Effect of dual tasking on intentional vs. reactive balance control in people with hemiparetic stroke

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Subramaniam S, Hui-Chan CW, Bhatt T. Effect of dual tasking on intentional vs. reactive balance control in people with hemiparetic stroke. J Neurophysiol 112: 1152–1158, 2014. First published May 28, 2014; doi:10.1152/jn.00628.2013.—To examine the effect of a cognitive task on intentional vs. reactive balance control in people with hemiparetic stroke (PwHS). Community-dwelling PwHS (n = 10) and healthy, age-similar controls performed two tests, which included the Limits of Stability Test (intentional control) and the Motor Control Test (reactive control), under single-task (ST) and dual-task (DT) conditions (addition of a cognitive task). Cognitive ability was measured on a word list generation task by recording the number of words enumerated in sitting (ST; for cognition) and during the balance tasks. The difference in response time between the ST and DT, defined as the “balance cost” was obtained ([ST - DT]/ST × 100] and compared between tests and across groups. The “cognitive cost” was similarly defined and compared. For both groups, the response time under DT condition was significantly greater than the reactive balance control task, leading to a higher balance cost for this task (P < 0.05). However, the cognitive cost was significantly greater for the intentional than the reactive balance control task for only the PwHS. DT significantly affected intentional than reactive balance control for PwHS. The significant decrease in both balance and cognitive performance under DT compared with ST conditions during intentional balance control suggests sharing of attentional resources between semantic memory and intentional balance control. Decreased performance on the cognitive task only during the reactive balance test indicates possible central nervous system’s prioritization of reactive balance control over cognition.

INDIVIDUALS WITH STROKE FREQUENTLY experience a spectrum of sensory, motor, and cognitive deficits that significantly increase the risk of falls (Sommerfeld and von Arbin 2004). Forty to seventy percent of community-dwelling, hemiparetic stroke survivors experience detrimental falls each year (Belgen et al. 2006; Lamb et al. 2003). Falls not only affect activities of daily living but more significantly hamper community mobility and reintegration (Baseman et al. 2010; Lord et al. 2004). Among the predictors of falls, balance impairment is believed to be the major neuromuscular factor that contributes to an increased risk of falls in people with stroke (Batchelor et al. 2012).

Stroke-induced sensorimotor impairments impact both intentional and reactive balance control (Di Fabio 1987; Dietz and Berger 1984; Marigold and Eng 2006). Studies examining intentional balance control have demonstrated that people with hemiparetic stroke have delayed or longer reaction times (time to initiate center of pressure excursion) and reduced voluntary center of mass excursions in all directions compared with healthy controls (Melzer et al. 2009). Similarly studies examining reactive balance control in people with hemiparetic stroke, via support surface (platform) translations or whole body (pull/push load-release) perturbations, have demonstrated delayed reaction times and smaller magnitudes of postural responses compared with healthy controls (Badke and Duncan 1983; Ikai et al. 2003; Marigold and Eng 2006).

In addition to balance impairments, evidence indicates that impaired attentional resources and/or decline in cognitive function also contribute significantly to fall risk (Fischer et al. 2014; Plummer et al. 2013; Plummer-D’Amto et al. 2010). Conceptually, it is postulated that balance centers within the central nervous system share resources with the centers for cognitive processing (Woollacott and Shumway-Cook 2002). Healthy individuals can allocate desired resources for both tasks, allowing them to achieve optimal dual-task (DT) performance (Huxhold et al. 2006). However, it is postulated that when such resources become limited due to aging or pathology such as a stroke, performance on either one or both of the tasks is compromised (termed as cognitive-motor interference) (Plummer et al. 2013).

Both the intentional and reactive balance control components are negatively impacted under DT conditions (cognitive and motor). Recent findings among healthy adults suggest that intentional balance control tasks demonstrate mutual cognitive-motor interference under DT conditions (Woollacott and Shumway-Cook 2002). For example, in the study by Melzer and Oddsson (2004), significant cognitive-motor interference within the intentional balance control system was observed with a decrement in both motor (longer postural reactions times and smaller center of mass excursions) and cognitive (higher reaction times or errors on the secondary task) performance under DT conditions.

