European Journal of Physical and Rehabilitation Medicine 2026 June;62(3):269-76
DOI: 10.23736/S1973-9087.26.09514-6

ORIGINAL ARTICLE

Early posturographic changes as predictors of functional recovery after stroke: a proof of concept

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ABSTRACT

BACKGROUND: Posturography could serve as an early predictor of recovery of postural control and balance, especially if structural parameters are identified.
AIM: This study aimed to explore the predictive value of posturographic measures for motor recovery after stroke using post-hoc analysis of a clinical trial cohort, to generate hypotheses for future confirmatory studies.
DESIGN: A post hoc analysis was conducted in a cohort of thirty-eight individuals with subacute post-stroke hemiparesis presenting with balance and gait impairments.
SETTING: All participants were recruited from the Rehabilitation Department of the Rey Juan Carlos Hospital (Spain).
POPULATION: Participants included in the study were individuals who had experienced a stroke.
METHODS: Posturographic variables were collected at baseline and after 4 weeks, and their changes were correlated with functional outcomes at follow-up. Univariate and multivariate binary logistic regression models were used to examine whether improvements exceeding the minimum detectable change in mediolateral structural parameters were associated with better functional outcomes based on Berg Balance Scale (BBS) scores ("*High response*)". Internal validation of the model was performed using bias-corrected and accelerated (BCa) bootstrap resampling."
RESULTS: Participants who showed significant improvements in all three structural parameters of the X-axis demonstrated a strong association with *High response* in the univariate model (OR=6.8; 95% CI: 1.20-35.56; P=0.03). This association remained independently significant in the multivariable analysis (adjusted OR 6.9; 95% CI: 1.13-42.09; P=0.04). In contrast, no significant associations were observed for anteroposterior parameters.
CONCLUSIONS: X-axis–related posturographic variables may have potential as predictors of rehabilitation response after stroke; however, given the post hoc nature of this analysis, these findings should be considered exploratory and require confirmation in prospective studies.
CLINICAL REHABILITATION IMPACT: Early improvements in mediolateral posturographic parameters may help identify individuals with stroke who are more likely to achieve meaningful balance recovery. However, given the exploratory, proof-of-concept nature of this study, these findings should be interpreted with caution and require confirmation in prospective studies, while potentially providing a starting point for future research in this area.

(*Cite this article as:* Díaz-López N, Marcos-Antón S, González-Cervantes S, del Puerto-Nevado L. Early posturographic changes as predictors of functional recovery after stroke: a proof of concept. Eur J Phys Rehabil Med 2026;62:269-76. DOI: 10.23736/S1973-9087.26.09514-6)

KEY WORDS: Stroke; Neurological rehabilitation; Biomarkers; Recovery of function; Postural balance.

Introduction

Stroke is one of the leading causes of adult disability worldwide,[1, 2] with only 14% of individuals achieving full functional recovery. Between 25-50% of survivors require some form of assistance with daily activities, and nearly half of stroke survivors experience some degree of long-term dependence.[3, 4] The ability of individuals to be independent after a stroke largely depends on the extent of motor function recovery. Post-stroke balance disorders are one of the main factors that determine the mobility and independence of these people and are therefore considered key rehabilitation targets.[5-7]

Predicting motor function recovery after stroke on an individual basis is challenging, but it could facilitate planning the most appropriate interventions by healthcare professionals, enabling the establishment of realistic and achievable goals for both people and their families.[3, 7] The people's age, stroke severity, prior motor function, the presence of cognitive deficits and motivational state have traditionally been considered as strong predictors of long-term recovery.[3] However, these factors do not allow for establishing a specific and individualized prognosis. In routine practice, functional assessment relies mainly on clinical scales, which, although widely used, often lack the sensitivity and objectivity required to detect subtle changes over time.[8]

Posturography has emerged as an objective tool for assessing and monitoring posture in both standing and sitting positions.[5, 6] This platform registers the displacement of the center of pressure (COP) over the individual's support base.[9] Despite its good results in terms of reliability and patient acceptance, posturography is not yet a standardized tool, possibly due to the large volume of data provided by a single assessment, which makes it difficult for its clinical interpretation or translation.

