$V_{UCM} = (n-d)^{-1} * N^{-1} * \sum (\theta_{UCM})^2$$

The variance in the segment configuration that affects the CoM_{ML} or CoM_{V} (V_{ORT}) was calculated as the average of the squared length of θ_{ORT} across 40 steps, and normalized by the DoFs within the orthogonal subspace:

$$V_{ORT} = d^{-1} * N^{-1} * \sum (\theta_{ORT})^2$$

ΔV was computed from V_{UCM} and V_{ORT} as below:

$$\Delta V = \frac{V_{UCM} - V_{ORT}}{V_{TOT}},$$

where

$$V_{TOT} = \left(\frac{1}{n}\right)(dV_{ORT} + (n-d)V_{UCM}).$$

Fisher's *z*-transformation was applied to ΔV, referring to previous studies (ΔV_Z).

The SS phase was divided into the first 1/3 (Early-SS), second 1/3 (Mid-SS), and third 1/3 (Late-SS), and the average UCM indices during each phase were used for further analysis [11].

Statistical analysis

To test the effects of CoM position and CoM variability during the three SS phases on future falls, two-way ANOVAs (*Phase*: Early-, Mid-, Late-SS phases, and *Group*: Faller and Non-faller) were performed.

To test the effects of *Phase* (Early-, Mid-, and Late-SS phase) and *Group* (Faller and Non-faller) on UCM indices, analyses of covariance (ANCOVA) adjusted for walking speed were performed in the ML and V directions separately. The walking speed was used for adjustment based on a previous study that revealed the effects of walking speed on UCM indices [12, 19]. Post-hoc analyses were carried out with Bonferroni comparisons if necessary. All analyses were performed with SPSS (Version 18, PASW Statistics, Chicago) and the significance level was set at $p = 0.05$.

Before statistical analysis, the data were tested for statistical assumptions of normality and sphericity. In cases of violations of normality or sphericity, we used log-transformation or the Greenhouse-Geisser correction, respectively.

Results

We excluded two subjects with no responses on the questionnaire from the

analysis. The subjects were divided into Faller (n = 12) and Non-faller (n = 16) groups. Physical characteristics are shown in Table 1. Walking speed in Fallers was lower than in Non-fallers ($p < 0.05$), but the other characteristics of Fallers were similar to those of Non-fallers. CoM_{ML} displacements during Early- and Late-SS phases were significantly larger than Mid-SS phase (*Phase* effect: $F(2,52) = 24.7$; $p < 0.001$, Fig.2a), and CoM_V displacements were greater in the order Early-, Late-, and Mid-SS phase (*Phase* effect: $F(2,52) = 83.8$; $p < 0.001$, Fig.2b). CoM_{ML} variability was greater in the order Mid-, Early-, and Late-SS phase (*Phase* effect: $F(2,52) = 85.5$; $p < 0.001$, Fig.2c), and CoM_V variability during Early-SS was significantly greater than in Late- and Mid-SS (*Phase* effect: $F(2,52) = 26.1$; $p < 0.001$, Fig2d). No *Group* effect and interaction were found in CoM displacements and variabilities.

Figure 3 shows the average UCM indices during each phase. In UCM indices in ML direction, there was no major effects and interaction. No major effects and interactions were also found in V_{UCM} in the V direction. In V_{ORT}, Faller displayed significantly greater value than Non-faller (*Group* effect: $F(1,25) = 5.44$; $p < 0.05$), with no interaction. ΔV_Z was significantly greater in the order of Late-, Early-, and Mid-SS (*Phase* effect: $F(2,50) = 3.41$; $p < 0.05$) with no *Group* effect and interaction.

