Postural strategies and attention allocation are differentially modulated across various sensory contexts and cognitive tasks in individuals with chronic stroke

RUNNING HEAD: Dual-task postural strategies in stroke

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This is the Author's Original Manuscript of an article published in final form in Jehu, D. A., Chan, L. L., & Pang, M. Y. (2020). Standing Balance Strategies and Dual-Task Interference Are Differentially Modulated Across Various Sensory Contexts and Cognitive Tests in Individuals With Chronic Stroke. Journal of Neurologic Physical Therapy, 44(4), 233-240, available online: https://doi.org/10.1097/NPT.0000000000000328.

Abstract

Background: Postural and cognitive deficits inherent with stroke have been linked with falls. Although some cognitive tasks have provoked a facilitatory effect on posture (i.e., decreased sway) in healthy populations, this has not been observed in individuals with neurological impairment. Identifying cognitive tasks that promote improved posture may increase safety during falls-risk assessments as well as therapeutic interventions.

Objective: The objective of this study was to assess balance and cognitive performance across different cognitive tasks and sensory conditions in individuals with stroke.

Methods: Ninety-two individuals with stroke were asked to stand on dual-force platforms while performing three cognitive conditions (no cognitive task, serial subtractions (SS), verbal fluency (VF)) across 4 sensory conditions (eyes open, fixed surface (EO/FS); eyes closed, fixed surface (EC/FS); eyes open, sway-referenced surface (EO/SR); eyes closed, sway-referenced surface (EC/SR)). An equilibrium score was computed based on the anterior-posterior sway angle. The number of correct verbal responses was recorded.

Results: Higher equilibrium scores were observed for the SS relative to VF relative to single-task conditions only during EC/SR ($p<0.001$). No differences in the number of correct verbal SS responses were observed between seated compared to standing conditions ($p>0.05$). More VF responses were reported in the seated compared to standing position; the EO/SR and EC/SR conditions exhibited more VF responses relative to the EO/FS and EC/FS conditions ($p<0.001$); and the EC/FS revealed greater VF responses compared to EO/FS ($p<0.001$).

Conclusions: This is the first study to report a facilitatory effect on postural control when performing cognitive tasks post-stroke. Individuals with stroke inappropriately prioritized the cognitive instead of the postural task. These findings have implications for researchers and clinicians in the design of fall prevention interventions to incorporate cognitive tasks that facilitate postural control for increased safety as well as to emphasize a posture-first attention priority to reduce falls-risk.

Keywords

Stroke, posture, cognition, attention prioritization

Introduction

Stability impairment is common among individuals with stroke. Impaired postural control leads to higher fall-risk and lower functional independence (1, 2), resulting in greater economic costs accompanied with premature institutionalization (3). Postural impairment post-stroke has been well-described and involves weight-bearing asymmetry, increased postural sway, body tilting, impaired anticipatory and reactive postural control, abnormal synergistic muscular activation (4). In addition to the motor dysfunction inherent with stroke (5), attention deficits (6), perceptual deficits, such as visuospatial neglect and kinesthetic deficiencies (7, 8), as well as impaired sensorimotor integration (7), are inherent in this population. Empirical evidence suggests that fall risk post-stroke is elevated when performing cognitive-motor tasks during daily activities (5). Nevertheless, the relative contribution of heightened attention demand on postural control post-stroke is not well understood.

Postural control is sensitive to cognitive manipulations; however, the literature remains mixed on the specific pattern of changes. Increased postural sway has been observed while simultaneously performing an arithmetic task compared to standing with eyes closed (9) as well as increasing levels of sway when performing no cognitive task, an easy Stroop task, and a difficult Stroop task, respectively (10). In contrast, decreased sway has also been demonstrated when performing a memory task relative to no task across various standing conditions (i.e., preferred stance, feet together, and eyes closed) post-stroke (11). Other work has reported a reduction in sway, but only as the difficulty level of the imposed cognitive tasks increased (i.e., no task vs a simple reaction time task vs a choice reaction time task) (12). In light of these disparate findings, dual-tasking has been postulated to depend on specific task factors, including the nature of the cognitive and postural tasks, as well as individual factors, such as the location of stroke, sensory deficits, muscles weakness, and the duration of time since the stroke (12).

