RESEARCH ARTICLE

Model-derived center-of-mass control characteristics associated with dynamic balance in patients with acute stroke

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Abstract

Standing stability tends to decline immediately after stroke because of impaired postural control. However, the association between center-of-mass (COM) control and dynamic balance ability in patients with acute stroke remains unclear. This study aimed to examine the associations between COM control parameters and dynamic balance ability by estimating COM displacement and acceleration using the equations of motion derived from direction-specific rigid-body link models. This cross-sectional study included 28 patients after stroke who wore an inertial measurement unit on the occipital protuberance and performed a static standing test with eyes open on a force platform. The middle 30 seconds of a 40-second measurement period were analyzed. COM displacement and acceleration in the anteroposterior (AP) and mediolateral (ML) directions were estimated from force-platform and head-mounted IMU data using the equations of motion of direction-specific rigid-body link models. COM control parameters were then calculated from displacement and acceleration, including the gradient, intercept, standard deviation, and correlation coefficient of linear approximations. Dynamic balance ability was assessed using the Functional Gait Assessment. Among mildly-to-moderately affected patients with acute stroke who were able to stand independently, lower variability in AP COM acceleration not explained by COM displacement, quantified as the standard deviation of residual acceleration (SIG_{AP}), was associated with higher Functional Gait Assessment (FGA) scores. An exploratory full-sample analysis showed a motor-paralysis status × direction interaction for the gradient of the fitted COM displacement–acceleration relationship; however, this interaction was not statistically significant in a sensitivity analysis excluding four participants who were unable to maintain the standardized stance. This finding should therefore be considered hypothesis-generating. Further studies are required to determine whether this association extends to patients with more severe impairments and whether it is associated with prospective fall outcomes.

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Introduction

Stroke is strongly associated with an increased risk of falls due to functional impairments [1]. Impairments in the temporal coordination of motor control after stroke may also contribute to post-stroke balance dysfunction. Immediately after stroke, a temporal mismatch between actual and imagined movements may occur [2], potentially disrupting the body's motor control system. Characterizing motor-control responses in patients with acute stroke may therefore provide further insight into the mechanisms underlying post-stroke balance impairment.

Although increased center of pressure (COP) sway after stroke has been documented [3–5], conventional measures such as COP area and velocity primarily quantify the magnitude of postural sway and do not directly characterize the relationship between center of mass (COM) displacement and corrective acceleration. A model-based approach combining force-platform and head-mounted inertial measurement unit (IMU) data enables the estimation of COM displacement and acceleration during quiet standing [6,7]. The resulting indices describe complementary aspects of COM control: the gradient (GRAD) reflects the magnitude of the restoring response, the intercept (IC) reflects asymmetry in this response, the standard deviation from the fitted relationship (SIG) reflects variability in acceleration that is not explained by COM displacement, and the correlation coefficient (CC) reflects the strength and direction of the linear coupling between full-band COM displacement and acceleration [8]. Previous applications of this approach have primarily involved healthy participants [6–8]. Therefore, model-derived COM control in patients with acute stroke, particularly its association with dynamic balance as assessed by the Functional Gait Assessment (FGA), remains insufficiently characterized.

The FGA is a performance-based assessment of dynamic balance during gait [9–11]. Although an FGA cutoff score of 22 has been proposed for screening fall risk in community-dwelling older adults [10], the FGA assesses balance performance rather than directly measuring fall occurrence. Accordingly, the FGA was used in the present study as a measure of dynamic balance performance.

Although quiet standing and gait differ in their task demands, both require continuous regulation of the COM relative to the base of support, which remains relatively fixed during quiet standing but changes continuously during gait. Because postural demands differ between directions, the anteroposterior (AP) and mediolateral (ML) components of COM control were considered separately. Several FGA tasks, including changes in walking speed, walking with vertical head movements, and stepping over obstacles, may place greater demands on AP COM regulation, whereas walking with horizontal head movements, turning, and narrow-base walking may place greater demands on ML regulation [9]. Accordingly, model-derived COM control characteristics during quiet standing may reflect aspects of sensorimotor control that are also involved in dynamic gait tasks. We hypothesized that the associations between the COM control indices and FGA scores would be direction-specific, although previous evidence in patients with acute stroke did not provide sufficient evidence to predict which direction or index would show the strongest association.

Motor dysfunction of the paretic side is commonly associated with impaired balance after stroke [12–14] and may also be associated with altered COM control. However, whether COM control differs according to the motor paralysis status in patients with acute stroke remains unclear. Given the reported association between motor dysfunction and postural sway [15], we hypothesized that COM control indices would differ between patients with and without motor paralysis.