Table 1. Physical characteristics

	Non-fallers (n = 16)	Fallers (n = 12)
Age (years)	73.8 ± 7.9	78.0 ± 4.7
Height (m)	1.6 ± 0.08	1.54 ± 0.11
Weight (kg)	58.4 ± 8.3	52.2 ± 8.1
BMI	22.7 ± 2.5	21.9 ± 2.2
Gait Velocity (m/s) *	1.1 ± 0.1	1.3 ± 0.1
FES score	34.9 ± 4.4	33.3 ± 4.5

*p <= 0.05 between Non-fallers and Fallers

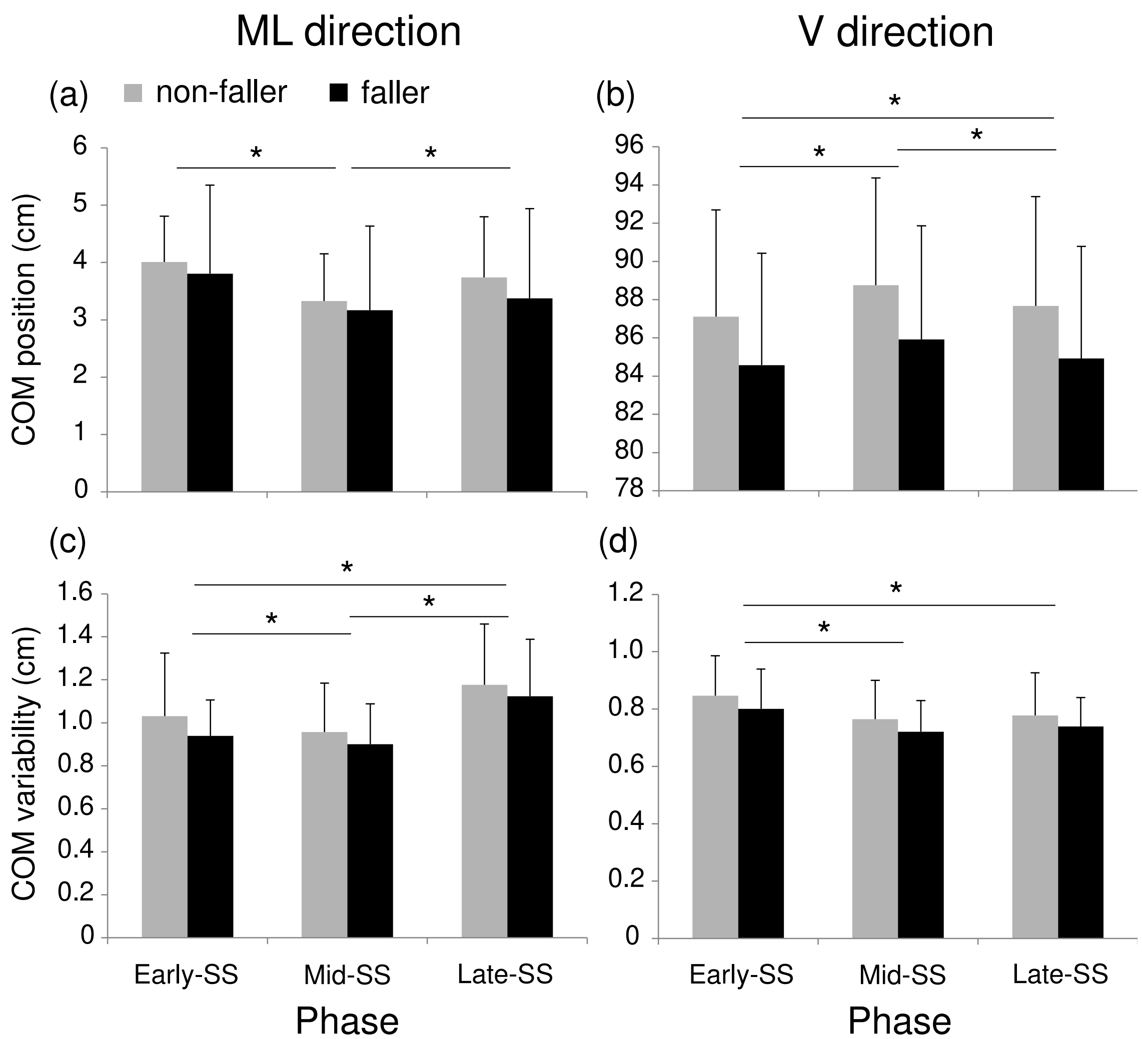

Figure 2. Averaged CoM position (a, b) and CoM variability (c, d) across subjects with standard deviation bars

