

Age-Related Differences in Segment-Specific Center-of-Mass Acceleration During One-Leg Standing: Associations With Pelvic–Spinal Alignment

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Abstract

Background

One-leg standing (OLS) is widely used to assess static balance, but OLS duration provides limited information regarding biomechanical control. Whether segment-specific center-of-mass (COM) acceleration differs between older and younger adults during OLS and whether these regional patterns are associated with sagittal pelvic–spinal alignment in older adults remain unclear. We compared segment-specific COM control during OLS between age groups and examined associations with pelvic–spinal alignment in older adults.

Methods

Seventeen older adults (72.4 ± 3.9 years) and 16 younger adults (20.3 ± 0.6 years) performed OLS. Three-dimensional motion capture was used to calculate root mean square (RMS) accelerations of the head, thorax, pelvis, and whole-body COM in the anteroposterior (AP) and mediolateral (ML) directions. Thoracic kyphosis, lumbar lordosis, and pelvic tilt were measured using a Spinal Mouse device. Welch's t-test and Pearson's correlation coefficients were used for group comparisons and associations, respectively.

Results

Older adults had greater ML COM RMS acceleration in the head, thorax, pelvis, and whole body (all $p \leq 0.022$; Cohen's $d = 0.83\text{--}1.96$), whereas AP outcomes did not differ significantly. In older adults, greater posterior pelvic tilt was associated with greater ML COM RMS acceleration of the head, pelvis, and whole body ($r = -0.654$ to -0.522), and greater thoracic kyphosis with greater pelvic ML COM RMS acceleration ($r = 0.492$). Lumbar lordosis was not significantly associated with COM outcomes.

Conclusions

Older adults showed greater ML COM acceleration during OLS, with these patterns associated with sagittal pelvic–spinal alignment. COM acceleration may complement OLS duration in characterizing lateral balance.

Background

Falls are a major cause of injury, disability, hospitalization, and loss of independence among older adults [1, 2]. Current international guidelines identify impaired postural control as an important modifiable component of fall risk [3]. Clarifying the biomechanical features of age-related postural impairments may improve balance assessments and inform rehabilitation.

Postural control requires the integration of visual, vestibular, and somatosensory information with coordinated neuromuscular responses that maintain the center of mass (COM) within the base of support [4, 5]. Age-related changes in sensory function, muscle strength, and motor coordination can compromise this system. Quantitative biomechanical analysis can characterize these changes beyond those captured by clinical performance tests alone.

One-leg standing (OLS) is widely used in clinical and community settings because it is simple and inexpensive. OLS performance declines with age, and a shorter OLS duration is associated with impaired physical function and fall risk [6, 7]. However, OLS duration indicates whether the task can be maintained, but not how balance is controlled. Individuals with similar OLS durations may use different postural control strategies, limiting the mechanistic information provided by duration alone.

From a biomechanical perspective, balance requires continuous regulation of the COM relative to the base of support. During OLS, the base of support is reduced to a single limb, increasing the mechanical demand for COM control, particularly in the mediolateral (ML) direction. Frontal-plane stability depends strongly on coordinated hip abductor–adductor and trunk control, whereas anteroposterior (AP) control relies more heavily on ankle mechanisms [8].

Whole-body COM may also obscure regional movement because motions of individual body segments can partially offset one another. Accordingly, segment-specific analysis of the head, thorax, and pelvis may provide information about regional postural control that is not evident from whole-body COM alone.

Previous studies have shown that whole-body COM acceleration is sensitive to age-related differences during quiet bipedal standing [9, 10] and that the relationship between the center of pressure and whole-body COM changes with age during OLS [11]. However, these approaches primarily treated the body as a single mechanical unit. They did not determine whether age-group differences are expressed similarly across the head, thorax, pelvis, and whole body or whether regional acceleration patterns are related to sagittal pelvic–spinal morphology.

Sagittal pelvic–spinal alignment may influence postural control by changing body mass distribution and the mechanical demands placed on the trunk and lower extremities. Age-related hyperkyphosis is associated with impaired physical performance and reduced back extensor strength [12, 13], and greater thoracic kyphosis alters spinal loading and trunk muscle demands [14]. Hyperkyphosis has also been associated with poor balance, mobility, physical performance, and falls [15–18]. Pelvic tilt may similarly be relevant because the pelvis links the trunk to the supporting limb and influences trunk orientation and hip mechanics. However, it remains unclear whether specific pelvic–spinal alignment measures are associated with regional COM control during OLS.

Previous studies have generally examined pelvic–spinal alignment in relation to physical performance, gait, or falls, whereas biomechanical studies of OLS have focused on duration, COP outcomes, or whole-body COM. Thus, two related questions remain unresolved: whether age-group differences during OLS

are expressed across the head, thorax, pelvis, and whole body; and whether thoracic kyphosis, lumbar lordosis, and pelvic tilt are associated with these regional COM patterns in older adults.

Therefore, this study compared segment-specific COM RMS acceleration during OLS between older and younger adults and examined associations between segment-specific COM RMS acceleration and thoracic kyphosis, lumbar lordosis, and pelvic tilt in older adults. From a physiological-anthropological perspective, we considered the head, thorax, pelvis, and whole body as mechanically interdependent regions whose coordinated motion may reflect age-related adaptation of whole-body postural control. We hypothesized that older adults would exhibit greater COM RMS acceleration across body regions and that sagittal pelvic–spinal alignment would be associated with segment-specific COM RMS acceleration in the older group.

Methods

Study Design and Participants

This cross-sectional observational study compared segment-specific COM RMS acceleration during OLS between older and younger adults and examined associations between sagittal pelvic–spinal alignment and segment-specific COM RMS acceleration in older adults. This report was prepared in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement [19].