The primary objective of this study was to use a force platform and a head-mounted IMU to examine direction-specific associations between model-derived COM control indices and FGA scores in patients with acute stroke. A secondary, exploratory subgroup analysis was conducted to examine whether COM control indices differed according to motor-paralysis status.

Materials and methods

Participants

We conducted a cross-sectional study to investigate dynamic balance ability and COM control characteristics. A cross-sectional design was selected because the primary objective was to examine the contemporaneous associations between model-derived COM control indices and FGA scores measured during the same assessment period, rather than to investigate temporal or causal relationships. Before data collection, we estimated the sample size required to detect a single two-sided Pearson correlation using G*Power 3.1.9.7, based on previous studies [8,16]. Assuming a correlation coefficient of $r = 0.502$, $\alpha = 0.05$, and power = 0.80, the required sample size was 28 participants. This calculation did not account for multiple testing across the eight COM control indices or for the covariate-adjusted regression model. The 28 participants included in the study were diagnosed with stroke based on computed tomography or magnetic resonance imaging. The study eligibility criteria were as follows: hospitalization for cerebral infarction or hemorrhage; age 18 years or older; stroke onset within 1 month of the study; and the ability to maintain a standing position for 30 seconds without assistance. Patients were excluded if they had a history of neurological disorders other than the index stroke that affected standing posture or if, as jointly determined by the treating clinician and the responsible physical therapist, cognitive impairment prevented them from understanding the study procedures, following the standardized task instructions, or providing informed consent.

This study was performed at the rehabilitation department of a university hospital between June 21, 2024, and November 30, 2025. Before performing the FGA and measuring COM control, a trained physical therapist administered the following screening tests: Functional Ambulation Categories [17]; Mini-Mental State Examination [18]; Stroke Impairment Assessment Set (SIAS) [19]; and Functional Independence Measure [20].

This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Review Committee of Saga University (approval no. 2024-03-03). Written informed consent was obtained from all participants after the study procedure and objectives were explained. This study was performed in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement.

FGA

In this study, the FGA was performed after the screening tests [9,10]. The FGA consisted of the following 10 tasks: walking on level ground; changing walking speed; walking with horizontal head rotation; walking with vertical head rotation; turning; stepping over an obstacle; walking in a tandem position; walking with eyes closed; walking backward; and climbing stairs. Each item was scored on a scale from 0 (severe impairment) to 3 (normal). The maximum FGA score was 30 points. The FGA was used as a measure of dynamic gait and balance performance. Although an FGA score of 22 or lower has been proposed as a cutoff for elevated fall risk in community-dwelling older adults [10], this threshold was not used to classify fall risk in the present acute-stroke sample.

Each FGA assessment was performed by one of three physical therapists trained in the standardized FGA protocol, using standardized instructions and scoring criteria. Although the assessors were not formally blinded, the FGA assessment was completed before the COM data were processed; therefore, the COM control results were unavailable to the assessors at the time of assessment. The assessors were not blinded to motor-paralysis status.

No participant used a cane, walker, or other walking aid during the FGA. One participant wore a habitual ankle-foot orthosis. Rest periods were provided as needed. The assessor remained close to the participant throughout the assessment to ensure safety. Four participants required physical assistance to prevent a fall during one or more FGA items. Items for which physical assistance was required were scored according to the standardized FGA scoring criteria. With the necessary safety assistance, all 28 participants completed all 10 FGA items, and no item-level data were missing.

COM control measurements

In accordance with a previous study [8], participants stood on a force platform (TF-3040; Tec Gihan, Kyoto, Japan) while wearing an IMU (IMS-WD, Tec Gihan, Kyoto, Japan) attached to the external occipital protuberance. The external occipital protuberance was selected because it is a palpable midline bony landmark that facilitates consistent placement with relatively limited soft-tissue movement and because the estimation method requires head acceleration as an input for estimating upper-body and whole-body motion. A trained examiner palpated the external occipital protuberance, centered the IMU over the landmark, aligned the sensor axes with the participant's AP and ML anatomical directions, and secured the sensor using a headband. The position, alignment, and secure attachment of the sensor were checked immediately before each trial and visually monitored throughout the trial. The sensor position was rechecked after each trial, and no obvious displacement was observed.

The participants were instructed to maintain a standing posture while facing forward with their hands at their sides, ensuring that no gap existed between their feet, and focusing on a marker placed 1.5 m in front of them. Patients unable to close the gap between their feet were instructed to stand with the narrowest possible stance. For these patients, the distances between the first metatarsals and between the heels were measured. Two 40-second eyes-open standing trials were also recorded.