Averaged across subjects data are shown in Non-fallers (grey bars) and Fallers (black bars) for three phases, Early-, Mid-, and Late-SS. Upper panels: CoM position in the ML (a) and in V (b) directions; Lower panels: CoM variability in the ML (c) and V (d) directions. V direction: vertical direction, ML direction: mediolateral direction

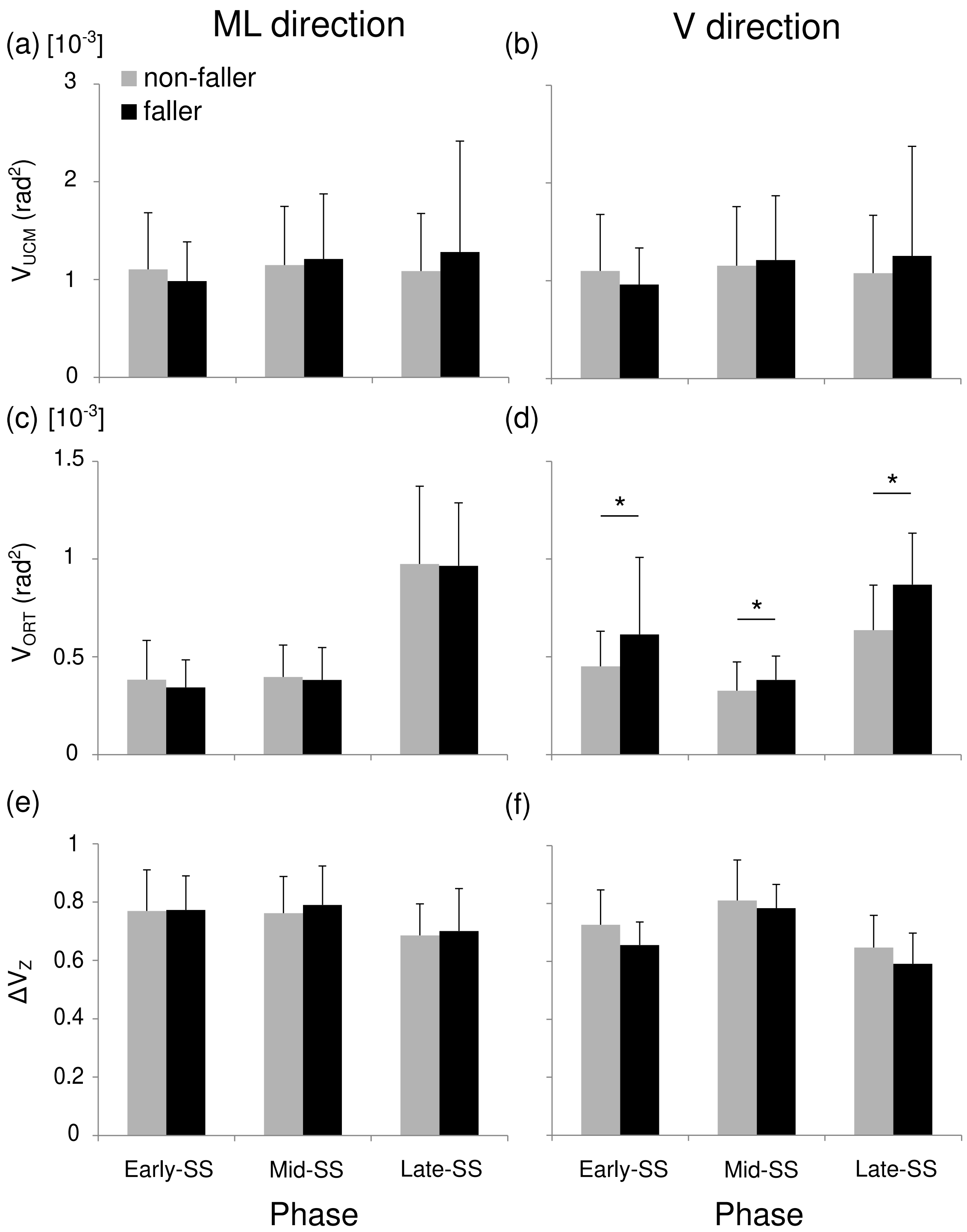

Figure 3. Averaged variance components across subjects with standard deviation bars

Averaged across subjects data are shown in Non-fallers (grey bars) and Fallers (black bars) for three phases, Early-, Mid-, and Late-SS. Upper panels: VUCM in the ML (a) and V (b) directions, Middle

panels: VORT in the ML (c) and V (d) directions, Lower panels: ΔVZ in the ML (e) and V (f) directions. Statistically significant differences are shown with one star ($p < 0.05$). For abbreviation, see the caption for Fig. 2.

Discussion

The purpose of this study was to investigate whether UCM indices to control the CoM trajectory during walking were related to future falls. The CoM displacement and variability were not significantly different between Fallers and Non-fallers in ML and V directions. No significant effect of fall experiences was also found for UCM indices in ML direction, and our hypothesis that high V_{ORT}, low V_{UCM}, and low synergy index at baseline visit is related to future falls was not supported. In the V direction, V_{ORT} in Fallers was greater than that in Non-fallers, with no difference in V_{UCM} and ΔV_Z. Thus, our hypothesis was partly supported in the V direction.

Previous studies showed that patients with Down syndrome and stroke patients displayed greater V_{UCM} stabilizing CoM than healthy people, unlike our findings [6, 20]. Motor and sensory dysfunctions would occur in such patients due to the disease, and to compensate for the disorders, they might establish a different strategy during walking, an increase in V_{UCM} to maintain CoM stability. On the other hand, older adults who will

experience falls would not be able to use this strategy, resulting in an increase in V_{ORT} and fall experiences.