No a priori sample-size calculation was performed; the study used a convenience sample of all eligible participants who completed the protocol.

Seventeen community-dwelling older adults (10 men and 7 women; age, 72.4 ± 3.9 years) and 16 younger adults (3 men and 13 women; age, 20.3 ± 0.6 years) participated in this study. Older participants were recruited from local community organizations via public advertisements and community health programs, whereas younger participants were university students.

Older participants were eligible if they were able to ambulate independently without an assistive device, had no history of falls requiring hospitalization within the preceding year, and were capable of maintaining OLS for at least 50 s. This threshold was used to ensure that participants could safely complete the 10-s transition period and subsequent 30-s analysis interval with an additional time margin. Exclusion criteria included neurological disorders (e.g., stroke or Parkinson's disease), vestibular disorders, severe musculoskeletal disorders affecting standing balance, a history of lower-extremity joint replacement, cognitive impairment that interfered with understanding the study procedures, and any other medical condition judged by the investigators as compromising safe participation.

Eligibility and exclusion criteria were assessed by participant interviews, review of self-reported medical history, and observation during the familiarization trial.

Younger participants were free from neurological, vestibular, or musculoskeletal disorders affecting balance and had no history of lower-extremity injury within the previous 6 months.

The study protocol was approved by the Ethics Committee of Chiba Prefectural University of Health Sciences (Approval No. 2017-34) and conducted in accordance with the Declaration of Helsinki. All participants received written and verbal explanations of the study procedures and provided written informed consent prior to participation.

One-leg Standing Procedure

All measurements were performed in a quiet, well-lit indoor biomechanical laboratory using the same force-plate, camera, and visual-target configuration for all participants. Participants wore tight-fitting clothing to minimize marker-movement artifacts and performed OLS barefoot. Before data collection, body height and mass were measured using a calibrated digital stadiometer and scale, respectively.

Participants initially stood quietly with one foot placed on each force plate. They were instructed to raise their preferred kicking limb while maintaining balance on the contralateral supporting limb. The preferred kicking limb was defined as the limb that the participant naturally selected to kick a ball. During OLS, the hip and knee of the raised limb were maintained at approximately 90° of flexion without contact with the supporting limb. Participants were instructed to maintain an upright posture with their arms folded across the chest and to look continuously at a visual target positioned at eye level approximately 3 m in front of them throughout the trial.

To familiarize participants with the testing procedure, a standardized practice trial was conducted before formal data collection. Subsequently, one successful measurement trial was used for the biomechanical analysis. If the first formal attempt was unsuccessful, one repeat attempt was permitted; all participants completed a successful trial within two formal attempts. Participants rested while seated for approximately 3 min between attempts to minimize carryover effects. A trial was considered successful if the participant maintained the required posture without placing the raised limb on the floor, contacting the supporting limb, moving the supporting foot, or requiring examiner assistance throughout the 40-s period comprising the excluded first 10 s and the subsequent 30-s analysis interval.

For safety, an examiner stood immediately behind each participant and provided manual support only if loss of balance occurred.

To minimize transient postural adjustments associated with the transition from bipedal stance to OLS, the first 10 s after limb elevation were excluded from the analysis. The subsequent continuous 30-s interval was used for all biomechanical analyses. This approach intended to minimize the influence of movement initiation and allow the analyzed data to reflect post-transition postural control rather than the initial balance response.

Motion Capture and Force-Plate Measurements

Three-dimensional marker trajectories were recorded using an eight-camera motion-capture system (MAC3D; Motion Analysis Corporation, Santa Rosa, CA, USA). Ground reaction force data were collected synchronously using two force plates (BP400600; AMTI, Watertown, MA, USA). Marker trajectories and force-plate signals were sampled at 100 Hz.

Reflective markers were attached according to the Helen Hayes marker set. Marker trajectories were low-pass filtered using a fourth-order, zero-lag Butterworth filter with a cutoff frequency of 6 Hz before biomechanical calculations. Three-dimensional biomechanical analyses were performed using Visual3D software (version 6.0; C-Motion Inc., Germantown, MD, USA).

Whole-body and segmental models were constructed in Visual3D using its default segment definitions and anthropometric parameters. Default segment masses are based on Dempster regression equations, and segment centers of mass are determined from the software-defined segment geometry. Segment-specific COM trajectories were calculated for the head, thorax, pelvis, and whole body throughout the analysis period.

Segment-Specific COM RMS Acceleration

COM acceleration was obtained in Visual3D by twice differentiating the filtered COM position trajectories with respect to time. The AP and ML directions were defined by the laboratory global coordinate system, with AP aligned with the participant's sagittal axis during the initial stance and ML perpendicular to it in the horizontal plane.

RMS acceleration was calculated separately in the AP and ML directions over the 30-s analysis interval as follows:

$$\text{RMS} = \sqrt{[(1/N) \sum_{i=1}^N a_i^2]}$$

where a_i is the COM acceleration at sample i and N is the number of samples in the 30-s analysis interval ($N = 3,000$ at a sampling frequency of 100 Hz). This measure summarizes the overall magnitude of acceleration across the analysis interval.

Pelvic–Spinal Alignment Measurements

Sagittal pelvic–spinal alignment was assessed using a Spinal Mouse® system (Idiag AG, Fehraltorf, Switzerland), a non-invasive, computer-assisted device that records the inclination of successive vertebral levels relative to vertical as it is guided along the spine. The accompanying software calculated regional spinal angles from the intersegmental inclination data. The device has demonstrated acceptable reliability for noninvasive assessment of sagittal spinal curvature [20].