Reactive balance tasks albeit demonstrate a motor-related cognitive interference (no change in balance performance but decline in cognitive performance) (Mersmann et al. 2013). Although traditionally reactive balance control was considered to be automatic and thus independent of cognitive processing (Dietz and Berger 1984), studies in the past decade have demonstrated the presence of cognitive-motor interference on reactive balance control (recovery from perturbations) (Maki and McIlroy 2007). Most studies have reported that for small perturbations requiring in-place recovery strategies, there is no effect of concurrent task on the postural response latencies in young and healthy older adults (ranging from 90 to 180 ms) (Akram and Frank 2009). However, the performance on the cognitive task is significantly reduced under the DT compared with the single-task (ST) condition (Huxhold et al. 2006;
Table 1. Demographics of stroke and healthy, age-similar control subjects

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Stroke Group (n = 10)</th>
<th>Control Group (n = 10)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>57.2 ± 7.17</td>
<td>61 ± 5.53</td>
<td>0.596</td>
</tr>
<tr>
<td>Height, in.</td>
<td>174 ± 5.9</td>
<td>171 ± 8.4</td>
<td>0.302</td>
</tr>
<tr>
<td>Weight, lb</td>
<td>72 ± 8.5</td>
<td>73 ± 8.3</td>
<td>0.643</td>
</tr>
<tr>
<td>Sex (male/female)</td>
<td>6/4</td>
<td>6/4</td>
<td>0.157</td>
</tr>
</tbody>
</table>

Values are means ± SD.

Rankin et al. 2000) and this effect is seen especially during the early postperturbation period (up to 250 ms) (Redfern et al. 2002).

Only few studies that have examined changes in posture and balance control report findings on both cognitive and balance control tasks (de Haart et al. 2004; Harley et al. 2006; Hyndman et al. 2006, 2009; Roerdink et al. 2006, 2009). Apart from inconsistent results between these studies regarding the type of cognitive motor interference (motor, cognitive, or mutual interferences), these studies focused mainly on postural sway, which, although essential, encompasses only the static element of human balance control. While examining cognitive-motor interference for stance posture control is important, the effects of cognitive-motor interference on other aspects of balance control need to be examined in this population.

Chronic stroke survivors demonstrate marked attention deficiency in their ability to switch attention under complex environmental conditions that could impact their safety in community living, compared with healthy controls (Plummer-D’Amato et al. 2010). Given the persistence of sensorimotor impairments and attentional deficits in chronic stroke survivors, it is important to determine whether these stroke-related impairments would have an additional impact on their intentional and reactive balance control under DT conditions.

The purpose of this study was to compare the cognitive-motor interference between intentional vs. reactive aspects of balance control and to examine the impact of stroke on such interference using a DT paradigm. Based on findings from the literature (Plummer et al. 2013), it was postulated that for both the healthy adults and stroke groups the motor cost for intentional balance control would be significantly greater than the reactive balance task (greater cost indicates worse performance under DT conditions), but there would be no difference in cognitive cost between the two balance tasks (because of a similar decrease in cognitive performance for both balance tasks under DT conditions). Due to the impact of stroke, both motor and cognitive costs would be significantly greater for the people with hemiparetic stroke than the healthy adults (indicating significantly worse performance under DT conditions on balance and cognition) for both intentional and reactive balance tasks.

METHODS AND PROTOCOLS

Methods

Subjects. Ten ambulatory adults with self-reported chronic hemiparetic stroke were recruited. Ten healthy subjects similar in age, sex, and height served as control participants in the study (Table 1). Recruitment of the participants was solicited by posting flyers at various stroke support groups, local neurologists’ offices, outpatient rehabilitation clinics, and research centers. The study was approved by the Institutional Review Board of the University of Illinois, and informed consent was obtained from all participants.