Several authors have categorized the relevant parameters from posturography into two main groups: global and structural variables,[10] to facilitate understanding and evaluation of results obtained. Additionally, structural indicators of mediolateral (X-axis) and antero-posterior (Y-axis) displacement have been highlighted as crucial in quantifying individual's postural control capacity,[5, 9] emphasizing the importance of specific evaluation of these parameters.[11-13]

Based on the published evidence suggesting a key role of mediolateral imbalance in post-stroke recovery, this study aims to preliminary examine the potential predictive value of specific posturographic variables in relation to balance control, which have not yet been used as predictive markers of functional recovery in stroke survivors. The findings of this study are intended to provide an initial framework and generate hypotheses for future research, which may eventually contribute to the identification of early objective markers to support clinical decision-making.

Materials and methods

Ethical considerations

This study constitutes a *post-hoc* analysis of data collected during a randomized clinical trial previously approved by the Research Ethics Committee of the Jimenez Díaz Foundation Health Institute (Spain) (Ethics Code: PIC0B7-17_HRJC) on October 17, 2017. The original trial is registered in the Australian and New Zealand Clinical Trials Registry (ANZCTR) under registration number ACTRN12620000107921.

All participants provided written informed consent prior to inclusion in the original study.

No new data was collected for this post hoc analysis, and no additional interventions were required from participants. The data were treated anonymously, and the ethical principles of the Declaration of Helsinki were respected throughout the study.

Study design

This study presents a post hoc analysis of data from a single-blind, randomized controlled trial with blinded assessment. The original trial was designed to evaluate the effectiveness of combining implicit motor imagery tasks with neurorehabilitation in improving postural control and balance in stroke survivors.[14] The analysis presented here was not pre-specified in the original protocol and has been performed for exploratory purposes.

The treatments applied in this study are described in detail using a standard table adapted from the TIDieR checklist.

The original randomized controlled trial followed the CONSORT reporting guidelines for randomized clinical trials.[14]

Participants

All participants were recruited from the Rehabilitation Department of the Rey Juan Carlos Hospital (Spain), referred to by the Neurology Department with a medical diagnosis of hemiparesis secondary to stroke. Participant data were collected between January 2018 to December 2021.

Inclusion criteria were: 1) a single stroke episode occurring within the previous six months; 2) age ≥18 years old; 3) ability to maintain static standing posture without support for at least one minute; 4) absence of comorbidities preventing intensive rehabilitation; 5) no use of assistive gait devices prior to stroke; and 6) no medical diagnosis of cortical blindness or pre-existing vision impairment that could interface with the intervention materials.

Baseline sociodemographic data were collected from the participants, including age, gender, stroke characteristics (time since onset, lesion location, National Institute of Health Stroke Scale score – NIHSS, time since the event) and cardiovascular risk factors (hypertension, dyslipidemia, diabetes mellitus, smoking habit, and heart disease).

Outcome measures

The Berg Balance Scale (BBS) was developed to assess postural control in individuals with different clinical conditions, including stroke. This scale has an excellent test-retest reliability, with an intraclass correlation coefficient (ICC) of 0.99, and is considered a gold standard assessment tool.[15] The scale consists of 14 items, and a maximum score of 56 points can be obtained. Scores below 40 are associated with a significant increase in the risk of falls.[16]

Posturography is a technique that uses a dynamometric platform to evaluate the postural control of a subject through analysis of COP displacement during the performance of the Romberg test in a standing position for 60 seconds.[17] It is based on the theory that COP oscillations reflect the individual's postural instability.[18] The force platform detects vertical pressures exerted and transmits them to a computer system to record the variations during the test. The Satel PF8CTM device was used to record global variables (sway area, sway path length and percentage of load asymmetry between lower limbs) and structural variables related to the mediolateral (X-axis) and antero-posterior (Y-Axis) displacements: displacement length, displacement amplitude and instability index for each of the axis.