COM data analysis

We defined the 30-second interval from 5 to 35 seconds within the acquired time-series data as the analysis window and used the average of the two trials for analysis. As a preprocessing step to estimate COM from the measured data, we applied a zero-phase high-pass filter (fourth-order Butterworth filter) with a cutoff frequency of 0.15 Hz to the horizontal force component of the force platform to remove low-frequency drift components. The force platform provided three-axis forces and moments, while the head IMU provided three-axis accelerations and angular velocities. The force-platform and head-mounted IMU signals were acquired synchronously at 100 Hz through the wired measurement system. We defined a common coordinate system based on the force-platform coordinates, with the forward direction as the x-axis, the left direction as the y-axis, and the vertical upward direction as the z-axis. The IMU attitude was estimated from the three-axis acceleration and angular-velocity signals using a magnetometer-free extended Kalman filter, and the measured acceleration was transformed from the sensor coordinate system to the force-platform coordinate system [6,7]. To remove high-frequency noise from all measured values, we applied a fourth-order Butterworth IIR low-pass filter (cutoff frequency: 5 Hz; sampling frequency: 100 Hz) and utilized the zero-phase filter function "filtfilt," in MATLAB R2025b. Offsets in the measured horizontal-force and horizontal-acceleration signals were corrected; no separate bias or drift correction was applied to the gyroscope signals.

The variables necessary for the balance assessment were estimated from the measured data using the equations of motion of direction-specific rigid-body link models described in previous studies [6,7]. In the sagittal plane, the AP model was a double-pendulum model consisting of the feet, lower body, and upper body, with the hip joint near the greater

trochanter serving as the boundary between the lower and upper body. In the frontal plane, the ML model comprised both feet, both legs, the pelvis, and the upper body. Under the parallel-leg constraint, the ML model was represented as a two-degree-of-freedom system, with the boundary between the lower and upper body located near the fifth lumbar vertebra. Force-platform and head-mounted IMU data were used to estimate whole-body COM displacement and acceleration and the relevant segment accelerations in the AP and ML directions.

Segment mass ratios, segment COM locations, inertial parameters, and segment lengths were assigned using the sex-specific anthropometric relationships detailed in S1 Appendix. Each participant's sex, measured height, and body mass were incorporated into the model coefficients; individual limb lengths and participant-specific deviations in segment mass ratios were not measured. COM displacement was obtained algebraically by solving the sex-specific simultaneous linear equations rather than by direct numerical integration of IMU acceleration. The complete AP and ML equations, definitions of the measured and estimated variables, model assumptions, anthropometric parameterization, and signal-processing procedures are provided in S1 Appendix.

For the calculation of GRAD, IC, and SIG, COM displacement was additionally high-pass filtered at 0.15 Hz to reduce slow shifts in the postural equilibrium position and to characterize the local displacement–acceleration relationship. In contrast, CC was calculated using offset-corrected COM displacement without this additional high-pass filtering, thereby retaining slow fluctuations in the overall COM trajectory.

GRAD describes the displacement-dependent acceleration response. A more negative GRAD indicates a greater opposing acceleration per unit COM displacement and is therefore consistent with a stronger model-derived restoring response. IC is the absolute value of the fitted intercept. Because both COM displacement and COM acceleration were offset-corrected before fitting, IC should not be interpreted as an instrumental acceleration bias or a simple positional offset. Instead, IC was interpreted as an operational index of asymmetry in the restoring relationship. A larger IC indicates greater asymmetry between the restoring responses associated with COM displacement in opposite directions, consistent with differences in the effective restoring gradients around the equilibrium position. SIG represents residual variability in COM acceleration that is not explained by COM displacement, with a larger value indicating a less consistent displacement–acceleration relationship.

CC was calculated using offset-corrected COM displacement without the additional 0.15-Hz high-pass filtering applied for GRAD, IC, and SIG. Retaining the slow component was intended to capture the extent to which low-frequency COM movement, including rambling-like fluctuations, remained coupled to acceleration. Values closer to −1 indicate more consistent inverse coupling, in which acceleration tends to oppose COM displacement, whereas values closer to zero indicate weaker linear coupling. Importantly, CC can approach −1 when acceleration consistently opposes displacement even when the magnitude of the restoring response is relatively small. Thus, GRAD represents the magnitude of the displacement-dependent response, whereas CC represents the consistency and direction of displacement–acceleration coupling over the overall COM trajectory.

Although these direction-specific rigid-body link models have been used in our previous studies, their criterion validity against marker-based motion capture has not been specifically established in patients with stroke.

Statistical analysis

The statistical analysis was performed in several steps. First, Pearson correlation coefficients were calculated to examine associations between FGA scores and the eight COM control indices. To control the family-wise type I error rate across these eight comparisons, *p* values were adjusted using the Bonferroni method. This analysis served as an exploratory screening step, and COM control indices that remained statistically significant after Bonferroni correction were carried forward to the subsequent regression analysis. For each retained index, two exploratory linear regression models were fitted with the FGA score as the dependent variable. Model 1 was unadjusted and included the retained COM control index as the explanatory variable, whereas Model 2 was adjusted for age. Because the COM control index was selected from the

same family of eight candidate indices, the *p* values for its regression coefficient in both models were also adjusted using a Bonferroni factor of eight. Regression coefficients were reported with unadjusted 95% confidence intervals.

