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Research Paper

Reliability of Center of Pressure Measures in Chronic Stroke Survivors: Influence of Motor and Cognitive Dual-tasking

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ABSTRACT

Introduction: Reliable balance measures are crucial for effective stroke rehabilitation. This study examines the between-day and within-day reliabilities of the center of pressure (CoP) measures in chronic stroke survivors in different standing positions under the influence of motor and cognitive dual-tasking.

Methods: Sixteen people (49.31±15.5 years, 5 females) with chronic stroke were assessed in two sessions, 48 hours apart. Participants completed three balance control conditions: Single-task, motor dual-task, and cognitive dual-task. They performed three trials of open-eye quiet standing and semi-tandem standing. Three trials of closed-eye quiet standing were conducted in the single-task condition. A 2-way random model of the intraclass correlation coefficient (ICC), standard error of measurement (SEM), and minimal detectable change (MDC) were calculated for CoP mean velocity, anterior-posterior (AP) and medial-lateral (ML) mean velocity, the standard deviation (SD) of AP and ML velocity, and sway area.

Results: Within-day ICC values were higher than between-day values (ICC: 0.78-0.96). Mean velocity and Mean±SD of velocity in the AP direction showed the highest relative and absolute reliabilities in an open-eye quiet standing position (ICC: 0.82-0.92, SEM: 0.67-1.24). Dual-tasking could increase the reliability of the CoP measures, except for the sway area (ICC: 0.53-0.93 changed to 0.84-0.96). MDCs ranged from 1.03 to 7.77 mm/s for velocity-based variables.

Conclusion: Assessing the postural control system during dual-task conditions provides more reliable CoP measures, especially in a semi-tandem standing position. These findings can provide clinicians with valuable insights into detecting specific balance problems that post-stroke individuals encounter.

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Highlights

- Within-day ICC were higher than between-day values in chronic stroke survivors.
- Mean velocity and AP direction velocity variables were the most reliable measures.
- Dual-tasking improved the reliabilities of CoP measures, except for the sway area.
- Semi-tandem standing reached acceptable reliability in dual-tasking.
- These findings can provide clinicians with valuable insights into detecting specific balance problems.

Plain Language Summary

This study explored how well balance measurements work in people recovering from strokes, especially when they are performing two tasks at the same time. Balance is a big issue for stroke survivors, as about half experience long-lasting physical difficulties, making them more prone to falls. In rehabilitation, reliable measures of balance are essential to track improvement and guide treatment. This study focused on assessing the reliability of center of pressure (CoP) measurements—essentially how people distribute their weight when standing—as a tool to evaluate balance. The researchers found that dual-tasking generally improved the reliability of CoP measures, particularly in challenging standing positions like semi-tandem (one foot slightly in front of the other). However, the area covered by the body's sway was less reliable during these tasks. The most reliable measure was the speed at which the CoP moved, both in total and in the front-to-back (anterior-posterior [AP]) direction.

1. Introduction

Approximately 50% of stroke survivors experience residual physical disabilities (Corriveau et al., 2004; Sawacha et al., 2013), leading to deficits in sensory, musculoskeletal, perceptual, and cognitive systems, affecting balance control and finally increasing the risk of falls (Corriveau et al., 2004; Jagroop et al., 2023; Sawacha et al., 2013). Therefore, the primary goal of stroke rehabilitation is to enhance balance control, requiring reliable balance measures to guide rehabilitation and monitor progress over time (Jette et al, 2009; Mansfield & Inness, 2015). Clinical balance scales fail to reveal underlying dyscontrol, which could potentially increase the risk of falling as the compensatory strategies used to complete tasks remain unknown (Mansfield & Inness, 2015).

The solution could be to record the center of pressure (CoP) excursion using a force platform in a laboratory setting (Jette et al., 2009; Sackley, 1991; Sawacha et al., 2013). CoP parameters can differentiate between fallers and non-fallers (Melzer et al., 2004; Melzeret al., 2010; Pajala et al., 2008) and are associated with clinical outcome measures in elderly and post-stroke individuals (Sawacha et al., 2013), but the intrinsic variability of CoP measures influences their reliability in postural control assessments. Additionally, reliability is not a static characteristic and varies based on the population (Gasq et al., 2014; Lafond et al., 2004).