Data preprocessing

This study constitutes an exploratory post-hoc analysis of a previously conducted clinical trial. Given the exploratory design and limited sample size, emphasis was placed on effect size estimation (odds ratios with confidence intervals) and bootstrap-based internal validation rather than on p-values alone, aiming to generate preliminary estimates and hypothesis-generating findings to inform future prospective studies in larger cohorts.

Regarding the outcome variable, to the best of our knowledge, no previous studies have distinguished between a 'high response' and a 'standard response' on the BBS when comparing pre- and post-treatment outcomes. Given that all participants exhibited improvement, the response variable was stratified using a distribution-based approach. A 'high response' was defined as a change in BBS score (ΔBBS; post-pre difference) above the sample median of the ΔBBS distribution. This sample-derived cutoff (10 points) yielded two categories: high responders (above-median improvement) and standard responders (below-median or equal-to-median improvement). Given the absence of clinically or biologically validated thresholds, this approach was used purely for exploratory purposes and should be interpreted as hypothesis-generating rather than clinically definitive.

To evaluate the impact of posturographic variables, a two-step preprocessing procedure was applied. First, pre–post differences for each parameter were calculated and classified according to the corresponding Minimum Detectable Change (MDC). As no established cut-offs for meaningful change in posturographic measures exist for this population, the MDC was estimated within our sample. This approach ensures that observed differences represent true changes beyond measurement error or random variability.

Differences exceeding the MDC were classified as "change," whereas differences less than or equal to the MDC were categorized as "no change." Only positive differences (indicating improvement) were considered as "change"; changes reflecting deterioration, although exceeding the MDC, were grouped within the "no change" category for this analysis.

The MDC was calculated as: $MDC = SEM \times z \times \sqrt{2}$, where SEM is the standard error of measurement and z corresponds to the 95% confidence level (1.96).

In the second step, improvement along the X-axis was defined as concurrent true changes (*i.e.*, exceeding the MDC) in all three X-axis-related parameters: length, amplitude, and instability. Similarly, improvement along the Y-axis was defined as true changes in all three Y-axis-related parameters: length, amplitude, and instability. Given the relatively small sample size, this criterion was adopted to reduce the likelihood of overestimating effects based on partial changes in individual parameters. Requiring concurrent improvement across all dimensions was intended to enhance the robustness and reliability of the results.

Statistical analysis

Clinicopathological characteristics of the participants were described. Categorical variables were reported as frequencies and percentages, whereas continuous variables were summarized as median values with interquartile range (IQR).

The association between clinical and processed posturographic variables and the outcome "high response" was evaluated using binary logistic regression models in both univariate and multivariate analyses. Variables showing potential prognostic relevance in the univariate analyses (*i.e.*, those reaching statistical significance or showing a trend toward significance) were subsequently included in the multivariate model.

Given the limited sample size and the potential risk of overfitting, internal validation was performed using 5000 bias-corrected and accelerated (BCa) bootstrap resamples to assess the stability of the regression coefficients. Based on the multivariable results and bootstrap validation, a parsimonious model was derived to reduce overfitting and improve interpretability.

A two-sided P value <0.05 was considered statistically significant.

All statistical analyses were performed using IBM SPSS Statistics version 21.0 (IBM Corp., Armonk, NY, USA).

Data availability

The data associated with the paper are not publicly available but are available from the corresponding author on reasonable request.

Results

Descriptive characteristics of the study sample

A total of 38 participants were included in the study. The median age was 65.5 years (interquartile range, IQR: 15.3). Regarding sex distribution, 16 participants (42.1%) were female and 22 (57.9%) were male. In terms of lesion localization, 22 persons (57.9%) presented right hemisphere involvement, while 16 (42.1%) had left hemisphere involvement.

Stroke severity, as assessed by the NIHSS, was classified as mild in 21 individuals (55.3%), moderate in 15 (39.5%), and severe in 1 (2.6%), with one person (2.6%) for whom NIHSS data were not available.