V_{ORT} in the V direction was significantly greater in Fallers than in Non-fallers. During walking, forward CoM movement while maintaining posture stability against the change in ground reaction force is necessary, especially during the SS phase, when posture is readily rendered unstable [21]. Previous studies showed that high muscle co-activation and low segment coordination would result in low posture stability by high signal-dependent noise and the transmission of perturbations along the vertical body axis [22, 23]. The increased vertical perturbation by external forces, such as ground reaction force, possibly resulted in high V_{ORT} and future falls.

Despite falls often occurring by incorrect transfer of the CoM to outside the BoS, interestingly, only V_{ORT} in the V direction constituted an adequate index to identify Fallers and Non-fallers. Earlier studies showed a directional difference in the aspects of locomotor control; less able subjects had high variability in the V direction due to low variability in the ML direction (i.e., Bernsteinian freezing of degrees of freedom) [24, 25]. Fallers in this study, however, would not use such a walking strategy since ΔV_Z reflecting freezing gait was similar to Non-fallers. To develop a deeper understanding of a walking pattern that leads to high V_{ORT} and future falls, evaluating the segment

configurations serving to stabilize anterior-posterior CoM might be needed.

CoM-relevant variables, walking speed, and FES have been used previously as an index for fall risks [26–28]. However, there were no differences in CoM displacement, CoM variability, and FES between groups. As we found a lower walking speed in Fallers, V_{ORT} adjusted for the walking speed in Fallers was greater than that in Non-fallers. The variance in segmental configurations that reflects CoM instability can serve as an index to evaluate potential fall risks independently of walking speed even for subjects with a normal functional level on indices of fall risks, such as CoM-relevant variables and FES.