To date, several studies have demonstrated acceptable CoP measures reliability in assessing balance in populations with disequilibrium problems (Mohammadi-Rad et al., 2022; Ruhe et al., 2010; Salavati et al., 2009; Terra et al., 2020), healthy elders (Lin et al., 2008; Moghadam et al., 2011; Salehi et al., 2010), and young adults (Fullin et al., 2022; Lo et al., 2022). Few studies have reported it throughout various stages of post-stroke recovery (Bower et al., 2014; Gasq et al., 2014; Gray et al., 2014; Martello et al., 2017). It is worth noting that only one study has specifically examined the reliability of CoP-based variables among chronic stroke survivors, in which a limited number of conventional variables were selected as a part of the main objective (Jagroop et al., 2023). However, during the chronic stage of stroke recovery, rehabilitative interventions have a significant net effect on the patient's improvement, as spontaneous brain recovery has almost plateaued (Bernhardt et al., 2017). Accordingly, assessing the reliability of CoP measures in the chronic stage of stroke recovery could provide deeper insights into clinical decision-making and upcoming research.

Individuals have limited cognitive capacity based on the attentional capacity theory (Kahya et al., 2019), so they cannot perform two simultaneous tasks efficiently, known as the dual-task effect (Arpaia et al., 2024). Research has indicated that older adults and individuals with age-related neurodegenerative conditions experience higher costs of dual-tasking (Kahya et al., 2019). This condition leads to an elevated risk of falls and loss of independence (Arpaia et al., 2024; Kahya et al., 2019), particularly in post-stroke individuals compared to healthy adults (Tisserand et al., 2018). It is notable that dual-tasking also leads to spatiotemporal locomotor adaptations, which may help post-stroke individuals maintain their balance during dual-task conditions (Ghai et al., 2017; Tisserand et al., 2018). Consequently, monitoring the balance control system during dual-tasking could be beneficial for a more accurate impairment diagnosis and tracking of rehabilitation outcomes. So far, a study has examined the reliability of CoP measures during different postural stability tasks in post-stroke patients, regardless of the influence of dual-tasking on CoP measures reliability (Gray et al., 2014). Therefore, in this study, we investigated the reliability of CoP measures under various dual-task conditions.

Moreover, the reliability of CoP measures in tandem standing in post-stroke individuals has not been studied. However, this narrow support-based position is commonly used to identify underlying deficiencies in the postural control system (Melzer et al., 2010) and predict the risk of falling (Pajala et al., 2008; Stel et al., 2003). Furthermore, tandem standing is a practical position to assess the ability for uneven weight distribution in individuals with leg-related motor disorders, as more weight is placed on the rear leg (Jonsson et al., 2005). We selected semi-tandem standing for this study to ensure participant's successful performance.

Thus, the present study aimed to examine the within-day and between-day reliabilities of CoP measures in different standing positions with the influence of motor and cognitive dual-tasking in chronic stroke survivors.

2. Materials and Methods

Study participants

Participants were 16 people with chronic stroke (>6 months post-stroke) who participated in an unpublished clinical trial. Common inclusion criteria were as follows: Ability to stand and walk independently for one minute, ability to hold semi-tandem standing independently for 30 seconds, and no recent limb surgery or uncorrected visual or auditory impairments. The exclusion criteria were as follows: Participants with a score higher than 2 on the modified Ashworth scale in calf muscle (Li et al., 2014), 2), a score lower than 24 on the mini-mental state examination-Persian version (Ansari et al., 2010), a standard deviation (SD) of ±1 or greater on the line bisection test (hemineglect history) (Plummer et al., 2003), and conditions that may affect their balance control except stroke were excluded. Age, height, weight, sex, and type of stroke were obtained from participants. They were also assessed by the Berg balance scale (BBS) (Salavati et al., 2012), the mini-balance evaluation system test (Mini-BEST) (Molhemi et al., 2024), and activities-specific balance confidence (ABC) (Hassan et al., 2015) (Table 1). BBS is a valid and reliable 14-item balance assessment tool for stroke patients. Each item is graded on a 5-point scale, and the total score ranges from 0 to 56. The inter-rater reliability (intraclass correlation coefficient [ICC]: 0.98) and the intra-rater reliability (ICC: 0.97) were very high in post-stroke survivors (Berg et al., 1995). Mini-BEST consists of 14 items that assess dynamic balance and have excellent intra-rater reliability (ICC: 0.97) and inter-rater reliability (ICC: 0.96) for stroke patients. Each item is graded on a 3-point scale with a score of 0 to 28 (Tsang et al., 2013). The ABC scale measures the psychological impact of balance impairment and falls. It is a valid and reliable scale (Internal consistency: 0.94 and test re-test reliability ICC: 0.85), rating confidence in performing activities from 0% to 100%. The percentage for each of the 16 items is averaged (Botner et al., 2005).

