Cognitive-Motor Interference During Dual-Tasking Among Healthy Adults and Chronic Stroke Survivors

By

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Contents

Abstract

Postural stability during dynamic postural tasks is achieved through an interaction between sensory systems, different movement strategies, and cognitive processing to attain the central goal of maintaining stability. Due to dynamic nature of the environment, events causing falls are unexpected and sudden. This places a substantial demand on an individual's ability to attend to sudden changes in the environment to prevent a fall. The overall purpose of this dissertation to understand attentional demands locomotor and balance tasks using a dual-task paradigm among healthy adults and how presence of cerebral injury such as a stroke impacts attentional demands of postural tasks.

Chapter 1 focuses on the interference between walking and different higher cognitive tasks focused on functions considered to play a role in locomotion. It also examines the effect of altering walking speed on the interference between walking and cognitive tasks. Healthy young adults walked at preferred and slow speeds while performing a visuomotor reaction time (VMRT), memory recall (word list generation), working memory (serial subtraction) and an executive function (Stroop) task. Effect of dual-tasking on walking and cognitive tasks was measured as the cost of dual-tasking for walking speed and cognitive performance. Results show that the motor and cognitive cost of dual-task walking depends heavily on the type and perceived complexity of cognitive task being performed. Cognitive costs for the Stroop task were low irrespective of walking speed, suggesting that at preferred-speed individuals prefer to prioritize complex cognitive tasks requiring higher processing resources over the walking. While performing VMRT, individuals preferred to prioritize more complex walking task over VMRT task resulting in lesser motor cost and increased cognitive cost for VMRT task.

Chapter 2 compares the cognitive-motor interference (CMI) pattern of walking among chronic ambulatory stroke survivors and young adults to understand the effect of chronic stroke on dual-tasking function in comparison with individuals without any effect of aging or neurological condition. Community-dwelling chronic stroke survivors and young adults performed visuomotor (VMRT), serial subtraction (SS) and Stroop tasks while sitting and walking. Dual-task walking led to significant decline in motor and cognitive performance in both the groups. The stroke group showed highest motor cost for SS task, whereas young group showed highest motor cost for Stroop task. Although cognitive costs for both the groups were highest for VMRT and least for Stroop tasks, the cost for SS task was significantly greater among stroke survivors than young adults. The findings suggest that CMI pattern in chronic stroke survivors differs significantly with the type of cognitive task. Gradual cognitive decline with chronicity of the condition superimposed with aging might have a role in altering the CMI pattern post stroke.

Chapter 3 examined the CMI of reactive balance control under dual-task condition in young healthy adults. Individuals were exposed to sudden large slip-like perturbations delivered in stance with (dual-task) and without a working memory task. This cognitive task was also performed in quiet stance. Dual-tasking significantly reduced postural stability and compensatory step length, and delayed the reaction time. The significant linear correlation between postural stability and compensatory step length present in the single-task balance condition, was absent in the dual-task condition. Cognitive task performance also declined under the dual-task condition. Our results indicate a mutual CMI pattern between the compensatory stepping responses to large perturbation and working memory tasks suggesting a potential overlap between attentional resources allocated for these two tasks.

Chapter 4 focuses on differences in balance recovery mechanisms contributing to fall risk during large forward (inducing SLIPS) versus backward (inducing TRIPS) perturbations among healthy adults and chronic stroke survivors. Younger adults, age-matched older adults and chronic stroke survivors were exposed to a single SLIP and TRIP through a motorized treadmill. Center of mass (COM) state stability, trunk and compensatory step kinematics were recorded. The incidence of SLIP related falls among stroke survivors was higher than that in healthy (young and age-matched) adults however, not for TRIPS. All the groups showed higher stability change from liftoff to touchdown during TRIPS than SLIPS. Higher stability during TRIPS in healthy individuals was attributed to the ability to control trunk flexion at step touchdown and lower peak trunk velocity as compared with SLIPS. Chronic stroke survivors increased compensatory step length during TRIPS versus SLIPS contributing to greater stability change. Nevertheless, they were unable to control trunk excursion and velocity as compared with healthy adults leading to a lower stability than healthy younger and age-matched adults during SLIPS and lower stability than younger adults during TRIPS. Difficulty in trunk control during SLIPS among all individuals and compensatory stepping response among stroke survivors emphasizes higher fall risk for SLIPS than TRIPS among these populations.

Lastly, Chapter 5 compares the CMI across different dynamic postural tasks and explores the effect of aging with and without a chronic stroke on the interference pattern. Young adults, age-matched older adults and older chronic stroke survivors performed an intentional balance task (limits of stability – LOS in forward direction), forward walking task, and forward compensatory stepping (reactive balance) tasks with and without a serial subtraction task. The maximum center of pressure excursion (MXE), gait velocity and COM position relative to base of support at step touchdown ($X_{COM/BOS}$), and correct responses on the cognitive task were recorded. The motor

and cognitive cost of dual tasking were computed for the three postural tasks. Among healthy adults (younger and age-matched), higher motor cost was associated with the reactive balance and gait tasks with the least motor cost for the LOS task suggesting greater interference and therefore, higher attentional demands for postural tasks that are perceived more unstable. Among chronic stroke survivors, all the postural tasks demanded similar attentional resources seen by similar motor costs for all three postural tasks. Motor cost for all the tasks was lowest in younger adults. Gait and reactive balance motor costs were similar between age-matched adults and stroke survivors however the LOS cost was lower in age-matched adults thank stroke survivors. Although stroke survivors show disproportionate ability to divide attention between motor and cognitive tasks, in the chronic phase, impaired CMI could be related to both aging and stroke related sensorimotor deficits.

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Chapter 1 – Effect of different cognitive tasks and walking speed on CMI of gait

1.1 Introduction

Walking is one of the most common circumstances during which people fall (Sartini et al, 2010). Irrespective of having any sensory or motor impairments, individuals with cognitive deficits pose relatively higher risk of falling compared to those without cognitive deficits (Axer, et al, 2010). These findings have raised interesting questions about cognitive-motor interference during walking. Thus, increasingly, investigators are attempting to understand the underlying mechanisms of cognitive-motor interference during walking and design dual-task paradigms for rehabilitation directed toward meeting demands of 'real life' situations.

The cognitive-motor interference (CMI) of dual tasking refers to deterioration of either motor or cognitive task performance when they are attempted simultaneously (Plummer-D'Amato et al, 2008). While walking, CMI has been demonstrated either by motor alteration of walking patterns—such as reduced gait velocity or increased gait variability or by cognitive decline in task performance across such domains as visuomotor processing, verbal fluency (e.g., word list generation), and working memory (e.g., serial subtraction). A general observation of CMI is that, when confronted by two attention-demanding activities, humans explicitly prioritize one task over the other based upon counterbalancing capabilities and available cognitive and/or motor reserves (Yogev-Seligmann et al, 2012). However, the diverse range of cognitive tasks employed across CMI studies make conclusions about prioritization (i.e., cognition versus walking) difficult to discern.

The nature of CMI across these varying cognitive domains has been studied in both younger and older adults. Dubost et al. (2008) observed that verbal fluency task did not show any effect on stride velocity in a cohort of young, healthy adults, nor did verbal fluency differ when walking versus sitting was assessed in this same sample. In contrast, an arithmetic task instigated a decline in gait speed and ability to enumerate numbers while dual-task walking compared to single-task conditions in another cohort of young healthy adults (Beauchet et al, 2005). Furthermore, some researchers have proposed the effect of concurrent cognitive task on walking also differs with age. For example, reaction times in older adults when responding to visual (but not auditory) stimuli are greater than in younger adults (Sparrow et al, 2002) while walking. Older adults also show greater decline in gait speed while dual-tasking compared to young adults (Li, Lindenberger, Freund, & Baltes, 2001).

Dual tasking paradigms have also been applied to individuals with neurological conditions in order to develop a more comprehensive understanding of fall risk in these vulnerable populations. Studies on cognitive-motor interference have shown that individuals with stroke (Haggard et al, 2000), or multiple sclerosis (Hamilton et al, 2009) present with poor ability to divide attention between motor and cognitive tasks compared to age-matched healthy adults. The digit span task significantly affected gait in those with Alzheimer’s disease, but it did not affect gait in young adults (Ebersbach, Dimitrijevic, & Poewe, 1995). Across these studies, results are often attributed to declines in cognitive function associated with the underlying neurological condition in question (Logie, Cocchini, Delia Sala, & Baddeley, 2004).

It is evident the CMI pattern varies largely based on the population being studied and the methodology being used. For example, the choice of cognitive task can heavily influence the CMI pattern in younger and older adults as well as individuals with cognitive and/or motor impairments (Ebersbach et al., 1995). It follows that one specific task may be inadequate to explain CMI in its entirety or to determine whether individuals prefer prioritizing cognitive tasks over walking or vice versa.

On the same lines manipulation of walking speed may alter such cognitive prioritization. For example, while increased gait speed may be indicative of safe travel under dual-task conditions, (e.g. crossing lights while talking over the phone), Dennis et al. (2009) demonstrated that walking at a faster speed resulted in more number of errors on the concurrent cognitive task compared to when walking at preferred speed. Other evidence suggests that walking at slower speed improves walking stability (England & Granata, 2007). It is thus likely that the increase in stability gained while walking at slower speed might provide additional neural resources for processing of the cognitive task. As such, the beneficial effects of slow walking to enhance cognitive motor performance in dual task condition have not received much attention.

This study attempts to determine the differences in cognitive-motor interference when performing cognitive tasks targeting different cognitive functions at varying walking speeds. Thus, the two-fold aim of this study was 1) to examine the effect of visuomotor, memory recall, working memory, and executive function tasks on motor and cognitive costs of dual-task walking and 2) to determine the effect of slow walking versus preferred-speed walking on cognitive cost of dual-task walking. The cost was determined by computing the difference between single and dual-task performance. We hypothesized that a higher motor cost will be associated with a particular cognitive task. Higher motor cost would indicate requirement of greater attentional resources for that cognitive task, under dual task conditions. Tasks showing higher cognitive cost would indicate prioritization of motor task (walking) under the respective dual-task conditions and lower cognitive cost would indicate prioritization of cognitive task under respective dual-task condition. We further hypothesized that compared to preferred-speed walking, slow walking while dual-tasking would improve the performance on the cognitive tasks i.e., decrease the cognitive cost of dual-task walking.

1.2 Experimental Procedures

Participants

Fifteen healthy young adults (M= 25.6, SD= 5.23years, 14 females, 1 male) participated in the study. Subjects were recruited from the University of Illinois at Chicago and informed consent was obtained. We chose to focus on younger adults to determine the typical pattern of CMI while performing varied cognitive tasks while walking. To understand the pattern of CMI of dual-task walking, subjects performed four different cognitive tasks while sitting and walking.

Gait Parameters

Gait speed was recorded using an electronic mat GaitRite (CIR Systems, Inc., Sparta, NJ). It consists of sensors embedded into 12 x 2 feet mat which measures spatial and temporal gait parameters via the accompanying GaitRite software (GaitRite Gold, Version 3.2. To record the steady state walking pattern, subjects were instructed to begin walking about 1 meter before stepping on the mat and to keep walking about 2 meters beyond the mat. Gait speed was recorded and defined as the distance walked in the walking time for that specific trial. Gait speed was selected to evaluate the change in motor function, as the effect of a concurrent cognitive task has shown to be most evident on this variable (Al-Yahya et al., 2011) and is consistently linked with functional outcomes (Holtzer, Wang, Lipton, & Verghese, 2012; Verghese, Wang, & Holtzer, 2011).

Cognitive Tasks

Subjects were asked to perform four different cognitive tasks in randomized order while seated and walking. 1) *Visuomotor reaction time (VMRT) task:* In a seated position, subjects were shown two visual stimuli that were flashed on a screen. The first (red) stimulus was a preparatory signal followed by a second (green) stimulus. Subjects responded to the second stimulus by pushing a push-button in their hand. The VMRT response was recorded as the amount of time (milliseconds) taken by the subjects to press the button upon presentation of second stimulus. To maintain the position of the hand consistent under single- and dual-task conditions, subjects were asked to sit in a chair without an armrest and place their hand, unsupported, by the side of their body. 2) *Word list generation (WLG)* task: Subjects were asked to generate words beginning with a specific letter, and the total number of words generated in 10s was summed (Dubost et al, 2008). This task focused on verbal fluency and semantic memory. 3) *Serial subtraction (SS) task:* In this task targeting working memory, subjects were instructed to count backwards by a specific number from a specific two-digit number. The number of correct responses in 10s was recorded (Beauchet et al, 2005). 4) *Stroop (STR) task*: This task measured cognitive interference, executive function, and information processing speed. Subjects were asked to name the color with which a color word was printed, for instance, the word ‘blue’ was printed in ‘red’ ink and the subject would need to respond ‘red’ to be correct. The words were displayed on 36 inch TV screen. Subjects were asked to name colors of a set of twenty-four words and the number of correct responses provided within 10s was measured (Stroop, 1935). The WLG, SS and STR tasks were conducted aloud and the responses were recorded using an audio recorder. The cognitive tasks were selected based upon the different categories of cognitive tasks commonly used in previous CMI studies. These tasks also represent the cognitive functions shown to have a role in walking function (Holtzer et al., 2012).

Experimental protocol

Subjects first received standardized instructions on how to perform the cognitive tasks followed by one familiarization trial. For the purpose of the study, the performance on gait parameters was described as the motor function and that on cognitive tasks as cognitive function.

a) Single-task condition:

Single-task trials were performed in two blocks. Block 1 comprised of performing 3 trials for each of the 4 cognitive tasks (i.e., 3 x 4 =12 trials) in sequentially randomized order while sitting (single-task cognition condition). Block 2 consisted of i) walking 3 trials on a GaitRite mat at their self-selected (i.e., preferred) speed without performing any cognitive task and ii) walking 3 trials on the GaitRite mat at self-selected slower speed without performing any cognitive task. The order of all the 6 trials walking trials from Block 2 was randomized. Sitting tasks were conducted before walking tasks (Fig. 1A).

b) Dual-task condition:

Dual-task trials were performed in two blocks: block 1 was comprised of dual-task walking at preferred-speed, and block 2 was comprised of dual-task slow walking. Each block consisted of 12 trials (3 trials x 4 cognitive tasks). All 12 trials within each block were sequentially randomized. During both preferred- and slow-speed dual-task conditions, subjects were not given any instructions regarding prioritization of either walking or cognitive task. All preferred-speed and slow speed dual-task walking trials were sequentially randomized (Fig. 1B). Subjects paused for about 30-45s between the trials to allow time for the assessor to set up next trial.

All single-task trials were performed before dual-task trials. To reduce practice effects for the cognitive tasks, an interval of 30 minutes was provided between single-task and dual-task conditions. To prevent experimenter bias, data for all the participants were collected by a single research assistant who was not involved in data analysis.

