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Effect of a visual dual task on postural stability—A comparative study using linear and nonlinear methods

Narges Ghamari[1] | **Rezvan Ghaderpanah**[2] | **Seyed Hassan Sadrian**[2] | **Nahid Fallah**[3]

[1]Bone and Joint Diseases Research Center, Shiraz University of Medical Sciences, Shiraz, Iran

[2]Department of Physical Medicine and Rehabilitation, Students Research Committee, School of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran

[3]Department of Health, Sports Physiotherapy Research Committee, University of Bath, Claverton Down, Bath, UK

Correspondence
Narges Ghamari, Bone and Joint Diseases Research Center, Shiraz University of Medical Sciences, Shiraz, Iran.
Email: nargesghamari@yahoo.com

Abstract

Background and Aims: The dual-task experimental paradigm is used to study the attentional demands of postural control. Postural control is impaired in poststroke patients, and dual-task balance studies address the visual needs of postural control in stroke patients. A nonlinear approach can help us understand the overall behavior of the dynamic system.

Methods: A total of 20 chronic stroke patients and 20 healthy subjects with similar age, height, and weight participated in this study. The stability and complexity of postural control were assessed using linear and nonlinear methods. All data and parameters (center of pressure [COP] velocity, anteroposterior and mediolateral directions displacement, length of COP path, and phase plane) were analyzed using the Kolmogorov–Smirnov test.

Results: When postural control was examined based on linear analysis, the results showed that the main effect of the group was not significant, but the main impact of position was significant for all parameters of the COP variation ($p < 0.05$). Examination of postural control based on nonlinear analysis also showed that the main effect of the group was not significant, and the main effect of status was significant only for the parameters of approximate entropy in both directions and short-term Lyapunov view in the anterior-posterior direction ($p < 0.05$).

Conclusion: According to the results of this study, the assessment of postural control and gait performance in poststroke patients, as well as the dual tasks they have to perform in daily life, is crucial for their independence in activities of daily living.

KEYWORDS

cognitive task complexity, nonlinear dynamics, postural balance, stroke

1 | INTRODUCTION

Stroke is the second most common cause of death and morbidity worldwide and the most common cause of permanent disability.[1] It frequently occurs in older individuals over the age of 65, with an estimated incidence rate of 7.6% per year.[2,3] Stroke often results in brain damage, affecting the corticospinal tract and leading to hemiparesis, a condition that severely limits voluntary movement.[4] Additionally, individuals with stroke frequently experience spatial orientation and head alignment disorders, which result in a complete lack of postural control and significant disruptions in dynamic situations.[5] This postural instability not only compromises the ability to maintain balance while standing, but also impairs the capacity to regain balance in the face of external destabilizing stimuli.[6] Consequently, individuals with compromised balance face a heightened risk of falling, leading to both economic burdens and social ramifications.[7,8] Given these challenges, stroke rehabilitation primarily focuses on enhancing fall prevention strategies, improving balance, and gait patterns.[9,10]

Effective postural stability is crucial for performing routine activities, and attentional cognitive processes play a key role in maintaining a stable posture. In the Romberg stance, which involves the subject putting their feet close together and standing upright with eyes closed, placing one foot in front of the other (tandem stance), standing on one leg, and controlling postural stability while walking has also been shown to be attention-intensive.[11] Consequently, it is expected that simultaneously performing cognitive and postural tasks would decrease the available attentional resources for postural control, leading to a decrease in postural stability.[12] The dual-task paradigm has been used to investigate the cognitive demand of postural control by examining how postural stability is affected when a postural task is performed concurrently with a cognitive task in numerous studies in healthy young and older people adults and patients with neurological disorders.[13,14]

Several studies have compared the performance between young adults and the elderly in dual-task situations to evaluate the role of aging in integrating visual information for postural control. Despite an overall increase in postural sway with aging, these dual-task studies have shown that the visual contribution to postural control remains relatively unaffected by age.[15,16] Furthermore, the effects of distance and gaze position on postural stability have been investigated by measuring the motion of the center of pressure (CoP) by Kapoula et al.[17] Their findings suggest that a narrow range of CoP displacements is associated with decreased velocity and range of body oscillation in both anterior-posterior and medial-lateral directions, regardless of age, at short distances.