Study procedure

CoP data were obtained using two adjacent strain gauge Kistler force platforms (model No. 9286BA, Switzerland). Assessments were carried out by the same rater in the exact location and time during two sessions, 48 hours apart, with three trials per session (Gray et al., 2014; Jagroop et al., 2023). The lighting and sound levels of the environment were controlled. Postural sway was measured in three conditions: Single-task, motor dual-task, and cognitive dual-task. In the single-task condition, participants maintained an open-eye quiet standing (open-quiet), an open-eye semi-tandem standing (open-tandem), and a closed-eye quiet standing (closed-quiet). In motor and cognitive dual-task conditions, the participants held quiet and semi-tandem standing (motor-quiet, motor-tandem, and cognitive-quiet, cognitive-tandem, respectively). During quiet standing, they were instructed to stand comfortably barefoot, as still and quiet as possible, on two adjacent force plates with their feet shoulder-width apart, arms at their sides, and gaze at the wall 2 m in front. Both feet were placed on the same plate, with a foot-width distance between them and the affected leg in front, during semi-tandem standing (Jonsson et al., 2005). The position of the feet remained the same throughout all assessment sessions. For motor dual-tasking, participants hold a tray containing a glass of water (Negahban et al., 2017). For cognitive dual-tasking, they conducted the congruent Stroop test, which has been previously validated and proven reliable in its Persian version (Sadri Damirchi et al., 2019). A board with 45 words was placed two meters away from participants for the Stroop task. Words were names of four colors written in the same color ink, and were arranged in 9 rows of 5 words (Negahban et al., 2017). All positions were held for approximately 30 s, with a 30-second break between trials. A physiotherapist supervised participants during assessments for safety.

Data processing

Force platform data were sampled at 100 Hz with a low-pass filter at 10 Hz. A MATLAB routine computed CoP measures for combining both plates (net-CoP). The Mean±SD of net-CoP velocity along anterior-posterior (AP) (Vap and SD.Vap) and medial-lateral (ML) directions (Vml and SD.Vml), mean velocity (Vmean), and sway area (Area) were chosen as their relevance in hemiplegic stroke patients was demonstrated (Gasq et al., 2014), and previously recommended (Palmieri et al., 2002). CoP velocity reflects the efficiency of the postural control system in counteracting postural sway via neuromuscular activity. The SD of velocity is the variability index of CoP velocity (Paillard & Noé, 2015). The lower the velocity and SD, the better the balance control. The sway area quantifies 95% of the ellipse formed by CoP excursion, representing the overall performance of the postural control system. Smaller sway area indicates better balance control performance (Paillard & Noé, 2015).

Statistical analysis

Data analysis was conducted using SPSS software, version 21. A 2-way random model of the (ICC with a corresponding 95% confidence interval (CI) was used to estimate relative reliability. Three assessment trials in a single session were used to examine within-day reliability. The average of 3 trials in 2 separate sessions was implemented for between-day reliability. Munro's classification for reliability coefficients used to represent the degree of reliability: 0–0.25 – little, if any correlation; 0.26–0.49 – low correlation; 0.5–0.69 – moderate correlation; 0.7–0.89 – high correlation, and 0.9–1 – very high correlation (Munro, 2005). Absolute reliability was determined using the standard error of measurement (SEM). SEM (SD ×indicates how much a change in measurement score is due to random error (Atkinson & Nevill, 1998). The minimal detectable change (MDC) was also calculated (MDC=1.96×√2×SEM), representing a clinically significant change between two measurement scores not due to random error (Atkinson & Nevill, 1998). The statistical significance level was set at 0.05.

3. Results

Demographic characteristics of participants are presented in Table 1.

Table 2 represents the Mean±SD for COP measures under different test conditions.

Within-day reliability

Table 3 presents within-day reliabilities. Generally, within-day ICCs were higher than between-day ICCs.

Single-task condition

ICCs ranged from 0.78 to 0.95, with high to very high reliability for all CoP measures. Lower relative and absolute reliabilities were seen in open-tandem than in open-quiet and closed-quiet positions. Reliabilities of the CoP measures were lower in the closed-quiet than in the open-quiet position, especially in terms of SEMs (0.74-222.39 vs 0.41-96.93, respectively). Sagittal plane measurements (Vap & SD. Vap) had higher reliabilities than the frontal plane (Vml & SD.Vml) in semi-tandem standing (Table 3).

Motor dual-task condition

ICCs ranged from 0.82 to 0.95. All CoP measures had high to very high reliability. Performing a secondary motor task improved the reliabilities of CoP measures in a motor-tandem position (ICC: 0.86-0.95 and SEM: 1.16-1.47) compared to the open-tandem position (ICC: 0.78-0.86 and SEM: 1.42-1.82), except for Area (Table 3).

Cognitive dual-task conditions

ICCs ranged from 0.60 to 0.96. All CoP measures had high to very high reliability, except for the sway area in the cognitive-quiet position. Cognitive dual-tasking improved reliabilities of CoP measures in a cognitive-tandem position (ICC: 0.84-0.98 and SEM: 0.82-1.89) compared to the open-tandem position (ICC: 0.78-0.86 and SEM: 1.33-1.82), except for Area (Table 3).