The device-derived variables used in this study were thoracic kyphosis, lumbar lordosis, and pelvic tilt angles. Thoracic kyphosis represents the summed sagittal inclination across the thoracic region, lumbar lordosis represents the corresponding lumbar curvature, and pelvic tilt represents sacral inclination relative to vertical. Positive pelvic tilt values indicated anterior tilt, whereas negative values indicated posterior tilt. Measurements were obtained with participants standing comfortably in their habitual upright posture. The examiner manually guided the Spinal Mouse from C7 to S3 along the spinal midline according to the manufacturer's protocol. Three consecutive measurements were obtained, and the mean value was used for analysis.

To evaluate measurement reproducibility, the same examiner performed three consecutive standing measurements in an independent sample of 11 participants using the procedure described above. Intrarater reliability for the mean of the three measurements was $ICC(1,3) = 0.74$ (95% CI, 0.30–0.92).

Statistical Analysis

Continuous variables are presented as mean $\pm$ standard deviation (SD). Normality of the data distributions was evaluated using the Shapiro–Wilk test.

Between-group comparisons of continuous variables were performed using Welch's t-tests, whereas sex distribution was compared using Fisher's exact test. Effect sizes were calculated using Cohen's d and interpreted according to conventional criteria [21].

Associations between sagittal pelvic–spinal alignment and segment-specific COM RMS acceleration in the older group were examined using Pearson's correlation coefficients. All tests were two-sided, and statistical significance was set at $p < 0.05$.

All statistical analyses were performed using Bell Curve for Excel version 4.10 (Social Survey Research Information Co., Ltd., Tokyo, Japan).

Use of generative AI-assisted technology

During manuscript preparation, the authors used ChatGPT (OpenAI) to improve language, organization, and readability. The authors reviewed and edited all outputs and take full responsibility for the content of the manuscript.

Results

Participant Characteristics

Participant characteristics are summarized in Table 1. The groups differed in age ($p < 0.001$), body mass ($p = 0.008$), body mass index ($p < 0.001$), and sex distribution (Fisher's exact test, $p = 0.032$) but not in body height ($p = 0.983$).

Table 1
Participant characteristics

Characteristic	Older adults (n = 17)	Younger adults (n = 16)	p value	Cohen's d
Age, years	72.4 ± 3.9	20.3 ± 0.6	< 0.001	18.33
Sex, male/female	10/7	3/13	0.032	—
Height, cm	160.9 ± 9.2	160.8 ± 9.0	0.983	0.01
Body mass, kg	60.8 ± 11.6	50.9 ± 8.0	0.008	0.99
Body mass index, kg/m ²	23.4 ± 3.5	19.6 ± 1.4	< 0.001	1.40

Values are presented as mean ± standard deviation or number. Between-group comparisons used Welch's t test for continuous variables and Fisher's exact test for sex. Cohen's d is calculated as older adults minus younger adults.

All participants completed the OLS protocol without requiring physical assistance from the examiner.

Age-Group Differences in Segment-Specific COM RMS Acceleration

Segment-specific COM RMS acceleration values (m/s²) are presented in Table 2. Between-group comparisons in the AP and ML directions are shown in Figs. 1 and 2, respectively. In the anteroposterior (AP) direction, no significant between-group differences were observed for the head (p = 0.413), thorax (p = 0.058), pelvis (p = 0.627), or whole body (p = 0.269).

Table 2
Segment-specific COM RMS acceleration during one-leg standing

Segment	Direction	Older adults (n = 17)	Younger adults (n = 16)	p value	Cohen's d
Head	AP	0.176 ± 0.041	0.191 ± 0.062	0.413	-0.29
Head	ML	0.203 ± 0.077	0.149 ± 0.050	0.022	0.83
Thorax	AP	0.214 ± 0.052	0.268 ± 0.097	0.058	-0.71
Thorax	ML	0.094 ± 0.020	0.071 ± 0.024	0.005	1.06
Pelvis	AP	0.135 ± 0.033	0.129 ± 0.038	0.627	0.17
Pelvis	ML	0.113 ± 0.043	0.062 ± 0.019	< 0.001	1.52
Whole body	AP	0.094 ± 0.018	0.106 ± 0.035	0.269	-0.40
Whole body	ML	0.071 ± 0.020	0.040 ± 0.010	< 0.001	1.96

Values are COM RMS acceleration (m/s^2), presented as mean $\pm$ standard deviation. Between-group comparisons used Welch's t tests. Cohen's d is calculated as older adults minus younger adults. AP, anteroposterior; ML, mediolateral; COM, center of mass; RMS, root mean square.

In the mediolateral (ML) direction, older adults demonstrated significantly greater COM RMS acceleration than younger adults for the head ($p = 0.022$, Cohen's $d = 0.83$), thorax ($p = 0.005$, $d = 1.06$), pelvis ($p < 0.001$, $d = 1.52$), and whole body ($p < 0.001$, $d = 1.96$). The largest between-group effect was observed for whole-body ML COM RMS acceleration.

Associations Between Pelvic–Spinal Alignment and Segment-Specific COM RMS Acceleration

Correlations between sagittal pelvic–spinal alignment and segment-specific COM RMS acceleration in older adults are presented in Table 3.

