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Postural control during quiet standing and voluntary stepping response tasks in individuals post-stroke: a case-control study

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Abstract

Background: Postural control impairments following a stroke have impact on mobility, reduce independence and increase the risk of falls. Assessing these impairments during tasks representative of real-life situations, such as quiet standing (QS) and voluntary stepping response (VSR) will enhance our understanding of how the postural control system is impaired in individuals post-stroke (IPS). It will also inform the development of a more targeted and effective rehabilitation to prevent falls in IPS.

Objectives: Identify the postural control impairments encountered by IPS during QS and VSR.

Methods: Twenty IPS and sixteen healthy controls were recruited to perform QS and VSR tasks while ground reaction forces and whole-body motion were measured. Displacement and speed variation of the COM, centre of pressure (COP) displacement and spatiotemporal data were calculated and compared between groups.

Results: During QS, IPS exhibited greater maximal COP displacement in mediolateral direction, COM displacement in vertical direction and COM speed excursions compared to controls. During VSR, IPS exhibited smaller step length, braking force, posterior foot placement in relation to the pelvis and COM anteroposterior excursion compared to controls. IPS presented less static and dynamic postural stability compared to controls.

Conclusions: Greater postural sway during QS, smaller anteroposterior COM displacement before losing balance and altered voluntary recovering steps during VSR could place IPS at more risk of falling when they face a postural challenge in the community. These novel results will improve the current knowledge base and should be considered in IPS rehabilitation.

Keywords: biomechanics, balance control, stroke, postural control, quiet standing, voluntary stepping response

Word count: 3016

Introduction

Stroke is a serious global health problem affecting 33 million in 2010[1] rising to 77 million by 2030.[2] It is the leading cause of disability in Europe and the United States of America.[3, 4] One of the numerous disabilities following a stroke is impairment in postural control, which has impact on mobility, reduce independence and increase the risk of falls.[5] All of these factors are known to affect self-efficacy, quality of life and the ability to maintain previous life roles.[6] Individuals post-stroke (IPS) exhibit asymmetrical load distribution and greater postural sway compared to healthy counterparts.[7] Also, during stance, their centre of pressure (COP) demonstrates larger and faster movements making them more at risk of falling.[8] Most previous studies focused on quiet standing (QS) tasks to assess the postural control impairments in IPS.[8, 9] However, other daily situations, known to be impaired in IPS, will challenge their postural control system such as bending the trunk to reach out for an object and taking a protective step following a perturbation.[10-13] During simulations of a slip or a trip, IPS exhibit many deficits known to increase their risk of falling, namely alterations in body movements and velocity and inefficient compensatory steps to avoid falling.[12, 13] Taking an efficient protective step after a perturbation is important, as using a multistep response is predictive of falls in daily life.[13, 14] Little attention has been paid to self-induced perturbation tasks that do not include a simulated trip or slip in previous studies. It is imperative to better understand the dynamic postural impairments during these challenging situations as they could also place IPS at risk of losing balance and fall. Furthermore, these tasks that do not include a simulated slip or trip could be more easily implemented in clinical contexts to evaluate postural control deficits or response to treatments in IPS, as they do not require specialised equipment. Ultimately, improving our knowledge about static and dynamic postural control impairments in

IPS could inform treatment targeted toward the specific deficits experienced by these individuals and could help increase their independence, participation in society and prevent falls.

Also, most previous studies analysed the COP trajectory to investigate postural control in IPS.[8, 9, 15] However, analysing the displacement of the centre of mass (COM) could also provide additional useful information about their postural control impairments[16] as it is the only variable that characterises body sway and have been identified as a strong predictor of risks of falls during highly challenging slip or trip-related perturbation tasks.[12, 13] However, its movement during less challenging postural control tasks, such as voluntary stepping response (VSR) and QS tasks, remains unclear for IPS. Thus, further studies are needed to determine how COM movements are altered in IPS during these tasks especially as it could be a good indicator of postural instability for these individuals.[16]

Thus, the main objective of this study was to identify the static and dynamic postural control impairments encountered by IPS using COP, COM and spatiotemporal outcomes. It was hypothesised that IPS will exhibit significant balance impairments known to increase the risk of falls, such as increased COP and COM displacement during static and dynamic postural control tasks and smaller recovering steps.