Table 1. Demographic and clinical characteristics of the participants (n=16)

Variables	Mean/Count	SD	Minimum	Maximum
Age (y)	49.31	15.5	27	76
Height (cm)	166.33	11.93	147	187
Weight (kg)	69.27	13.06	52	86
Sex	Male: 11 Female: 5			
Stroke type	Ischemic: 8 Hemorrhagic: 5 Unknown: 3			
Hemiparetic side	Right:6 Left:10			
BBS (score out of 56)	51.81	4.51	42	56
Mini-BEST (score out of 28)	20.43	5.42	12	27
ABC (score out of 100)	70.96	19.28	23.43	70.96

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Abbreviations: BBS: Berg balance scale; Mini-BEST: Mini-balance evaluation system test; ABC: Activities-specific balance confidence.

MDCs ranged from 1.03 mm/s for Vml (cognitive-quiet) to 5.77 mm/s for SD. Vap (closed-quiet), and from 268.60 (open-quiet) to 616.25 (closed-quiet) for Area (Table 3).

Between-day reliability

Table 4 presents between-day reliabilities.

Single-task condition

ICCs ranged from 0.53 to 0.96, with moderate to very high reliability for all CoP measures. The open-tandem position showed lower relative and absolute reliabilities than open-quiet and closed-quiet positions (Table 4). The absolute reliability of CoP measures in a closed-quiet position was almost lower than in an open-quiet position (SEM: 0.99-156.01 versus 0.91-159.17, respectively). Sagittal plane variables had higher reliabilities than the frontal plane variables in open-quiet and open-tandem positions.

Motor dual-task condition

ICCs ranged from 0.83 to 0.94, with high to very high reliability for all CoP measures. Reliabilities were higher in the motor-quiet position than in the motor-tandem position (ICC: 0.90-0.93 and SEM: 0.74-210.61 vs ICC: 0.87-0.92 and SEM: 1.43-245.32, respectively). Again, performing a secondary motor task improved the relative and absolute reliabilities of CoP measures compared to the single-task condition, except for Area (Table 4).

Cognitive dual-task condition

ICCs ranged from 0.66 to 0.96, with high to very high reliability for all CoP measures, except for the Area in the cognitive-quiet position. Cognitive dual-tasking improved the relative and absolute reliabilities of CoP measures compared to the single-task condition, except for Area (Table 4).

MDCs ranged from 1.37 mm/s for Vml (cognitive-quiet) to 7.77 mm/s for SD. Vml (open-tandem) and from 409.06 (cognitive-tandem) to 635.06 (motor-tandem) for Area (Table 4).

4. Discussion

This study aimed to determine the within-day and between-day reliability of COP measures in different standing positions while imposing a motor or cognitive dual-task on the postural control system. Nearly high to very high reliabilities were found for CoP measures. The mean velocity and Mean±SD of velocity in the AP direction showed the highest relative and absolute reliabilities.

Table 2. Test re-test mean of the CoP measures in all conditions

Cop Measure	Single-task			Motor dual-task			Cognitive Dual-task		
	Test Position	Mean±SD		Test Position	Mean±SD		Test Position	Mean±SD	
		Test	Re-test		Test	Re-test		Test)	Re-test
Vml (mm/s)	Open-quiet Closed-quiet Open-tandem	9.78±2.62 10.69±2.77 15.05±4.5	9.42±1.56 10.81±2.47 15.14±3.03	Motor-quiet Motor-tandem	9.95±3.31 14.87±4.24	9.51±2.25 14±4.4	Cognitive-quiet Cognitive-tandem	10.47±2.21 16.12±4.3	10.23±1.67 16.36±3.53
SD.Vml (mm/s)	Open-quiet Closed-quiet Open-tandem	12.41±3.51 13.6±3.48 19.61±5.92	11.92±2 13.8±3.24 19.2±3.86	Motor-quiet Motor-tandem	12.65±4.6 18.82±5.38	12.1±3.06 18.43±5.83	Cognitive-quiet Cognitive-tandem	13.33±2.92 21.23±5.41	12.94±2.12 21.29±4.73
Vap (mm/s)	Open-quiet Closed-quiet Open-tandem	12.23±2.33 16.47±4.16 14.81±3.77	12.6±2.11 17.39±4.54 14.98±3.23	Motor-quiet Motor-tandem	12.55±3.36 14.53±4.37	12.48±3.22 13.97±4.49	Cognitive-quiet Cognitive-tandem	13.58±2.25 16.45±4.88	14.02±2.09 17.11±5.8
SD.Vap (mm/s)	Open-quiet Closed-quiet Open-tandem	15.65±3.09 21.43±5.52 19.3±5	16.09±2.75 22.68±6.01 19±4.68	Motor-quiet Motor-tandem	16.03±4.65 18.84±5.93	15.92±4.26 17.99±5.8	Cognitive-quiet Cognitive-tandem	17.34±3.08 21.58±5.71	18.08±2.69 22.29±7.88
Vmean (mm/s)	Open-quiet Closed-quiet Open-tandem	17.34±3.66 21.56±5.2 23.26±6.12	17.38±2.61 22.43±5.28 22.91±4.71	Motor-quiet Motor-tandem	17.74±5.12 22.86±6.54	17.36±4.15 21.71±6.58	Cognitive-quiet Cognitive-tandem	19±3.26 25.75±6.33	19.16±2.44 26.07±6.82
Area (mm^2)	Open-quiet Closed-quiet Open-tandem	550.63±700.24 640.82±746.46 897.88±838.02	415.83±433.5 757.01±840.56 807.28±499.67	Motor-quiet Motor-tandem	623.04±811.53 879.94±708.19	512.6±502.157 765.38±471.91	Cognitive-quiet Cognitive-tandem	526.71±404.46 769.63±537.86	436.19±181.27 805.33±549.1