Subject eligibility. Inclusion criteria for the study consisted of confirmation of a chronic (>6 mo) hemiparetic stroke without presentation of any aphasia (confirmed by the participant’s physician) and the ability to stand independently for at least 5 min without the use of an assistive device. Hemiparetic status was reconfirmed by the examiners via the manual muscle test. Subjects with a mean manual muscle test score of ≤4/5 for both upper and lower extremity were included. Participants with other neurological (e.g., Parkinson’s disease, vestibular deficits, peripheral neuropathy, or unstable epilepsy), musculoskeletal, and cardiovascular disorders were excluded. Participants with cognitive deficits as measured using Short Orientation-Memory-Concentration Test of Cognitive Impairment (>10 indicates cognitive impairment) were excluded as well (Davous et al. 1987). Short Orientation-Memory-Concentration is also positively correlated with screening tests for aphasia suggesting individuals with higher score on Short Orientation-Memory-Concentration would show worse language functioning (Al-Khawaja et al. 1996). Inclusion/exclusion criteria for control group were similar to those for the stroke group excluding the diagnosis of stroke incidence and hemiparesis.

Subjects were also tested on clinical measures of motor impairment (Fugl Meyer), sensory impairment (Semmes Weinstein Monofilament Test), balance (Berg Balance Scale), and mobility (Timed-up and Go Test) (Table 2).

Protocols

Subjects performing a cognitive task in isolation while seated and subjects completing a voluntary or reactive balance control tasks without a cognitive task were defined as ST conditions. The details of each test are further described below.

Intentional balance control task. Intentional balance control was assessed using the Limits of Stability Test protocol of the Equitest (Computerized Dynamic Posturography) (Koozekanani et al. 1980). The Equitest consists of a two adjacently placed movable force platform for recording the ground reaction forces underneath each leg and a movable surround (Nashner and Peters 1990). The movable surround was kept in the fixed position for testing purposes.

Subjects were secured in a safety harness and stood on two force platforms with one foot on each of the platforms. Subjects were asked to lean their body in a given direction without losing balance, stepping, or reaching for assistance. The force platform records the

Table 2. Demographics of stroke subjects

<table>
<thead>
<tr>
<th>Subject (n = 10)</th>
<th>Involved Side (L/R)</th>
<th>Stroke Type (H/I)</th>
<th>Onset, yr</th>
<th>BBS/56</th>
<th>TUG, s</th>
<th>Fugl Meyer (LE)</th>
<th>SW Monofilament Exam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Means ± SD</td>
<td></td>
<td>5/5</td>
<td></td>
<td></td>
<td>Dorsal Planter</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. L, left; R, right; H, hemorrhagic; I, ischemic; BBS, Berg Balance Scale; TUG, Timed Up and Go Test; LE, lower extremity; SW, Semmes Weinstein.

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The duration of each large perturbation trial was average height of 1.5 m, the displacement would be equal to 4.7 cm.

Subjects were instructed to intentionally shift their weight to the target highlighted on the screen as fast as possible, upon hearing a beep, such that their “avatar,” moved from the center of the screen to the target location. The targets were chosen to be directly in front and directly behind the center [forward (FWD) and backward (BWD) conditions]. These directions were chosen to allow comparison with the reactive balance control tests, which were limited to these two directions. Two familiarization trials were conducted, after which data were collected for the FWD and BWD conditions (1 trial in each direction with each trial lasting 8 s). The outcome measures recorded by the software included response time, movement velocity, and maximum excursion. Response time was the time in seconds between the command to move and the onset of participant’s movement. Movement velocity was the average speed of center of gravity movement in degrees per second. Maximum excursion was the maximum distance up to which the participant was able to shift his or her center of mass towards the target while still maintaining it within his or her theoretical limits of stability without taking a step.

Reactive balance control task. Reactive balance control was assessed using the Motor Control Test protocol of the Equitest (Computerized Dynamic Posturography). Subjects’ initial starting position was similar to that of the starting position during intentional balance control protocol, and subjects wore the same safety harness system. Subjects were instructed to stand still and were asked to expect a sudden movement of the platform upon a sound of a beep and also to maintain their balance without taking a step or falling. The standard Equitest protocol for the Motor Control Test at each perturbation-magnitude consisted of three trials that lasted for 25 s duration. Out of the three perturbation-magnitude profiles available, subjects were tested on the largest perturbation-magnitude for FWD and BWD translations, where the translation amplitude was calculated by the formula, displacement = \( \frac{2.25 \times \text{[height (in m)]}}{72} \). Based on an average height of 1.5 m, the displacement would be equal to 4.7 cm. The duration of each large perturbation trial was \( \approx 8 \) s. The change from baseline in the center of pressure (calculated from the force plates) reflected the reactive response initiated by the central nervous system to restore balance. The response time was quantified as the time between translation (stimulus) onset and initiation of the individual’s active response.