Dual-task Cost

The effect of dual-tasking on both gait and cognitive parameters was assessed by comparing the absolute values for all cognitive and gait parameters between single- and dual-task conditions. To compare the motor and cognitive function across the different dual-task conditions, the motor and cognitive dual-task cost was measured using following formula (Kelly et al., 2010):

[(Single-task — Dual-task)/Single-task*100].

Higher cost indicated poor performance on the individual tasks, and lower cost indicates better performance on the individual tasks. The differential challenge of the cognitive task was determined based upon the motor cost of gait speed under the respective dual task conditions.

1.3 Statistical Analysis

To analyze the effect of the different task conditions on the various gait parameters (Aim 1), each variable was analyzed using 1 x 5 repeated measure analysis of variance (ANOVA) with task conditions as the within-group factor (walking only, VMRT, WLG, SS, and STR tasks). Paired t-tests were performed between cognitive performance scores in the seated and walking conditions for each cognitive task. The motor and cognitive costs across the four dual-task conditions were compared using 1 x 4 repeated measures ANOVA. Significant findings were followed up with post hoc analysis to determine the effect of specific cognitive tasks on different gait speed (motor function). The analysis was first conducted using all the individual trials and compared to that using means of three trials in each condition. As the results using both the methods were similar, final analysis included means on three trials in each condition.

The cognitive tasks that exhibited highest and lowest cognitive costs in preferred-speed dual-task walking condition were further used to analyze the effect of slow walking on motor and cognitive cost of dual-tasking (Aim 2). This was done via a 1 x 3 repeated measures ANOVA performed for slow walking with task conditions as the within-group factor (walking only, VMRT and STR) and gait speed as the dependent factor. Similarly, to analyze the effect of walking speed on cognitive performance 1 x 3 repeated measures ANOVA was performed with task conditions as within-group factors (sitting, preferred-speed and slow walking). Paired t-tests were performed for motor and cognitive costs between preferred-speed and slow walking conditions, each for the VMRT and STR tests. The statistical significance level was set at 0.05. The analyses were performed using SPSS version 19.0. Chicago, IL.

1.4 Results

a. Effect of cognitive task condition on preferred-speed walking.

Dual-task motor cost:

The type of cognitive task had a significant effect on gait speed [F (4, 44) = 49.928, $p < 0.001$, $\eta^2 = 0.92$) with a significantly lower gait speed during all four dual-task conditions compared to the single-task preferred-speed walking ($p < 0.05$ for ST compared to VMRT, WLG, SS and STR) (Fig. 2A). Gait speed was slowest in the Stroop test (STR) condition compared to other dual-task conditions ($p < 0.001$ for STR and VMRT; $p < 0.01$ for STR and

WLG; $p < 0.05$ for STR and SS). There was no significant difference between WLG and SS dual-task conditions ($p > 0.05$). However, the gait speed for these conditions was significantly lower than that in the VMRT condition ($p < 0.05$ for all comparisons). A comparison of motor costs revealed that motor cost was significantly higher for the STR condition compared to the VMRT, WLG, and SS conditions ($p < 0.05$ for all comparisons). Motor cost for the WLG and SS conditions was significantly higher than the VMRT condition ($p < 0.01$ for all comparisons). There was no significant difference between the WLG and SS conditions ($p > 0.05$) (Fig. 2B).

Dual-task cognitive cost:

Overall, the performance on cognitive tasks declined while walking compared to sitting. Compared to the sitting VMRT condition, there was an increase in reaction time on the VMRT task ($p < 0.01$, Fig. 3A) during dual-task conditions, with fewer words generated on the WLG task ($p < 0.01$, Fig. 3B), fewer correct responses on the SS task ($p < 0.05$, Fig. 3C), and fewer correct responses on the STR task ($p < 0.01$, Fig.3D). The cognitive cost of dual-task walking was greatest for the VMRT task compared to the other three tasks ($p <0.01$ for all comparisons, Fig 4), whereas the cognitive cost was lowest for the STR condition ($p < 0.01$ for all comparisons). There was no difference in cognitive cost between the WLG and SS conditions ($p > 0.05$).

b. Effect of cognitive task condition on slow walking.

Dual-task motor cost:

Compared to single-task slow walking, subjects further decreased their gait speed under the STR condition ($p < 0.01$, Fig.5A). On the other hand, gait speed for the VMRT task condition did not differ significantly from single-task slow walking ($p> 0.05$).

The motor cost for the STR condition was significantly lower during slow walking compared to preferred-speed ($p < 0.05$). However, there was no significant difference in motor cost for the VMRT condition ($p > 0.05$, Fig. 5B).

Dual-task cognitive cost:

Compared to the sitting VMRT condition, there was a significant increase in visuomotor reaction time on the VMRT task in both preferred-speed and slow walking conditions [F (3,40) = 20.35, $p < 0.01$, $\eta^2 = 0.337$]. The visuomotor reaction time was greater in slow walking condition compared to sitting ($p < 0.01$). Compared to preferred-speed walking, visuomotor reaction time was also greater but did not reach the significance level ($p > 0.05$, Fig. 6A). Subjects did not show any significant difference in performance on the STR task while slow walking compared to sitting ($p > 0.05$) (Fig. 6B). However, subjects showed a significantly better performance on the STR task during slow walking compared to preferred-speed walking ($p < 0.01$). The cognitive cost for the STR task was significantly lower for slow walking compared to preferred-speed walking ($p < 0.01$), whereas there was no difference between the cognitive costs for the VMRT task at the two speeds ($p > 0.05$) (Fig.6C).

1.5 Discussion

This study explored the effect of different type of cognitive tasks and gait speeds on cognitive-motor interference of dual-task walking in healthy young adults. Compared to single-task conditions, young adults showed alteration in their walking pattern (demonstrated by increased motor cost) and deterioration in performance of the cognitive task (demonstrated by increased cognitive cost) during all four (VMRT, WLG, SS, and STR) dual-task conditions. The CMI of dual-task walking differed with respect to the type of cognitive task performed. The motor cost for STR dual-task condition was highest and that for VMRT condition was least. As per our hypothesis, it can be suggested that performing STR task concurrently while walking requires greater attentional resources compared to other cognitive tasks. In contrast, performing VMRT task requires the least attentional resources in comparison with other tasks. Additionally, slow walking led to reduction in cognitive cost of dual-task walking for STR task, but not for VMRT task.

Effect of Cognitive Task on Cognitive-Motor Interference at Preferred-Speed Walking

During preferred-speed, dual-task walking, a significant decrease was observed in gait speed compared to single-task walking. Previous studies have reported a similar decrease in gait speed during dual-task conditions (Beauchet et al, 2002; Beauchet et al, 2005; (Al-Yahya et al., 2011; Yogev-Seligmann et al., 2010). Such modulation in gait speed is often achieved by decrease in step length and cadence (Dubost et al., 2008; Verghese et al., 2007) and increase in double support time (Verghese et al., 2007).

At preferred-speed dual-task walking, we found that motor cost was lowest for the VMRT task compared to that for the WLG, SS and STR tasks. The cognitive cost was highest and motor cost was least for the VMRT task compared to the other tasks. It can thus be suggested that

VMRT task is considered less challenging compared to the walking task. Subjects therefore preferred to prioritize their walking over performance on the VMRT task. Such cognitive-motor interference demonstrated in this study during dual-task walking can be further explained by the 'capacity sharing model' for central processing (Kahneman, 1973; McLeod, 1977). The capacity sharing model assumes that the central processing capacity is limited; thus, when two tasks sharing common neural circuitry are performed at the same time, both the tasks are processed, but sharing of the central processing capacity between the tasks slows down processing. The sharing of planning and processing resources in the current study may have occurred due to sharing of neural circuitry within substrates such as the supplementary motor area and cerebellum, both required for locomotor function and the VMRT task (Johansen-Berg and Matthews, 2002; la Fougere et al, 2010).

Subjects also showed an increase in motor cost for the WLG and SS dual-task conditions compared to the VMRT condition (VMRT < WLG and SS). In keeping with the capacity sharing theory, these results suggest sharing of central processing resources between semantic memory tasks (such as WLG), working memory tasks (such as SS), and locomotor tasks (Kahneman, 1973; McLeod, 1977). Furthermore, our results indicate that the amount of attentional resources utilized under dual-task conditions for both the WLG and SS tasks may be similar given there were no difference in motor and cognitive costs between the two tasks. This suggests that both WLG and SS tasks interference to similar extent with the walking task.

The motor cost at preferred-speed was highest for STR dual-task condition compared to the WLG, SS, and VMRT dual-task conditions, whereas the cognitive cost was lowest for STR task condition compared to other three conditions cognitive tasks. It is proposed that in a situation requiring performance of a novel and more complex cognitive task, concurrently with an overly learned task, subjects tend to heavily prioritize the performance of the cognitive task (Schmidt and Wrisberg, 2008). This is commensurate with other studies suggesting the tradeoff between the cognitive tasks and gait depends on the degree of novelty and complexity of the cognitive task and perceived threat to stability (Yogev-Seligmann et al., 2012). Further, the capacity sharing model assumes that when two tasks sharing central resources are performed concurrently, the central capacity will be shared and processing of both the tasks will be delayed. Such a delay in processing was observed by decline in performance on both walking and STR tasks in dual-task conditions. However, it is assumed that allotment of attentional capacity can be regulated voluntarily (McLeod, 1977). As a result, a higher motor cost and a lower cognitive cost for STR dual-task condition suggests that subjects might have prioritized STR task over walking by allocating greater attentional resources to STR. Although we are not able to determine the neural substrates with the current paradigm, but others have shown that dorsolateral pre-frontal cortex is activated in both STR and locomotor tasks (la Fougere et al, 2010; Zoccatelli et al, 2010) which indicates sharing of neural resources. Thus, based on above postulations and our findings, it can be inferred that individuals prioritized the novel cognitively demanding task such as STR over a well-practiced task such as walking, when the two tasks were performed simultaneously.

Stroop test which is based on conflict between the color word and color of ink of the printed color word (e.g. the color RED printed in blue ink), demands considerable attention, planning, and information processing to avoid instinctive responses and is considered a “gold standard” measure for attention (McLoed, 1991). Studies have shown that Stroop test is accompanied by activation of several brain regions such as anterior cingulate cortex, supplementary motor area, retrosplenial gyrus, insula, middle frontal gyrus, and cerebellum in addition to other centers

(Zoccatelli, Beltramello, Alessandrini, Pizzini, & Tassinari, 2010). As opposed to STR task, other cognitive tasks are associated with more focused activation of brain areas such as prefrontal cortex for working memory and visuomotor tasks (Toni, Rushworth, & Passingham, 2001; Voytek & Knight, 2010), and inferior temporal gyrus for memory recall (Mehrholz, Elsner, Werner, Kugler, & Pohl, 2013). The pattern of neural activation for STR task suggests involvement of extensive network of brain areas which may lead to use of greater processing resources. Although the complexity of STR task compared to other tasks has not been established so far, one study suggests that Stroop Word Color task is more complex than simple reaction time task (Dalecki, Bock, & Hoffmann, 2013). In addition, in our study, as the subjects showed highest motor cost and least cognitive cost in STR condition, it is likely that STR task requires greater processing resources compared to other cognitive tasks, leading to prioritization of cognitive performance over gait.

5.2 Effect of Slow Walking on Cognitive Motor Interference

Consistent with our second hypothesis, compared to preferred-speed dual-task walking, young adults reduced the cognitive cost for the STR task while further decreasing their gait speed. The gait speed further decreased in STR condition seen by increased motor cost for this condition. In contrast, during the VMRT dual-task condition, subjects maintained their gait speed, observed by no significant increase in motor cost between slow and preferred-speed walking during the dual-task condition. Similarly, no significant difference was observed in cognitive cost between the two gait speeds.

McLeod (1977) proposed that allocation of attentional resources to two different tasks may be modulated voluntarily. Depending on the characteristics of the tasks, processing information of one task can be speeded as over the other. Based on this theory, it was hypothesized that voluntary modulation (reduction) of gait speed via explicit instruction of 'slow walking' would enable greater allocation of resources for the cognitive task. As hypothesized, during slow walking, subjects were able to prioritize the cognitive task over the locomotor task when the complexity of the cognitive task increased. Thus, it is possible that the stability gained by the reduction in gait speed during slow walking may have allowed for increased processing time for the cognitive task in the STR dual-task condition. While performing the VMRT task, that is perceived as less complex(Dalecki et al., 2013), subjects preferred to prioritize the motor task to maintain performance (the intended self-selected slow-speed) while dual-task walking.

The natural response to a challenging walking situation is execution of ‘posture first’ strategy, that is, prioritization of gait stability by slowing down (Verghese et al, 2007). This study shows that this strategy can also be beneficial in allocating greater attentional resources toward optimizing the performance on more attention-demanding complex cognitive tasks and may not be required for the less complex cognitive tasks.

In the past, reduced gait speed while walking has been identified as a strong predictor of future falls in older adults (Montero-Odasso et al, 2005). While some researchers suggest that fallers walk significantly slower than non faller (Wolfson et al, 1990), others have concluded that fallers and non-fallers do not differ in their gait pattern (Feltner et al, 1994). Since walking is a challenging task in itself, performing a secondary task while walking increases the challenge. It is therefore likely that gait alterations such as reduced gait speed might be adopted to enhance the stability while walking under challenging circumstances. Under more complex ‘real life’ situations—such as walking in a crowded mall or a street, getting on and off a crowded bus, or catching a train at a station—people recourse to strategies that help in executing the necessary tasks like reading traffic signs, attending to bus stops, or reading train schedules at minimal risk of injury. This is often done by prioritization of cognitive tasks over motor tasks. Thus, instead of perceiving decreased speed as the negative effect of dual-task walking, slow walking appears to be a beneficial strategy employed in challenging circumstances.