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Abbreviations: CoP: Center of pressure; V: Velocity; Ml: medial-lateral; Ap: Anterior-posterior; Open-quiet: Open-eyes quiet standing; Closed-quiet: Closed-eyes quiet standing; Open-tandem: Open-eyes semi-tandem standing; Motor-quiet: Motor dual-task quiet standing; Motor-tandem: Motor dual-task semi-tandem standing; Cognitive-quiet: cognitive dual-task quiet standing; Cognitive-tandem: Cognitive dual-task semi-tandem standing; Vmean: Mean velocity; Area: Sway area.

Table 3. Within-day ICCs, SEM, and MDC of the CoP measures in all conditions

CoP Measure	Single-task				Motor Dual-task				Cognitive Dual-task			
	Test Position	ICC (95% CI)	SEM	MDC	Test Position	ICC (95% CI)	SEM	MDC	Test Position	ICC (95% CI)	SEM	MDC
Vml (mm/s)	Open-quiet Closed-quiet Open-tandem	0.93 (0.85-0.98)* 0.91 (0.79-0.97)* 0.78 (0.5-0.92)*	0.41 0.74 1.42	1.14 2.05 3.94	Motor-quiet Motor-tandem	0.89 (0.76-0.96)* 0.93 (0.84-0.97)*	0.75 1.16	2.07 3.22	Cognitive-quiet Cognitive-tandem	0.95 (0.88-0.98)* 0.85 (0.66-0.94)*	0.37 1.37	1.03 3.79
SD.Vml (mm/s)	Open-quiet Closed-quiet Open-tandem	0.93 (0.85-0.97)* 0.91 (0.79-0.96)* 0.79 (0.52-0.92)*	0.53 0.97 1.77	1.47 2.69 4.90	Motor-quiet Motor-tandem	0.86 (0.68-0.95)* 0.94 (0.84-0.98)*	1.14 1.43	3.17 3.96	Cognitive-quiet Cognitive-tandem	0.94 (0.86-0.98)* 0.84 (0.64-0.94)*	0.52 1.89	1.44 5.24
Vap (mm/s)	Open-quiet Closed-quiet Open-tandem	0.90 (0.77-0.96)* 0.90 (0.77-0.96)* 0.83 (0.62-0.94)*	0.67 1.43 1.33	1.84 3.98 3.69	Motor-quiet Motor-tandem	0.96 (0.90-0.98)* 0.94 (0.86-0.98)*	0.64 1.10	1.78 3.05	Cognitive-quiet Cognitive-tandem	0.90 (0.77-0.96)* 0.98 (0.95-0.99)*	0.66 0.82	1.83 2.27
SD.Vap (mm/s)	Open-quiet Closed-quiet Open-tandem	0.90 (0.76-0.96)* 0.88 (0.72-0.95)* 0.86 (0.68-0.95)*	0.87 2.08 1.75	2.41 5.77 4.85	Motor-quiet Motor-tandem	0.95 (0.88-0.98)* 0.95 (0.88-0.98)*	0.95 1.30	2.64 3.59	Cognitive-quiet Cognitive-tandem	0.90 (0.75-0.96)* 0.96 (0.91-0.99)*	0.89 1.58	2.48 4.37
Vmean (mm/s)	Open-quiet Closed-quiet Open-tandem	0.92 (0.82-0.97)* 0.90 (0.78-0.96)* 0.85 (0.65-094)*	0.74 1.67 1.82	2.04 4.63 5.05	Motor-quiet Motor-tandem	0.94 (0.86-0.98)* 0.95 (0.88-0.98)*	1.02 1.47	2.82 4.08	Cognitive-quiet Cognitive-tandem	0.93 (0.84-0.97)* 0.95 (0.89-0.98)*	0.64 1.52	1.79 4.22
Area (mm^2)	Open-quiet Closed-quiet Open-tandem	0.95 (0.89-0.98)* 0.93 (0.84-0.97)* 0.84 (0.63-0.94)*	96.93 222.39 199.88	268.60 616.25 553.87	Motor-quiet Motor-tandem	0.90 (0.77-0.96)* 0.82 (0.59-0.93)*	158.80 200.21	440.03 554.79	Cognitive-quiet Cognitive-tandem	0.60 (0.12-0.84) 0.86 (0.68-0.95)*	114.64 205.45	317.68 569.31