Postural control is also responsive to the available sensory input (13-17). For instance, previous work has shown less path length of the center of pressure during dual-tasking in more challenging conditions (e.g., eyes open/fixed surface (EO/FS) vs eyes closed/sway-referenced surface (EC/SR)) in patients with degenerative cerebellar disorders, indicating less postural instability (13). Nevertheless, the authors posited that a stiffening strategy, characterized by an increase in co-contractions of agonist and antagonistic muscle groups, may have contributed to the improved stability in more challenging conditions (13). Similarly, young adults also appear to adopt a stiffening strategy as detected by less range of the center of pressure in the anterior-posterior direction with perturbed proprioception (i.e., support surface tilt), no vision (i.e., eyes closed), and visual-vestibular conflict (i.e., tilted visual surround) relative to unperturbed sensory feedback (14). Furthermore, greater stiffening has been observed post-stroke relative to controls during reduced or inaccurate sensory feedback (15). This suggests that suffering from a stroke may provoke a reduced ability to reweight sensory information (15), and an increased reliance on visual and vestibular inputs (15, 16).

The specific pattern of changes in sway during dual-tasking across sensory conditions is inconsistent (9, 11, 14, 18). For example, some work has reported that posture is unaffected by the addition of a cognitive task, even when both visual and proprioceptive information were either unavailable or unreliable among controls (14). Conversely, other work has shown greater velocity of the center of pressure during a difficult compared to a simple memory task or no cognitive task while standing on foam with eyes closed in both older adults and those post-stroke, indicating greater instability (18). The lack of differences in velocity of the center of pressure across cognitive tasks when standing on a firm surface with eyes open or closed suggests that posture may be more sensitive to cognitive manipulations during challenging sensory conditions (18). Notably, further elucidating the role of cognitive-motor interference on balance across sensory conditions may provide important information for falls-risk assessments post-stroke.

The aim of this study was to assess dual-tasking across various cognitive (i.e., arithmetic and verbal) and sensory conditions (i.e., EO/FS to primarily assess sensory integration; eyes closed/fixed surface (EC/FS) to assess somatosensory function; eyes open/sway-referenced surface (EO/SR) to assess visual function; EC/SR to assess vestibular function) among individuals with chronic stroke. It was hypothesized that completing a cognitive task during sensory conditions would increase postural sway (6, 12, 19), and that dual-tasking would lead to deteriorated cognitive task performance than single-tasking due to the greater attention demand (20).

Methods

Participants

Participants were recruited via convenience sampling from several community stroke self-help groups between May 2014 and September 2016 for this cross-sectional study. The inclusion criteria were: 1) diagnosis of chronic hemispheric stroke (onset≥6 months); 2) aged ≥ 50 years; 3) community-dwelling; and 4) ability to follow two-step commands. Exclusion criteria were: 1) diagnosis of other neurological conditions; 2) diseases that adversely influence balance; 3) receptive or expressive aphasia; and 4) pain during standing or walking.

Sample size calculation

Poor postural stability has been observed during dual-tasking in healthy individuals (η_p^2=0.061, p<0.05)

(17). A similar effect size was estimated for the interaction effect across sensory and visual postural tasks. With an alpha level of 0.05 and a power of 0.8, a minimum sample size of 60 individuals with stroke was requisite.