Materials and methods

Participants

Twenty IPS and 16 healthy age-matched adults (controls) were recruited to participate to this case-control study (Table 1) from July 2017 to December 2019. Sample size was determined based on the results of preliminary data. In this study, we sought to include IPS, at any time following a stroke, with at least the minimum level of mobility to safely take part to the protocol.

Thus, the results would be generalisable to the widest possible group of IPS with minimum mobility levels, meaning they might encounter some of the balance challenges the study posed in everyday life. For this reason, we included anyone who was able to stand independently and who had sufficient dynamic postural control to be able to safely take part to the study. Potential participants were excluded if they had cognitive deficits that affected the understanding of instructions or provision of informed consent (as indicated by Mini-Mental State Examination (MMSE) < 24), had visual problem that cannot be corrected with glasses, or had other neurological, cardiovascular, or musculoskeletal conditions (e.g. lower extremities amputation, injury, osteoporosis or etc.) that could have impeded their ability to perform any instrument testing without any braces or orthoses. IPS were included if they suffered of a stroke of any aetiology and controls were included if they had no self-reported health issues which may have affected their balance.

IPS were invited to take part through community stroke support and exercise groups in Greater Manchester, United Kingdom, whereas controls were recruited by poster advertisements and email invitations to University staff and students, participants of previous studies who have agreed to be contacted for further studies and carers/partners of IPS. The University of Salford, College of Health and Social Care Research Ethics Committee approved the study, and all participants provided written informed consent. The manuscript also conforms with the STROBE guidelines.

Instrumentations

Kinematic data were collected with ten 100Hz cameras (Vicon, Oxford Metrics) with reflective markers attached on the participants' anterior superior iliac spines, posterior superior iliac spines, lateral thighs, lateral and medial femoral epicondyles, lateral legs, lateral malleolus, 2nd metatarsal heads, calcaneal tubercles, forehead, backhead, C7, T10, jugular notch, xiphoid process, right back, acromions, lateral humeral epicondyles, lateral arms, lateral forearms, left and right distal of radius, left and right ulnar head, and the 2nd metacarpal heads according to the Plug-in gait full body kinematic model. Kinetic data were collected at a sampling rate of 1 000 Hz with two force plates (AMTI, USA) embedded in the floor and synchronised with the kinematic data.

Experimental protocol

First, demographic data regarding age, sex, weight, height, number of falls in the last 12 months and stroke duration (IPS only) were collected by self-report. Participants also filled the consent form and the Activities-specific Balance Confidence (ABC) scale.[17] Then, Mini-Mental Status Exam (MMSE),[18] Fugl-Meyer motor Assessment Lower extremity (FMA-LE) and sensation (FMA-S) scales (IPS only),[19] Dynamic Gait Index (DGI)[20] and Mini-Balance Evaluation-Systems test (mini-BESTest)[21] (only the anticipatory and reactive postural control sections) were administered to participants.

A calibration trial was recorded during relaxed standing in which participants placed their feet in a natural, self-selected posture, attempting equal weight bearing on both feet. A comfortable position was used as it allows for a more practical and realistic evaluation of postural control of IPS without changing postural stability compared to a standardised position.[22] Then, participants had to stand on a force plate for 30 seconds and try to move as little as possible with both feet always in contact with the force plate (QS task) until an audio cue appears as a signal to start leaning forward with whole body until they feel they are losing balance and take a step to prevent themselves from falling (VSR task). These two tasks were chosen as they can easily be implemented in clinical contexts with minimal equipment. The VSR task was previously used by members of our research team to efficiently determine postural control differences between IPS and controls.[23] All participants were barefoot during all testing trials. No support of any kind was permitted during data collection. Three to five practice trials were allowed to promote familiarity with the test and ensure response stability. Then, ten trials were collected for each participant. Resting was permitted as needed to prevent fatigue. To assure participants' safety and prevent a fall during the tasks, a research assistant stood beside them to provide support as needed.