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Abbreviations: SEM: Standard error of measurement; MDC: Minimal detectable change; CoP: Center of pressure; ICC: Intraclass correlation coefficients; CI: Confidence interval; V: Velocity; Ml: Medial-lateral; Ap: Anterior-posterior; Open-quiet: Open-eyes quiet standing; Closed-quiet: Closed-eyes quiet standing; Open-tandem: Open-eyes semi-tandem standing; Motor-quiet: Motor dual-task quiet standing; Motor-tandem: Motor dual-task semi-tandem standing; Cognitive-quiet: Cognitive dual-task quiet standing; Cognitive-tandem: Cognitive dual-task semi-tandem standing; Vmean: Mean velocity; Area: Sway area.

*ICC>0.70.

Table 4. Between-day ICCs, SEM, and MDC of the CoP measures in all conditions

CoP Measure	Single-task				Motor Dual-task				Cognitive Dual-task			
	Test Position	ICC (95% CI)	SEM	MDC	Test Position	ICC (95% CI)	SEM	MDC	Test Position	ICC (95% CI)	SEM	MDC
Vml (mm/s)	Open-quiet Closed-quiet Open-tandem	0.78 (0.38-0.92)* 0.82 (0.49-0.94)* 0.65 (-0.51-0.88)	0.91 0.99 1.94	2.53 2.75 5.38	Motor-quiet Motor-tandem	0.93 (0.81-0.98)* 0.89 (0.69-0.96)*	0.72 1.36	2.01 3.78	Cognitive-quiet Cognitive-tandem	0.93 (0.78-0.98)* 0.89 (0.69-0.96)*	0.49 1.24	1.37 3.43
SD.Vml (mm/s)	Open-quiet Closed-quiet Open-tandem	0.77 (0.34-0.92)* 0.83 (0.51-0.94)* 0.53 (-0.42-0.84)	1.23 1.28 2.8	3.41 3.54 7.77	Motor-quiet Motor-tandem	0.93 (0.82-0.98)* 0.92 (0.78-0.97)*	1 1.53	2.78 4.23	Cognitive-quiet Cognitive-tandem	0.90 (0.72-0.96)* 0.93 (0.79-0.97)*	0.77 1.3	2.13 3.59
Vap (mm/s)	Open-quiet Closed-quiet Open-tandem	0.83 (0.53-0.94)* 0.90 (0.77-0.96)* 0.83 (0.62-0.94)*	0.84 1.91 1.33	2.34 5.31 3.7	Motor-quiet Motor-tandem	0.93 (0.80-0.98)* 0.87 (0.63-0.95)*	0.84 1.5	2.33 4.16	Cognitive-quiet Cognitive-tandem	0.90 (0.72-0.97)* 0.89 (0.68-0.96)*	0.65 1.68	1.8 4.67
SD.Vap (mm/s)	Open-quiet Closed-quiet Open-tandem	0.84 (0.54-0.94)* 0.78 (0.37-0.92)* 0.81 (0.45-0.93)*	1.08 2.45 1.93	3 6.78 5.35	Motor-quiet Motor-tandem	0.92 (0.78-0.97)* 0.87 (0.63-0.95)*	1.21 1.98	3.36 5.49	Cognitive-quiet Cognitive-tandem	0.86 (0.61-0.95)* 0.96 (0.91-0.99)*	1.02 2.25	2.82 6.23
Vmean (mm/s)	Open-quiet Closed-quiet Open-tandem	0.82 (0.48-0.94)* 0.78 (0.38-0.92)* 0.66 (0-0.88)*	1.24 2.22 2.74	3.43 6.16 7.59	Motor-quiet Motor-tandem	0.94 (0.82-0.98)* 0.88 (0.68-0.96)*	1.11 2.15	3.07 5.97	Cognitive-quiet Cognitive-tandem	0.88 (0.67-0.96)* 0.91 (0.75-0.97)*	0.98 1.89	2.72 5.24
Area (mm^2)	Open-quiet Closed-quiet Open-tandem	0.92 (0.76-0.97)* 0.96 (0.88-0.98)* 0.89 (0.69-0.96)*	159.17 156.01 217.04	441.07 432.30 601.42	Motor-quiet Motor-tandem	0.90 (0.71-0.96)* 0.83 (0.52-0.94)*	203.22 229.18	563.11 635.06	Cognitive-quiet Cognitive-tandem	0.66 (0.05-0.88) 0.92 (0.77-0.97)*	157.94 147.62	437.66 409.06