Table 3
Correlations between pelvic–spinal alignment and segment-specific COM RMS acceleration in older adults

Alignment variable	Segment	AP, r (p value)	ML, r (p value)
Thoracic kyphosis	Head	0.025 (0.924)	0.461 (0.063)
	Thorax	0.012 (0.962)	0.192 (0.459)
	Pelvis	0.356 (0.161)	0.492 (0.045)
	Whole body	−0.098 (0.709)	0.335 (0.189)
Lumbar lordosis	Head	0.160 (0.541)	−0.127 (0.629)
	Thorax	0.242 (0.350)	−0.183 (0.482)
	Pelvis	0.071 (0.788)	−0.327 (0.201)
	Whole body	0.181 (0.488)	−0.148 (0.570)
Pelvic tilt	Head	0.015 (0.955)	−0.522 (0.032)
	Thorax	0.190 (0.466)	−0.470 (0.057)
	Pelvis	−0.250 (0.333)	−0.654 (0.004)
	Whole body	0.180 (0.490)	−0.522 (0.031)

Values are Pearson correlation coefficients with two-sided p values in parentheses. Positive pelvic tilt values indicate anterior pelvic tilt; therefore, negative correlations indicate greater COM acceleration with more posterior pelvic tilt. AP, anteroposterior; ML, mediolateral; COM, center of mass; RMS, root mean square.

Greater posterior pelvic tilt was associated with greater ML COM RMS acceleration of the head ($r = -0.522, p = 0.032$), pelvis ($r = -0.654, p = 0.004$), and whole body ($r = -0.522, p = 0.031$; Fig. 3). Greater thoracic kyphosis was associated with greater ML COM RMS acceleration of the pelvis ($r = 0.492, p = 0.045$; Fig. 4). Lumbar lordosis was not significantly associated with any COM RMS acceleration outcome.

No sagittal alignment measure was significantly correlated with any AP COM RMS acceleration outcome.

Discussion

Principal Findings

This study examined age-group differences in segment-specific COM control during OLS and its relationship with sagittal pelvic–spinal alignment. Older adults had greater ML COM RMS acceleration than younger adults across all analyzed regions and the whole body, whereas AP outcomes did not differ significantly. In the older group, greater posterior pelvic tilt was associated with greater ML COM RMS acceleration of the head, pelvis, and whole body, and greater thoracic kyphosis was associated with greater pelvic ML COM RMS acceleration. These findings indicate that age-group differences in OLS are not confined to a single segment but are expressed across an integrated head–thorax–pelvis–whole-body system.

The principal contribution of this study is the characterization of segment-specific coordination rather than the treatment of the body as a single rigid unit. Previous studies identified greater whole-body COM acceleration during quiet bipedal standing in older adults [9, 10] and age-related changes in COP–COM regulation during OLS [11]. The present findings extend that work by showing how lateral acceleration is distributed across regional COMs and by linking selected regional patterns to pelvic–spinal morphology. This segment-specific perspective may reveal age-related adaptations in postural organization that are obscured when only COP or whole-body COM is analyzed.

These findings extend previous work on balance in older adults by demonstrating that the observed group differences were evident at both the whole-body and regional levels. International guidelines emphasize the importance of assessing factors underlying impaired balance and fall risk in older adults [3]. Segment-specific COM analysis may provide complementary biomechanical information; however, its prospective clinical value remains unclear.

Age-Group Differences in Mediolateral Control

The principal group differences were observed in the ML direction. This pattern is biomechanically plausible because OLS markedly narrows the base of support in the frontal plane. Therefore, maintaining balance under these conditions requires coordinated contributions from the hip abductors, trunk musculature, and sensorimotor systems.

Winter et al. [8] demonstrated that frontal-plane balance during quiet standing depends predominantly on a hip load–unload mechanism rather than on ankle torque alone. Although their model was developed under bipedal standing conditions, OLS places greater demands on frontal-plane control because only one lower limb is available to generate corrective moments. Accordingly, age-related declines in hip abductor strength, trunk control, and neuromuscular coordination may contribute disproportionately to impaired ML balance.

This interpretation is also consistent with the framework proposed by Horak [4], who emphasized that postural stability depends on coordinated interactions among biomechanical constraints, movement strategies, sensory orientation, and dynamic control. Age-related reductions in muscle strength, neuromuscular responsiveness, sensory integration, and adaptability of movement strategies may affect several of these domains. Consequently, older adults may rely more heavily on trunk and hip strategies to maintain equilibrium during demanding balance tasks such as OLS.

Another possible explanation is an age-related decline in sensorimotor integration. Peterka [5] proposed that successful postural control depends on the continuous integration of visual, vestibular, and somatosensory information to estimate body orientation and generate appropriate corrective responses. Age-related declines in these sensory systems may reduce the accuracy and timing of corrective movements, potentially contributing to greater COM fluctuations in the frontal plane, where the base of support is particularly constrained during OLS.

No significant age-group differences were observed in AP COM RMS acceleration. This directional contrast is consistent with the greater reliance of AP control on ankle mechanisms and ML control on coordinated hip and trunk motion [8]. The multisegmental demands of frontal-plane control may make it more sensitive to age-related sensorimotor and strength deficits. ML instability during gait and reactive balance has also been associated with fall risk in older adults [3, 22].

Collectively, the results identified lateral balance control as a prominent feature of the observed age-group differences during OLS. Greater ML COM RMS acceleration may reflect altered coordination of the trunk–pelvis–hip system; however, the present kinematic data do not identify the underlying muscular or sensory mechanisms.

Regional Distribution of COM Acceleration

Group differences were distributed across anatomical regions. OLS duration, COP displacement, and whole-body COM characterize overall aspects of balance performance or control but do not characterize the movement of individual body segments. Segment-specific analysis of the head, thorax, and pelvis therefore provides regional information within an interdependent linked system rather than representing independent control units.

Upright stance depends on coordinated interactions among body segments rather than stabilization of the body as a single rigid unit [4, 5]. Motion in one region may be offset by motion elsewhere, meaning that whole-body COM alone may mask regional differences in postural organization.