Cognitive task. Each subject performed a world list generation task in a sitting position (ST condition). The world list generation task is relatively complex and requires the integration of multiple cognitive skills for efficient and systematic search and retrieval of semantic stores (Boringa et al. 2001). Subjects were given a letter of the alphabet and asked to recite as many words starting from that letter, as fast as possible for a given duration. After two trials of familiarization, four trials were conducted using four different letters. The four letters used were S, R, P, and N. Two of the trials matched the duration of the intentional balance control task test (1 for FWD and 1 for BWD condition), and the other two matched the duration of the reactive balance control task. These trials served as the cognitive condition for the ST. The number of words accurately recited for the duration of the trial was recorded.

DT conditions, subjects performed the intentional and reactive balance control tests in conjunction with the word list generation task. For the intentional balance control test, subjects were asked to start reciting words from the given alphabet letter as soon as they heard the start beep (which indicated the start of balance tests) while simultaneously shifting their weight in a given direction with feet in place. For example they were instructed as follows: “As soon as you hear the beep start saying as many words as you can from the letter “S” while simultaneously trying to move your avatar from the center box to the box in front of it without losing your balance, stepping, or reaching for assistance.” Similarly for the reactive balance control test they were asked to recite as many words as possible starting from the given letter, while trying to maintain their balance and upright posture without taking a step or falling upon sudden movement of the platform underneath their feet. To minimize the potential for learning, participants were given different letters for each trial for each test under DT conditions. To allow for accurate comparison of cognitive performance between ST and DT conditions, the same alphabet letters were used for the seated cognitive task (ST) and the balance tasks under DT conditions. The letter for each trial condition remained the same between subjects. During testing, subjects were not specifically instructed to prioritize either the cognitive or the balance task.

All tests were completed in one session, lasting \( \approx 45 \) min. The order of all the test trials was randomized, including the trials for ST and DT balance tests and that of intentional and reactive balance control tests. Each subject was given a total of four familiarization trials, two trials each for ST and DT conditions (1 in FWD and 1 in BWD) for both intentional and reactive balance control tests (Jbabdi et al. 2008). To avoid fatigue, a 1- to 2-min rest period was provided between trials. To avoid a recall bias, an interval of 15 min was given between the seated cognitive task and the balance tests.

Test-retest reliability of the measures. The test-retest reliability of the Equitest has been previously established (Hageman et al. 1995). However, to establish the test-retest reliability of the intentional and reactive balance control under DT conditions, five healthy young volunteers (mean age = 26 \( \pm \) 5 yr), who met the subject eligibility criteria, performed these two selected tests on the Equitest under DT conditions (word list generation) in FWD and BWD directions, on two sessions, 1 wk apart. Intraclass correlation coefficients revealed high test-retest reliability for all the measures of interest (range: 0.80–0.97).

Statistical analysis. Means \( \pm \) SD of the absolute values of response time (for both tests) were computed and presented for both groups for the ST and the DT conditions. To allow for comparison between intentional and reactive balance control, the cognitive and response time costs were computed respectively for number of words recited and response time (common dependent variable between the 2 tests) for both the intentional and reactive balance control tests for the FWD and BWD conditions. This was done using the following formula: DT cost = \( [(ST - DT)/ST \times 100] \) (Bock 2008; Schwenk et al. 2010). The changes in the response time cost and the cognitive cost between the intentional balance control and reactive balance control tests, for both the stroke and control groups were compared using 2 \( \times \) 2 ANOVAs. Significant test X group interactions were resolved with post hoc t-tests. Since the response latency was expected to increase during DT conditions, a greater cost (lower performance) would be indicated by greater negative values. A value of 0 indicated no difference in response time between ST and DT, and positive values indicated a reduced cost under DT conditions. Age, weight, and height were compared between the stroke subjects and the control subjects using independent t-tests. A \( \chi^2 \) test was used to compare the sex distributions of the groups. A significance level (alpha) of 0.05 was chosen for statistical comparisons. Analyses were performed using the SPSS version 17.0 of the commercially available Statistical Package for the Social Sciences (SPSS).