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Abbreviations: SEM: Standard error of measurement; MDC: Minimal detectable change; CoP: Center of pressure; ICC: Intraclass correlation coefficients; CI: Confidence interval; V: Velocity; Ml: Medial-lateral; Ap: Anterior-posterior; Open-quiet: Open-eyes quiet standing; Closed-quiet: Closed-eyes quiet standing; Open-tandem: Open-eyes semi-tandem standing; Motor-quiet: Motor dual-task quiet standing; Motor-tandem: Motor dual-task semi-tandem standing; Cognitive-quiet: Cognitive dual-task quiet standing; Cognitive-tandem: Cognitive dual-task semi-tandem standing; Vmean: Mean velocity; Area: sway area.

*ICC>0.70.

Results on mean velocity in the quiet standing mirror before results on healthy elders (Kwon et al., 2022; Moghadam et al., 2011; Ruhe et al., 2010), elderly fallers (Swanenburg et al., 2008), and post-stroke individuals (Gasq et al., 2014; Gray et al., 2014). Mean velocity is more reliable than displacement or sway area, as it is not solely dependent on the CoP position (Gray et al., 2014; Ruhe et al., 2010), and is commonly preferred since it can minimize the extreme effects of peak values (Jagroop et al., 2023). Our findings, especially in dual-task conditions, also confirmed its high reliability.

Additionally, the Mean±SD of velocity in the AP direction were more reliable than in the ML direction in semi-tandem standing. Frontal plane variables are likely less reliable due to stroke survivors' varying ability to control balance in the ML direction. It is possible that asymmetry in weight bearing, along with difficulty in shifting weight to the affected limb (Gray et al., 2014), resulted in inconsistent measures of CoP in the ML direction across sessions. This inconsistency led to reduced reliability in the variables related to the frontal plane, which is noticeable in the semi-tandem standing position. However, there have been no studies on the reliability of tandem standing in post-stroke individuals. Swanenburg et al. (2008) reported that when stance width increases, a disproportionate decrease occurs in the angular motion of ankles and feet. In semi-tandem standing, the base of support increases in the AP direction, affecting force level variability similar to a broader stance in a side-by-side position (Jonsson et al., 2005). This, in turn, may improve the reliability of sagittal plane variables. Further research could reveal the exact rationale for this finding.

Compared to quiet standing positions, CoP measures in the semi-tandem standing had lower relative and absolute reliability during single-tasking; however, implementing a dual-task assessment enhanced reliability except for the sway area (Tables 3 and 4). It is believed that dual-tasking can improve performance by directing attention toward an external source of attention. This condition leads to automatic motor function, allowing for more effective performance by shifting motor control from higher cognitive to basic noncognitive centers (Ghai et al., 2017). Automating postural control may decrease performance variability and increase the reliability of the measurements. However, further investigations are needed to prove this opinion. Terra et al. (2020) found that reliability decreased in the cognitive dual-task compared to the single-task condition when evaluating patients with Parkinson's disease. Disagreement is possibly due to significant methodological differences. They studied patients with Parkinson disease, aged 71±7.8 years. They used simple mathematical operations as a secondary task, and participants stood with their back foot's big toe 5 cm behind the front foot's heel (Terra et al., 2020). However, based on our study, assessing balance under dual-task conditions provides more reliable CoP measures for diagnosing balance impairments and tracking therapeutic outcomes in chronic post-stroke individuals.

Closing eyes had no significant effect on CoP parameters' reliability in our study, which aligns with the findings of other studies on post-stroke patients (Gasq et al., 2014) and elders (Li et al., 2016; Lo et al., 2022; Moghadam et al., 2011; Salehi et al., 2010). However, future studies may reveal the exact effect of closing eyes on the reliability of CoP measures when assessing balance in stroke survivors.