As for vascular risk factors, hypertension was present in 27 participants (71.1%), dyslipidemia in 13 (34.2%), and diabetes mellitus in 14 (36.8%). A total of 15 subjects (39.5%) reported a smoking habit, and eight (21.1%) had a history of cardiopathy.

The median time from the cerebrovascular event to the assessment was 22.5 days (IQR: 71), indicating a wide variability in time since stroke onset among the participants.

The main results are shown in Table I.

TABLE I.—*Clinical characteristics of included patients.*

Variable	Value (N.=38)
Age, median (IQR)	65.5 (15.3)
Gender	
Female	16 (42.1%)
Male	22 (57.9%)
Localization	
Right hemisphere	22 (57.9%)
Left hemisphere	16 (42.1%)
NIH Stroke Scale	
Mild	21 (55.3%)
Moderate	15 (39.5%)
Severe	1 (2.6%)
N/A	1 (2.6%)
HTA	
No	11 (28.9%)
Yes	27 (71.1%)
Dyslipidemia	
No	25 (65.8%)
Yes	13 (34.2%)
Diabetes mellitus	
No	24 (63.2%)
Yes	14 (36.8%)
Smoking habit	
No	23 (60.5%)
Yes	15 (39.5%)
Cardiopathy	
No	30 (78.9%)
Yes	8 (21.1%)
Days from event, median (IQR)	22.5 (71)

N/A: not available.

Posturographic X-axis improvement predicts high response in patients undergoing post-stroke rehabilitation

Univariate and multivariate logistic regression analyses were conducted to identify variables associated with the established outcome ("High response") in our post-stroke series. According to our dichotomization criteria, 18 patients were classified as having a high response and 20 as having a standard response.

Most demographic and clinical variables, including age (OR: 0.65; 95% CI: 0.18-2.36; P=0.52), sex (OR: 2.00; 95% CI: 0.53-7.49; P=0.30), localization (OR: 1.85; 95% CI: 0.50-6.83; P=0.35) as well as common vascular risk factors (hypertension, diabetes, dyslipidemia, smoking habit or cardiopathy) were not significantly associated with outcome in the univariate analysis. Similarly, the NIHSS severity category (moderate-severe *vs.* mild) showed no statistically significant association (OR: 1.71; 95% CI: 0.46-6.37; P=0.42).

Regarding days from event, people who initiated rehabilitation more than 22 days after ictus showed a trend toward an unfavourable outcome (standard response) (OR: 0.27; 95% CI: 0.07-1.03; P=0.06), though statistical significance was not reached.

Among posturographic parameters, improvement in the Y axis (OR: 4.25; 95% CI: 0.73–24.77; P=0.11) and XY axis (OR: 3.27; 95% CI: 0.54-19.61; P=0.19) did not reach statistical significance. However, improvement along the X axis was significantly associated with High response in the univariate model (OR: 6.8; 95% CI: 1.20-35.56; P=0.03) (Table II).

In the multivariate analysis, which included variables that were either statistically significant (X-axis related improvement) or showed a trend toward significance in the univariate analysis (days from event), only X-axis related improvement remained a statistically significant predictor (OR: 6.9; 95% CI: 1.13-42.09; P=0.04), suggesting that improvement along the X-axis may serve as an independent predictive factor of a high response in individuals undergoing post-stroke rehabilitation (Table II).

Bootstrap internal validation using 5000 BCa resamples confirmed the robustness of the association (bootstrap P=0.022). Given the lack of an independent contribution of days from event and to minimize potential overfitting, a parsimonious model including only X-axis improvement was retained as the final predictive model (Table III).

Table III.—*Final parsimonious multivariate logistic regression model for established outcome (High response) in patients with cerebrovascular accident (CVA).*

Variable	Adjusted OR	95% CI	P value
X axis-related improvement	6.9	1.13-42.09	0.04

OR: odds ratio; CI: confidence interval (Wald method). Internal validation was performed using 5000 bias-corrected and accelerated (BCa) bootstrap resamples (bootstrap P=0.022). P≤0.05 denotes statistical differences.