Second, an exploratory, hypothesis-generating subgroup analysis was conducted to examine whether COM control indices differed between participants with and without lower-limb motor paralysis. Participants were classified as having motor paralysis if at least one of the hip, knee, or ankle items on the Stroke Impairment Assessment Set motor scale had a score <5; participants with scores of 5 for all three items were classified as having no motor paralysis.

For each COM control index, a linear mixed-effects model was fitted using the log-transformed absolute value of the index as the dependent variable. Motor-paralysis status, COM control direction (AP or ML), and the motor-paralysis status × direction interaction were included as fixed effects, and age was included as a covariate. A participant-specific random intercept was included to account for the correlation between repeated AP and ML measurements within each participant. A diagonal residual covariance structure was specified to allow residual variance to differ between the AP and ML directions. Models were estimated using restricted maximum likelihood. When the motor-paralysis status × direction interaction was statistically significant, two prespecified between-group contrasts were evaluated separately for the AP and ML directions. These two contrasts were treated as a single family of comparisons; Bonferroni-adjusted *p* values were assessed at a two-sided significance level of 0.05, and simultaneous 97.5% confidence intervals were reported. To evaluate the potential influence of a nonstandard stance, all four linear mixed-effects models were repeated after excluding the four participants who were unable to maintain the standardized feet-together stance.

Because of the small and imbalanced subgroup sizes, these subgroup analyses were considered exploratory and hypothesis-generating and were not intended to provide confirmatory evidence.

All statistical analyses were performed using IBM SPSS® (version 29; IBM Corporation, Armonk, NY, USA). Unless otherwise specified, statistical significance was defined as a two-sided $p < 0.05$.

Results

Patient characteristics are presented in Table 1. During the study period, 233 patients were assessed for eligibility. Of these patients, 28 participants completed the FGA and COM measurements and were included in the correlation and regression analyses. All 28 participants were also included in the exploratory subgroup analysis: 6 participants had lower-limb motor paralysis and 22 did not. No outcome data were missing (S1 Fig). No observations were excluded from the primary correlation and regression analyses or from the full-sample mixed-effects analyses because of incomplete FGA data, missing COM data, inadequate measurement quality, or technical problems. The four participants who were unable to maintain the standardized feet-together stance were retained in the full-sample analyses and were excluded only from the sensitivity analyses.

During COM control measurements, four patients were unable to keep their feet together while standing stationary. Among these patients, the mean distance between the first metatarsals was 0.5 cm (±1.4 cm), and the mean distance between the heels was 0.6 cm (±2.3 cm). The patients' postural control parameters are shown in Table 2.

The correlations between the FGA score and the COM control indices were as follows: $GRAD_{AP}$, $r = 0.345$ (95% CI, −0.032 to 0.636; Bonferroni-adjusted $p = 0.580$); $GRAD_{ML}$, $r = -0.141$ (95% CI, −0.488 to 0.245; adjusted $p = 1.000$); IC_{AP}, $r = -0.246$ (95% CI, −0.567 to 0.140; adjusted $p = 1.000$); IC_{ML}, $r = 0.116$ (95% CI, −0.269 to 0.469; adjusted $p = 1.000$); SIG_{AP}, $r = -0.657$ (95% CI, −0.827 to −0.376; adjusted $p = 0.001$); SIG_{ML}, $r = -0.469$ (95% CI, −0.717 to −0.116; adjusted $p = 0.095$); CC_{AP}, $r = 0.370$ (95% CI, −0.004 to 0.653; adjusted $p = 0.421$); and CC_{ML}, $r = 0.466$ (95% CI, 0.112 to 0.715; adjusted $p = 0.099$) (Fig 1). After Bonferroni correction, only the association between SIG_{AP} and FGA score remained statistically significant. Accordingly, SIG_{AP} was carried forward to the exploratory regression analyses.

The unadjusted regression model was statistically significant ($F(1, 26) = 19.774$, model $p < 0.001$; $R^2 = 0.432$; adjusted $R^2 = 0.410$). SIG_{AP} was negatively associated with the FGA score ($B = -1.027$, $SE = 0.231$, $\beta = -0.657$, 95% CI, −1.502 to −0.552; $t(26) = -4.447$; Bonferroni-adjusted $p = 0.001$). The age-adjusted model was also statistically

Table 1. Descriptive characteristics of the study participants after stroke.