Linear methods or static postural balance assessments have certain limitations, such as a lack of valid and reliable measures for pathological changes, insufficient neurophysiological evidence confirming static balance, and an inability to detect the interaction of the components of the postural control system involved in postural balance maintenance.[18] Nonlinear postural balance control analysis facilitates understanding complex biological conditions, including heart-rate disturbances, epileptic attacks, and blood pressure control. Moreover, this provides predictive and diagnostic tools for these dynamic conditions. Nonlinear approaches used for examining the variability of biological rhythms could be used to characterize complexity in human motor function. The concepts of variability in human movement with a focus on nonlinear dynamics may appreciate understanding the overall behavior of dynamic systems.[19,20]

Despite the importance of investigating the visual demand of postural control in stroke patients, there is a limited number of dual-task balance studies in this population. Therefore, the aim of our study was to evaluate the impairment of visually demanding dual postural control tasks in patients with cerebral stroke compared to age-, sex-, height-, and weight-matched healthy individuals. Additionally, we sought to interpret the data obtained from postural control performance and analyze it using both linear and nonlinear dynamic measures. This dynamical approach which analyzes the constituent components and designs the pattern of changes, provides us with a more predictable pattern of system behavior. Specifically, we focused on patients with chronic cerebral stroke, defined as those with a minimum duration of 6 months since the stroke event. Postural stability was analyzed using the measurement of mean stability parameters in the performance of various visual demanding dual tasks across different time intervals, and visual function attributes.

2 | METHODS

2.1 | Participants

A total of 20 subjects were randomly selected from cerebrovascular accident patients referred to rehabilitation clinics in Tehran, using simple random sampling. This involved assigning a unique identification number to each eligible patient and then using computer-generated randomization software to randomly select the 20 participants. With a 95% confidence interval (CI), 80% power, and 10% loss rate, a total sample size of 46 (23 patients and 23 healthy controls) was calculated using two independent sample t test with equal variances. Finally, 20 stroke patients and 20 healthy subjects who were well-matched in terms of age, sex, height, and weight, participated in the study without any sample loss. Each group consisted of 14 males and six females. Additionally, stroke patients were required to meet specific criteria related to stroke duration, hemiparesis score, absence of neurological comorbidities (including cerebellar disorders), ability to stand unassisted, and cognitive function.

2.2 | Screening

The inclusion and exclusion criteria for this study were as follows:

1. Stroke patients with hemiparesis (score 0, 1, or 2 on the National Institutes of Health Stroke Scale [NIHSS] hemiparesis score).

2. Individuals who had been diagnosed with cerebral stroke at least 6 months before study enrollment.
3. Absence of evident neurological comorbidities, including cerebellar and vestibular disorders and orthopedic disorders of the lower extremities.
4. Score 0 or 1 on the NIHSS motor assessment item related to sitting, standing, and walking (evaluating patients to be necessarily able to stand unassisted for 5 min).
5. Objective assessment of the ability to follow therapist's instructions, utilizing a standardized set of 1, 2, or 3 step commands.
6. Absence of cognitive problems (score ≥25 on mini-mental status examination [MMSE]).
7. The visual acuity score (VAS) score of at least 25 out of 40 (meaning the person can read at 25 m what people with normal vision can read at 40 m).
8. Evaluation by an optometrist who determines that there are no ocular diseases such as refractive errors, hemianopia, and unilateral spatial neglect.
9. Height <190 cm measured with a tape measure.
10. Ability to recognize Arabic numerals from 1 to 10.
11. The ability to read and write.

During the test administration, patients who exhibited uncooperative behavior or had a high frequency of falls were excluded from the study. For the selection of stroke patients, we specifically chose individuals with hemiparesis while ensuring the absence of prior or current issues related to attention in their brain. To assess the influence of attention impairments on their postural instability during dual tasking, we employed the expertise of a specialist neurologist who evaluated their attention using the Test of Everyday Attention. In particular, we focused on divided attention as a key aspect of their performance assessment. To quantify divided attention, we utilized the Dual Task Decrement score, which is derived by subtracting the time-per-target score from the telephone search task subset from the time-per-target score that is weighted for accuracy of tone counting.

2.3 | Task procedure

After explaining the aims and procedures of the study, informed consent was obtained from all participants. A questionnaire was also completed to collect general demographic data, and then all qualified participants were examined by an ophthalmologist. The investigators then measured body sway, and participants were asked to perform a supra-postural task while standing. Sway under these conditions was compared to sway under "steady posture." While standing on the force plate, participants were required to perform dual-task trials in random order to manipulate vision. In the first experiment, participants' postural sway was assessed while performing a supra-postural task in four conditions: one group of participants looked at a blank target, and another group looked at a target with text while performing a visual search task (visual search task with targets vs. inspection task with empty targets), crossed with a variation (near or far) in the distance between the targets. During the inspection task with a blank target, participants looked at a screen with a white background and were instructed to keep their eye gaze within the boundaries of the target. To monitor compliance with this instruction, eye movements were recorded using an eye-tracking system. However, during the visual search task with an explicit target, participants looked at a white screen with Arabic numerals (2, 3, 4, 6, and 8) and were instructed to read this digit when prompted by the experimenter. At the end of each task, participants reported the total number of digits and their number. Participants were asked to count the numbers displayed on the target screen at different intervals at the end of the trials to assess the relationship between groups in the performance of other supra-postural dual tasks. In the second experiment, participants were assessed while performing secondary balance tasks, including tasks that challenged their postural stability with eyes open and eyes closed. To assess postural sway, the patients were asked to stand on the force plates with their eyes open and closed. In this step we did not utilize visual task.