RESULTS

The stroke group and the control group were similar in demographics (age, gender, and height represented in Table 1). Subjects had a mild motor impairment indicated by a score of <34 on the Fugyl Meyer. Participants scores on Semmes Weinstein Monofilament Exam indicate that although subjects had reduced sensation performance, they did not have loss of protective sensation as they were able to sense filaments. 
Subjects were at a fall risk demonstrated by the scores on the Berg Balance Scale and Timed-up and Go Test (Table 2).

### Intentional vs. Reactive Balance Control

Both groups had a longer response time for intentional balance control test compared with the reactive balance control test (means ± SD presented in Table 3). The 2 × 2 ANOVA revealed that both stroke and control subjects had a significantly greater response time cost for intentional balance control (more negative values) compared with the reactive balance control (main effect of test, $P < 0.05$ for both FWD and BWD directions) with no difference between the groups (main effect of group, $P > 0.05$, no test × group interaction, $P > 0.05$; Fig. 1, A and B).

**Table 3. Raw scores of reaction time for intentional and reactive balance control**

<table>
<thead>
<tr>
<th></th>
<th>Stroke Group</th>
<th></th>
<th>Control Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ST</td>
<td>DT</td>
<td>ST</td>
<td>DT</td>
</tr>
<tr>
<td>Intentional balance control RT, s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWD</td>
<td>0.82 (0.22)</td>
<td>1.10 (0.27)</td>
<td>0.86 (0.16)</td>
<td>1 (0.15)</td>
</tr>
<tr>
<td>BWD</td>
<td>0.66 (0.29)</td>
<td>1 (0.42)</td>
<td>0.81 (0.04)</td>
<td>0.98 (0.16)</td>
</tr>
<tr>
<td>Reactive balance control RT, s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWD</td>
<td>0.19 (0.1)</td>
<td>0.17 (0.5)</td>
<td>0.13 (0.05)</td>
<td>0.14 (0.05)</td>
</tr>
<tr>
<td>BWD</td>
<td>0.19 (0.4)</td>
<td>0.22 (0.3)</td>
<td>0.14 (0.1)</td>
<td>0.16 (0.1)</td>
</tr>
</tbody>
</table>

Values are means (SD). RT, reaction time; ST, single task; DT, dual task; FWD, forward direction; BWD, backward direction.

<5.07/10 g. Subjects were at a fall risk demonstrated by the scores on the Berg Balance Scale and Timed-up and Go Test (Table 2).

### Intentional vs. Reactive Balance Control

During the ST condition for cognition, both the healthy control and stroke groups accurately recited about four to six words out of the five to seven total words that were recited. During the DT conditions for both of the balance tests, the total number of words recited was four to five with three to four correct words recited by healthy controls and only two correct words recited by people with hemiparetic stroke. Both groups demonstrated a lower cognitive performance (fewer number of words) in the DT condition compared with the ST condition for both intentional and reactive balance control). The cognitive cost comparison revealed a significant main effect of the test ($P < 0.05$) with a significant test × group interaction ($P < 0.05$) for both FWD and BWD directions. For the stroke group, the cognitive cost was significantly greater for intentional balance control compared with the reactive balance control for both FWD and BWD ($P < 0.05$). However, for the healthy control group, there was no difference in cognitive cost between the two balance control tasks ($P > 0.05$) for both the FWD and BWD directions. While the stroke group demonstrated a greater cognitive cost for the intentional balance control compared with the control group, there was no difference in cognitive cost between the two groups for the reactive balance control task ($P > 0.05$; Fig. 1, C and D).

### DISCUSSION

The present study examined the influence of a concurrent cognitive task on intentional and reactive balance control in community-dwelling stroke survivors. The results, as postulated, demonstrated that the response time cost for the intentional balance task was significantly greater than the reactive...
balance task for both the healthy control and stroke groups. However, there was no significant effect of stroke on the response time cost for both balance tests. Although the cognitive cost was similar between the two balance tasks for the healthy controls, contrary to that hypothesized, the stroke group had a greater cognitive cost only for the intentional balance than for the reactive balance task.