Data processing

Biomechanical data were processed using Visual3D software (C-motion, Inc., Germantown, MD, USA). Kinematic data were low-pass filtered using a 4^{th} order Butterworth filter with a cut-off frequency of 10 Hz and individual segment coordinate systems were defined using anatomical markers. The variables measured during the QS task were the anterior/posterior (AP) and medial/lateral (ML) COP displacement and AP/ML/vertical maximal COM displacement and speed excursion (maximal subtracted by minimal speed). During the VSR task, the variables measured were step length and width (normalised to leg length), step duration, AP/ML/vertical COM excursion (between initial forward leaning and toe off), braking force (normalised to body mass), anterior foot placement in relation to pelvis (AFPP) and posterior foot placement in relation to pelvis (PFPP). Step length and width were respectively calculated using the stepping limb's heel and medial malleolus markers. A negative value for the step width refers to a step taken towards the other foot. A negative value for the COM excursion in ML and vertical directions respectively refers to the COM moving towards the stepping limb and the ground. The braking force was calculated by dividing the maximal AP force, measured using the force plate under the stepping foot, by the mass of the participant. AFPP and PFPP were respectively defined as the AP absolute distance between the COM and the heel marker of the stepping and support limbs.

Statistical analysis

IBM SPSS v.27.0.0.1 was used to compare the descriptive and biomechanical data of the IPS and the control groups using Mann Whitney tests for data that showed abnormal distribution and independent t tests for data that showed normal distribution according to Shapiro–Wilk's test ($p<0.05$). Cohen's d effect sizes and 95% confidence intervals were calculated to compare the biomechanical data between the IPS and control groups. The level of statistical significance was set at $p<0.05$ and d≥0.50 for all analyses.

Results

There was no statistically significant difference in age, weight, height, MMSE score and falls in the last 12 months between the IPS and the control groups. Greater ABC, mini BESTest and DGI scores ($p<.001$) were observed for the control compared to the IPS group (see Table 1). Individualised information is available in Supplementary material.

During the QS task, the IPS group exhibited greater COP displacement in ML direction (2.99 (CI=2.56-3.42) vs 2.30 cm (CI=1.73-2.64), d=0.92, p=0.011), COM displacement in vertical direction (0.59 (CI=0.47-0.71) vs 0.32 cm (CI=0.25-0.39), d=1.24, p=0.001) as well as COM speed excursion in AP (4.27 (CI=3.49-5.04) vs 3.03 cm/s (CI=2.53-3.52), d=0.90, p=0.012), ML (3.06 (CI=2.49-3.63) vs 1.99 cm/s (CI=1.50-2.49), d=0.97, p=0.007) and vertical (2.35 (CI=1.51-3.18) vs 1.33 cm/s (CI=0.78-1.88), d=0.68, p=0.030) directions compared to the control group. No between-group differences were observed for COP displacement in AP direction and COM displacement in AP and ML directions. All between-group comparisons during the QS task are presented in the Table 2.

Only 19 of the 20 IPS completed the VSR task as one participant did not feel confident enough and was afraid of falling. The IPS group exhibited smaller step length (49.19 (CI=40.67-57.71) vs 89.84% (CI=56.31-123.37), d=-0.92, $p<0.001$), braking force (1.40 (CI=1.02-1.78) vs 2.91 N/kg (CI=2.41-3.41), d=-1.81, $p<0.001$), PFPP (29.79 (CI=24.47-35.10) vs 43.18 cm (CI=38.84-47.52), d=-1.37, $p<0.001$) and COM excursion in AP direction (15.76 (CI=12.71-18.81) vs 20.49 cm (CI=17.90-23.07), d=-0.83, $p=0.020$) compared to the control group. No between-group differences were observed for step width and duration, COM excursion in ML and vertical directions and for AFPP. All between-group comparisons during the VSR task are presented in the Table 2.