Postural control tasks were performed to understand how participants were influenced by visual information. These tasks included (1) standing on the force plate with eyes closed using blindfolds and (2) standing on the force plate with eyes open while viewing a plus sign (+) on a white screen at a distance of 2 m. All of the above conditions were tested three times. Supra-postural tasks were randomly assigned using a random number generator to ensure equal distribution of tasks among participants. To minimize the potential practice effect, participants were allowed to repeat the task only once if they reported deep breathing, coughing, head-turning, yawning, or if they forgot to count digits during the task. A single experimenter performed all tests assigned to participants. On each trial, the acquisition of CoP oscillometric data took 70 s, and a total study duration of two and a half hours was estimated. One person stood nearby the entire time to ensure patient safety during the experimental procedure. Data obtained during each trial were recorded using the force plate. The description of interventions was provided using the Template for Intervention Description and Replication checklist.[21]

2.4 | Analysis

All data from all participants were then statistically analyzed. Normal distribution was tested using the Kolmogorov–Smirnov test. Postural stability was analyzed using the measurement of mean stability parameters in the performance of various visual demanding dualtasks across different time intervals, and visual function attributes. Postural stability analysis involved the assessment of linear parameters analyzed in this study including mean COP velocity and displacement (anteroposterior and mediolateral directions), amplitude (average displacement from the mean COP), the total length of COP travel, and phase plane.

Recordings were processed to determine linear and nonlinear parameters using MATLAB (MathWorks Inc., v.2011) the data obtained were subsequently analyzed using SPSS v.22. A digital scale and tape measure were also used to measure weight and height. Visual tasks were conducted using specialized tools appropriate for each task. For instance, a visual search task was performed using a computer monitor, and the display of visual stimuli was controlled using dedicated software. A Kistler force plate (v.4.0, A2812) was used to collect COP data with a sampling frequency of 100 Hz. In this study, postural sway variability was quantified using linear and nonlinear dynamic methods. Specifically, postural stability control was assessed by analyzing parameters such as COP sway amplitude, COP sway velocity, and COP sway area. Postural control complexity was evaluated through measures such as sample entropy, fractal dimension, and recurrence quantification analysis.[22] Participants' visual acuity was assessed by an optometrist using the VAS. To ensure the cognitive abilities of participants, visual acuity was assessed by an optometrist using the Snellen chart, and mental status was evaluated using the MMSE, a widely accepted screening tool for assessing cognitive impairments.[23,24] However, it is important to note that the MMSE cut-off score employed in our study was not intended to exclude individuals with mild cognitive impairments from participation, but rather to establish a baseline level of cognitive function for the sample population.

Using repeated measures (analysis of variance [ANOVA]), we compared indices of postural stability and complexity of postural control measured during the performance of visually demanding tasks associated with maintaining a steady stance. When differences were significant in the analysis of ANOVA, posthoc comparisons were performed. To address multiple comparisons in the analysis of visual task results, we employed the adjusted Bonferroni procedure, which adjusts the significance level to account for the increased risk of type I error.[25] Additionally, to examine the effects of visual inputs on stability and complexity of postural control between groups, we conducted posthoc tests using Turkey's honest significant difference method, a commonly used approach for pairwise comparisons in the scientific community.[26] Intra- and intergroup comparisons were performed.

3 | RESULTS

Table 1 compares chronic stroke patients and healthy subjects' demographic data (age, height, and weight). The average age of both groups was 59 years, the average height was 165 cm, and the average weight was 72 kg. No significant difference was found between the participants in terms of baseline characteristics. Patients in our study were 39–45 months poststroke.

Table 2 and Figure 1 shows the postural stability control parameters, and Table 3 shows the effects of each postural stability parameter in each condition with each group and their interaction effect. In comparing the stroke survivors to healthy controls, we observed a statistically significant increase in the total postural sway area, total length of COP path, phase plane portrait, mean COP velocity with increasing visual task complexity, and target distance. These differences were found to be statistically significant ($p < 0.05$).

The results of this study demonstrated that the main effect of the condition was significant for all parameters of postural sway ($p < 0.05$), but the main effect of groups (stroke patients vs. healthy subjects) did not show the significance for any parameter ($p > 0.05$). However, there were significant interaction effects between condition and group for all measured parameters of postural sway except the total area of sway ($p < 0.05$).

The multivariate analysis compared mean velocity, CoP path length, phase plane, and total sway area. The different showed significantly higher values for postural sway velocity with eyes closed compared with the open eyes condition ($p < 0.05$).