Previous research has reported lower reliability for the CoP sway area in stroke patients (Aryan et al., 2023; Gasq et al., 2014; Gray et al., 2014), which contradicts our findings. The lack of research on the sway area of CoP in chronic post-stroke individuals makes it challenging to identify the root of the discrepancy. However, the broad age range of our participants (27 to 76 years) can obscure the test re-test inconsistency; as pointed out by Ruhe et al. (2010), differences in trial duration and foot position may have contributed to inconsistent results. As we found, some studies have shown that sway area is a reliable CoP measure in older adults (18-20, 35, 36) and adults with Parkinson disease (Terra et al., 2020). This outcome could be attributed to some similarities between participants of previous studies and recent populations.

Within-day reliability

Higher within-day ICCs were found than between-day ICCs, consistent with studies on young and old individuals (Benvenuti et al., 1999; Lin et al., 2008; Ruhe et al., 2010). Gray et al. (2014) concluded that averaging ten internal perturbation trials in post-stroke patients improved between-day reliability compared to within-day reliability of CoP measures. However, this population has achieved high within-day reliability in fewer trials (Gray et al., 2014; Jagroop et al., 2023). Fatigue may cause decreased reliability in pathologically affected or elderly individuals during extra trials (Gray et al., 2014; Ruhe et al., 2010).

According to the results, measurements in quiet standing showed high absolute reliability in all three conditions. Jagroop et al. (2023) found lower absolute reliability than our findings in quiet standing in chronic stroke individuals. However, they measured the RMS of CoP velocity. SEM was 4.9 mm for the RMS of Vml and 3.7 mm for the RMS of Vap. Their participants were older (mean age: 64±9.5 years), and they conducted two assessment trials despite identifying that three trials would result in an ICC higher than 0.9 (Jagroop et al., 2023).

In quiet standing, MDCs were lower than in previous results (Aryan et al., 2023). Aryan et al. (2023) investigated the within-session reliability of CoP measures in subacute post-stroke individuals. They reported higher SEMs, and consequently higher MDCs, for Vap and Vml in quiet standing than we found (SEM: 2.83, MDC: 7.84 vs SEM: 0.67, MDC:1.84 for Vap; and SEM: 1.59, MDC:4.41 vs SEM: 0.41, MDC: 1.14 for Vml) (Aryan et al., 2023). It was suggested that balance measures may be less stable among people in early stroke recovery stages (Jagroop et al., 2023), resulting in higher MDCs in their study.

Between-day reliability

Most measures of CoP had high to very high between-day reliability (Table 4). Correspondingly, dual-tasking could increase the reliability of measurements in quiet standing except for the CoP sway area. Gray et al. (2014) found similar results for the load drop task during quiet standing (ICC: 0.78-0.89) than primary quiet standing (ICC: 0.52-0.98). Swanenburg et al. (2008) examined the reliability of CoP measures in fallers and non-fallers under single and dual-task conditions. They reported no significant differences in reliability between test conditions (Swanenburg et al., 2008). However, the mean velocity ICC increased from 0.70 to 0.94 in the fallers performing a secondary cognitive task. Interestingly, they also revealed a decrease in sway area reliability in fallers due to cognitive dual-tasking (ICC 0.69 changed to 0.57), like a study on healthy elders (Moghadam et al., 2011) and our findings. Further investigation is necessary to determine the cause of reduced sway area reliability during dual-task assessment.

It is important to note that the study results may not apply to people other than those with hemiplegic stroke or at different stages of recovery. Additionally, our sample size was limited, which could influence the generalizability of the results, as it may not encompass heterogeneous postural control mechanisms among chronic stroke survivors.

In summary, CoP measures in various positions and conditions are reliable enough to assess balance in chronic stroke survivors. Measuring CoP excursion during dual-task conditions is a more reliable method while evaluating the postural control system, especially in semi-tandem standing. Improving balance assessments by using more reliable measures during dual-tasking can help us understand balance impairments and lead to better rehabilitation interventions.

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the Ethics Committee of the University of Social Welfare and Rehabilitation Sciences, Tehran, Iran (Code: IR.USWR.REC.1398.13664596). All subjects signed an informed consent form before participating in the survey. Participants participated in an unpublished clinical trial (Code: IRCT20220703055350N1).

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Authors' contributions

Conceptualization and methodology: Mitra Parsa, Mohammad Ali Sanjari, Hossein Negahban, and Iraj Abdollahi; Software: Mohammad Ali Sanjari; Formal analysis: Enayatollah Bakhshi and Mitra Parsa; Investigation: Mitra Parsa and Mohammad Ali Sanjari; Data curation: Haniyeh Fakur Haddadiyan, Mitra Parsa, and Mohammad Ali Sanjari; Resources, and writing the original draft: Mitra Parsa; Review, and editing: Mitra Parsa, Mohammad Ali Sanjari, and Hossein Negahban; Supervision: Mohammad Ali Sanjari, Hossein Negahban, Iraj Abdollahi, and Enayatollah Bakhshi.

Conflict of interest

The authors declared no conflict of interest.

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