Discussion

The main objective of this study was to identify the static and dynamic postural control impairments encountered by IPS using COP, COM and spatiotemporal outcomes. It was hypothesised that IPS would exhibit significant balance impairments known to increase the risk of falls, such as increased COP and COM displacements and speed excursions during static and dynamic postural control tasks and smaller recovering steps. Our results provide new insights about static and dynamic postural control deficits in IPS compared to healthy counterparts. Consistent with our hypotheses, greater COM vertical displacement was observed during QS, revealing more postural sway in IPS, known to increase the risk of falls.[24] It is the first study to measure COM movements to analyse postural control in IPS during QS and thus our results could not be directly compared with those of previous studies. However, Yu et al.[16] observed greater COM acceleration and scalar distance between COP and COM in IPS compared to controls during QS, suggesting impaired postural control. We also observed greater COM speed excursion in all planes during QS. Greater COM displacement is a strong predictor of falls in IPS during slip-related perturbation tasks[12, 13] and the inability to control the dynamic COM state (velocity and position) is a causative factor of falls.[13, 25] The greater COM displacement and speed excursions observed in our study are novel and will add to the current body of knowledge by revealing that dynamic COM state is altered in IPS not only during highly challenging dynamic tasks, but also during easier static task. These results could perhaps be explained by the stroke-related impairments (e.g., proprioceptive impairments, muscle weakness, limb paralysis, post-stroke brain damage affective cognitive processing and sensorimotor integration) and thus greater postural sway results from these deficits. For example, greater postural sway, identified with COP measurements, was observed in IPS with impaired ankle proprioception.[26] Further studies are needed to better understand how the COM movements and speed excursions are altered in IPS during QS and to correlate these impairments with clinical tests.

IPS also exhibited greater COP displacement in ML direction during QS, which is consistent with a previous study that found greater ML RMS COP displacement for IPS compared to healthy counterparts.[15] ML stability seems to be mostly related to plantar cutaneous mechanoreceptors activity,[27] which gives information to the central nervous system about how the foot is positioned on the ground and how the body is leaning over the feet.[28] As many as 89% of IPS will exhibit somatosensory deficits,[29] known to be detrimental to postural control for this population.[30] Deficits in plantar cutaneous sensation may be one of the underlying factors explaining the greater ML COP displacement observed in this study and perhaps the high incidence of falls experienced by IPS. Surprisingly, no between-group statistically significant difference in COM ML displacement was found even though COM and COP movements are related during QS. However, the increased COM ML displacement in IPS compared to controls observed in our study almost reached statistical significance (p=0.072) and the effect size was moderate (d=0.73). With a greater number of participants, this difference could perhaps reach statistical significance and thus change this result. Future studies should try to correlate the loss of plantar cutaneous sensation with postural control ability in IPS.

During the VSR task, IPS exhibited a smaller AP COM excursion compared to controls. This result suggests that IPS lose balance with less COM anterior displacement and could place them at greater risk of falling following a postural perturbation. No comparison could be made with previous studies, as it is the first to measure the COM movements during a forward leaning task. However, Portnoy et al.[8] observed a greater minimal anterior distance of the COP from the base of support and a smaller AP COP displacement during a functional reach task. These are consistent with our results and suggest that IPS lose balance with less anterior body displacement. The greater AP COM excursion found in our study could perhaps explain the shorter recovering step, the smaller PFPP and braking forces observed in IPS compared to controls. As COM travels less anteriorly, a shorter step is required to recover balance. As there was no difference in step duration, it can be hypothesised that the AP momentum of the stepping leg was decreased for IPS, explaining the smaller braking forces for these individuals. On the other hand, if this recovering step is too short, it may be inadequate to recover balance and force the IPS to use a multistep response to recover, which is known to predispose the individuals with poor postural control to fall.[14] Our results are consistent with those of Gray et al.,[22] which found that IPS took longer to initiate a shorter lateral voluntary step compared to controls. Preventing a fall often requires increasing the body's base of support with a quick and fast step to slow down the momentum of the body's COM.[22] The inability of IPS to react to external or self-induced perturbations with an efficient step place them at greater risk of falling. In light of our results, we suggest that clinicians treating IPS use QS and VSR tasks to quantify their postural control deficits.