The greater ML COM RMS acceleration observed across the head, thorax, pelvis, and whole body suggests a broadly distributed difference in lateral postural control rather than an isolated regional difference. However, cross-sectional kinematic data cannot determine whether this pattern reflects age-group status, differences in sex distribution or BMI, or unmeasured sensory and muscular factors.

Head control is relevant because visual and vestibular function is influenced by head movement and orientation. Greater ML head COM RMS acceleration may reflect greater instability of head movement; however, sensory function was not measured in this study [4, 5]. Therefore, the relationship between head COM acceleration and sensory control should be evaluated directly rather than inferred from kinematic data alone.

The thorax contributes substantially to upper-body mass, whereas the pelvis transfers trunk loading to the supporting limb and is controlled by the hip and trunk musculature. Greater ML COM RMS acceleration of the pelvis and thorax may therefore reflect altered coordination of the trunk–pelvis–hip system; however, kinetic and electromyographic data are needed to identify the underlying mechanisms.

Pelvic–Spinal Alignment and Segment-Specific COM RMS Acceleration

Sagittal pelvic–spinal alignment was associated with selected ML COM RMS acceleration outcomes in older adults. Greater posterior pelvic tilt was associated with greater ML COM RMS acceleration of the head, pelvis, and whole body, whereas greater thoracic kyphosis was associated with greater ML COM RMS acceleration of the pelvis. These exploratory correlations indicate covariation rather than a causal effect of alignment on postural control.

Sagittal alignment may influence body position and the mechanical demands required to maintain equilibrium relative to the supporting limb. Thoracic kyphosis and posterior pelvic tilt may modify trunk geometry and lumbopelvic mechanics [12, 23], providing a plausible biomechanical basis for their associations with ML COM RMS acceleration.

Posterior pelvic tilt may alter trunk orientation relative to the hip and modify the mechanical conditions under which the hip abductors stabilize the pelvis. As lateral balance relies strongly on coordinated hip and trunk control, such changes could contribute to greater ML motion [4, 8]. This proposed mechanism remains speculative because hip moments and muscle activity were not measured. Empirical evidence specifically relating pelvic tilt to balance control is limited; most available alignment studies have focused on thoracic kyphosis, mobility, or falls [15–18]. Thus, the observed pelvic-tilt associations may represent a novel finding, but they require confirmation in larger, prospectively designed studies.

Thoracic kyphosis may influence balance by altering upper-body geometry and lumbopelvic loading. This interpretation is broadly consistent with reported associations between hyperkyphosis and impaired physical function or falls [15, 18]; however, the modest correlation observed in the present study requires confirmation.

Because the spine and pelvis function as an integrated system, the observed correlations may reflect interrelationships among lumbopelvic and thoracic alignment rather than isolated effects of a single anatomical structure.

From a rehabilitation perspective, the observed associations provide a rationale for investigating whether interventions targeting spinal alignment and trunk–pelvic control influence lateral balance. The present cross-sectional study did not test an intervention and could not establish whether modifying sagittal alignment would reduce COM motion or fall risk. Therefore, longitudinal and interventional studies are warranted.

Clinical Implications

These findings suggest two potential clinical implications. First, OLS duration and segment-specific COM RMS acceleration describe different aspects of balance performance; successful task completion does not characterize the magnitude or regional distribution of COM fluctuations. Second, noninvasive assessment of sagittal alignment may provide complementary information for characterizing lateral balance in older adults. However, the clinical utility and predictive value of these measures require prospective evaluation.

Study Limitations

First, the sample size was modest, and no a priori sample-size calculation was performed. Therefore, the estimates, particularly the correlations, should be interpreted as exploratory, and the findings require confirmation in larger cohorts. In addition, multiple correlations were examined without adjustment for multiplicity, increasing the risk of false-positive findings.

Second, the older and younger groups differed in terms of sex distribution and body mass index. Because the small sample size did not support a robust multivariable adjustment, residual confounding factors cannot be excluded. Accordingly, the observed between-group differences cannot be attributed to age alone.

Third, only relatively healthy community-dwelling older adults who could maintain OLS for the required duration were included. These findings may not be generalizable to frail older adults or individuals with neurological, vestibular, or substantial musculoskeletal impairments.

Fourth, the cross-sectional design precludes causal conclusions regarding pelvic–spinal alignment and postural control. Longitudinal studies are needed to determine the temporal relationship between these factors.

Finally, the analysis was based on a single successful trial, and only kinematic outcomes were examined. Trial-to-trial variability, joint kinetics, muscle activation, sensory function, and dynamic spinal kinematics were not assessed. Spinal alignment was measured during static standing rather than during OLS. These factors should be addressed in future studies. In addition, the pelvic–spinal alignment reliability estimate

was derived from a small independent sample and had a wide confidence interval, indicating uncertainty in measurement reproducibility.

Conclusions

Community-dwelling older adults demonstrated greater ML COM RMS acceleration across the head, thorax, pelvis, and whole-body during OLS than younger adults, whereas AP outcomes did not differ significantly between the groups. In the older group, posterior pelvic tilt and thoracic kyphosis were associated with selected ML COM acceleration outcomes.

These findings suggest that age-related differences during OLS were reflected predominantly in ML COM RMS acceleration and that these lateral acceleration patterns covary with sagittal pelvic–spinal alignment. Because the analyzed regions are mechanically interdependent, these findings should be interpreted as regional characteristics within an integrated whole-body postural system rather than as evidence of independent segmental control.

Larger longitudinal studies with appropriate adjustment for potential confounders are needed to confirm these exploratory associations and determine their clinical relevance.