This test also showed that the changes in CoP path length were significantly higher in closed-eye than in other conditions ($p < 0.05$). CoP path length variables were significantly lower in close-distance blank target inspection tasks than long-distance blank-target tasks, long-distance visual search tasks, and open-eye tasks ($p < 0.05$).

Similarly, the postural stability of all participants was significantly worse in the blindfolded tasks compared to the other conditions in terms of the mean and standard deviation of the phase plane portrait ($p < 0.05$). Moreover, this parameter showed significantly lower values when performing close-distance blank target inspection tasks compared to long-distance blank target inspection tasks and open-eye tasks ($p < 0.05$).

The nonlinear parameters associated with the complexity of postural control are summarized in Table 4 and Figure 2. Moreover, the comparison between all forms of nonlinear parameters during the performance of different visually demanding tasks and crucial interactions are shown in Table 5 using multivariate analysis. The results show that stroke patients had significantly higher values for sway area, path length, phase plane portrait, and sway velocity in a quiet posture with increased complexity and at long distances than healthy adults. However, the approximate displacement entropy in the anteroposterior (AP) and mediolateral (ML) directions and the Lyapunov exponents (LEs) in the AP direction did not differ significantly from each other under the different conditions ($p < 0.05$). The main effect of the group (stroke patient vs. healthy

TABLE 1 Demographic features across patients with chronic cerebral stroke and healthy controls.

characteristics	Stroke patients	Healthy individuals	*p*-value
Age (years)	59.10 ± 7.99	59.00 ± 8.41	0.969
Height (cm)	165.87 ± 9.16	165.90 ± 9.65	0.993
Weight (kg)	72.53 ± 14.98	71.97 ± 15.10	0.906
Gender (male/ female)	14/6	14/6	–
Poststroke length	43.5 ± 1.89	–	–

Note: The data are presented in mean ± *SD*.

TABLE 2 Postural stability performance of participants across six different conditions in terms of linear parameters.

	Open eyes		Closed eyes		Blank inspection				Visual search			
					STD		LTD		STD		LTD	
variables	Stroke	Healthy	Stroke	Healthy	Stroke	Healthy	Stroke	Healthy	Stroke	Healthy	Stroke	Healthy
CoP path length (cm)	108.67 ± 15.83	103.13 ± 17.40	120.82 ± 14.14	110.46 ± 16.05	104.76 ± 16.03	102.04 ± 18.98	110.12 ± 15.09	103.83 ± 17.63	105.68 ± 15.74	103.17 ± 18.88	109.86 ± 16.64	104.85 ± 19.13
Sway velocity (cm/s)	1.55 ± 0.22	1.72 ± 0.2	1.72 ± 0.2	1.57 ± 0.22	1.49 ± 0.22	1.45 ± 0.27	1.57 ± 0.21	1.48 ± 0.25	1.50 ± 0.22	1.47 ± 0.26	1.56 ± 0.23	1.49 ± 0.27
Phase plane portrait	3.65 ± 0.48	3.45 ± 0.54	4.08 ± 0.48	3.69 ± 0.51	3.49 ± 0.52	3.39 ± 0.63	3.69 ± 0.48	3.47 ± 0.56	3.51 ± 0.50	3.43 ± 0.61	3.67 ± 0.54	3.48 ± 0.62
Area of sway (cm^2)	5.72 ± 4.05	4.32 ± 3.07	6.69 ± 5.21	4.2 ± 3.67	4.18 ± 3.99	2.87 ± 2.73	5.2 ± 4.35	4.15 ± 3.72	3.57 ± 3.07	3.43 ± 3.51	4.93 ± 4.85	3.10 ± 1.99

Abbreviations: cm, centimeter; LTD, long target distance; s, second; STD, short target distance.

control group) was not evident for any of the parameters related to postural control complexity ($p > 0.05$). The interaction effect of these two factors did not cause any significant change in the nonlinear parameters, except for the AP LE ($p > 0.05$).

Participants were asked to count the numbers displayed on the target screen at different intervals at the end of the trials to assess the relationship between groups in the performance of other supra-postural dual tasks. The results of the present study showed that the patients with stroke counted a lesser number of numerals. In addition, they also have lower adequacy compared with healthy subjects, although these differences were not significant ($p > 0.05$) (Table 6).