Experimental protocol

Collection of demographic data

Informed consent was obtained, and all procedures were aligned with the Declaration of Helsinki. Demographic information, including age, height, weight, number of falls within the last 12 months, and time since stroke, was obtained via participant interviews (Table 1). Participants also completed the Montreal Cognitive Assessment (MoCA), which screens cognitive impairment (21). Its score ranges from 0 to 30 and evaluates 7 cognitive domains including: visuospatial/executive functions; naming; verbal memory registration; attention; abstraction; delayed verbal memory; and orientation. A score under 22 was indicative of cognitive impairment (21). Participants completed the Activities-specific Balance Confidence Scale (ABC), which is a 16-item scale assessing balance confidence during common activities of daily living, with lower scores reflecting lower confidence (22). Participants completed the 15-item Short Form Geriatric Depression Scale (GDS), with larger scores reflecting greater depression (23). Finally, participants completed the 7-point Chedoke-McMaster Stroke Assessment (CMSA), which measures motor impairment in the affected leg and foot, with lower scores reflecting greater impairment (24).

Balance tasks

Participants performed eight 20 s trials of the modified Clinical Test of Sensory Interaction on Balance protocol (i.e., EO/FS vs EC/FS vs EO/SR vs EC/SR) in single- (i.e., no cognitive task) and dual-task (i.e., serial subtractions (SS); verbal fluency (VF)) contexts, using the SMART Balance Master (NeuroCom International Inc. Clackamas, Oregon). Trials were randomized using a computer-generated sequencing method. Participants stood in a quiet laboratory with their feet apart in a designated position on dual force plates, with arms at their sides, with their gaze directed at an eye-level target, and they articulated as many numbers or words as possible, when applicable. During the dual-task conditions, participants were asked to allocate their attention equally between tasks. Participants were secured with a safety harness that did not impede limb or body movement. When participants could not complete a given trial (i.e., a “fall”), they proceeded to the following trial. For sway-referenced conditions, the support surface tilted in sagittal plane. This mechanism was designed to provide unreliable proprioceptive information. Both the sequence of the sensory conditions and the type of cognitive task were randomized. A familiarization trial of each test was performed prior to the experimental protocol. Rest periods were provided after the completion of each sensory condition as well as upon request. Data were averaged across each experimental condition and used for analysis.

An equilibrium score (ES) for each trial was automatically generated by the system as follows:

$$ES=[12.5°-(\theta_{max}-\theta_{min})]/12.5° x 100$$

where, 12.5° was the hypothesized limit of stability, θ_{max} was the maximal anterior sway angle, and θ_{min} was the maximal posterior sway angle (25). A score of 100 was reflective of complete equilibrium, and a score of 0 was either attributed to a fall or a sway range that exceeded 12.5° in the anterior-posterior direction (26).

Cognitive tasks

The two commonly used neuropsychological tasks employed during balance testing were SS and VF, targeting verbal memory and verbal function and language skills, respectively (27). The SS task involved participants counting backwards by 3's from a random number between 90 and 100. If participants lost track, they were instructed to continue with the last number they remembered in order to maintain cognitive effort. The number of correct answers and total responses were recorded. VF was assessed by naming as many items as possible in one of the following categories: countries, clothes, food, fruits or vegetables. These categories were paired in the single and dual-task sensory conditions.

Following the experimental protocol, SS and VF tasks were assessed in the seated position (i.e., single-task condition). The number of correct responses over a 20 s period was recorded.

Statistical analyses

The effects of imposing the SS and VF tasks on postural stability were assessed using a 4 (Sensory Condition: EO/FS vs EC/FS vs EO/SR vs EC/SR) × 3 (Task: No Cognitive Task vs Dual-Task with SS vs Dual-task with VF) 2-way repeated measures analysis of variance (ANOVA). The dependent variable was equilibrium scores.

The influence of the balance tasks on SS task performance was compared via a 1-way (Balance Condition: Seated vs EO/FS vs EC/FS vs EO/SR vs EC/SR) repeated measures ANOVA. The dependent variable was the number of correct responses generated during the SS task.