Age (years)	**66.7 ± 13.0**
Sex, n (%)	Male: 14 (50.0%) Female: 14 (50.0%)
Stroke type, n (%)	Ischemic: 26 (92.9%) Hemorrhagic: 2 (7.1%)
Lesion side, n (%)	Left: 15 (53.6%) Right: 11 (39.3%) Bilateral: 2 (7.1%)
AFO used during the FGA, n (%)	1 (3.6%)
Time since stroke onset (day)	10.5 ± 3.9
FAC (score)	3.9 ± 1.2
MMSE (score)	27.6 ± 2.3
SIAS (score)	72.5 ± 4.2
FIM (score)	110.8 ± 15.1
FGA (score)	20.0 ± 8.0
1. walking with eyes open (second)	6.80 ± 1.79
8. walking with eyes closed (second)	9.14 ± 3.39

The data are presented as means ± standard deviations or n (%). FAC, functional ambulation categories; MMSE, mini-mental state examination; SIAS, stroke impairment assessment set; FIM, functional independence measure; FGA, functional gait assessment; AFO, ankle foot orthosis.

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Table 2. Model-derived COM control indices in the AP and ML directions.

	AP	**ML**
GRAD	−7.94 ± 1.98	−3.78 ± 1.07
IC	0.25 ± 0.14	0.19 ± 0.10
SIG	13.99 ± 5.11	7.88 ± 2.36
CC	−0.30 ± 0.09	−0.56 ± 0.12

Values are presented as mean ± standard deviation. AP, anteroposterior; ML, mediolateral; GRAD, slope of the linear relationship between COM displacement and acceleration; IC, absolute value of the intercept of the fitted line; SIG, standard deviation of the residual acceleration around the fitted line; CC, Pearson correlation coefficient between COM displacement and acceleration; COM, center of mass.

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significant ($F(2, 25) = 9.520$, model $p < 0.001$; $R^2 = 0.432$; adjusted $R^2 = 0.387$). The magnitude of the association between SIG_{AP} and the FGA score remained similar after adjustment for age ($B = -1.023$, $SE = 0.238$, $\beta = -0.655$, 95% CI, −1.513 to −0.533; $t(25) = -4.298$; Bonferroni-adjusted $p = 0.002$).

In the exploratory full-sample analysis, 6 participants were classified as having lower-limb motor paralysis and 22 as not having lower-limb motor paralysis (Fig 2). Among the six participants classified as having motor paralysis, the median (interquartile range [IQR]) SIAS motor subscale scores were 4 (IQR, 4–4) for the hip, 5 (IQR, 4.25–5) for the knee, and 3.5 (IQR, 3–4) for the ankle.

For GRAD, a significant motor-paralysis status × direction interaction was observed ($F(1, 26) = 9.208$, $p = 0.005$). The main effect of direction was significant ($F(1, 26) = 191.254$, $p < 0.001$), whereas the main effect of motor-paralysis status ($F(1, 25) = 1.582$, $p = 0.220$) and the age effect ($F(1, 25) = 0.305$, $p = 0.586$) were not significant.