4 | DISCUSSION

The primary aim of this study was to investigate whether behavioral complexity affects postural stability through a nonlinear dynamic method. The results of the nonlinear CoP parameters of this study (approximate entropy and LE in AP & ML directions) did not differ significantly between stroke patients and healthy subjects. Group effects analysis revealed significant differences in the approximate entropy of both directions and the short-term LE of the AP direction by the nonlinear dynamic approach. Stroke patients achieved significantly higher AP directional entropy and lower ML directional entropy than healthy subjects in visual tasks. Regardless of short- or long-term conditions, stroke patients achieved lower and higher LEs in the AP and ML directions, respectively, compared with healthy controls. The approximate entropy and the LE are parameters that evaluate stability based on a nonlinear approach. It is important to note that these nonlinear parameters have been shown to be reliable and valid measures for assessing minimal changes in postural control not only in stroke patients but also in individuals with residual deficits following brain injury.[27]

Approximate entropy measures the complexity of time series data and quantifies the regularity and predictability of the signal. Systems with regular and predictable time series (future) states have less complexity.[28,29] Given this, postural control may appear more complex in stroke patients compared with healthy individuals, and a more predictable state of postural control is expected in healthy individuals. In contrast, injury to components of postural control is associated with a decrease in complexity; therefore, the above conclusion cannot be applied to stroke patients. According to the dynamic system view, the correct state of postural control should be determined based on the normal amplitude. Parameters higher or lower than the normal amplitude range represent an impairment of the system.[30,31] Therefore, two states are possible in the approximate entropy changes of postural control: (1) the entropy changes of stroke patients and healthy subjects are within the normal amplitude range (2) or stroke patients suffer from severe impairment of the components of the postural control system. The results of this study show that the difference in approximate entropy between the groups is not significant. Therefore, this difference seems to be within the

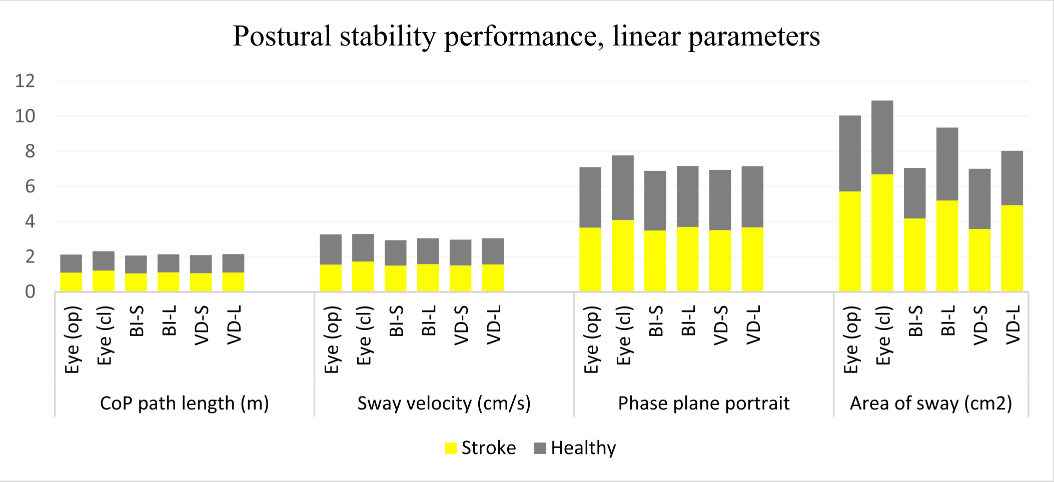

FIGURE 1 Postural stability performance evaluated by linear parameters. BI-L, blank inspection at long target distance; BI-S, blank inspection at short target distance; cl, closed; Op, open; VD-L, visual search at long distance; VD-S, visual search at short distance.

TABLE 3 Main effects of condition, group and interaction effect between group and condition on stability parameters.

Variables	Mean of square roots	Degree of freedom	*F*	*p*-value
Length of CoP path (cm)				
Condition	1448.393	5	28.925	0.000*
Group	1755.240	1	1.114	0.298
Group* condition interaction	82.71	5	3.124	0.01*
Mean of sway velocity (cm/s)				
Condition	0.296	5	28.925	0.000*
Group	0.358	1	1.114	0.298
Group* condition interaction	0.017	5	3.124	0.01*
Phase plane portrait				
Condition	1.881	5	27.177	0.000*
Group	2.727	1	1.411	0.242
Group* condition interaction	0.124	5	3.420	0.006*
Area of sway (cm^2)				
Condition	45.659	5	5.372	0.002*
Group	111.766	1	1.816	0.186
Group* condition interaction	5.984	5	1.218	0.302

Note: The *F* is the *F*-statistic, calculated by dividing the mean square between the groups by the mean square within the groups.

Abbreviations: Cm, centimeters; s: seconds.

*$p < 0.05$.

normal amplitude range of the postural control system. It is important to consider that poststroke learning processes may have contributed to the observed findings in the task of postural control. Patients in our study were 39–45 months poststroke, and their own attempts to become independent along with the physical exercises performed in various rehabilitation centers may have facilitated improvements in their balance and postural control abilities. These poststroke learning processes could have influenced the results observed in our study.

The LE expresses the degree of divergence of adjacent trajectories arising from the phase plane and is an important measure of the predictability of the system and its sensitivity to changes in initial conditions for the analysis of periodic, chaotic, or random time series. Higher values of LE indicate more divergence and instability. The stability of a dynamical system is inversely correlated with LE, so system stability increases as the LE decreases.[32,33] For this reason, it seems logical that patients suffering from stroke have a small Lyapunov spectrum and higher dynamic position stability compared with a healthy population.