The impact of the balance tasks on the number of responses generated in the VF task performance was evaluated through a 4 (Sensory Condition: EO/FS vs EC/FS vs EO/SR vs EC/SR) × 2 (Task: Single-task vs Dual-task) 2-way repeated measures ANOVA. Because each sensory condition was paired with a specific word category, these same four-word categories were also used during seated single-tasking, which explains the use of the 2-way repeated measures ANOVA. The dependent variable was the number of correct responses generated in the VF task.

The level of significance was set to α<0.05. Post-hoc comparisons with Bonferroni adjustment were conducted following all significant main and interactions effects.

Results

Participant characteristics

After screening 104 individuals with stroke, 98 were eligible, but 6 of which could not complete all the testing procedures due to fatigue. As a result, complete datasets were obtained from 92 individuals with stroke. Participant characteristics are displayed in Table 1.

Effect of adding a cognitive task on postural control

The sensory condition × task interaction effect ($F_{(3.32,5324.42)}=17.44$, $p<0.001$, $n_p^2=0.161$) revealed a higher equilibrium score for the SS task relative to the VF task relative to the single-task only during EC/SR (both $p<0.001$; Figure 1). No other interactions emerged ($p>0.05$).

The main effect of Sensory Condition ($F_{(1.77,190795.83)}=314.54$, $p<0.001$, $n_p^2=0.776$) revealed the highest equilibrium score for EO/FS, and progressively lower scores in the EC/FS, followed by EO/SR, followed by EC/SR conditions ($p<0.001$; Figure 1).

The main effect of Task ($F_{(1.50,1090.90)}=7.03$, $p=0.003$, $n_p^2=0.072$) revealed that the SS task exhibited significantly greater equilibrium scores relative to the VF task ($p=0.002$) and single-task ($p=0.003$) conditions (Figure 1). No differences emerged between the VF task and single-task ($p=0.16$)

Effect of adding the balance task on cognitive performance

Serial subtractions

No main effect of condition ($F_{(4,364)}$=1.85, p=0.12; Figure 2) was observed for the number of correct responses across the seated and standing conditions.

Verbal fluency

The main effect of task was significant ($F_{(1,91)}$=16.11, p<0.001, n_p^2 =0.15; Figure 3), such that more VF responses were reported in the seated compared to standing position. The main effect of Condition ($F_{(1.62,237.93)}$=51.73, p<0.001, n_p^2 =0.36) revealed that the EO/SR and EC/SR conditions exhibited greater VF responses relative to the EO/FS and EC/FS conditions (p<0.001), and the EC/FS revealed greater VF responses compared to EO/FS (p<0.001). No Task x Condition interaction emerged ($F_{(2.21,247.17)}$=1.78, p=0.15).

Discussion

The purpose of this study was to examine the influence of dual-tasking on postural and cognitive performance during the modified Clinical Test of Sensory Interaction on Balance protocol in individuals with chronic stroke. The main findings were that: 1) postural control was facilitated the most during the SS task, followed by the VF task relative to no cognitive task, but only in the most difficult postural condition that targeted vestibular function (i.e., EC/SR); and 2) dual-task cognitive performance was differentially modulated depending on the type of cognitive task while dual-task postural performance diminished as the level of difficulty of the postural task increased.

Postural control strategies depend on the difficulty of the postural task and the neuropsychological process targeted in individuals with stroke