Table II.—*Analysis of the relation between clinical and interventional variables and outcome in patients with cerebrovascular accident (CVA) by Uni and Multivariate analysis.*

Variables	Univariate		Multivariate	
	OR (CI)	P value	OR (CI)	P value
Age				
≤65 years	1	0.52		
>65 years	0.65 (0.18-2.36)			
Gender				
Female	1	0.30		
Male	2 (0.53-7.49)			
Localization				
Right	1	0.35		
Left	1.85 (0.50-6.83)			
Days from event				
≤22 days	1	0.06	1	0.09
>22 days	0.27 (0.07-1.03)		0.28 (0.06-1.24)	
NIH Stroke Scale				
Mild	1	0.42		
Moderate-severe	1.71 (0.46-6.37)			
Risk factors				
HTA				
No	1	0.21		
Yes	0.39 (0.09-1.67)			
Dyslipidemia				
No	1	0.43		
Yes	0.57 (0.15-2.26)			
Diabetes mellitus				
No	1	0.27		
Yes	0.47 (0.12-1.82)			
Smoking habit				
No	1	0.94		
Yes	0.95 (0.26-3.51)			
Cardiopathy				
No	1	0.87		
Yes	1.27 (0.24-5.44)			
Posturography variables				
X axis-related improvement				
No	1	0.03*	1	0.04*
Yes	6.8 (1.20-35.56)		6.9 (1.13-42.09)	
Y axis-related improvement				
No	1	0.11		
Yes	4.25 (0.73-24.77)			
XY axis-related improvement				
No	1	0.19		
Yes	3.27 (0.54-19.61)			

*P≤0.05 denotes statistically significant differences.

Discussion

The present study was performed as an exploratory post hoc analysis to evaluate the predictive capacity of values obtained through posturographic analysis in relation to the improvements in motor function in stroke survivors.

Comparison with previous studies

Previous studies evaluating balance using dynamometric platforms have shown that posturographic parameters provide information on postural control that is sometimes difficult to capture using clinical scales alone.[19-21] Patterson *et al.* described that individuals with low scores on BBS exhibited reduced weight-bearing on the more affected limb during posturography, suggesting a compensatory postural strategy that the BBS did not detect.[22] These findings support the use of tools such as posturography to evaluate significant balance impairments in post-stroke patients.

In addition, several studies have identified that static balance impairments in stroke survivors tend to manifest predominantly in the frontal plane and that such disturbances may be associated with functional recovery.[11-13] However, to date, these findings have not been used as indicators of functional improvement.

In this context, the study by Jonsdottir *et al.*[23] analyzed the relationship between posturographic parameters and clinical measures related to fall risk. Their results showed that subjects with BBS scores above 46 had normalized mediolateral displacement, suggesting a relationship between frontal plane stability and improved postural control. However, it was also found that some individuals who experienced falls had relatively normal values in this plane, whereas others with low BBS scores but without falls had elevated values for mediolateral displacement. Regarding this increase in frontal plane parameters, the authors suggest that some stroke survivors may adopt it as a protective compensatory strategy, preferring asymmetric weight-bearing standing to avoid compromising their balance.[19, 23, 24]

Main findings and clinical implications

In the present study, mediolateral displacements measured by posturography were significantly correlated with the most significant improvements in BBS score. This relationship suggests that frontal plane parameters not only reflect a compensatory strategy but could be used as objective predictors of balance recovery. Our findings are consistent with previous studies highlighting the prognostic importance of balance[25] and reporting significant correlations between balance improvement and functional recovery.[25, 26] Van Nes *et al.*[21] concluded that lateral balance is more affected and more sensitive to functional changes, finding a strong association between lateral control and BBS score. Kollen *et al.*[27] determined that improvements in static balance are more relevant than gains in lower limb strength or muscle synergy for enhancing gait capacity in post-stroke subjects.