Abbreviations

AP: anteroposterior; BMI: body mass index; CI: confidence interval; COM: center of mass; ICC: intraclass correlation coefficient; ML: mediolateral; OLS: one-leg standing; RMS: root mean square; SD: standard deviation.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of Chiba Prefectural University of Health Sciences (Approval No. 2017-34) and was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent before participation.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current 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

YT conceived and designed the study and collected the data. YT and KF analyzed and interpreted the data. YT drafted the manuscript, and KF critically revised it for important intellectual content. YF advised on the overall conduct of the study and ethical considerations and critically reviewed the manuscript. All authors read and approved the final manuscript.

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Authors' information

Not applicable.

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Figures

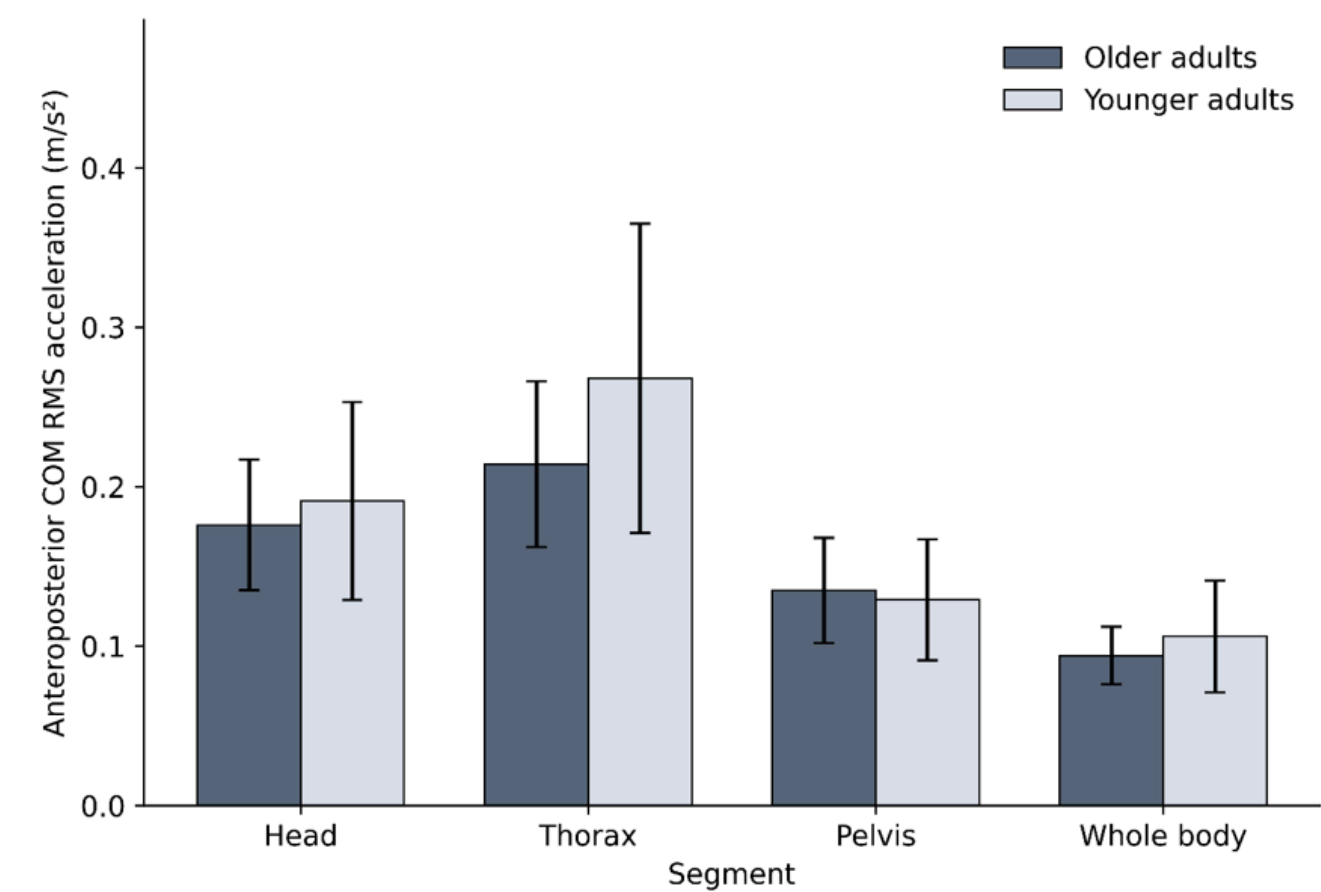


Figure 1

Anteroposterior center-of-mass RMS acceleration by age group. Bars indicate means, and error bars indicate standard deviations.