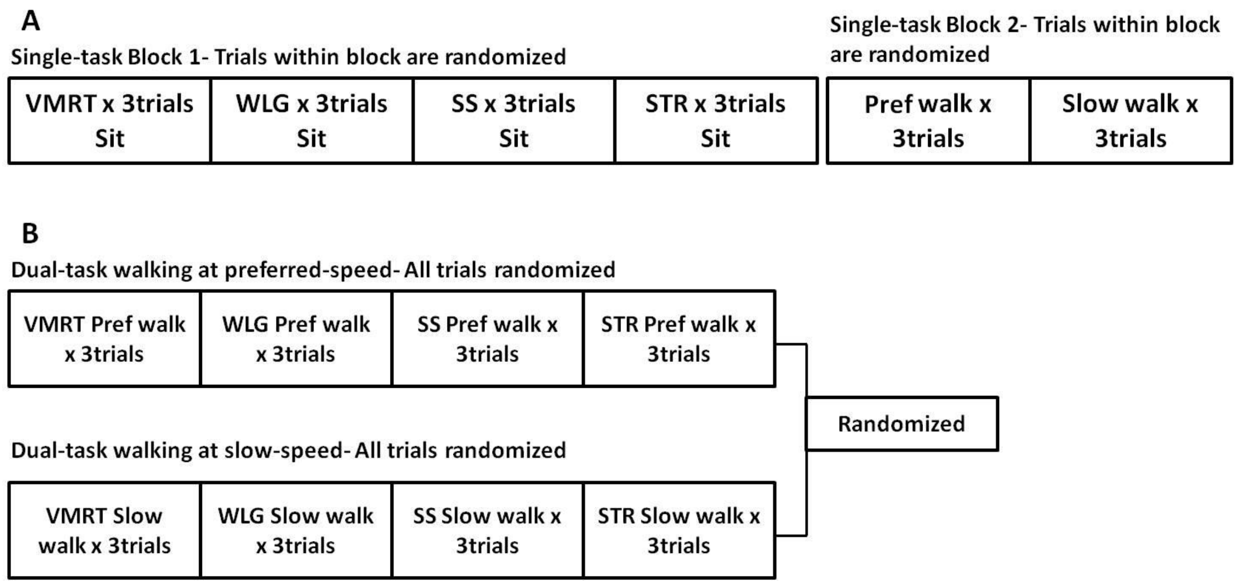
This study differs from other studies exploring CMI pattern in two ways. First, most of the previous studies have used only one cognitive task to explore CMI (Beauchet et al, 2005; Beauchet et al, 2002; Ebersbach et al, 1995). Considering that different cognitive tasks compete for cognitive resources to varying extents, using only one cognitive task may not be sufficient to explain the CMI pattern in its entirety. Secondly, studies using more than one cognitive task in their experimental protocol have used similar attention demanding cognitive tasks (such as spatial attention task and letter 2-back working memory task) as a result of which there was no effect of the type of cognitive task observed on gait parameters (Nadkarni et al, 2010). In this study, discrete differences in the type and complexity of cognitive tasks facilitate the understanding that simultaneous performance of tasks requiring higher cognitive functions, such as selective attention, planning, and working memory while walking lead to explicit prioritization of the cognitive task over the locomotor task. Further the effect of CMI on self-selected slow walking has not been examined.

This study also has implications from both clinical and physiological perspectives. Firstly, as clinicians are increasingly becoming aware of the importance of testing dual-task walking function, it is important to consider the type of cognitive task chosen. Different types of cognitive tasks may result in different patterns of cognitive-motor interference, informing specific type of cognitive activities that may be used for dual-task walking rehabilitation. Secondly, based on the results of this study, it can be inferred that tasks involving selective attention, planning, and working memory may lead to activation of additional cortical centers other than those involved in locomotion in an attempt to optimize performance on cognitive task while maintaining walking stability by decreasing walking speed (increased motor cost).Considering that slow walking aided in allocating higher attentional resources for better performance of a complex cognitive task, dual-task rehabilitation strategies should be targeted toward training modulation of gait speed according to perceived hazard and threat to balance from the cognitive task in order to prevent falls while walking.

In summary, the pattern of cognitive-motor interferences varies with the type of cognitive task being performed while walking. At preferred-speed walking, performing cognitive tasks employing executive function and planning increase motor cost in order to optimize the performance on the cognitive task. Slow walking can aid in improving the performance cognitive tasks requiring considerable planning and thus, should be explored as a strategy for dual-task gait training.

1.6 Figures:

Figure 1.



A.Tasks performed in single-task condition. Tasks in block 1 were performed before block 2. (Pref= preferred-speed, VMRT= visuomotor reaction time, WLG= word list generation, SS= serial subtraction, STR= Stroop test). B. Tasks performed in dual-task condition at preferred-speed and slow-speed.

Figure 2.

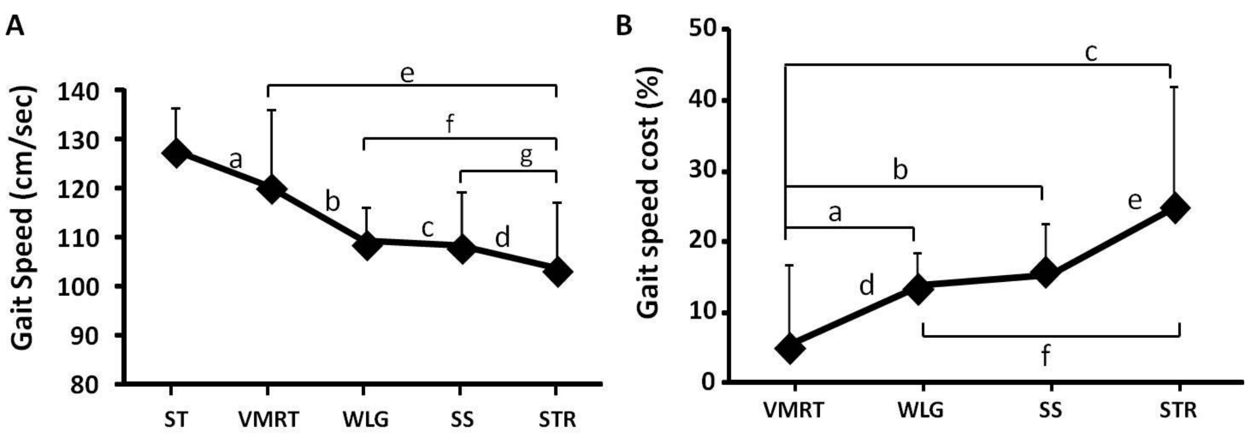
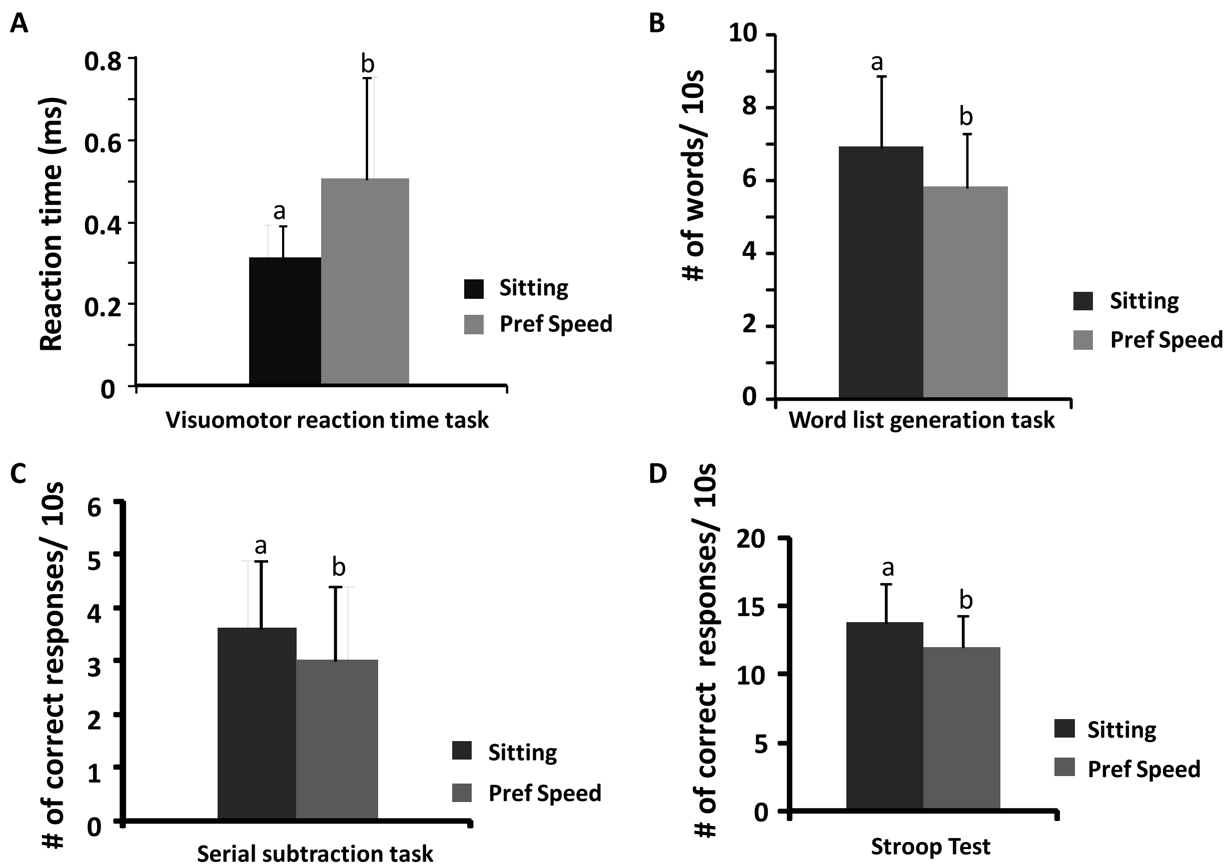


Figure shows changes in gait speed (A) and motor cost for gait speed (B) in single-task (ST), visuomotor reaction time (VMRT), word list generation (WLG), serial subtraction (SS) and

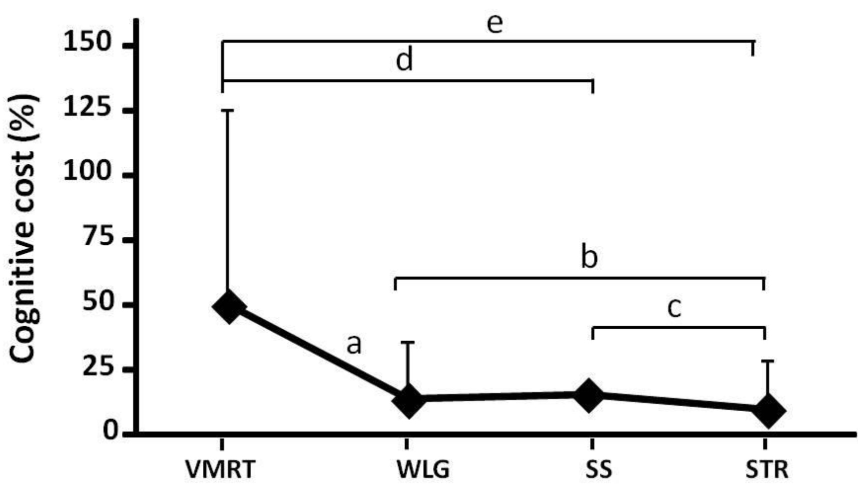
Stroop test (STR) dual-task conditions. Significant differences are indicated by letters a, b, c, d, e, f, and g. Significance level was set at $p < 0.05$.

Figure 3.



Performance on cognitive tasks while walking at preferred-speed compared to sitting (ST) as seen by increase in visuomotor reaction time (VMRT), and decrease in number of words generated in word list generation task (WLG), number of correct responses on serial subtraction task (SS) and number of correct responses on Stroop test (STR). Significant differences at $p < 0.05$ are indicated by different letters.

Figure 4.



This figure displays the cognitive cost of dual-task walking at preferred-speed. Significant differences between dual-task conditions i.e. visuomotor reaction time (VMRT), word list generation (WLG), serial subtraction (SS) and Stroop test (STR) tasks (a,b,c,d,and e = p<0.05).

Figure 5.

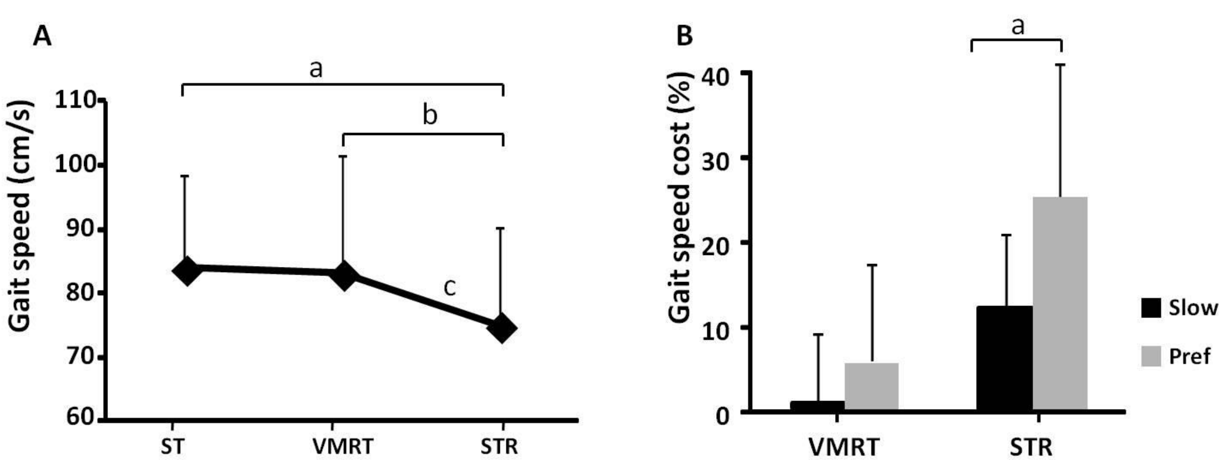


Figure showing the effect of dual-task slow walking on gait speed (A) and motor cost of gait seed (B) under two dual-task conditions (visuomotor reaction time = VMRT, and Stroop test = STR). Overall, subjects demonstrated further decline in gait speed for STR over VMRT condition. Significant differences are indicated by letters a, b = p< 0.05.

Figure 6.