Both cognitive tasks had varying degrees of influence on the specific postural strategy adopted, but only in the most challenging sensory condition (i.e., EC/SR assessing vestibular function). More specifically, performing SS facilitated posture (i.e., higher equilibrium scores) even more than VF relative to quiet standing during EC/SR. It is thought that quiet standing provides a greater opportunity to focus internally on posture thereby constraining the automaticity of postural control (28) which was manifested by a lower equilibrium score in the EC/SR condition. In contrast, it has been postulated that performing a distracting task draws attention away from consciously controlling posture and affords posture to be more automatically controlled thereby requiring less recruitment of cognitive resources (29). Furthermore, automatic tasks have been shown to be less vulnerable to distractions in perceptual processes and interference of a competing task (30). This may, in part, explain the greater equilibrium scores in the EC/SR condition when performing a cognitive dual-task. It is possible that this facilitation of postural control was not observed in the EO/FS, EC/FS, and EO/SR conditions because the postural task needs to be sufficiently difficult to reach neural resource limits before a facilitatory postural strategy is adopted (29). Identifying cognitive tasks and sensory conditions wherein posture can be facilitated has important considerations for the design of interventions because individuals with neurological impairment have greater movement reinvestment and conscious control of movement thereby disrupting coordination and stability (31, 32).

In contrast to our results, previous literature has shown greater sway parameters during various cognitive tasks including simple and choice reaction time tasks (12), memory tasks (6, 19), arithmetic problems (9) and easy as well as difficult versions of the Stroop (10) post-stroke. In fact, a systematic review has shown that other populations with neurological impairment have also only shown a deteriorated effect on postural control when performing cognitive dual-tasks (28), and this was suggested to be a consequence of the bottleneck and capacity model theories (33, 34). The bottleneck theory deduces that parallel processing may become challenging when similar cognitive processing operations are employed (35), while the capacity theory predicates that attention is limited because the system can only cope with a certain amount of information at a time (36).

Interestingly, the SS task had a greater facilitatory effect on postural control than the VF task, perhaps because they target different neuropsychological processes (27). More specifically, SS can be categorized into Verbal Memory: Verbal Automatisms, while VF can be categorized into Verbal Function and Language Skills: Discourse (27). Conceivably, previous work may have not shown facilitatory effects on postural control because the postural task was not difficult enough (29) or that the specific cognitive task was not targeting the same neuropsychological process.

Dual-task priority and interference

The task prioritization model postulates that changes in dual-task performance could occur in either or both tasks (37). Our results revealed that the prioritization of the motor or cognitive task differed depending on the cognitive task performed. In line with previous literature (15), equilibrium scores decreased when sensory input was removed or perturbed regardless of whether it was during quiet standing or when performing a cogntive task. Importantly, a systematic review has reported that increased postural sway was linked to an increased incidence of falls post-stroke (38). For the VF task, the number of accurate VF responses was greater in the seated compared to standing conditions; however, the number of accurate VF responses increased as the level of difficulty of the postural task increased, suggesting that during more simple postural tasks, individuals with stroke prioritized the postural task but during difficult postural conditions they inappropriately prioritized the VF task. This pattern was not observed during the SS task as no differences in the number of accurate SS responses were shown between the seated and standing conditions or between the levels of difficulty of the postural task; this stable cognitive performance indicates that individuals with stroke inappropriately adopted a cognitive-priority strategy instead of posture-first. Importantly, limited attentional resources have predicted falls (39-41), and increased postural sway has been related to greater incidence of falls (42-44). Flexible and appropriate allocation of attention resources are important during dual-tasking to achieve task goals while maintaining postural safety (45). Because an inappropriate allocation of attention resources may result in balance disturbances and/or falls, designing interventions to emphasize a posture-first strategy in individuals with stroke may improve balance and reduce falls.

The minimal clinically important difference (MCID) provides an interpretation of clinical meaningfulness by supplying information on the smallest difference on a given test that would lead a clinician to consider a change in treatment (46). However, the MCID of equilibrium scores on the sensory organization test or any cognitive tasks are not known in individuals with stroke (47). Future research is necessary to determine the MCID of both tasks should these tasks be used in assessment following interventions in order to determine whether meaningful changes in balance and cognition occur following training. These findings have important implications as incorporating cognitive tasks that promote a facilitation of posture into fall prevention programs may provoke improvements in posture and cognition while enhancing safety. Notably, no studies have examined the reliability or validity of dual-task posture in any population, including stroke (48). Only one study has explored convergent validity in individuals with Parkinson's disease (49). Therefore, psycometric properties of dual-task postural control tasks in individuals with stroke should be established first before exploration with therapeutic interventions.