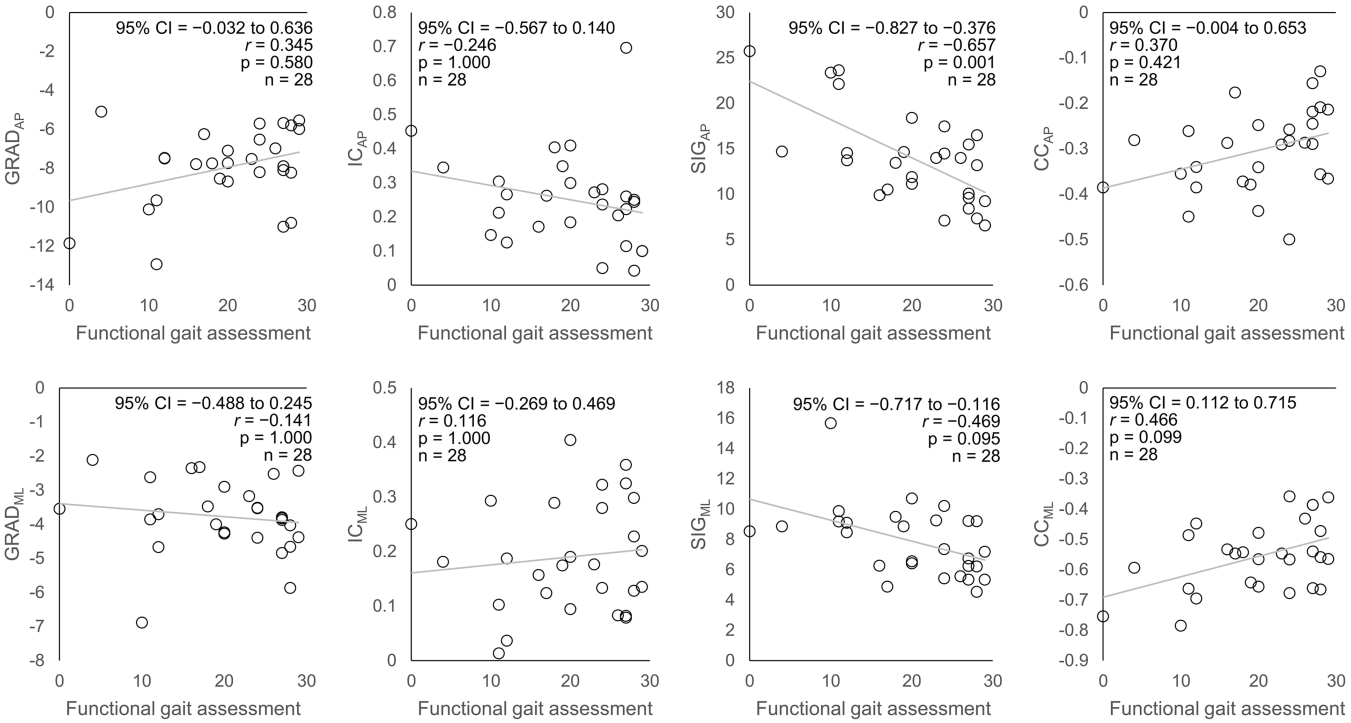

Fig 1. Plot illustrating correlations between functional gait assessment results and center of mass control parameters. Each panel shows the 95% confidence interval, Pearson correlation coefficient (r), Bonferroni adjusted *p*-value, and sample size (n = 28). The solid lines represent the fitted linear regression lines. COM, center of mass; AP, anteroposterior direction; ML, mediolateral direction; GRAD, slope of the linear relationship between COM displacement and acceleration; IC, absolute value of the intercept of the fitted line; SIG, standard deviation of the residual acceleration around the fitted line; CC, Pearson correlation coefficient between COM displacement and acceleration.

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Age-adjusted estimated marginal means on the log-transformed scale and their back-transformed geometric means, with 95% confidence intervals, are presented in S1 Table. No between-group difference was detected in the AP direction (Bonferroni-adjusted $p = 1.000$). In the ML direction, the estimated absolute GRAD was lower in participants with motor paralysis than in those without motor paralysis. The difference in the log-transformed values between the non-paralysis and motor-paralysis groups was 0.313 (SE = 0.119; Bonferroni-adjusted 97.5% CI, 0.029–0.597; Bonferroni-adjusted $p = 0.028$), corresponding to a geometric mean ratio of 1.37 (97.5% CI, 1.03–1.82).

Significant main effects of direction were also observed for SIG ($F(1, 26) = 166.369$, $p < 0.001$) and CC ($F(1, 26) = 92.364$, $p < 0.001$), but not for IC ($F(1, 26) = 3.447$, $p = 0.075$). No significant motor-paralysis status × direction interactions were observed for IC ($p = 0.623$), SIG ($p = 0.067$), or CC ($p = 0.950$). In the full-sample models, none of the age effects was statistically significant.

The magnitude of GRAD and SIG was greater in the AP direction than in the ML direction, whereas the absolute magnitude of CC was smaller in the AP direction than in the ML direction.

Four participants were unable to maintain the standardized feet-together stance, including two participants with motor paralysis and two without motor paralysis. The sensitivity analysis excluding these participants included 24 participants: 4 with motor paralysis and 20 without motor paralysis. The main effect of direction remained significant for GRAD ($F(1, 22) = 117.097$, $p < 0.001$). However, neither the main effect of motor-paralysis status ($F(1, 21) = 3.913$, $p = 0.061$) nor the motor-paralysis status × direction interaction ($F(1, 22) = 3.799$, $p = 0.064$) was statistically significant. The age effect was also not significant ($F(1, 21) = 2.098$, $p = 0.162$). Because the omnibus interaction was not statistically significant,