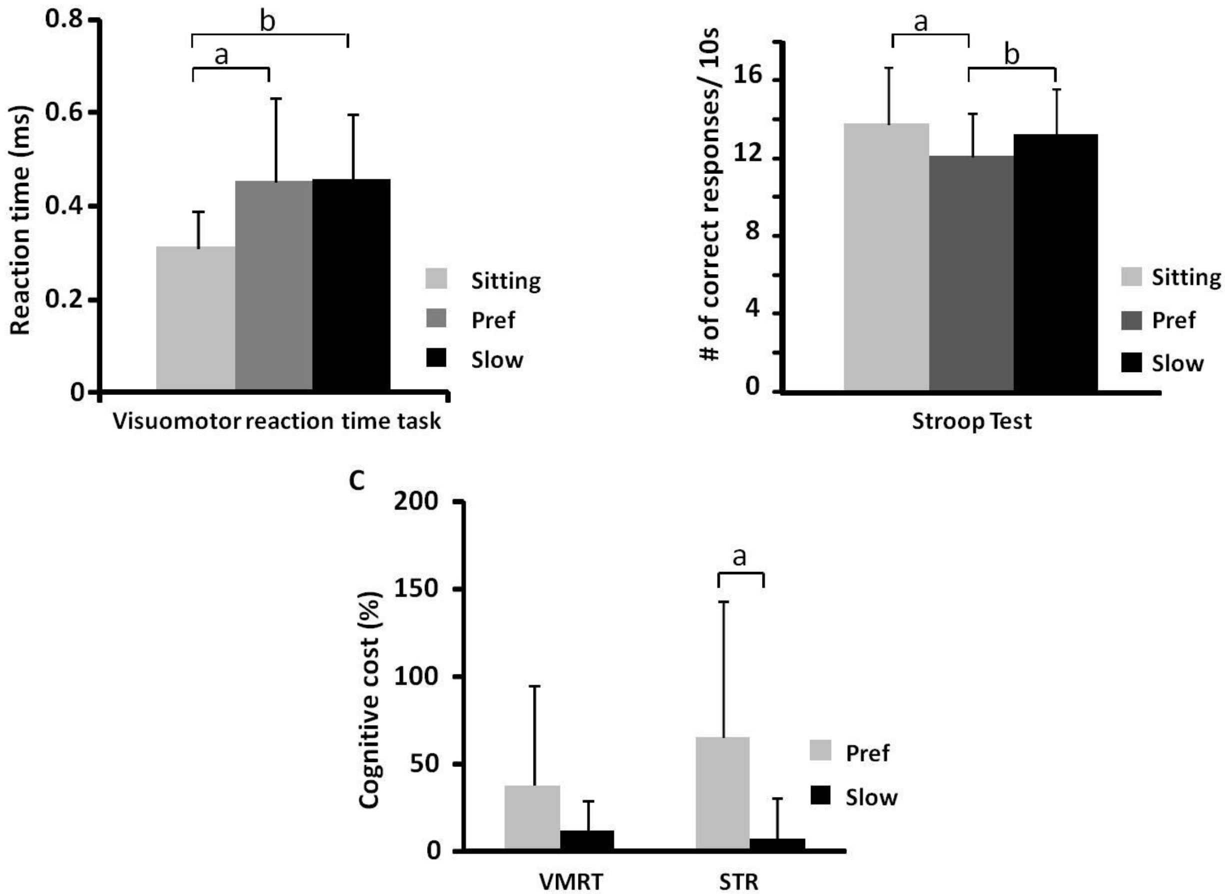


Figure demonstrating changes in visuomotor reaction time (VMRT) and number of correct responses in 10s on Stroop test (STR) for sitting (ST), preferred-speed (Pref) and slow walking conditions (A &B). A significant increase in number for correct responses was seen for STR during slow walking, letters a,b = $p < 0.05$. The effect of walking speed (C) can be observed by significant decline ($p < 0.05$) in cognitive cost for Stroop test during slow walking compared to preferred-speed (Pref) walking.

This is an Accepted Manuscript of an article published by Taylor & Francis in Topics of Stroke Rehabilitation on 12/22/2014 online: Patel, P., & Bhatt, T. (2014). Task matters: influence of different cognitive tasks on cognitive-motor interference during dual-task walking in chronic stroke survivors. Topics in stroke rehabilitation, 21(4), 347-357. See appendix B.

Chapter 2 – Influence of different cognitive tasks on CMI in chronic stroke survivors

2.1 Introduction

Changes in cognitive-motor interference with cerebral damage due to stroke are not clearly understood. To better understand the effect of stroke-related cognitive decline on dual-tasking ability, it may be more appropriate to investigate cognitive-motor interference in stroke survivors under the age of sixty with healthy young and age-match adults. Furthermore, the incidence of stroke in relatively younger population is increasing with significant cognitive deficits persisting longer than in those who had a stroke after the age of 50 years (Kissela et al., 2012; Schaapsmeerders et al., 2013). Therefore, this study aims to compare the effect of explicitly different cognitive tasks (such as visuomotor, working memory, and executive function tasks) on cognitive-motor interference of dual-task walking between community-dwelling stroke survivors and young healthy adults. We hypothesized that the cognitive-motor interference pattern will differ between people with chronic hemi-paretic stroke and healthy young adults based on the cognitive task being performed. Specifically, while healthy adults will prioritize executive function tasks over gait under dual-task walking conditions, due to significant deficits in working memory post-stroke (Schaapsmeerders et al., 2013), we hypothesized that individuals with chronic hemiparetic stroke would show a greatest decline in gait performance under working memory dual-task condition compared to young adults.

2.2 Methods

Participants

Ten community-dwelling chronic stroke survivors participated in the study (M= 56.8 years, SD= 5.9 years). Subjects from an existing study database were contacted for participation in the study. The information about type of stroke was obtained from subjects' physicians. The participant characteristics are described in Table 1. The inclusion criteria were 1) ability to walk 10m with a speed of $\geq$ 0.58 m/s without any assistive device i.e., least limited and unlimited community ambulators (Perry, Wiggins, Childs, & Fogarty, 2013), and 2) intact cognitive function determined by score of $\geq$ 20 on Short Orientation Memory Concentration test (SOMCT) (Katzman et al., 1983). This test focuses on different aspects of cognitive functions such as orientation, attention, recall, working memory, and language. It is also positively correlated with screening tests for aphasia, suggesting individuals with higher score on SOMCT show better language functioning (Al-Khawaja, Wade, & Collin, 1996). The control group included 15 healthy young adults (M= 25.6, SD= 5.23years). The young adults were chosen as the control group to compare stroke survivors' responses to healthy, non-aging nervous system. The pattern of cognitive-motor interference was assessed for all subjects performing three different cognitive tasks during sitting and walking.

Gait Assessment

Gait parameters were recorded using an electronic mat GaitRite (CIR Systems, Inc., Sparta, NJ). It consists of sensors embedded into 12 x 2 feet mat which measures spatial and temporal gait parameters via the accompanying GaitRite software (GaitRite Gold, Version 3.2). To record the steady state walking pattern, subjects were instructed to begin walking about 1 meter before stepping on the mat and to continue walking about 2 meters beyond the mat. Gait velocity was measured while the subjects walked on the mat and was defined as the distance walked in the walking time for that specific trial.

Cognitive tasks

Subjects were asked to perform three different cognitive tasks in randomized order while seated and walking. 1) *Visuomotor reaction time (VMRT) task:* In a seated position, subjects were shown two visual stimuli that were flashed on a screen. The first (red) stimulus was a preparatory signal followed by a second (green) stimulus. Subjects responded to the second stimulus by pushing a push-button in their hand. The VMRT response was recorded as the amount of time (milliseconds) taken by the subjects to press the button upon presentation of second stimulus. To maintain the position of the hand consistent under single- and dual-task conditions, subjects were asked to sit in a chair without an armrest and place their hand, unsupported, by the side of their body. This task assessed the visuospatial cognitive function. 2) *Serial subtraction (SS) task:* In this task targeting working memory, subjects were instructed to count backwards by a specific number from a specific two-digit number. The number of correct responses was recorded (Beauchet, Dubost, Herrmann, & Kressig, 2005). 3) *Stroop (STR) task*: This task measured cognitive interference, executive function, and information processing speed. Subjects were asked to name the color with which a color word was printed, for instance, the word 'blue' was printed in 'red' ink and the subject would need to respond 'red' to be correct. Subjects were asked to name colors of a set of twenty-four words and the number of correct responses provided within ten seconds was measured (Stroop, 1935).

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Subjects performed three different cognitive tasks in randomized order while seated and walking. 1) *Visuomotor reaction time (VMRT) task:* In a seated position, subjects were presented with visual stimuli on a screen. The first (red) stimulus indicates a preparatory signal followed by a second (green) stimulus. Subjects responded to the second stimulus by pushing a push-button in their hand. The VMRT response was recorded as the amount of time (milliseconds) taken by the subjects to press the button upon presentation of second stimulus. To maintain the position of the hand consistent under single- and dual-task conditions, subjects sat in a chair without an armrest and place their hand, unsupported, by the side of their body. This task assesses the visuospatial cognitive function. 2) *Serial subtraction (SS) task:* In this task targeting working memory, subjects were instructed to count backwards by a specific number from a specific two-digit number. The number of correct responses were recorded (Beauchet et al., 2005). 3) *Stroop (STR) task*: This task measures cognitive interference, executive function, and information processing speed. Subjects named the color with which a color word was printed, for instance, the word 'blue' was printed in 'red' ink and the subject was asked to respond 'red' to be correct. Subjects will be asked to name colors of a set of twenty-four words and the number of correct responses provided within ten seconds was measured (Stroop, 1935).

Experimental protocol

Standardized instructions on how to perform the cognitive tasks followed by one familiarization trial will be provided. For the VMRT task, if the subjects push the button after the red stimulus instead of the green stimulus, one more familiarization trial will be provided. For the purpose of the study, the performance on gait parameters is described as the motor function and that on cognitive tasks as cognitive function.

Single-task (ST) condition: This condition comprised of - i) performing each of the 3 cognitive tasks (in sequentially randomized order) while seated (ST cognition condition), and ii) walking on a GaitRite mat without performing any cognitive task. Three trials were performed for walking in single-task condition.

Dual-task conditions: Dual-task conditions consisted of 9 trials (3 walking trials x 3 cognitive tasks). All 9 trials will be sequentially randomized. No instructions regarding prioritization of either walking or cognitive task will be provided. To reduce practice effects for the cognitive tasks, an interval of 30 minutes will be provided between single-task and dual-task conditions. To prevent experimenter bias, data was collected by a single research assistant who was not involved in data analysis.

Dual-task Cost: The effect of dual-tasking on both gait and cognitive parameters will be assessed by comparing the absolute values for all cognitive and gait parameters between single- and dual-task conditions. To compare the motor and cognitive performance across the different dual-task conditions, and between the control and stroke groups, the motor and cognitive dual-task cost will be measured using the following formula:

$$\frac{\text{Single} - \text{task} - \text{Dual} - \text{task}}{\text{Single} - \text{task}} \text{ x } 100$$

Higher cost would indicate poor performance on the individual tasks, and lower cost would indicate better performance on the individual tasks.

2.3 Statistical Analysis

The dependent variables included gait velocity, motor cost, visuomotor reaction time, number of correct responses on SS and STR tasks. The independent variables were group (young and stroke) and type of cognitive tasks (VMRT, SS, and STR).

To evaluate the effect of different cognitive tasks on gait velocity among both the groups 2 x 4 repeated measures ANOVA was performed with task conditions (walking only, VMRT, SS, and STR) as within-group factor and groups (young and stroke) as between-groups factor. The effect of dual-task conditions on motor cost for gait velocity on both the groups was analyzed by 2 x 3 repeated measures ANOVA with dual-task conditions (VMRT, SS and STR) as within-group factor and groups (young and stroke) as between-groups factor. Significant interactions and main effects were resolved using planned paired t-tests.

To assess cognitive performance, paired t-tests were performed for scores on cognitive tasks between sitting and walking conditions. To compare the cognitive performance on all three tasks between the two groups, 2 x 3 repeated measures ANOVA was performed for cognitive cost with dual-task conditions (VMRT, SS, and STR) as within-group factor and groups (young and stroke) as between-groups factor. Planned paired t-tests were performed to resolve significant interactions and main effects.

2.4 Results

Compared to single-task walking, under dual-task conditions both young and stroke groups showed a significant decline in performance on gait and cognitive parameters. However, the pattern of cognitive-motor interference differed between the young and stroke groups.

Motor Cost of Dual-Task Walking:

Overall, both groups decreased their gait velocity under dual-task conditions compared to single-task condition (main effect of task $p < 0.05$) with the stroke group walking significantly slower than the young adults in all dual task conditions relative to single-task conditions (main effect of group, $p < 0.05$). Among stroke group, the change in velocity was slowest for SS dual-task conditions compared to VMRT and STR dual-task conditions. Among the young group, the gait velocity was slowest for STR task compared to other dual-task conditions (significant task x group interaction, $p < 0.01$). Thus, the pattern of decrease in velocity with respect to the cognitive task observed in stroke group, i.e., SS < STR< VMRT ($p < 0.05$ for SS and STR, $p < 0.01$ for SS and VMRT, and $p < 0.01$ for VMRT and STR), differed from that observed in the young group, i.e., STR< SS< VMRT ($p < 0.01$ for STR and VMRT, $p < 0.05$ for STR and SS, $p < 0.05$ for VMRT and SS, Fig. 1).

Dual-task conditions had a significant effect on motor cost of gait velocity among both the groups. The motor cost differed between the groups within same dual-task condition (significant task x group interaction, $p < 0.01$, Fig. 2). The motor cost of gait velocity in the stroke group was highest for SS and least for VMRT dual-task conditions ($p < 0.05$ for all comparisons, Fig. 2), whereas in the young group, motor cost was highest for STR dual-task condition and least for VMRT condition ($p < 0.05$ for all comparisons). The stroke group showed significantly greater motor cost than young group for VMRT and SS dual-task conditions ($p < 0.05$). However, there was no significant difference in motor cost for STR condition between the groups.

Cognitive Cost of Dual-Task Walking:

Compared to sitting, both young and stroke groups showed a significant decline in cognitive performance under dual-task conditions. There was a significant increase in visuomotor reaction time ($p < 0.01$ for young and stroke groups, Fig 3A), decrease in number of correct responses on SS task ($p < 0.05$ for young and stroke groups, Fig. 3B), and decrease in number of correct responses on STR task ($p < 0.01$ for young and stroke groups, Fig 3C) while dual-task walking compared to sitting.

The type of cognitive task had a significant impact on the cognitive costs of dual-task walking within young and stroke groups (main effect task, $p < 0.05$). For both groups, the cognitive cost for

VMRT was highest compared to other tasks ($p < 0.05$ between VMRT and SS and VMRT and STR for both groups) and least for STR task ($p < 0.05$ between SS and VMRT for both groups). However, the cognitive cost for SS task was significantly greater for stroke group compared to young group (significant group x task interaction, $p < 0.05$) and not different for VMRT and STR ($p > 0.05$ between the stroke and young) (Fig. 4).

2.5 Discussion

As hypothesized, the cognitive-motor interference pattern differed with respect to the cognitive task being performed and between the stroke group and young adults. Several dual-task walking studies have proposed that dual-task walking interference can be attributed to sharing of central resources between walking and cognitive tasks (Hausdorff, Schweiger, Herman, Yogev-Seligmann, & Giladi, 2008; Nadkarni, Zabjek, Lee, McIlroy, & Black, 2010). Whether individuals prefer to prioritize the cognitive task over walking depends on the novelty and complexity of the cognitive task, and their ability to maintain balance under challenging situation (P. Patel, Lamar, & Bhatt, 2014; Yogev-Seligmann et al., 2012). In our study, young adults progressively increased motor cost from VMRT to STR tasks (VMRT < SS < STR) and declined cognitive cost from VMRT to STR tasks (VMRT> SS> STR). This suggests that during healthy state functioning, tasks focusing on executive function such as STR are perceived to be more complex, demanding greater attentional resources for planning and information processing compared to working memory and visuomotor tasks. Therefore, healthy individuals deteriorated on the walking task and exhibited the highest motor cost while performing the STR.