Considering the dynamic systems approach, it can be understood that stroke patients can maintain local dynamic stability within the permanence limits of healthy individuals. This interpretation of postural stability may be due to the fact that the intergroup comparison of gait and upright standing showed no significant differences under challenging environments. This supports the recovery of skills in postural control in patients that have been developed over time. Regardless of task type and difficulty, approximate entropy and the LE increased with increasing distance from the target. Both stroke patients and healthy control subjects showed a similar increasing pattern of approximate entropy in the AP and ML directions.

Similarly, two groups reported an increasing pattern of long-term AP & ML LEs when particle distance changed from close to far. As a result, LEs decreased in healthy subjects and increased in stroke patients with increasing distance. However, a different pattern of

TABLE 4 Assessment of postural control performance under different conditions across each group in terms of nonlinear parameters.

Variables	Open eyes	Closed eyes	Blank inspection		Visual search	
			STD	LTD	STD	LTD
Approximate entropy in AP direction						
Stroke	3.45 ± 0.46	3.93 ± 0.41	3.51 ± 0.46	3.58 ± 0.47	3.64 ± 0.40	3.64 ± 0.41
Healthy	3.13 ± 0.53	3.64 ± 0.47	3.29 ± 0.51	3.38 ± 0.5	3.31 ± 0.45	3.64 ± 0.41
Approximate entropy in ML direction						
Stroke	3.01 ± 0.51	3.41 ± 0.43	3.08 ± 0.53	3.1 ± 0.57	3.03 ± 0.52	3.12 ± 0.57
Healthy	3.03 ± 0.48	3.29 ± 0.42	3.11 ± 0.33	2.98 ± 0.49	3.16 ± 0.43	3.33 ± 0.41
Long-term Lyapunov exponent in AP direction						
Stroke	0.0953 ± 0.32	−0.1367 ± 0.26	−0.0046 ± 0.3499	0.1474 ± 0.36	0.0565 ± 0.44	0.024 ± 0.34
Healthy	−0.0748 ± 0.67	−0.1047 ± 0.43	−0.0159 ± 0.68	0.0173 ± 0.59	0.1349 ± 0.34	0.098 ± 0.44
Long-term Lyapunov exponent in ML direction						
Stroke	0.1167 ± 0.28	−0.0064 ± 0.25	0.023 ± 0.28	0.1359 ± 0.3	−0.0813 ± 0.33	0.0726 ± 0.28
Healthy	−0.0069 ± 0.59	−0.0389 ± 0.27	0.0940 ± 0.36	0.0262 ± 0.24	−0.0868 ± 0.41	−0.1093 ± 0.26
Short-term Lyapunov exponent in AP direction						
Stroke	10.73 ± 1.08	9.90 ± 1.12	10.56 ± 1.24	10.99 ± 1.87	10.51 ± 2.03	10.10 ± 1.13
Healthy	9.99 ± 1.35	10.42 ± 1.32	9.79 ± 1.09	10.67 ± 1.39	9.87 ± 1.09	10.62 ± 1.56
Short-term Lyapunov exponent in ML direction						
Stroke	10.07 ± 1.38	8.82 ± 1.04	10.05 ± 1.14	9.57 ± 1.19	9.65 ± 1.1	9.77 ± 1.09
Healthy	10.38 ± 1.01	9.87 ± 1.41	9.88 ± 0.98	10.32 ± 1.29	10.09 ± 1.35	10.21 ± 1.01

Note: The data are presented in mean ± *SD*.

Abbreviations: AP, anteroposterior; LTD, long target distance; ML, medial-lateral; P, anterior-posterior; STD, short target distance.