RMS, root mean square

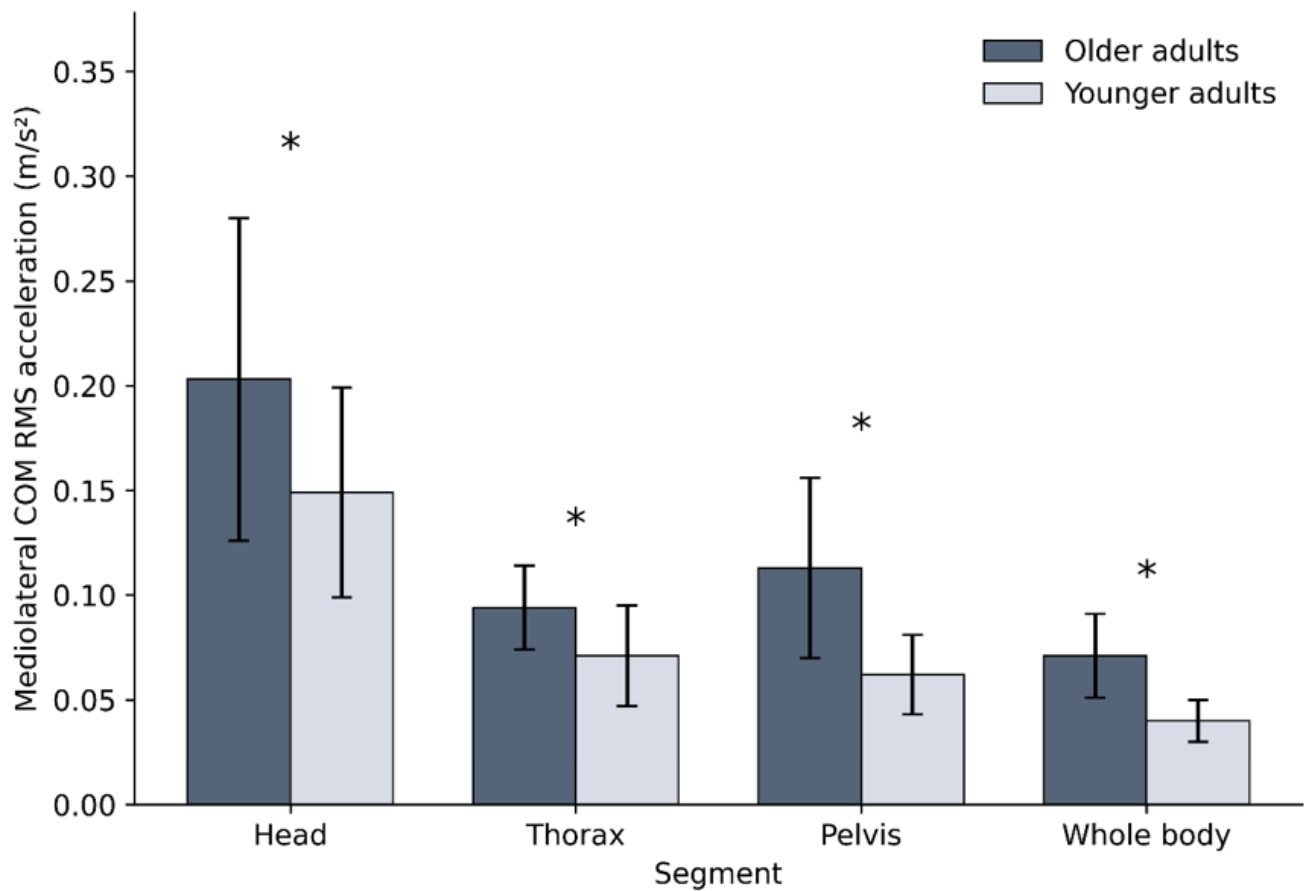


Figure 2

Mediolateral center-of-mass RMS acceleration by age group. Bars indicate means, and error bars indicate standard deviations. Asterisks indicate significant between-group differences for the corresponding segments ($p < 0.05$).