Limitations

This study has a few limitations. The results of this study can only be generalized to ambulatory community-dwelling individuals with chronic stroke. To our knowledge, psychometric properties of dual-task posture and cognitive tasks have not been established in individuals with stroke.

Conclusion

This is the first study to report a facilitatory effect on postural control when performing cognitive tasks in individuals with chronic stroke. In general, these results suggest that a cognitive-priority strategy was adopted instead of posture-first, compounding attention and postural deficits inherent with stroke. Evaluating changes in dual-task interference across postural and cognitive conditions provides insight into shifts in attention allocation as well as overall dual-task capacity. This study is significant because the ability to quickly change the allocation of attention in different dual-task situations is likely a critical facet of dual-task performance to ensure safety during activities of daily living. Altogether, these findings have implications for researchers and clinicians in the design of fall prevention interventions to incorporate cognitive tasks that facilitate postural control for increased safety as well as to emphasize a posture-first attention priority to reduce falls-risk.

Conflict of interest statement

The authors have no conflict of interest to declare.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors Contributions

DJ and LC contributed in the analysis and interpretation of the data and writing of the manuscript. MP contributed in the conception and design of the study, interpretation of the data, and writing of the manuscript.

Table 1. Participant demographics.

Variables	Stroke Participants (*n*=92)

Age (years) [Mean (SD)]	62.7 (7.8)
Sex [Number of female (%)]	24 (26.1)
Body mass index (kg/m^2) [Mean (SD)]	24.3 (3.6)
Type of stroke (Ischemic/Hemorrhagic) (*n*)	55/36
Time since onset of stroke (months) [Mean (SD)]	106.3 (62.1)
Walking aid indoor (None/Cane/Quadripod) (*n*)	83/5/4
Walking aid outdoor (None/Cane/Quadripod) (*n*)	37/43/12
MoCA score [Mean (SD)] (0-30)	24.7 (3.1)
CMSA leg score [Median (IQR)]	5 (4,6)
CMSA foot score [Median (IQR)]	4 (3,6)
ABC (%) [Mean (SD)]	72.2 (15.7)
GDS total score [Mean (SD)]	4.5 (3.5)
Fallers [*n* (%)]	20 (21.7)

Mean ±SD presented unless indicated otherwise.

CMSA: Chedoke-McMaster Stroke Assessment; ABC: Activities-specific Balance Confidence scale; GDS: Geriatric Depression Scale; IQR: Interquartile range; MoCA: Montreal Cognitive Assessment; SD: standard deviation.

Figure Captions

Figure 1. Mean (± 1 SD) of the equilibrium score during serial subtraction (SS) and verbal fluency (VF)

tasks across sensory contexts.

Note. EO/FS: Eyes Open/Fixed Surface; EC/FS: Eyes Closed/Fixed Surface; EO/SR: Eyes Open/Sway-Referenced Surface; EC/SR: Eyes Closed/Sway-Referenced Surface.

Figure 2. Mean (± 1 SD) of the number of correct serial subtraction responses across sensory contexts

Note. EO/FS: Eyes Open/Fixed Surface; EC/FS: Eyes Closed/Fixed Surface; EO/SR: Eyes Open/Sway-Referenced Surface; EC/SR: Eyes Closed/Sway-Referenced Surface.

Figure 3. Mean (± 1 SD) of the number of correct verbal fluency responses across sensory contexts.

Note. EO/FS: Eyes Open/Fixed Surface; EC/FS: Eyes Closed/Fixed Surface; EO/SR: Eyes Open/Sway-Referenced Surface; EC/SR: Eyes Closed/Sway-Referenced Surface.

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