Our previous study verified that older adults with fall history had a high stability of the swing foot through segmental coordination resulting from high V_{UCM} relative to V_{ORT}, especially in the V direction [11]. Taken together with the current results, one possibility is that Fallers used the segmental configurations to stabilize the vertical swing foot as a preferential variable, leading to unstable CoM in the V direction. Similar findings were obtained in subjects with motor disability; the patients had CoM instability due to kinematic compensations to elevate the swing foot [13]. To reveal whether the CoM trajectory should be adopted as a performance variable to prevent falls during walking, comparisons of synergy indices to stabilize the swing foot and CoM

trajectories are needed in future studies.

One limitation of this study is that a questionnaire was applied to classify Fallers and Non-fallers, which might have led to recall bias. Despite the limitations, we believe this common method showed relatively low recall bias, as it involved the period of one year. Second, there was no information about the causes of falls. We focused on CoM stability, but falls from other causes (e.g., stumbling) might be included in this study.

Conclusions

Overall, our study is the first to demonstrate the relationships of kinematic synergy stabilizing CoM during walking with future falls. Although some measures previously used to evaluate fall risk (e.g., CoM variability and FES) could not distinguish between older adults with and without future falls, the high variance in segmental configurations that affects the CoM stability in the vertical direction was related to future falls independently of walking speed. The UCM index would predict future falls and can serve as an index for fall risks even in subjects with a normal level on some previous fall risk indices.

Abbreviations

CoM: center of mass; BoS: base of support; SS phase: single support phase; UCM: uncontrolled manifold; V_{UCM}: variance in the UCM subspace; V_{ORT}: variance in the subspace orthogonal to the UCM; C7: 7th cervical vertebra; T10: 10th thoracic vertebra; ML direction: mediolateral direction; V direction: vertical direction

Ethics approval and consent to participate

All procedures have been conducted according to the principles expressed in the Declaration of Helsinki. All subjects gave written informed consent according to the procedure approved by the Research Ethics Committee of Kyoto University (R0433-4).

Consent for publication

Not applicable.

Availability of data and materials

All datasets in this study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

MY contributed to the study concept and design, subjects' recruitment, data collection, and data analysis. All authors (MY, HT, IS, JS, and NI) had taken part in the discussion and contributed to data interpretation and the manuscript preparation. The final manuscript was approved by all authors.