The present findings demonstrated that performance of a concurrent attention demanding cognitive task increased the response time on intentional balance control in both chronic stroke survivors and older healthy adults (response time cost > 0). Thus compared with the ST condition, under the DT condition, they required a longer time to initiate an intentional shift of their center of mass from the resting state in an attempt to reach the desired target location. The findings of our study are in line with the previous studies that have reported similar changes in balance control under DT conditions for healthy older adults and people with stroke (Brown et al. 2002; Harley et al. 2006; Hyndman et al. 2006, 2009; Melzer et al. 2010). Subjects in both groups (healthy and stroke) also demonstrated a cognitive decrement, indicated by significantly fewer numbers of words recited under DT than ST condition (cognitive cost > 0). Although studies examining the effects of cognitive-motor interference on intentional balance control in stroke survivors report a significant effect of dual tasking on postural measures, contrary to our findings, they found no change on cognitive measures (Kurz et al. 2013). However, similar to our findings, other studies have reported presence of mutual cognitive-motor interference by demonstrating significant changes in both balance and cognition in stroke survivors (Harley et al. 2006; Plummer et al. 2013).

The results from this study can be interpreted based on the “limited capacity theory” (Meyer and Kieras 1997). This theory postulates that when the attentional demands of two tasks sharing similar recourses exceed the available resources (due to increasing task difficulty or due to a pathology), the performance of either one or both the tasks would be affected. Stroke did not have an additional negative impact on response time for intentional balance under DT conditions; however, it did affect cognitive performance. It is postulated that due to the impact of stroke further limiting the available shared resources, subjects might have opted to allocate greater attentional resources towards the balance task under the DT conditions. Such prioritization of attentional resources could have led to a significant decrement in the cognitive performance compared with the healthy controls.

Compared with performance on the intentional balance task, there was no decrement in the response time on the reactive balance task (examining reactive balance control) under DT conditions compared with the ST conditions for both groups (response time cost close to 0). Upon the sudden platform translation, subjects were able to initiate a reactive response in the correct direction to restore the center of mass within the base of support. Furthermore, adding an attention-demanding task did not affect reactive postural correction; however, it did affect the cognitive task performance (cognitive cost > 0). Such deterioration in cognitive cost was not significantly impacted by stroke. Our results are comparable to previous findings from healthy young and older populations, which suggest that the central nervous system prioritizes reactive balance control by sacrificing processing of cognitive task under DT performance (motor-related cognitive interference) (Plummer et al. 2013), even for perturbations eliciting response latencies of ~150 ms (Brauer et al. 2002; Maki et al. 2001; Mersmann et al. 2013; Redfern et al. 2002).

Although traditional view postulates that reactive postural responses might be reflexive or automatic in nature (Horak 1990), in the current study, the number of words generated declined in DT condition for the Motor Control Test (cognitive cost > 0). This would probably suggest involvement of higher brain centers in controlling reactive balance. It can be postulated that the central nervous system utilizes the “posture first” strategy to prioritize balance over cognition only during reactive balance control, while in intentional balance control, there is mutual cognitive-motor interference demonstrated with changes in both balance and cognition. The efficacy of cognitive processing in balance control could be influenced by the difficulty and any postural constraints affecting the concurrent cognitive task (Huxhold et al. 2006). It is possible that the threat associated with the “unpredictable” perturbation was prioritized, as it was perceived as a higher challenge than the cognitive task to prevent oneself from fall-induced injuries. Such an explanation fits with the bottleneck theory, which postulates that when two tasks compete for processing resources at the same time, a bottleneck results and one task will be delayed or otherwise impaired (Maslovat et al. 2013). The similar response time and cognitive costs between the stroke and healthy control groups indicated that stroke does not impact such prioritization for reactive balance under stance conditions.

The differential effect of dual tasking between the intentional balance task and the reactive balance task supports the shared cognitive resources postulation. On the contrary if the poor balance control was due to paresis (essentially an execution problem), a similar response for intentional and reactive balance control should be expected. Also, if balance decrements were due to impairments within somatosensory system poststroke, a better intentional balance control should be expected. However, in this study, a deterioration of this control was observed compared with that of the reactive balance control. Intentional balance control is postulated to stem from collaterals from descending cortical pathways for controlling voluntary motor movements (primary and supplementary motor cortices) that also have extensive connections with the frontal and prefrontal area involved with semantic memory (Dufosse et al. 1982). In comparison, the reactive balance control involves feedback mechanisms mediated by the brainstem and spinal cord, which include short (monosynaptic) and long-latency and triggered reflexes (polysynaptic), and forms the “automatic” balance control system (Stapley and Drew 2009). However, these subcortical centers receive extensive connections from supplementary motor areas and influence reactive balance when task demands are high, such as during high-intensity perturbations (Drew et al. 2002) or dynamic tasks such as obstacle avoidance during gait (Weerdesteyn et al. 2004).