The strong association found between posturographic measures in the frontal plane and BBS scores supports the notion that these variables (sway length, amplitude, and instability index) can be used as objective predictive markers of independent motor recovery. Clinically, these findings may justify prioritizing interventions that target the frontal plane, since improvements in medio-lateral instability appear to contribute to functional recovery. The inclusion of instrumented assessments could support the individualization of interventions, particularly in the early stages of rehabilitation, when predicting functional outcome is essential for setting realistic goals.

Limitations of the study

This study has several limitations that should be acknowledged. Firstly, it represents an exploratory secondary analysis of data from a previously conducted trial and was performed in a relatively small sample. Consequently, the findings should be considered hypothesis-generating.

Furthermore, the use of the minimal detectable change (MDC) as a criterion for defining meaningful change constitutes an additional limitation. Although the MDC ensures that observed differences exceed measurement error and instrument variability, it is a statistically derived threshold and does not necessarily reflect clinically meaningful improvement from the patient's perspective. Moreover, as the MDC was calculated within our own sample due to the absence of established cut-off values for posturographic measures in this population, its generalizability to other cohorts may be limited. As a result, changes classified as "no change" may still hold clinical relevance, and reliance on the MDC may lead to a conservative estimation of treatment effects.

In addition, the variability in time since stroke onset – which is inherent to the recruitment process – could influence recovery trajectories. This variable was explored as a potential predictor, but future studies should stratify participants by time windows to better isolate its impact on recovery.

Strengths of the study

Some strengths of this study should also be acknowledged. The use of objective posturographic measures alongside clinical scales provides complementary information on balance that may not be fully captured by clinical assessment alone. In addition, the focus on mediolateral parameters offers further insight into the role of frontal plane control in post-stroke recovery, an aspect that has received relatively limited attention. From a methodological perspective, internal validation using BCa bootstrap resampling was conducted to mitigate the risk of overfitting associated with the small sample size, providing additional support for the stability of the regression estimates, although the findings should still be interpreted with caution and confirmed in larger studies.

Overall, the findings should be considered preliminary; however, they provide initial evidence regarding the potential clinical utility of posturography and may inform the design of future confirmatory studies in larger cohorts.

Conclusions

These proof-of-concept findings highlight the potential relevance of mediolateral balance in post-stroke recovery and support the use of objective posturographic measures in rehabilitation assessment. However, given the exploratory and post hoc nature of this analysis, prospective, adequately powered studies are required to confirm these results and further define their clinical applicability.

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Conflicts of interest
The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.
Funding
This work was funded by the General Research Grants Programme (PAIGRAL) of Villanueva University to support translation and open-access publication.
Data availability
The data associated with the paper are available from the corresponding author upon reasonable request.
Randomized controlled trials
This study was registered in the Australian and New Zealand Clinical Trials Registry (registration number: ACTRN12620000107921).
Ethical approval
All procedures performed in this study involving human participants received ethical approval from the competent authorities, as described in the appropriate section of the manuscript, and have been conducted in accordance with the 1964 Helsinki Declaration and its later amendments. The authors confirm that this article does not report any studies involving embryos, gametes and human embryonic stem cells conducted by the authors. The authors confirm that this article does not report any studies involving animals conducted by the authors.
Informed consent
Written informed consent was obtained from all participants prior to inclusion in the study and for publication of their data, as described in the appropriate section of the manuscript.
Authors' contributions
Noelia Díaz-López conceived the initial idea for the research and, together with Laura del-Puerto-Nevado, made substantial contributions to the conception and design of the manuscript. Noelia Díaz-López, Selena Marcos-Antón and Laura del-Puerto-Nevado contributed to the acquisition, analysis and interpretation of the data, and Selena Marcos-Antón also participated in the construction and management of the database. All authors participated in drafting the manuscript, and Laura del-Puerto-Nevado and Sergio González-Cervantes revised it critically. All authors read and approved the final version of the manuscript.
History
Manuscript accepted: May 29, 2026. - Manuscript revised: May 8, 2026. - Manuscript received: March 6, 2026.