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Figures

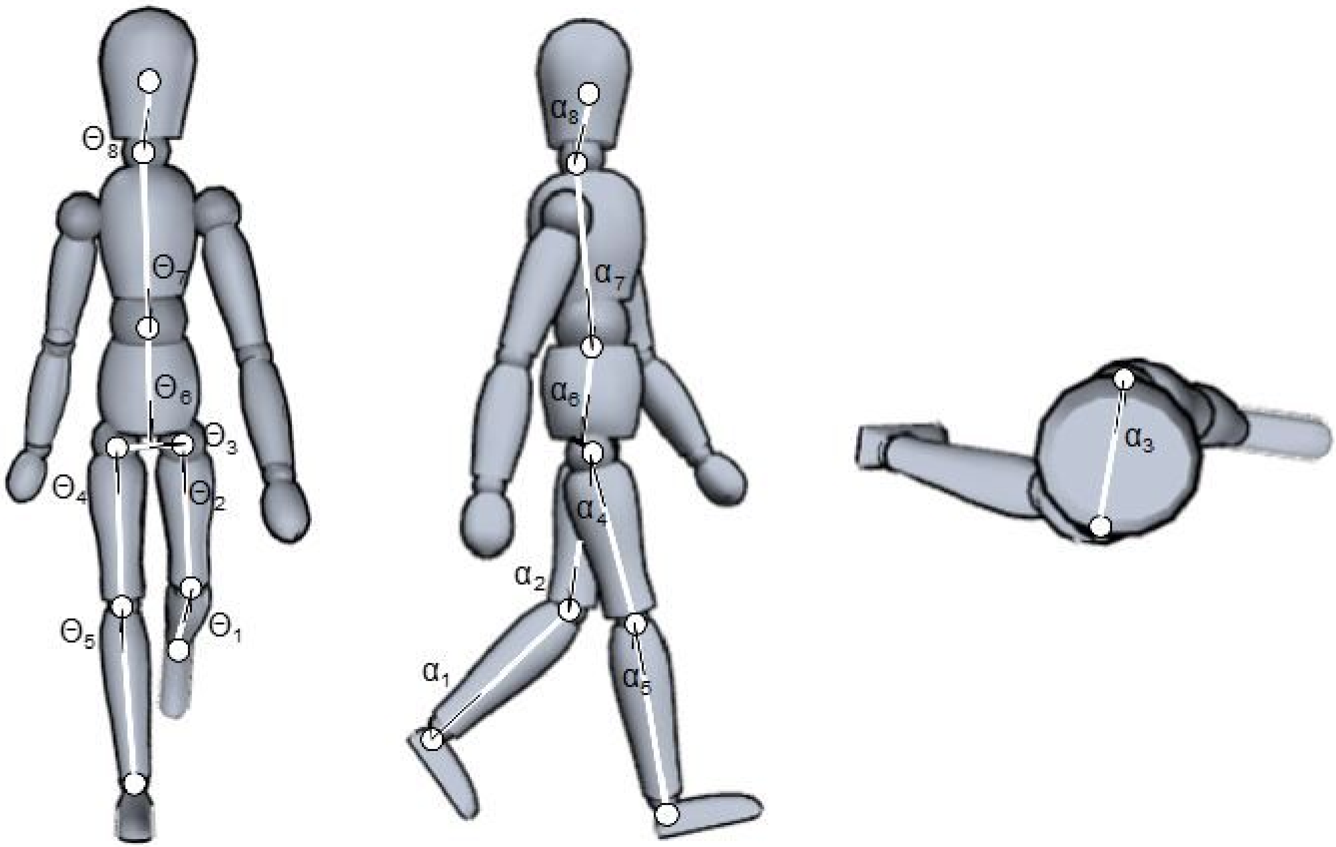

Figure 1

Illustrations of the segmental angles for the geometric model. Eight segments and 16 degrees of freedom are used for the analysis; 8 degrees of freedom in the frontal plane (Θ1: left shank, Θ2: left thigh, Θ3: pelvis, Θ4: right thigh, Θ5: right shank, Θ6: lower trunk, Θ7: upper trunk, Θ8: head) and 8 degrees of freedom in sagittal and transverse plane (α1: left shank, α2: left thigh, α3: pelvis, α4: right thigh, α5: right shank, α6: lower trunk, α7: upper trunk, α7: head).