The first limitation that should be considered for this study is that the data collection session took place in a highly controlled environment. The participants knew when and how they were going to lose balance and that the risks of falling were minimal during the VSR task. In real life situations, falls generally occurs during unexpected perturbations with little time to prepare or react [31]. The results of our study may not be representative of these situations. As IPS may experience fear of falling, they may have taken a conservative approach in taking the step during VSR. Future studies should investigate if similar postural control deficits are observed during unexpected postural perturbations. The second limitation of this study is that IPS may have experienced more fatigue than their healthy counterparts during the data collection as they present decreased physical fitness.[32] Physical exertion is known to increase postural sway in IPS.[33] To prevent IPS from experiencing fatigue, rest periods were given as needed to the participants. The third limitation is the difference in male/female ratio between the groups. Previous studies suggested slight differences in postural control between genders in other population.[34, 35] However, it remains unclear whether gender affects postural control of IPS during static and dynamic postural stability tasks.

Conclusion

IPS present less static and dynamic postural stability compared to healthy counterparts. The postural control impairments are observed when standing upright as well as when leaning forward and taking a step to recover and avoid falling. Greater postural sway during QS, highlighted by greater COM vertical displacement and COM speed excursions, as well as smaller AP maximal COM displacement before losing balance and altered recovering steps during VSR likely place IPS at more risk of falling when they face a postural challenge in the community. These results will inform more targeted and effective treatments to prevent falls in IPS.

Declaration of interest statement

The authors have no conflict of interest in this study.

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Table 1 Demographic data

	Individuals post-stroke	Controls
Age (yrs)	67.4 (11.5)	68.9 (8.1)
Gender ratio (M/F)	(16/4)	(7/9)
Height (m)	1.70 (0.09)	1.67 (0.09)
Weight (kg)	81.1 (11.6)	71.6 (15.9)
MMSE (/30)	28.6 (1.8)	29.3 (1.3)
ABC (/100)	63.0 (24.9)*	98.5 (2.2)*
Mini BESTest (/12)	5.2 (4.0)*	11.7 (0.8)*
DGI (/24)	15.4 (6.3)*	23.8 (0.6)*
Falls last 12 months	1.2 (3.2)	0.1 (0.3)
Stroke duration (yrs)	8.1 (9.3)	--
FMA-LE (/34)	22.4 (9.7)	--
FMA-S (/12)	11.2 (1.5)	--

Significant between-group differences (p<0.001) are identified with *.
Results are expressed as mean (SD) except for gender ratio.
MMSE: Mini-Mental Status Exam, Mini BESTest: Mini-Balance Evaluation-Systems test, DGI: Dynamic Gait Index, FMA-LE: Fugl-Meyer motor Assessment Lower extremity, FMA-S: Fugl-Meyer motor Assessment sensation.

Table 2. Biomechanical parameters during QS and VSR tasks

		Individuals post-stroke	Controls	Cohen's d	*p* value
QS	COP displacement AP (cm)	2.97 (2.41-3.52)	2.30 (1.82-2.77)	0.64	0.068
	COP displacement ML (cm)	2.99 (2.56-3.42)	2.18 (1.73-2.64)	0.92	0.011
	COM displacement AP (cm)	9.73 (5.25-14.20)	4.21 (2.12-6.30)	0.88	0.111
	COM displacement ML (cm)	2.24 (1.45-3.04)	1.37 (0.99-1.75)	0.73	0.072
	COM displacement vertical (cm)	0.59 (0.47-0.71)	0.32 (0.25-0.39)	1.24	0.001
	COM speed excursion AP (cm/s)	4.27 (3.49-5.04)	3.03 (2.53-3.52)	0.90	0.012
	COM speed excursion ML (cm/s)	3.06 (2.49-3.63)	1.99 (1.50-2.49)	0.97	0.007
	COM speed excursion vertical (cm/s)	2.35 (1.51-3.18)	1.33 (0.78-1.88)	0.68	0.030
VSR	Step length (%)	49.19 (40.67-57.71)	89.84 (56.31-123.37)	-0.92	<0.001
	Step width (%)	2.08 (0.44-3.71)	1.87 (-1.90-5.64)	0.04	0.220
	Step duration (ms)	281.14 (246.33-315.94)	297.16 (269.18-325.13)	-0.26	0.455
	COM excursion AP (cm)	15.76 (12.71-18.81)	20.49 (17.90-23.07)	-0.83	0.020
	COM excursion ML (cm)	-0.26 (-2.38-1.86)	-1.08 (-2.18-0.02)	0.23	0.500
	COM excursion vertical (cm)	-0.50 (-1.52-0.51)	-0.58 (-1.12--0.05)	0.05	0.888
	Braking force (N/kg)	1.40 (1.02-1.78)	2.91 (2.41-3.41)	-1.81	<0.001
	AFPP (cm)	14.54 (8.40-20.69)	17.45 (13.72-21.18)	-0.28	0.080
	PFPP (cm)	29.79 (24.47-35.10)	43.18 (38.84-47.52)	-1.37	<0.001