On the other hand, the stroke group showed highest motor cost for SS task and a significantly greater cognitive cost as well, compared to the young group. Such a deviation in cognitive-motor interference from healthy young adults might be attributed to stroke-related impact to the regions associated with working memory in addition to aging-related decline in cognitive function. While the cognitive profile of individuals with stroke has not been studied extensively, a significant impairment in working memory has been demonstrated in the acute stages of stroke (Philipose, Alphs, Prabhakaran, & Hillis, 2007), which persist for at least 3 months post-stroke (Riepe, Riss, Bittner, & Huber, 2004). Further studies on humans with unilateral prefrontal cortex (PFC) lesions have shown a strong association between PFC damage and deficits in working memory tasks such as mental arithmetic (Rossi, Bichot, Desimone, & Ungerleider, 2007; Tanaka et al., 2012; Voytek & Knight, 2010). Thus, greater impact of working memory task on cognitive-motor performance in this population might be indicative of greater damage to prefrontal cortex (PFC) compared to other areas of the frontal cortex pertaining to cognitive functioning.

In contrast to our findings, Plummer et al. (2008) observed that a working memory task (auditory 1-back task) had the least effect on gait speed when compared to auditory visuospatial clock and a spontaneous speech task(Plummer-D'Amato et al., 2008). A possible reason for this finding could be that subjects were given as many as seven practice trials for the cognitive tasks prior to testing. Learning the cognitive tasks might have given subjects a better opportunity to allocate greater attentional resources toward walking under dual-task condition, thus, having lesser impact on gait velocity and none on the cognitive task (Tanaka et al., 2012). While spontaneous speech had the largest effect on gait velocity, it also focused on more than one aspect of cognitive function, making it difficult to identify the specific cognitive component of speech largely responsible for causing interference with gait.

Our findings suggest that in the case of chronic stroke survivors, influence of working memory might be more dominant in dual-task walking function. Cognitive deficits through clinical tests have been recorded as early as 3 months of event occurrence (M. D. Patel, Coshall, Rudd, & Wolfe, 2002). While subtle changes in cognitive function from residual damage may not be immediately apparent in day-to-day activities, situations placing sizeable demand on motor and cognitive systems seem to unmask the gradual decline in cognitive function. Long-term evaluation of cognitive function in stroke survivors has shown that over the period of several years, cognitive recovery is not complete. These individuals continue to show substantial deficits in higher cognitive functions including but not limited to working memory, information processing, and attention compared to age-matched controls (Schaapsmeerders et al., 2013). All subjects included in this study presented with chronic stroke. Although cognitive assessment showed intact cognitive function in these subjects, it can be speculated that higher motor and cognitive cost for SS task might be a consequence of progressive decline in working memory function due to the impact of stroke.

In addition to severity of stroke, motor assessments such as upper extremity power and ability to walk have been used extensively to determine outcomes post-stroke (Counsell, Dennis, McDowall, & Warlow, 2002; Reid et al., 2010). Reports indicate that people with reasonably satisfactory recovery most often show better outcomes post-acute and sub-acute stroke (Reid et al., 2012). Despite its negative effect on functional outcomes, cognitive recovery after stroke has received astonishingly lesser attention. A recent study reported that performing a working memory task (e.g., counting backwards while walking) can better differentiate fallers from non-fallers compared to a verbal fluency task in people with stroke (Baetens et al., 2013). Based on the higher impact of the working memory task on dual-tasking ability shown in the current study and previous literature, the use of such a test is recommended for determining mild impairments in gait and balance and functional outcomes such as fall-risk post-stroke. Furthermore, timely evaluation of functional mobility under challenging circumstances might also aid in early detection of cognitive decline post-stroke.

A large number of stroke survivors that are unable to walk during stroke onset achieve assisted or independent ambulation within 4 months of stroke (Jang, 2010). Since walking is a complex activity and motor recovery is not complete, these individuals present with higher risk of falls while walking. While conventional (Liston, Mickelborough, Harris, Hann, & Tallis, 2000; Podubecka et al., 2011) and novel gait-training programs (Krishnan, Ranganathan, Kantak, Dhaher, & Rymer, 2012; Mehrholz et al., 2013) might be sufficient to advance stroke survivors to independent ambulation, successfully negotiating challenges of community ambulation requires training in multi-modality environment. Community ambulation requires simultaneous execution of other attention-demanding activities for example, finding a new address, following instructions on phone, paying attention to lights while crossing, and negotiating obstacles. Therefore, community ambulation is perhaps more challenging than walking in a controlled setting such as a hospital or home.

Incorporating cognitive elements to conventional rehabilitation programs has shown improved dual-task walking function, step execution accuracy, foot reaction time, and improved cognitive function among elderly with and without cognitive impairments (Coelho et al., 2013; de Bruin, van Het Reve, & Murer, 2013; Holtzer et al., 2012; Melzer & Oddsson, 2013). However, utility of such interventions for improving walking function and preventing falls in stroke population still remains to be explored. To assist stroke survivors in meeting the demands of 'real life' walking conditions and to prevent adverse outcomes like falls, it is essential to include cognitive tasks focusing on higher cognitive functions, such as working memory, to conventional gait rehabilitation programs.

This study addressed limitations in current literature in three different ways. Firstly, we chose distinctly different cognitive tasks targeting specific cognitive functions particularly important for walking, i.e., visuospatial attention (VMRT task), working memory (SS task), and executive function (STR task) (Martin et al., 2013; Yardley, Gardner, Leadbetter, & Lavie, 1999). None of these tasks required extensive use of speech, as tasks requiring talking have been reported to cause additional interference with walking due to articulation and respiratory demands of talking [46]. Secondly, most of the subjects in the stroke group were under the age of 60 years. Thus, it can be speculated that the cognitive-motor interference observed was likely due to underlying stroke-related cognitive decline. Lastly, to evaluate the impact of stroke on cognitive-motor interference pattern, the stroke group was compared to healthy young adults to compare the responses to healthy non-aging nervous system. Although this study would provide a meaningful extension to existing knowledge about CMI among chronic stroke survivors, the results must be understood in light of some limitations. The study is limited by a heterogeneous population of stroke survivors and small sample size. Future studies differentiating the pattern of CMI one the basis of site of lesion, education level, pre- and post-stroke occupation and dexterity are essential.

Lastly, although performance on the short orientation memory concentration test is highly correlated with aphasia, separate screenings to identify aphasia were not conducted.

The findings of this study conclude that the cognitive-motor interference post stroke depends heavily on the type of cognitive task. The reorganization of cortical structures during recovery along with the stroke-induced gradual and progressive cognitive decline could have contributed to the cognitive-motor interference pattern observed in this population. Thus, future studies designing dual-task paradigms for chronic stroke population should consider using cognitive tasks directed towards working memory function during rehabilitation.

Clinical Messages

- Stroke-related cognitive decline alters pattern of cognitive-motor interference from that observed in healthy individuals.
- Working memory tasks cause greater decline in motor and cognitive function than other tasks while dual-task walking in stroke survivors.
- Novel rehabilitation interventions targeting dual-tasking ability can augment cognitive, motor and functional outcomes.

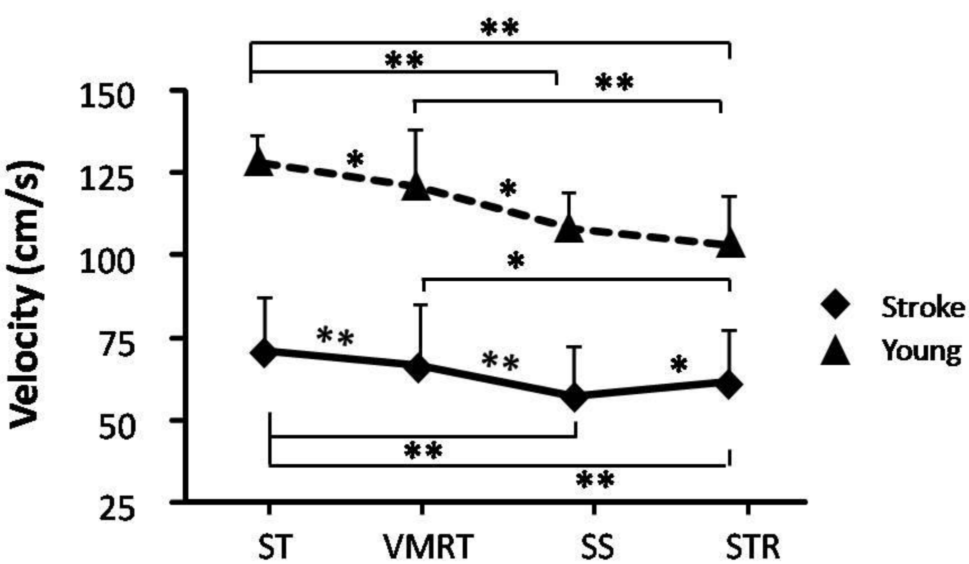
2.6 Tables and Figures

Table 1. *Characteristics of participants in stroke group*

Variable	*Number*	*M*	*SD*
Age (years)		56.80	5.95
Time since stroke (years)		4.6	2.58
10m walk (s)		9.03	2.21
SOMCT score (max=28)		25.43	2.60
Side of lesion(L/R)	7/3		
Type of stroke (Ischemic/ Hemorrhagic)	6/4		

SOMCT= Short orientation memory concentration test

Figure 1. *Gait velocity in single-task and dual-task conditions*



This figure shows significant differences in velocity in single-task (ST), visuomotor (VMRT), serial subtraction (SS) and Stroop test (STR) walking conditions among both young and stroke groups. * indicates $p < 0.05$, and ** indicates $p < 0.01$.

Figure 2. *Motor cost for gait velocity in dual task conditions*

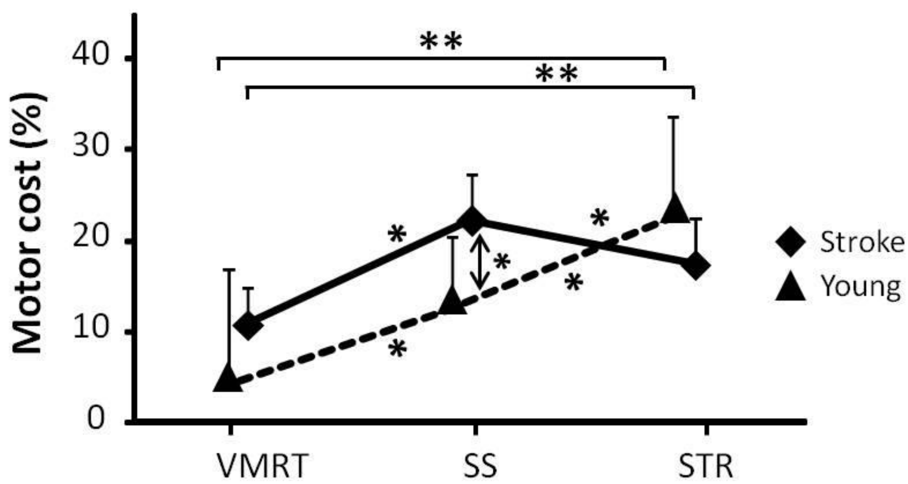


Figure showing differences in motor cost for gait velocity between visuomotor (VMRT), serial subtraction (SS) and Stroop test (STR) dual-task conditions within and between the two groups. Significant changes are indicated by * $p < 0.05$, and ** $p < 0.01$.

Figure3. *Cognitive performance in single task (sitting) and dual-task (walking) conditions*

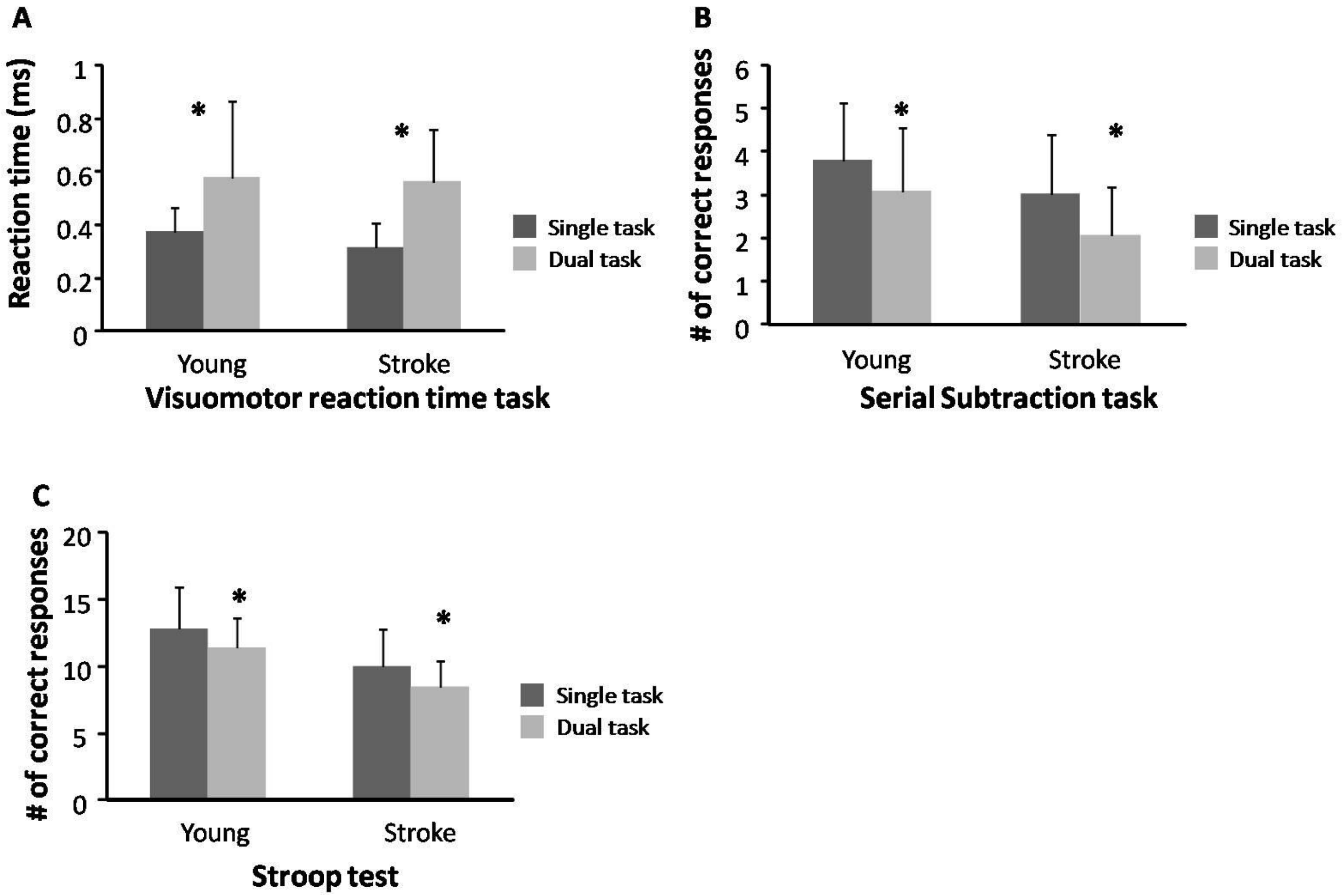
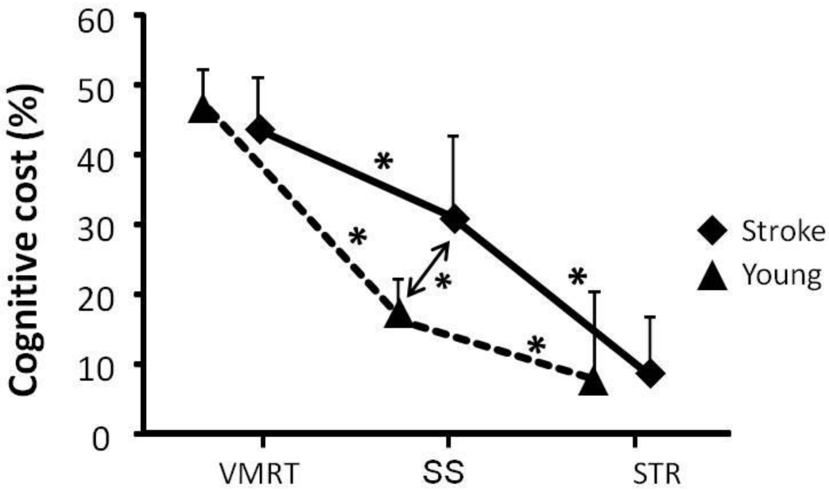


Figure displaying significant differences in scores on visuomotor reaction time task (3A), serial subtraction task (3B) and Stroop test (3C) between single and dual-task conditions among young and stroke groups. * indicates $p < 0.05$.