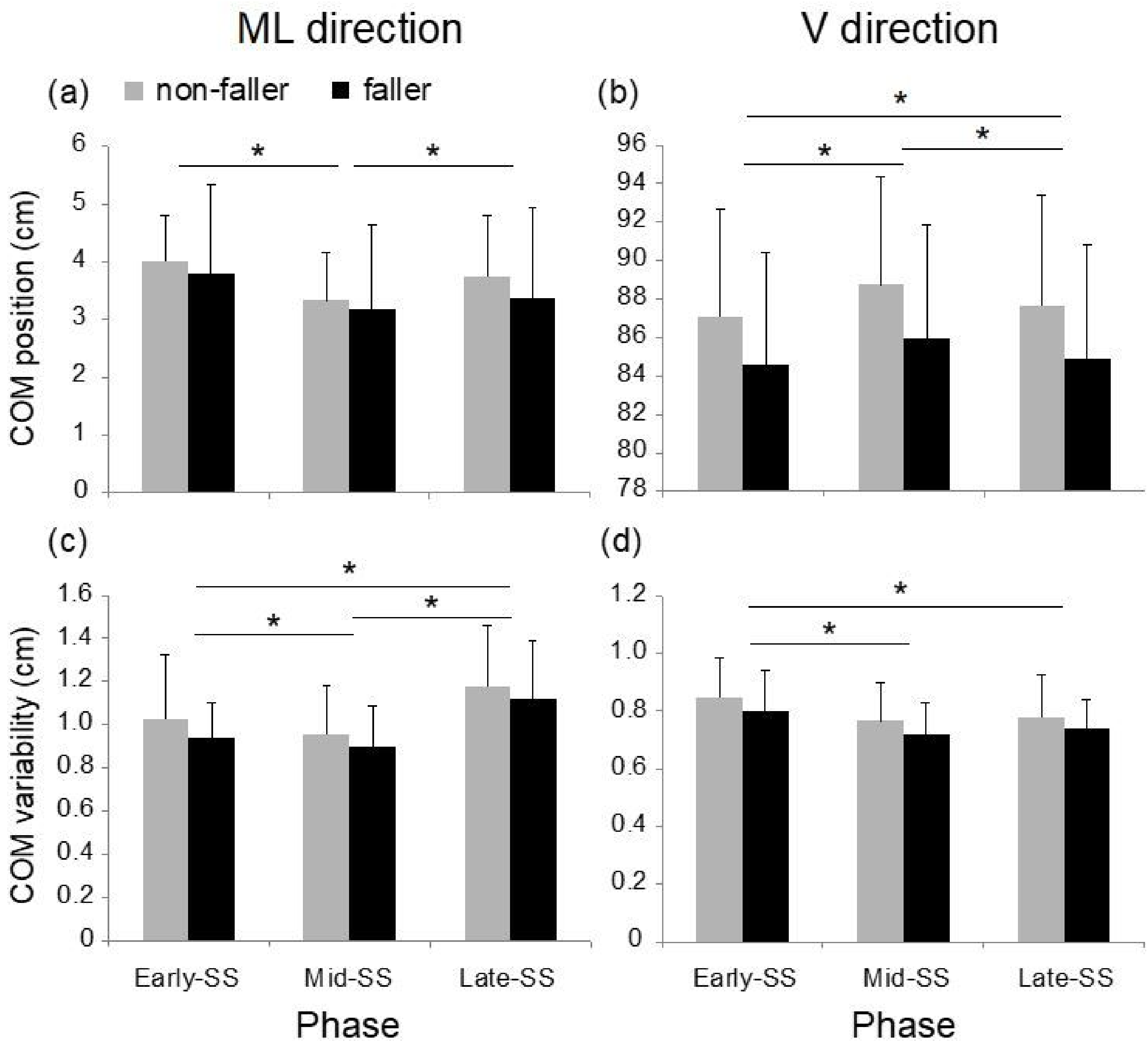

Figure 2

Averaged CoM position (a, b) and CoM variability (c, d) across subjects with standard deviation bars Averaged across subjects data are shown in Non-fallers (grey bars) and Fallers (black bars) for three phases, Early-, Mid-, and Late-SS. Upper panels: CoM position in the ML (a) and in V (b) directions; Lower panels: CoM variability in the ML (c) and V (d) directions. V direction: vertical direction, ML direction: mediolateral direction