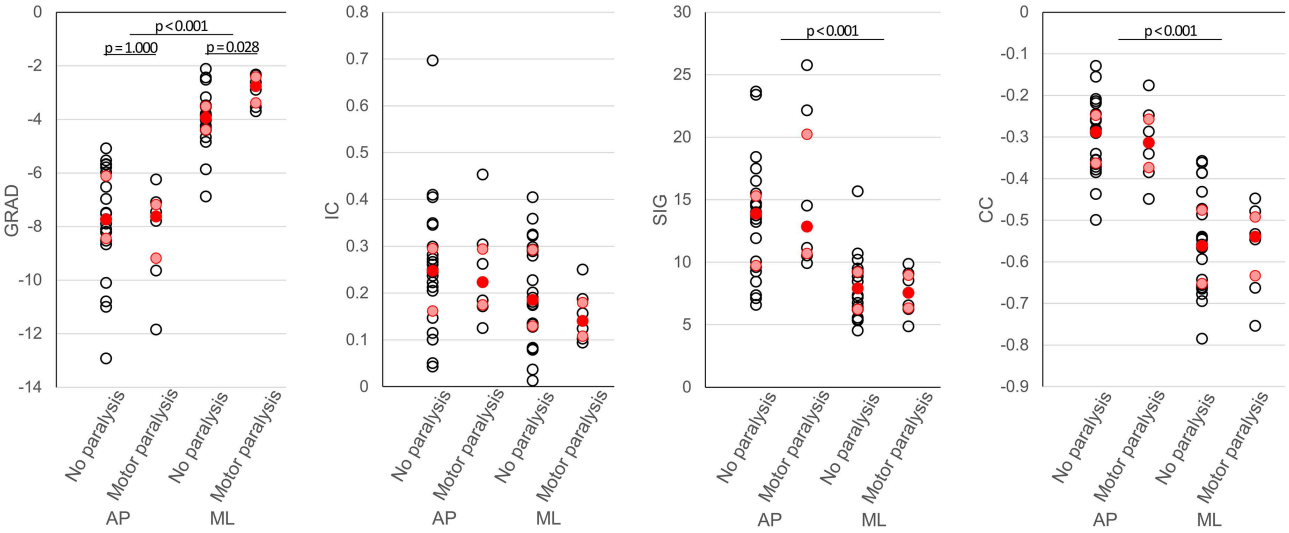

Fig 2. Exploratory comparison of COM control indices according to motor-paralysis status and control direction. Participants with motor paralysis (n = 6) and those without motor paralysis (n = 22) are shown separately for the AP and ML directions. Black circles represent individual observations, the red line represents the median, and the orange lines represent the first and third quartiles. Because of the small and imbalanced subgroup sizes, these comparisons should be interpreted as exploratory. For GRAD, the omnibus motor-paralysis status × direction interaction was significant ($p = 0.005$). The Bonferroni-adjusted p-values for the between-group comparisons were 1.000 in the AP direction and 0.028 in the ML direction. The plotted points represent observed values, whereas inferential analyses were performed using log-transformed absolute values. COM, center of mass; AP, anteroposterior direction; ML, mediolateral direction; GRAD, slope of the linear relationship between COM displacement and acceleration; IC, absolute value of the intercept of the fitted line; SIG, standard deviation of the residual acceleration around the fitted line; CC, Pearson correlation coefficient between COM displacement and acceleration.

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direction-specific between-group comparisons from the sensitivity model were not interpreted. Complete full-sample and sensitivity-analysis model results are provided in S1 and S2 Tables, respectively.

Given the small number of participants with motor paralysis and the imbalance between the groups, this finding should be interpreted as exploratory and hypothesis-generating.

Discussion

The present study included patients with acute stroke who were able to stand independently and had a mean SIAS score of 72.5, indicating relatively mild impairment. Nevertheless, their mean FGA score was 20. An FGA cutoff score of 22 has been proposed for identifying fall risk in community-dwelling older adults [10]. However, because this cutoff was not derived from patients with acute stroke, its applicability to the present population remains uncertain. The FGA score in the present study should therefore be interpreted primarily as indicating reduced dynamic balance performance rather than as directly indicating an increased risk of falls. These participant characteristics also indicate that our findings are primarily applicable to mildly-to-moderately affected patients with acute stroke who retain the ability to stand independently.

In the present study, lower SIG_{AP} values were associated with higher FGA scores. SIG quantifies residual variability around the linear relationship between COM displacement and acceleration, with higher values indicating greater variability in COM acceleration that is not explained by COM displacement. Thus, the observed negative association indicates that participants with lower variability in model-derived AP COM control tended to demonstrate better dynamic balance performance. This finding represents a cross-sectional association and should not be interpreted as evidence that reducing SIG_{AP} would improve FGA performance. SIG_{AP} may warrant further investigation as a model-derived measure related

to dynamic balance performance, but its value for treatment selection, outcome prediction, or intervention targeting has not been established.

One possible explanation for the direction-specific association is that several FGA tasks, including changes in walking speed, walking with vertical head movements, and stepping over obstacles, require substantial control of the body in the AP direction. Previous studies have reported altered activity across multiple brain regions and disruptions of neural networks following acute stroke [21,22]. COM control also depends on integrated neural systems, including the reticulospinal and vestibulospinal pathways [23,24]. However, the task content of the FGA does not establish the mechanism underlying the observed association. Neural activity and pathway integrity were not assessed in the present study; therefore, these neurophysiological explanations remain speculative. Longitudinal and interventional studies, including prospective assessment of actual falls, are required to determine the temporal direction and clinical implications of this association.