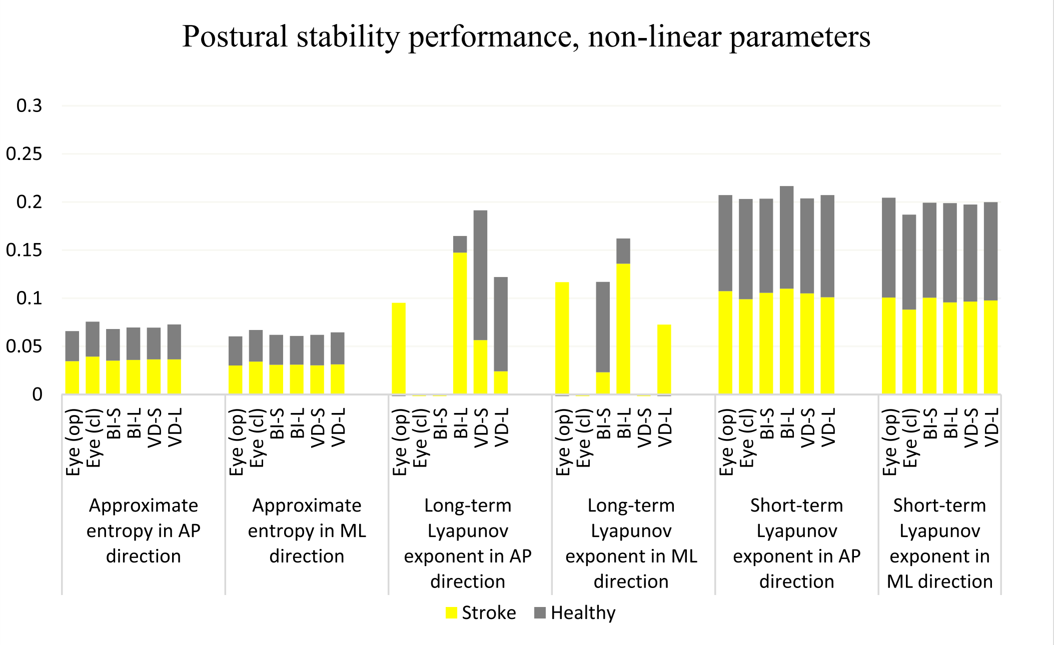

FIGURE 2 Postural stability performance evaluated by nonlinear parameters. *All parameters except for long-term Layapunov exponent in AP and ML directions in this figure are divided by 100 for better comparison. AP, anteroposterior; ML, medial-lateral.

TABLE 5 main effects of condition, group and interaction effect between group and condition across nonlinear postural control parameters.

Variables	Mean of square roots	Degree of freedom	*F*	*p*-value
Approximate entropy in AP direction				
Condition	1.527	5	13.78	0.000*
Group	2.97	1	2.526	0.068
Group* condition interaction	0.141	5	1.581	0.167
Approximate entropy in ML direction				
Condition	0.860	5	6.082	0.000*
Group	0.038	1	0.043	0.837
Group* condition interaction	0.172	5	1.644	0.15
Long-term Lyapunov exponent in AP direction				
Condition	0.355	5	1.293	0.278
Group	0.174	1	0.626	0.434
Group* condition interaction	0.101	5	0.511	0.767
Long-term Lyapunov exponent in ML direction				
Condition	0.213	5	1.363	0.251
Group	0.243	1	2.49	0.123
Group* condition interaction	0.084	5	0.714	0.614
short-term Lyapunov exponent in AP direction				
Condition	3.456	5	2.298	0.067
Group	3.516	1	0.579	0.451
Group* condition interaction	3.682	5	3.297	0.007*
short-term Lyapunov exponent in ML direction				
Condition	3.837	5	5.159	0.000*
Group	12.5.4	1	2.704	0.108
Group* condition interaction	1.510	5	2.03	0.076

Note: The *F* is the *F*-statistic, calculated by dividing the mean square between the groups by the mean square within the groups.

Abbreviations: AP, anteroposterior; ML, medial-lateral.

*$p < 0.05$.

variations was observed in the AP and ML direction of short-term LEs with increasing distance. With increasing distance, an increase in short-term LEs LE in the ML direction was observed in both groups. In the AP direction, healthy controls and patients showed increased and decreased short-term LEs, respectively.

The discussion of approximate entropy reminds us that predictability decreases with the increasing complexity of the posture control system.[34] In the present study, increasing complexity was observed with increasing distance. Accordingly, it can be said that individuals increase the complexity of postural control to place a higher demand on visual information to maintain and compensate for the postural stability required when performing tasks over long distances. Thus, it appears that studying the contribution of visual information in long-distance tasks is more challenging than in short-distance tasks. Furthermore, it is worth considering the potential influence of visual impairments, such as near-sightedness and far-sightedness, on the complexity of postural control. Consistent with this study, other research has also found that visually demanding tasks are more difficult at long distances.[35] Because the difference between groups in dynamic parameters was not significant with increasing distance, this may indicate that the changes in complexity in patients are likely within normal limits of variation.

The evidence shows that practicing two simultaneous component tasks in dual-task situations can disrupt one or both components because attention must be divided between multiple systems simultaneously.[36] Moreover, it seems that a search task with a target demands more visual information, which could be the reason for the failure of a postural control system based on a dynamic system perspective. The results of the present study show that the posture control system moved toward a discontinuous (alternating) and irregular state when the explicit target search tasks changed. Therefore, we can confirm the traditional theory that these patients have impairments in the postural control system. Specifically, in our study, both healthy and stroke patients exhibited impairments in the postural control system when performing more difficult visual search tasks with targets.