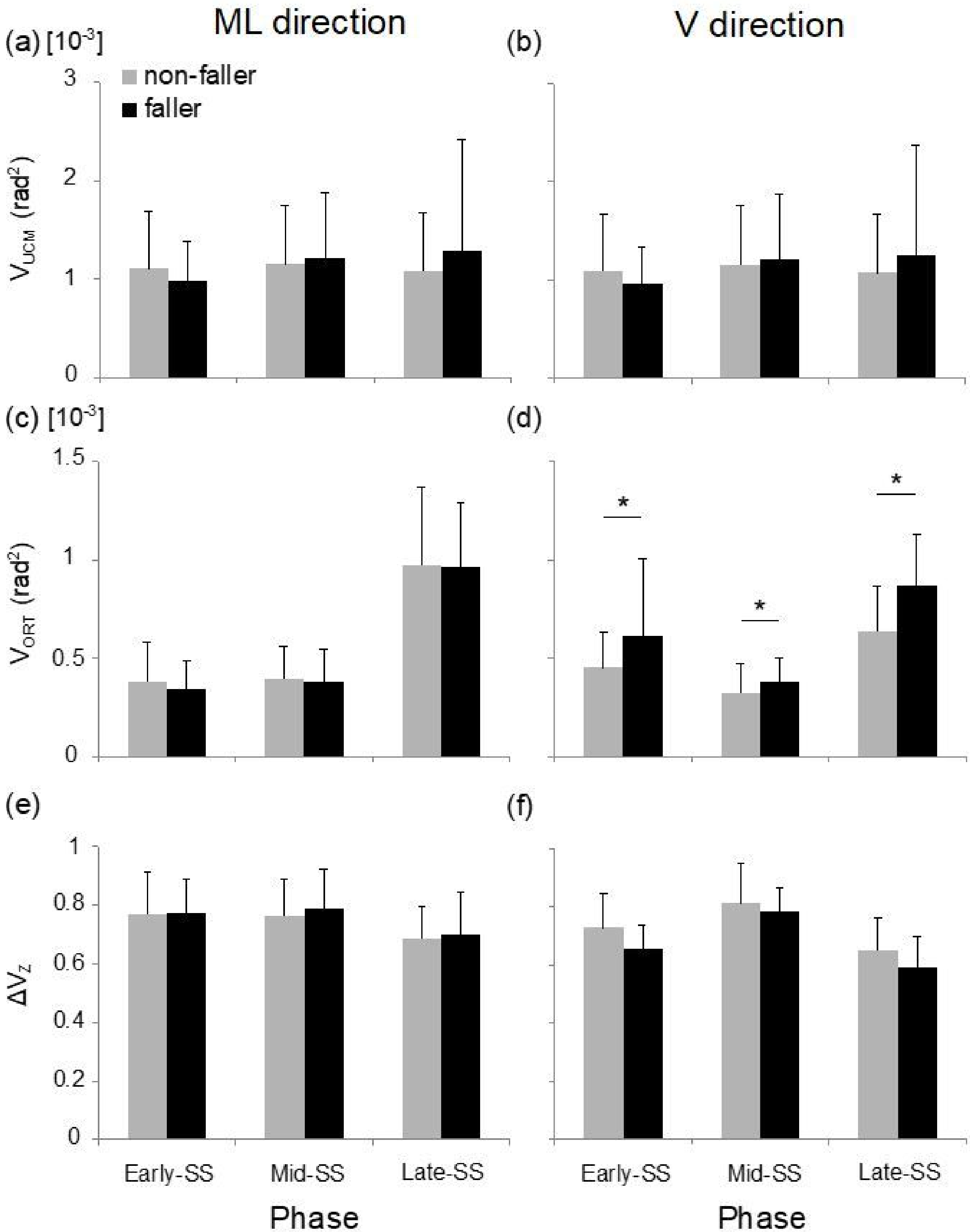

Figure 3

Averaged variance components across subjects with standard deviation bars Averaged across subjects data are shown in Non-fallers (grey bars) and Fallers (black bars) for three phases, Early-, Mid-, and Late-SS. Upper panels: VUCM in the ML (a) and V (b) directions, Middle panels: VORT in the ML (c) and V (d) directions, Lower panels: ΔVZ in the ML (e) and V (f) directions. Statistically significant differences are shown with one star ($p < 0.05$). For abbreviation, see the caption for Fig. 2.