Figure 4. Cognitive cost for dual-task conditions



This figure shows the significant differences (* $p < 0.05$) in cognitive costs of dual-task walking for visuomotor (VMRT), serial subtraction (SS) and Stroop test (STR) tasks within, and between young and stroke groups.

This is an Accepted Manuscript of an article published by Taylor & Francis in Journal of Motor Behavior on 01/03/2015 online: Patel, P. J., & Bhatt, T. (2015). Attentional demands of perturbation evoked compensatory stepping responses: Examining cognitive-motor interference to large magnitude forward perturbations. Journal of motor behavior, 47(3), 201-210. See appendix B.

Chapter 3 – Attentional demands of perturbation evoked compensatory stepping responses

3.1 Introduction

Owing to the dynamic nature of the environment, events causing falls are unexpected and sudden. This places substantial demands on individual's ability to attend to sudden changes in the environment in order to prevent a fall (Hill, Schwarz, Flicker, & Carroll, 1999; Hsiao & Robinovitch, 1998a; Maki & McIlroy, 1997b, 2007). Change in support reactions, particularly compensatory stepping is a preferred response to re-establish stability from unexpected perturbations (Jensen, Brown, & Woollacott, 2001; McIlroy & Maki, 1996; Rogers, Hanke, & Janssen, 1996). These reactions are considered more attention demanding than the feet in-place reactions considering the need for executing a quick and appropriate response in the presence of environmental constraints (Maki, McIlroy, & Fernie, 2003; Horak, 2006). Therefore, in the recent past there has been great interest in understanding the attentional control of reactive balance responses (i.e. feet-in-place and change in support responses) (Brauer, Woollacott, & Shumway-Cook, 2002; Norrie et al., 2002; Zettel, McIlroy, & Maki, 2008).

The use of dual-task paradigms has added a different perspective towards understanding the attentional demands of reactive balance responses. The 'capacity sharing' theory proposed by Pashler (Pashler, 1994b) is an important theory explaining the interference between two attention demanding tasks. This theory posits that the central capacity is limited therefore; performing two tasks requiring similar attentional resources can interfere with each other. Consequently, processing of either one of both the tasks might be delayed. In accordance with this theory, if reactive balance responses are influenced by higher brain centers, performing an additional cognitive task would result in a deterioration of performance on either one of both the tasks. When both cognitive and motor performances are reduced a mutual interference is to be postulated, whereas a decrease in motor but not cognitive performance is postulated due to a cognitive-related motor interference. A decline in cognitive but not motor performance is postulated due to a motor-related cognitive interference (Plummer et al., 2013).

Most of the balance studies using dual-task paradigm have shown the presence of motor-related cognitive interference pattern such that dual-tasking resulted in a decline in the performance on the cognitive task without affecting the performance on the reactive balance task. These studies provide evidence concluding that reactive balance responses require attentional resources (Brauer et al., 2002; Brown, Shumway-Cook, & Woollacott, 1999b; Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001; Redfern, Muller, Jennings, & Furman, 2002). However, the effect of dual-tasking on the reactive balance task itself is not clearly understood. Only one study suggests that the center of pressure excursion during the later phase (> 250 ms post-perturbation) of postural recovery is larger while performing a cognitive task compared to that while performing a reactive balance task alone (Norrie et al., 2002). Although, this study provides some evidence that dual-tasking may affect the reactive balance response, the analysis in this study was restricted to feet in-place strategy (Norrie et al., 2002).

One of the reasons for the predominance of observed motor-related cognitive interference (reduced performance on cognitive task but not on reactive balance task) and the absence of a mutual interference effect (deterioration in both cognitive and motor tasks) could be the relatively gradual and small magnitude perturbations used in most of the studies in the literature.

Perturbation accelerations such as 0.75m/s^2 for 0.6s (Maki et al., 2001) or 0.19 m/s^2 for 0.3s with displacement of 0.15m (Brauer et al., 2002) may not be challenging enough for healthy young adults to recruit additional attentional resources for maintaining balance. Secondly, previous dual-task studies have reported the influence of cognitive task on reactive balance over several trials. Considering that humans show behavioral adaptations when exposed to repeated external perturbations, averaging over several trials may not reflect the actual effect of dual-tasking on reactive balance responses (Bhatt, Wening, & Pai, 2006a; Grabiner, Bareither, Gatts, Marone, & Troy, 2012; Marigold, Bethune, & Patla, 2003; Marigold & Patla, 2002). Lastly, while several studies have investigated reactive balance responses on small perturbations, failed recoveries resulting in falls often occur during large perturbations.

Therefore, to better understand how cognitive tasks interfere with a reactive balance task, it is essential to observe the impact of a concurrent cognitive task on fall-risk and reactive balance responses induced by 'real-life' like perturbations. The aim of our study was to examine the effect of a concurrent cognitive task on postural stability and compensatory stepping response to a sudden large magnitude forward perturbation. We hypothesized that a mutual cognitive-motor interference pattern would be observed where both the balance and cognitive tasks would show deterioration under dual-task conditions. Thus, dual-tasking will not only reduce postural stability (will induce greater COM displacement relative to BOS) and affect the compensatory stepping response (increase muscle response latency, step initiation time, and reduce compensatory step length) but also result in deterioration of the cognitive task (reduced accuracy as indicated by the percentage of correct letter-number sequences generated).

3.2 Methods

Participants

The study was approved by the institutional review board of the University of Illinois at Chicago. Seventeen healthy (e.g. without any neurological, musculoskeletal, or cardiopulmonary conditions) young adults (*M* = 24.84 years, *SD* = 2.76; 7 males and 10 females) participated in the study after obtaining informed consent. The reactive balance response from the initial seven subjects was analyzed to determine the sample size *a priori*. The sample size was estimated using the mean differences between the single-task and dual-task conditions for step initiation time and postural stability (COM position relative to BOS) at touchdown of the stepping limb, assuming an α of 0.05 and power of 0.80.

Reactive balance task

Forward directed external perturbations were induced in stance using an instrumented treadmill (ActiveStep by Simbex, Lebenon, NH). The microprocessor-controlled, stepper motor within the treadmill base allows rapid forward accelerations of the treadmill belt induce slip-like perturbations. Individuals were instructed to maintain a comfortable stance position with their feet positioned shoulder width apart at the center of the treadmill belt. A safety harness prevented subjects' knees from touching the treadmill belt in case of a fall. Large forward perturbations with the velocity of 0.86 m/s, distance 0.38 m, and acceleration of 21 m/s^2 for 0.33s were. Subjects were informed that the treadmill belt will move suddenly in forward direction however, the exact timing of the perturbation onset was not known to the subjects. Subjects were instructed to execute a natural response to maintain their balance and prevent themselves from falling (Zettel et al., 2008). All the subjects demonstrated a compensatory stepping response during the familiarization trials. A fall was identified by recording the change in the hip height post-perturbation relative to the standing baseline. The hip height was measured as the vertical of the midpoint of the two hip markers to the treadmill belt marker. A subject was said to have fallen if the post-slip onset hip height dropped more than 3 standard deviations below the mean of pre-slip onset hip height (Yang, Bhatt, & Pai, 2009). This outcome was subsequently verified by visual inspection of the video recording of each trial.

Cognitive task

The cognitive task consisted of generating an alternating sequence of numbers and letters for 30 seconds, for example 1-A, 2-B, 3-C, 4-D. This task is known as the alphanumeric sequencing task or the Oral Trail Making task and focuses on higher cognitive functions such as information processing speed, working memory and ability to shift attention flexibly (Grigsby & Kaye, 1995). This task was first performed while sitting primarily to familiarize the subjects with the task. The task was then performed in standing for 30s and the responses were audio recorded. The performance on cognitive task was recorded by measuring the accuracy of responses i.e. percentage of correct letter-number pairs generated over a period of 30s.

Experimental protocol

After familiarization to the reactive balance and alphanumeric tasks (see Figure 2A), subjects performed each of the tasks under following conditions:

Single-task condition: The single-task condition comprised of i) performing the reactive balance task without the alphanumeric task (single-task balance), and ii) performing the alphanumeric task in standing position (single-task cognition). One trial for each of the single-task conditions was performed (see Figure 2B).

Dual-task condition: The dual-task condition comprised of performing the reactive balance concurrently with the alphanumeric task. Subjects were instructed to generate the alphanumeric sequence of numbers and letters for 30s. Each perturbation trial was matched to be 30s long within which a single perturbation was delivered, however, the exact timing of the perturbation onset was not known to the subjects. The subjects were given a verbal command "Start" at the beginning of each trial for initiating the cognitive task. The cognitive task and the ActiveStep trial were initiated simultaneously however; the perturbation (treadmill belt acceleration) occurred randomly 10-15s after triggering the ActiveStep. No instruction regarding prioritization of either the balance or the alphanumeric task was provided.

Order of trials: All the subjects first performed the single-task cognition trial. The dual-task trials were performed in two different orders. The first block of nine consecutive subjects performed the single-task balance trial before the dual-task trial. The next eight consecutive subjects performed these trials in the reverse order. To prevent the learning of the reactive balance task, all the subjects walked at a comfortable speed for 2 minutes on the treadmill between the single-task balance and the dual-task trials (see Figure 2C).

Data collection

An eight-camera motion capture system recording at 120 Hz was used for measuring body kinematics (Motion Analysis, Santa Rosa, CA). Helen Hayes marker set with 29 reflective markers for head, trunk, upper extremity, and lower extremity was used to record kinematics and compute center of mass (COM) (Figure 1c). Delyses Trigno Wireless 16-bit system was used to record surface EMG from bilateral tibialis anterior muscles (Delsys Inc, MA). The EMG system was connected to motion capture through a 64 Ch analog to digital converter (National Instruments Corporation, Austin, TX). The EMG data were sampled at the rate of 1200 Hz.

3.3 Data analysis

Postural stability: Postural stability on the reactive balance task was assessed by measuring COM position at liftoff and touchdown of the stepping limb relative to BOS. Therefore, at liftoff, a more posterior (more negative) COM position would indicate greater instability. Similarly, during touchdown, more posterior (less positive) COM position would indicate greater instability. The COM position was normalized to foot length ($X_{COM/BOS}$).

Compensatory Stepping Response: The compensatory step kinematics were assessed by recording the step initiation time (ms) and compensatory step length (cm). The step initiation time was measured as the time elapsed between perturbation onset and liftoff of the stepping limb heel. The compensatory step length (cm) was measured as the distance between the stepping limb heel position at perturbation onset and touchdown of the compensatory step.

Neuromuscular response: The EMG signals were band pass filtered at 20 to 500 Hz and then rectified. The signals were then low pass filtered using fourth order Butterworth filter with a cut off frequency of 50 Hz. The EMG onset latency of tibialis anterior muscle was identified when the EMG amplitude exceeded 3 SDs from the mean baseline amplitude computed for a period of 500 ms prior to perturbation onset (Maki et al., 2001). This was referred to as the reaction time. The reaction time was recorded for both stepping and stance limbs. The sample traces of treadmill belt displacement, COM displacement relative to the BOS and EMG response from stepping limb are demonstrated in Figure 3. All kinematic and EMG analysis was performed in Matlab using custom written algorithms.

3.4 Statistical Analysis

A paired *t*-test was used to analyze the change in the reactive balance variables (postural stability, step initiation time, compensatory step length, and reaction time – dependent variables) between the single-task and dual-task conditions (independent variables). A Pearson's product-moment correlation coefficient was computed between of COM displacement during liftoff and compensatory step length to assess the relationship between postural stability and compensatory step length in both single-task and dual-task conditions. The effect of dual-tasking on cognitive task was assessed by comparing the accuracy rate on alphanumeric task in both single-task and dual-task conditions. A measure of the effect size, Cohen's *d* for pairwise comparison of the variables was calculated by dividing the test statistic *t* by the square root of sample size *N* ($t/\sqrt{N}$) (Keppel, 1991). The statistical level of significance was set at $p < 0.05$. All statistical analyses were conducted using the SPSS version 19.0 (Chicago, IL).

3.5 Results

All the subjects demonstrated a compensatory stepping response and there were no falls. Results showed that dual-tasking affected the performance on both reactive balance and cognitive tasks. Compared to single-task condition, the postural stability decreased while concurrently performing the alphanumeric task. This was demonstrated by significantly greater posterior COM position during liftoff $t(16) = 3.82$, $p < 0.05$, $d = 0.92$ and touchdown $t(16) = 2.36$, $p < 0.05$, $d = 0.57$ in the dual-task condition (see Figures 4A and B). Effect of dual-tasking was evident on both spatial and temporal parameters of the compensatory stepping response. The subjects took significantly longer to initiate a compensatory step in response to sudden backward loss of balance $t(16) = -2.57$, $p < 0.05$, $d = 0.62$ while simultaneously performing the alphanumeric task. The compensatory step length also significantly reduced $t(16) = -2.29$, $p < 0.05$, $d = 0.55$ in the dual-task compared to the single-task balance condition (Figures 4C and D).