4.1 | Recommendations and limitations

The postural stability assessment using linear metrics is insufficient to detect subtle internal changes in the system. To determine the variations in time series and conclude appropriate reliable inclusion, the linear measures of muscle activity should be bound to nonlinear metrics analysis. The researchers are encouraged to pay attention to this suggestion in future studies. Future research could investigate the specific effects of visual impairments on postural control during visually demanding tasks at different distances. This would provide valuable insights into how different visual impairments impact the complexity and performance of postural control. Individuals may have increased complexity in finding an appropriate center of balance point in response to visual input, which requires further research in the future.

The results indicate that using a visual search task with targets could challenge the postural control ability of stroke survivors, especially at long distances. Therefore, it can be a complementary part of therapeutic exercises in clinical rehabilitation centers. Further research is needed for protocol-based implementation of these visually challenging dual tasks.

In the future, it would be beneficial to assess the dual task postural ability of stroke patients based on dysfunction, such as

TABLE 6 Comparison of visual functions in quiet posture between stroke patients and healthy subjects in the dual task of counting digits.

Variables	Participants	Mean ± *SD*	*p*-value
Numerals count at long target distance	Stroke patients	31.18 ± 10.67	0.106
	Healthy individuals	36.8 ± 10.8	
Numerals count at short target distance	Stroke patients	28.76 ± 11.3	0.151
	Healthy individuals	33.55 ± 9.23	
The ratio of correctly counted numerals to incorrectly counted numerals at long target distance	Stroke patients	0.91 ± 0.12	0.102
	Healthy individuals	0.97 ± 0.08	
The ratio of correct counted numerals to incorrect counted numerals at short target distance	Stroke patients	0.92 ± 0.14	0.822
	Healthy individuals	0.93 ± 0.06	

cerebellar atrophy patients or bilateral vestibulopathy patients. This approach would allow for a more targeted analysis of the specific mechanisms underlying dual task postural instability in stroke patients. Additionally, increasing the sample size of the study would provide more robust and reliable data, as well as a more precise view of the dual task postural ability of stroke patients as a whole.

One limitation of our study was the undefined lesion pattern of the stroke patients, which made it difficult to assess the potential impact of different stroke lesion patterns on dual task postural ability. This leads to a lack of heterogeneity among subjects which hinders the generalizability of our findings. Furthermore, the duration of data collection in our study was relatively long, which could introduce the confounding factor of fatigue. We acknowledge that fatigue can potentially impact postural stability outcomes. Therefore, future studies should consider monitoring and accounting for the effects of fatigue during data collection. Additionally, it is important to consider the potential influence of the training effect on the postural stability outcomes observed in our study. To overcome this limitation, future studies could perform subgroup analysis for stroke patients with different stroke lesion patterns, providing more specific data on the dual task postural ability of these patients. By doing so, we can gain a better understanding of how different types of stroke lesions affect dual task postural ability and ultimately improve the rehabilitation strategies for stroke patients.

5 | CONCLUSION

Shifting of visual task from “visual search with explicit target” to “inspection task with blank target” regardless of the type and difficulty of task results in a rise of approximate entropy and all LE variables, except for long-term LE variables in ML direction, which decreased. All variables of LE except long-term LE in AP direction showed a different pattern similar to the transition of visual search tasks from explicit target to blank target. Consequently, healthy individuals showed enhanced scores while stroke patients showed reduced scores. Both groups demonstrated a reduction in AP direction of LEs. The transition of task type from a search task with an explicit target to an inspection task with blank target was associated with decreased complexity. Moreover, this study showed that the complex difference between stroke patients and healthy controls is insignificant. Therefore, the complexity increase of the system with concurrent targeted visual search tasks may be related to more demand for attention allocation in these dual tasks.

AUTHOR CONTRIBUTIONS

Narges Ghamari: Conceptualization; Data curation; Investigation; Methodology; Project administration; Resources; Validation; Writing—review & editing. **Rezvan Ghaderpanah**: Formal analysis; Investigation; Resources; Writing—original draft; Writing—review & editing. **Seyed Hassan Sadrian**: Formal analysis; Methodology; Validation; Writing—original draft; Writing—review & editing. **Nahid Fallah**: Investigation; Methodology; Writing—original draft; Writing—review & editing. All authors have read and approved the final version of the manuscript Narges Ghamari had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The manuscript has been approved by all authors and has never been published or under consideration for publication elsewhere. We confirm that all figures and tables are original and created by authors. We guarantee that all authors listed on the title page have read the manuscript and attest to the validity and legitimacy of the data. We would also like to undertake that we have read the plagiarism policy and submitted the article with complete responsibility. The Medical Ethics Committee approved this study at Tehran University of Medical Sciences according to the declaration of Helsinki (IR.98-01-56-19855).

TRANSPARENCY STATEMENT

The lead author Narges Ghamari affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

ORCID

Narges Ghamari http://orcid.org/0000-0001-6925-5042
Rezvan Ghaderpanah http://orcid.org/0000-0002-4274-4628

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