Results are displayed as means (95% confidence intervals). AFPP: Anterior foot placement in relation to pelvis, AP: Antero-posterior, COP: Centre of pressure, COM: Centre of mass, ML: Medio-lateral, PFPP: Posterior foot placement in relation to pelvis, QS: Quiet standing, VSR: Voluntary stepping response.

Participant No.	Age (y)	Weight (kg)	Height (cm)	Sex (M/F)	Type of stroke	Stroke duration (y)	Hemiplegic side	Stepping foot	MMSE (/30)	ABC (/100)	FMA-LE (/34)	FMA-S (/12)	Mini BESTest (/12)	DGI (/24)
1	60	76.0	175.0	M	Hemorrhagic	6	R	R	30	56	7	12	1	N/A
2	71	82.6	170.0	M	Hemorrhagic	44	R	R	29	43	21	12	0	N/A
3	66	66.6	168.0	M	Hemorrhagic	8	R	R	30	81	26	12	5	N/A
4	62	88.9	170.0	M	Hemorrhagic	4	R	R	29	58	22	12	7	20
5	47	98.0	178.0	M	Hemorrhagic	7	L	L	30	79	20	10	6	12
6	45	95.0	173.0	M	Hemorrhagic	3	L	L	28	29	23	7	6	16
7	77	70.0	168.0	M	Ischemic	4	R	R	30	59	22	11	3	16
8	64	69.9	179.0	M	Hemorrhagic	3	L	L	29	89	28	10	8	19
9	84	77.1	179.0	M	Hemorrhagic	7	L	R	26	86	34	11	5	16
10	54	83.0	182.0	M	Ischemic	3	R	R	30	89	34	12	10	23
11	55	91.0	155.0	F	Hemorrhagic	9	R	L	28	55	4	12	1	9
12	80	77.0	162.5	F	Ischemic	3	R	L	27	77	30	10	6	15
13	80	65.0	156.5	M	Unknown	3	R	50%L, 50%R	29	100	32	12	11	24
14	75	102.0	183.0	M	Hemorrhagic	6	L	L	30	94	33	12	12	24
15	75	86.0	166.0	M	Ischemic	10	R	R	30	24	12	12	1	3
16	73	64.0	168.0	F	Hemorrhagic	9	L	L	30	18	20	12	2	10
17	81	91.0	157.0	F	Hemorrhagic	4	L	R	30	75	34	12	11	23
18	65	79.0	163.5	M	Ischemic	7	L	L	26	73	17	12	8	14
19	60	91.0	170.5	M	Hemorrhagic	3	L	N/A	27	36	4	8	0	6
20	75	68.0	174.5	M	Ischemic	10	R	L	24	38	24	12	1	12

Supplementary material: Individualised information for individuals post-stroke

Abbreviations

ABC: Activities-specific Balance Confidence scale
DGI: Dynamic Gait Index
F: Female
FMA-LE: Fugl-Meyer motor Assessment Lower extremity
FMA-S: Fugl-Meyer motor Assessment Sensation
L: Left
M: Male
Mini BESTest: Mini-Balance Evaluation Systems test
MMSE: Mini-Mental State Exam
N/A: Data not available
R: Right