The differences in the EMG response in the single-task versus the dual-task conditions can be observed in Figures 5A and B. The latency of the tibialis anterior muscle contraction for both the stepping limb $t(15) = -2.72$, $p < 0.05$, $d = 0.66$ (Figure 5C) and the stance limb $t(16) = -2.77$, $p < 0.05$, $d = 0.67$ (Figure 5D) increased in the dual-task compared to the single-task balance condition. Overall, there was a strong positive correlation between the COM displacement at liftoff and compensatory step length in the single-task condition ($r = 0.644$, $p < 0.05$). A more posterior COM displacement significantly correlated with larger compensatory step length. In the dual-task condition however, the COM displacement did not correlate with the compensatory step length ($r = 0.122$, $p > 0.05$). The scatterplot summarizes these results (Figure 6).

Dual-tasking not only impacted the reactive balance task but also altered the performance on the alphanumeric task. A clear deterioration in the performance on the alphanumeric task was observed in the dual-task versus the single-task cognition condition. Specifically, the accuracy rate of the number-letter pairs generated declined in the dual-task condition $t(16) = 2.47$, $p < 0.05$, $d = 0.59$ (see Figure 7).

3.6 Discussion

The purpose of this study was to determine the effect of a concurrent cognitive task on the postural stability and compensatory stepping response in presence of a large magnitude sudden forward perturbation. As hypothesized, the presence of a secondary cognitive task reduced the postural stability and altered the compensatory stepping response. There was also a decline in performance of the cognitive task in the dual-task versus the single-task condition.

These results are indicative of a mutual cognitive-motor interference suggesting sharing of attentional resources between the reactive balance and cognitive tasks.

In the dual-task condition, the postural stability ($X_{COM/BOS}$) declined significantly compared to the single-task balance condition. Subjects exhibited a larger posterior COM displacement relative to the BOS during liftoff while concurrently performing the cognitive task as compared to performing the reactive balance task alone. Previous studies have demonstrated the importance of controlling the COM position with respect to the BOS for preventing loss of balance during external perturbations (Pai, 2003). Specifically, maintaining the COM in an anterior position relative to the BOS is crucial for resisting loss of balance induced by an external perturbation (Bhatt et al., 2006a)).

Perturbation-induced backward loss of balance resulting from an inability to control the COM position could be compensated by a prompt and well-modulated large stepping response to re-establish the relationship between the COM position and the BOS (Maki & McIlroy, 2007). We however observed that the subjects reduced their step length and increased their step initiation time in the dual-task condition suggesting the inability to counter the destabilizing external forces through an effective recovery response. Further, even after execution of a compensatory step i.e. at touchdown, the COM position was more posterior (i.e. closer to the edge of the BOS) in the dual-task compared to single-task condition suggesting that the subjects were more unstable in the dual-task condition even after re-establishing their BOS.

The delay in step initiation was accompanied by a delayed onset of tibialis anterior muscle response to the perturbation in both the limbs under dual-task condition. It is observed that perturbation intensities eliciting a stepping strategy evoke long latency responses in postural muscles ranging from 80-120ms (F. B. Horak, Diener, & Nashner, 1989; F. B. M. Horak, J. M., 1996). Unlike short latency responses occurring at the spinal cord level, there is a general consensus that long latency responses are regulated at the supraspinal level and can be modulated by intent or central set (Jacobs & Horak, 2007; Kurtzer, Pruszynski, & Scott, 2008). Thus, the prolonged onset of tiblias anterior muscle activity observed in the dual-task condition supports sharing of higher attentional resources between the reactive balance and cognitive tasks. Overall in our study, the fact that the individuals showed compromised postural stability and compensatory stepping response in the dual-task condition suggests that performing a higher order cognitive task requiring similar cortical resources may delay the processing of the reactive balance task, exposing the individuals to a higher risk of loss of balance.

The postulation that the postural stability declines under the dual-task condition can be further reinforced by the observed relationship between the COM displacement and compensatory step length. As documented in the literature, there was a linear modulation of COM position with the step length such that an increase in COM displacement at liftoff was associated with a larger step length in single-task condition (Bhatt & Pai, 2005; Hsiao & Robinovitch, 1999a). On the contrary, such a modulation between COM position at liftoff and compensatory step length was absent in the dual-task condition. Despite a more posterior COM displacement in the dual-task condition, subjects were unable to modulate a corresponding increase in their step length based on the perceived instability. Overall, these findings support the view that dual-tasking might have led to sharing of the higher cognitive resources altering accurate parameterization of motor output required for the compensatory step modulation based on the degree of balance loss.

The effect of dual-tasking was also observed by a motor-related cognitive interference. The accuracy of responses on the alphanumeric task reduced in the dual-task compared to the single-task cognition condition. This finding was similar to previous dual-task studies reporting a decline in cognitive task performance under the dual-task condition (Maki et al., 2001; Rankin, Woollacott, Shumway-Cook, & Brown, 2000; Redfern et al., 2002; Zettel et al., 2008). Considering that the alphanumeric task requires generating alphabets and numbers in order, but in an alternate sequence, it involves rapid information processing, working memory and ~~the~~ capacity to shift attention (Grigsby & Kaye, 1995). These results thus demonstrate that both motor (reactive balance task) and cognitive (alphanumeric task) performance reduced under the dual-task condition, supporting the presence of a mutual cognitive-motor inference between the two tasks occurring from a potential overlap of neural circuits governing these tasks.

At present, limited evidence exists to understand the attentional demands of the compensatory stepping responses during a reactive balance task. In contrast to our findings, previous studies examining the cognitive-motor interference of reactive balance have demonstrated that dual-tasking affects the performance only on the cognitive task (motor-related cognitive interference) without affecting the reactive balance task (Brauer et al., 2002; Maki et al., 2001; Zettel et al., 2008). As most of these studies have examined the cognitive-motor interference using small magnitude perturbations, it is postulated that the individuals are able to rapidly switch attention to the reactive balance task, and maintain postural stability at the cost of the cognitive task performance when perturbing intensities are small (Brauer et al., 2002; Brown et al., 1999b; (Maki & McIlroy, 2007); Maki et al., 2001; Subramaniam, Hui-Chan, & Bhatt, 2014; Zettel et al., 2008).

Two main theories have been proposed to explain the dual-task interference between the reactive balance and cognitive tasks. The ‘bottle-neck’ theory proposes that if two tasks require same processing resources, one of the two tasks is processed first and the processing of the second task is delayed until the first task is processed (e.g., motor-related cognitive interference) (Pashler, 1994a). As we observed a decline in both the reactive balance and cognitive task performance, the our findings could however, be explained by the ‘capacity sharing’ model of dual-tasking which assumes that when performing two tasks that share similar attentional resources, there is a high probability that the performance on both the tasks can be compromised (e.g., mutual cognitive-motor interference) (McLoed, 1977; Pashler, 1994a; Plummer et al., 2013).

In the context of current findings, the mutual cognitive-motor interference pattern observed denotes that large magnitude of perturbations may cause a higher degree of interference between the cognitive and reactive balance tasks. Furthermore, considering that perturbation induced reactive balance task is not an overly learned task such as walking, movements are likely be carried out at the associative stage of motor learning requiring inputs from the motor cortex for error detection and feedback (Schmidt, 2005). Consequently, preoccupying cognitive resources in the form of a cognitive task performance might have resulted in a delay in processing the error information about the additional balance task by interrupting the cortex’s ability to provide the feedback for corrective responses. Direct recordings from animals have shown increased firing of motor cortex neurons during postural corrections to perturbations (Beloozerova & Sirota, 1993; Beloozerova, Sirota, Orlovsky, & Deliagina, 2005b; Beloozerova et al., 2003). Obtaining direct recordings from the cortex to understand the influence of cortical control on reactive balance in humans is not entirely feasible. Therefore, dual-task studies provide a significant insight into modulation of reactive balance responses through higher cortical centers.

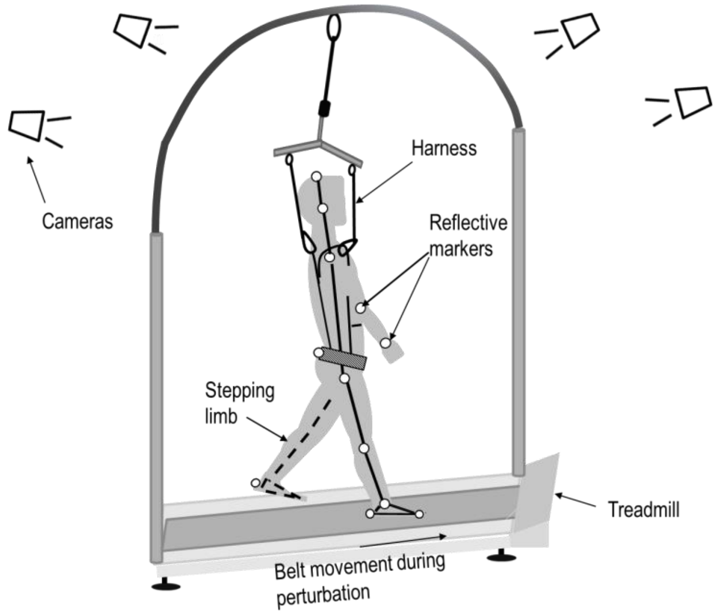
Even though the subjects in our study were healthy young adults, they were more unstable upon step completion in the dual-task versus single-task condition. Thus, individuals with neurological disorders causing both motor and cognitive impairments might be at a greater risk of falling even if a successful stepping response is initiated. Yet whether a similar mutual cognitive-motor inference pattern persists in neurological populations who are at a high risk of falling remains to be determined. Similarly, given the age-related deterioration in the sensory, motor and cognitive systems, it remains to be tested if such mutual cognitive-motor interference can enhance fall-risk from large-scale environmental perturbations in the healthy older adults. In addition, although our study examined the interference of reactive balance task with a specific cognitive task, it likely that the cognitive-motor interference pattern may vary with the type of cognitive task being performed. Future research is required to understand the effect of different higher cognitive tasks on reactive balance for a more comprehensive understanding of the interference pattern.

This study provides preliminary evidence that dual-tasking in presence of large perturbation causes mutual cognitive-motor interference, affecting not only the postural stability and effective compensatory stepping response, but also the performance of the ongoing cognitive task. The ability to redirect adequate attentional resources to a reactive balance task diminishes while performing a cognitively challenging task increasing the likelihood of falls resulting from unpredictable environmental perturbations. As falls most often occur due to large magnitude perturbations, it might be important to assess balance in challenging circumstances such as dual-tasking amongst those people predisposed to falls. Further, fall prevention interventions should also focus on simultaneous cognitive-balance training to prepare individuals for similar real-life circumstances.

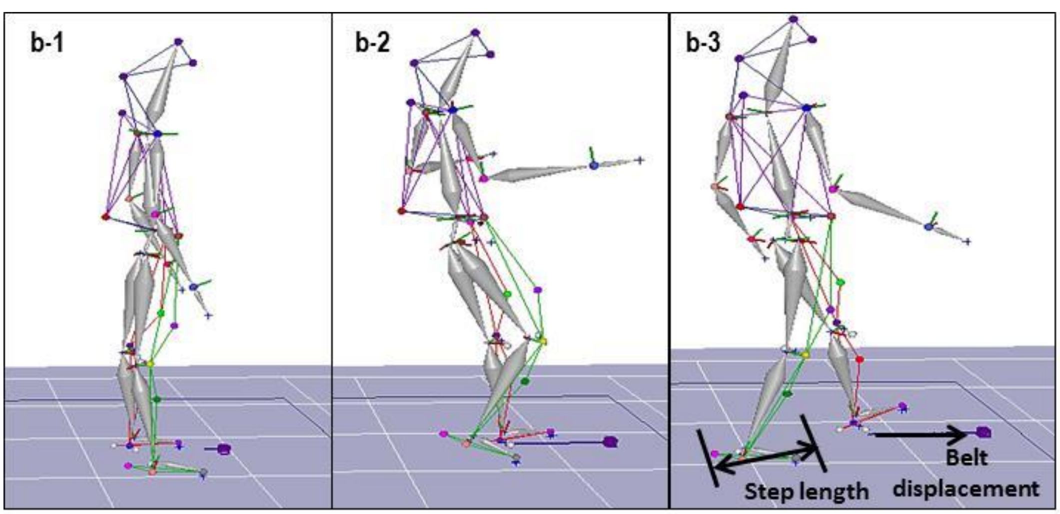
3.7 Figures

Figure 1.

a)

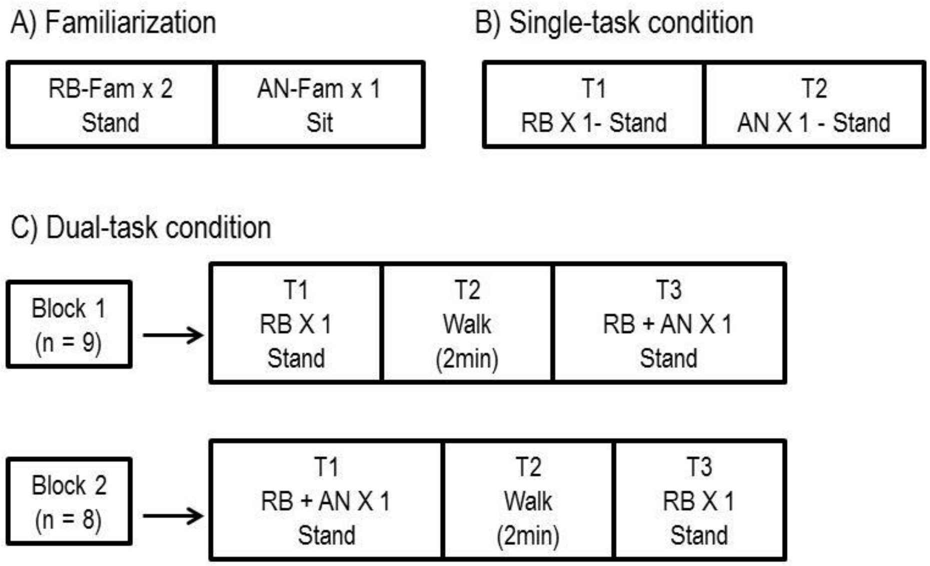


b)



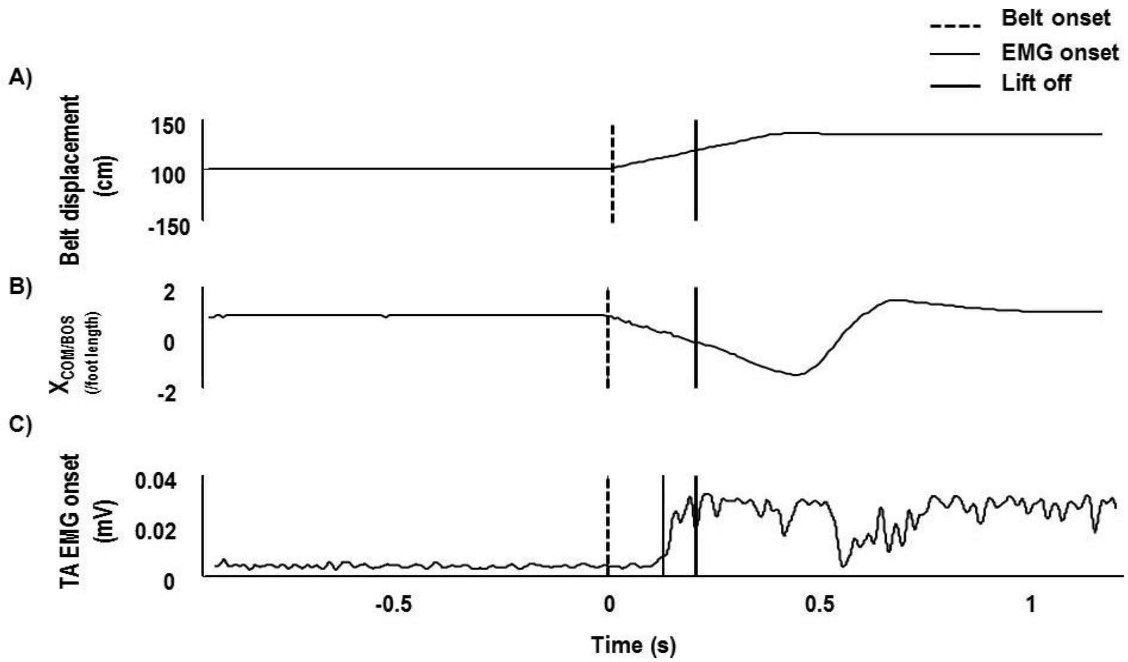
(a) Schematic representation of the experimental set-up, and (b) motion capture sequence of events during perturbation. Image b-1 represents the event of perturbation onset, image b-2 represents the event of stepping limb liftoff and image b-3 and represents the event stepping time touchdown.