RMS, root mean square

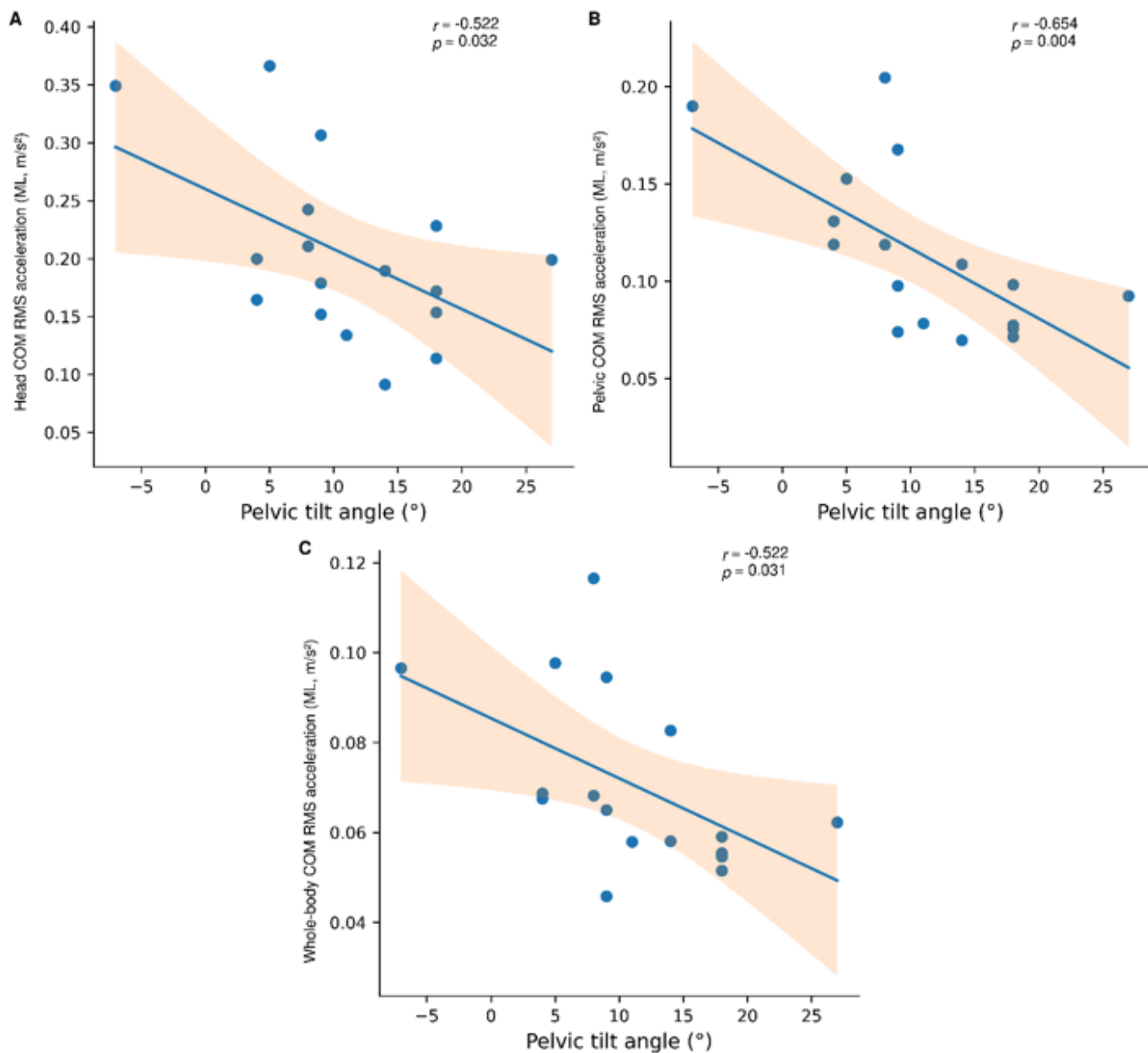


Figure 3

Pelvic tilt and mediolateral center-of-mass RMS acceleration in older adults: (A) head, (B) pelvis, and (C) whole body. Positive pelvic tilt values represent anterior pelvic tilt. Solid lines indicate linear regression fits, and shaded areas indicate 95% confidence intervals.

RMS, root mean square

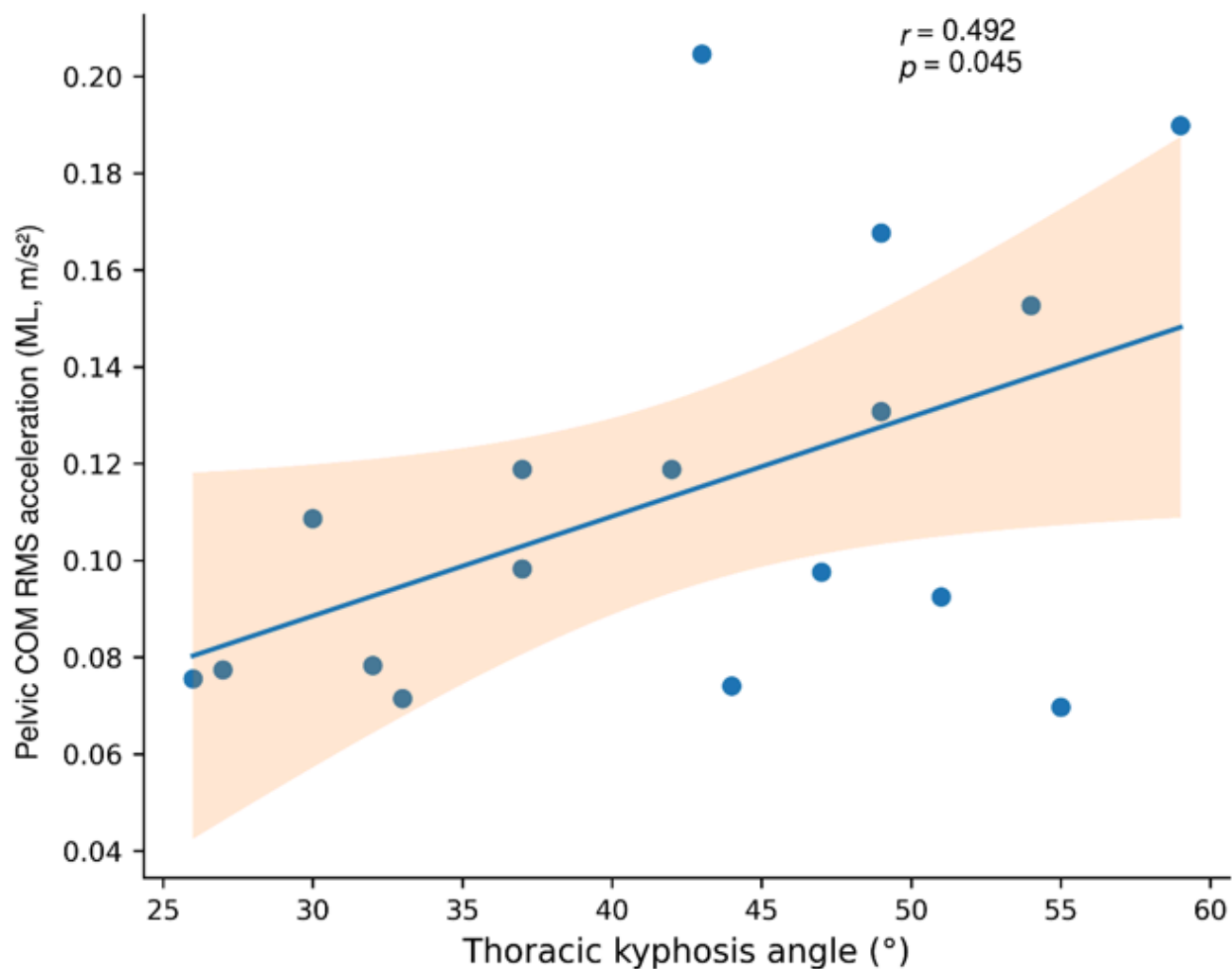


Figure 4

Thoracic kyphosis and pelvic center-of-mass RMS acceleration in older adults. The solid line indicates the linear regression fit, and the shaded area indicates the 95% confidence interval.

RMS, root mean square