Based on the results of this study, it is postulated that the centers of intentional balance control and semantic memory may share attentional resources required for successful task performance, with the central nervous system able to equally prioritize both balance and cognition when healthy. However, there is a shift in such prioritization towards balance control.
when impacted by a cortical insult, resulting in a decline of balance and cognitive functions. In comparison it is proposed that the centers of reactive control and semantic processing operate modularly (or nonoverlapping) under healthy conditions and hence are unaffected by dual tasking. However, increased task demands (via addition of a cognitive task) when added on a compromised brain (with reduced capacity) may require recruitment of greater descending cortical control for prioritization of balance, thereby leading to an inadequate allocation of resources for the cognitive task.

The results of our study need to be interpreted in light of its limitations. While the study was designed to have age-similar controls, the stroke participants in the study were relatively older and hence the findings could have been confined by early effects of aging. The study had a small sample size and the stroke participants were chronic and relatively high functioning. Furthermore, the study did not control for the side of hemispheric lesion (left vs. right), which could have impacted the findings. However, previous findings indicate that the side of lesion does not significantly impact semantic memory (Hyndman et al. 2006). The study used a screening tool to rule out cognitive deficits; hence mild cognitive deficits could have been missed. Future studies should consider using a more sensitive tool for assessing cognitive deficits. Also, response time was the only primary outcome variable to allow for a direct comparison between intentional and reactive balance control. Future studies should thus explore ways of comparing spatial variables such as control of center of mass between the two tasks. Last, during the voluntary balance task individuals received visual feedback regarding target location to be achieved and their balance performance during the trial. Such feedback requiring additional goal formulation could tax the executive function and make the motor task itself cognitively more challenging. However, this task mimics real-life situations where voluntary control of one’s limits of stability is usually associated with a similar visual goal (for example, reaching forward for an object); reactive tasks, however, are not.

The findings in our study could have significant clinical implications. Increased response times on self-initiated balance tasks (such as functional reaching and voluntary stepping) and reactive tasks (compensatory stepping) are postulated to be predictors of fall risk (van den Bogert et al. 2002; Wojcik et al. 1999). As response times were significantly greater under DT conditions, especially for intentional balance control, clinical interventions for fall-risk reduction should be targeted towards designing paradigms, combining balance training with secondary cognitive tasks imposing significant attentional demands, thus inducing plasticity related changes. Such training could potentially increase the amount of available attentional resources to maintain optimal cognitive performance during postural tasks that threaten the balance control system.

In conclusion this study enhances the literature on cognitive-motor interference by providing evidence on the direct comparison between attentional demands of the two different aspects of balance control: intentional and reactive. The cost analysis provided a quantitative measure for allowing such DT comparison, which could account for the variability between subject groups and the two balance tasks. While the intentional balance task demonstrated a mutual cognitive-motor interference, the reactive task demonstrated a motor-related cognitive interference (Plummer et al. 2013). The mutual cognitive-motor interference was significantly enhanced by the impact of stroke. It is suggested that such cognitive motor interference should be accounted for while designing clinical interventions for improving poststroke posture and balance control.

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DISCLOSURES

No commercial party having a direct financial interest in the research findings reported here has conferred or will confer a benefit on the authors or on any organization with which the authors are associated.

AUTHOR CONTRIBUTIONS

Author contributions: S.S. performed experiments; S.S. analyzed data; S.S. interpreted results of experiments; S.S. prepared figures; S.S. drafted manuscript; S.S., C.W.-Y.H.-C., and T.B. edited and revised manuscript. C.W.-Y.H.-C. and T.B. conception and design of research; C.W.-Y.H.-C. and T.B. approved final version of manuscript.

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