The exploratory full-sample analysis identified a motor-paralysis status × direction interaction for GRAD, with a lower estimated magnitude of ML GRAD among participants with motor paralysis. However, this interaction did not remain statistically significant after excluding the four participants who were unable to maintain the standardized feet-together stance. This difference between the analyses may reflect the influence of stance position or individual observations; however, the reduction from six to four participants with motor paralysis also decreased statistical precision. Therefore, the present findings do not provide conclusive evidence that ML GRAD differs according to motor-paralysis status and should be regarded as hypothesis-generating.

The present study did not assess corticospinal tract integrity, lesion location, or the neural networks involved in COM control. Therefore, the subgroup difference observed in the full-sample analysis cannot be attributed to corticospinal tract damage or any specific neural mechanism. Larger, prospectively designed studies using a standardized stance condition and incorporating neuroimaging or neurophysiological measures are needed to investigate this possible association.

This study had several limitations. First, because the COM control indices and FGA scores were assessed concurrently in this cross-sectional study, temporal order and causality cannot be established, and reverse causation remains possible. Although age was included in the adjusted model, residual confounding by time since stroke onset, stroke severity, lesion side, walking ability, motor impairment, functional independence, cognitive status, and other sensorimotor impairments cannot be excluded. With only 28 participants, simultaneous adjustment for these factors would have increased the risk of overfitting and unstable estimates. Moreover, actual falls were not assessed; therefore, implications for fall prediction or prevention cannot be inferred. Larger longitudinal and interventional studies with more comprehensive adjustment for potential confounders are needed. Second, SIG_{AP} was selected from eight candidate COM control indices and subsequently evaluated by regression in the same sample. Although Bonferroni correction was applied and the regression analyses were considered exploratory, the regression coefficient and R^2 estimates may still be optimistic and require validation in an independent cohort. Third, the motor-paralysis subgroup analysis was exploratory and involved markedly unequal group sizes, with 6 participants with motor paralysis and 22 without. Four participants were unable to maintain the standardized feet-together stance and were retained in the full-sample analysis using the narrowest stance they could safely maintain. After their exclusion, the sensitivity analysis included only 4 participants with motor paralysis and 20 without, and the GRAD interaction was no longer statistically significant. The subgroup finding may therefore be sensitive to stance position, individual observations, and limited statistical precision. Furthermore, motor paralysis was defined using a clinical scale rather than direct measures of lesion location or corticospinal tract integrity; thus, no causal or neuroanatomical conclusions can be drawn. Fourth, this single-center study included predominantly mildly-to-moderately affected patients who could stand independently for at least 30 seconds and complete the FGA. The findings may not generalize to patients with severe stroke, inability to stand independently, cognitive impairment that prevents understanding the study procedures or following task instructions, or greater motor and balance deficits. The absence of a healthy control group also precludes conclusions regarding differences from individuals without stroke. Finally, the direction-specific rigid-body link models have not been specifically validated in patients with stroke against an external reference method. Stroke-related asymmetry and

impaired trunk or neck control may violate model assumptions, including stable segment geometry and consistent head–trunk coupling, and introduce estimation error of unknown magnitude and direction. The results should therefore be interpreted as model-derived estimates rather than direct COM measurements. Future studies should establish the criterion validity of this method in patients with stroke across a broader range of motor and postural impairments.

Despite these limitations, lower variability in model-derived AP COM control during quiet standing was associated with better dynamic balance performance in this sample. Whereas previous studies of postural control have primarily used COP sway area or sway velocity as outcome measures, the present model-derived approach enabled characterization of the relationship between COM displacement and acceleration.

Conclusion

In mildly-to-moderately affected patients with acute stroke who were able to stand independently, COM displacement and acceleration during standing were estimated using direction-specific rigid-body link models. Lower SIG_{AP} values were associated with higher FGA scores, indicating that lower variability in model-derived AP COM control was associated with better dynamic balance performance. Because of the cross-sectional design, the direction and causal nature of this association cannot be determined. Further longitudinal and interventional studies, including validation of the COM estimation method in patients with stroke and prospective assessment of actual falls, are needed to clarify the clinical implications of this association.

Supporting information

S1 Appendix. Equations and processing procedures for model-derived center-of-mass estimation.
(PDF)

S1 Data. Participant-level Functional Gait Assessment scores and model-derived center-of-mass control indices.
(PDF)

S1 Fig. Flow diagram of participant screening and inclusion.
(PDF)

S1 Table. Full-sample linear mixed-effects model results for model-derived center-of-mass control indices (n = 28).
(PDF)

S2 Table. Sensitivity-analysis linear mixed-effects model results after exclusion of participants with nonstandard stance (n = 24).
(PDF)

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