Figure 2.



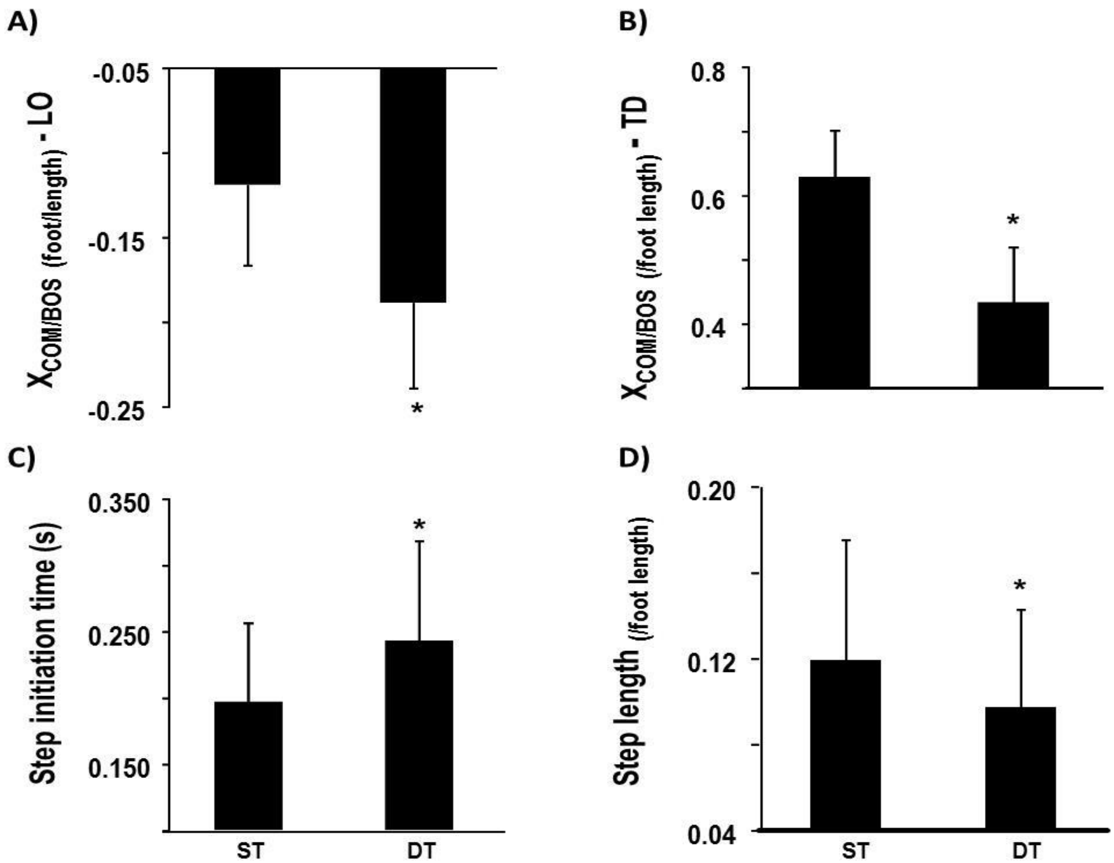
Experimental protocol of the trials in (A) familiarization condition (B) single-task condition and (C) dual-task condition. The order of dual-task trials differed between the two blocks (RB = reactive balance task and AN = alphanumeric task).

Figure 3.



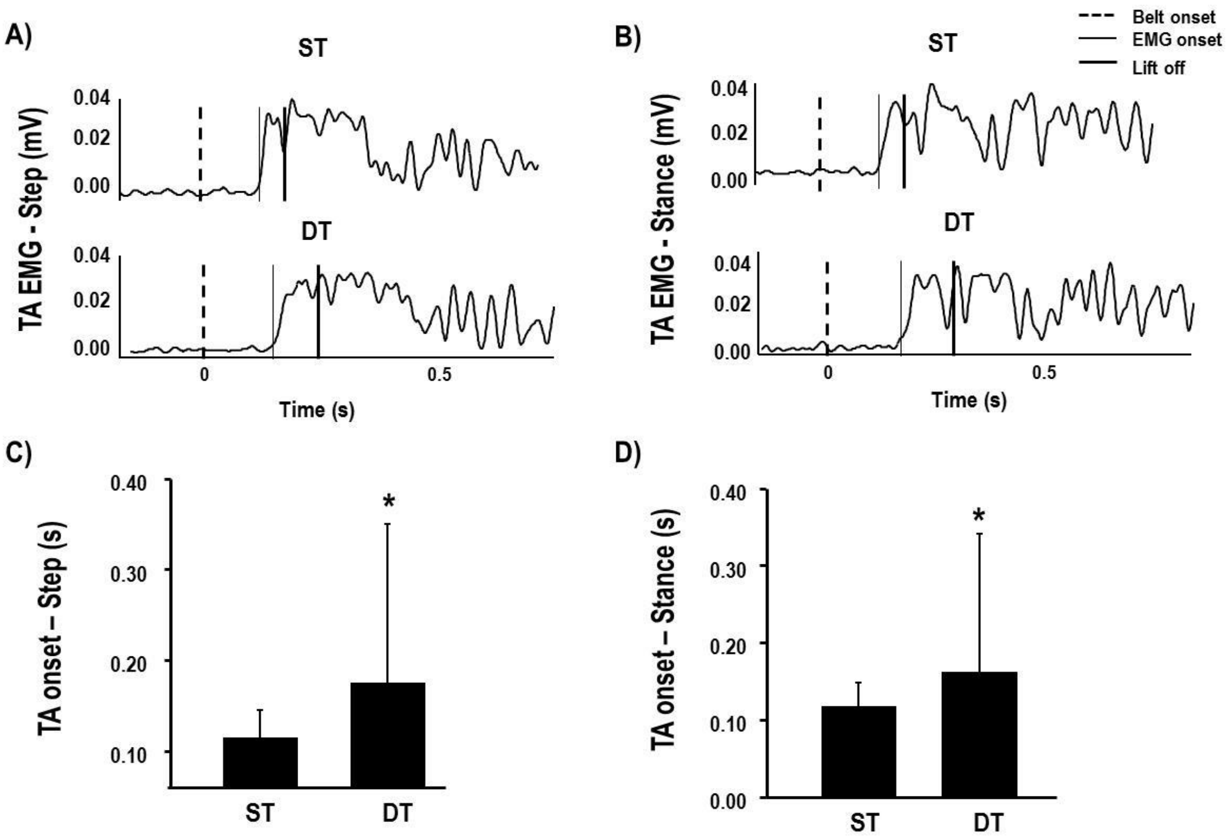
The figure demonstrates representative traces of A) the a typical trajectory of the treadmill belt displacement during perturbation, B) the COM displacement relative to BOS, and C) the tibialis anterior (TA) muscle activity of the stepping limb post-perturbation.

Figure 4.



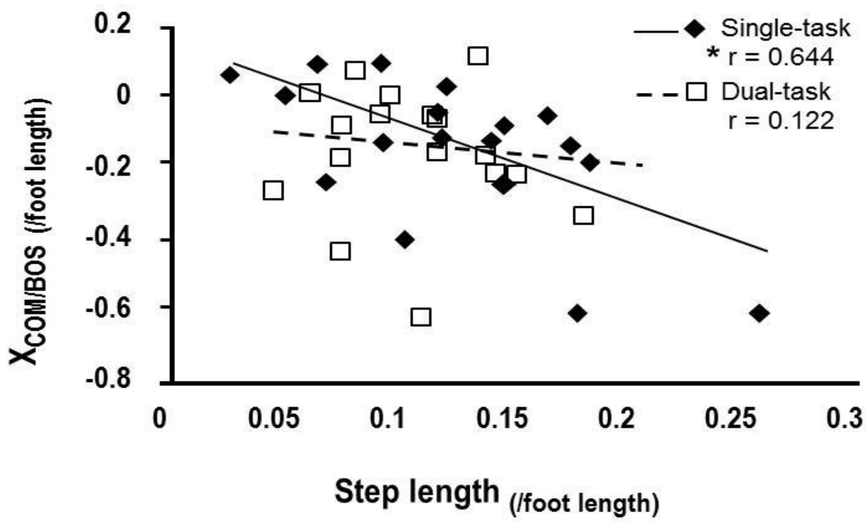
Mean differences (±SE) in postural stability ($X_{COM/BOS}$) and compensatory step kinematics in single-task (ST) versus dual-task (DT) conditions. Significant differences * $p < 0.05$ were observed in posterior COM displacement relative to BOS at (A) liffoff (LO) and (B) at touchdown (TD), (C) step initiation time and (D) compensatory step length between the conditions.

Figure 5.



Representative trace of tibialis anterior (TA) EMG response for stepping (A) and stance (B) limbs in single-task (ST) and dual-task (DT) conditions. Figures C and D represent the means (±SE) of the TA muscle onsets of the stepping and stance limbs respectively. Significant delay in both TA muscle onsets in dual-task conditions are indicated by * $p < 0.05$.

Figure 6.



Scatter plot showing the relationship between COM displacement relative to BOS ($X_{COM/BOS}$) at liftoff and compensatory step length in single-task and dual-task conditions. Significant positive correlation was observed between the two variables in single-task condition (* $p < 0.05$) whereas; there was no correlation in the dual-task condition.

Chapter 4 – Fall risk during opposing stance perturbations among healthy adults and chronic stroke survivors

4.1 Introduction

The incidence of falls among community-dwelling chronic stroke survivors ranges from 40-70% (Mackintosh, Hill, Dodd, Goldie, & Culham, 2005; Weerdesteyn, de Niet, van Duijnhoven, & Geurts, 2008). Several stroke survivors demonstrate independent mobility during the chronic stage of recovery however, quite often the motor recovery in incomplete (Jorgensen, Nakayama, Raaschou, & Olsen, 1999). Independent mobility with persisting balance deficits contribute significantly towards occurrence of falls in this population (Lamb et al., 2003). Clinical measures like gait speed and Berg Balance Scale have been used to predict falls post stroke, however, in the chronic phase of recovery determining fall-risk with these clinical measures, especially in functionally mobile individuals remains a challenge (Harris, Eng, Marigold, Tokuno, & Louis, 2005) (Mansfield, Inness, Wong, Fraser, & McIlroy, 2013). Therefore, understanding the mechanisms of balance recovery from environmental disturbances inducing a sudden loss of balance could provide a better insight into causes of falls in this population.

Falls among chronic stroke survivors commonly occur during walking or activities involving transitioning between tasks (Batchelor, Hill, Mackintosh, Said, & Whitehead, 2012). Depending on the intensity of external perturbations individuals adopt either in-place, ankle and hip strategies for balance recovery from smaller perturbations (F. B. Horak & Nashner, 1986) or change-in-support i.e. a compensatory stepping or grasping for recovery from larger perturbations (Maki & McIlroy, 1997a). Large external postural disturbances require a sufficiently large and rapid compensatory stepping response through coordinated movements between upper and lower body segments to arrest center of mass excursion and prevention a fall (Maki & McIlroy, 1997a). In response to small perturbations, chronic stroke survivors show delayed latencies of postural muscles and impaired intra-limb coordination during backward perturbations (Marigold & Eng, 2006). During larger perturbations as well, stroke survivors show reduced center of mass control affected by multiple stepping response with a shorter first compensatory step (Salot, Patel, & Bhatt, 2016), delayed step initiation (Mansfield et al., 2013; Salot et al., 2016), impaired trunk control (Honeycutt, Nevisipour, & Grabiner, 2016), parallel with inadequate vertical limb support from paretic limb (Kajrolkar & Bhatt, 2016). Such impairments in reactive balance control have been identified has contributing factors towards falls in this population.

In addition to the individual's reactive balance abilities, preventing a fall from a large disturbance could be related to the direction of balance loss. For example, Hsiao and Robinovitch (1998) showed that younger adults demonstrate significantly greater proportion of falls into the harness during backward and lateral loss of balance as opposed to fewer falls during forward loss of balance (Hsiao & Robinovitch, 1998b). Further, Carbonneau and Smeesters (2014) demonstrated that healthy young adults can generally recover balance with a single step at greater maximum forward lean angles during forward cable pull perturbations than backward perturbations (Carbonneau & Smeesters, 2014). Similar findings have been observed among older adults who demonstrate ~ 25% falls during TRIPS (Pavol, Owings, Foley, & Grabiner, 1999) in comparison with ~45% falls seen during SLIPS (Bhatt, Yang, & Pai, 2012). It is proposed that arresting backward motion of the trunk during a slip is more challenging than forward trunk movement during a trip resulting in higher falls incidence during slips (Grabiner et al., 2008). Based on the recent and past studies showing higher incidences of falls from backward loss of balance, it could be argued that at the same perturbation intensity, balance recovery from SLIPS is likely more challenging than backward perturbations. It therefore follows that an effective compensatory step could be deemed more important to re-establish balance during a backward balance loss.

Although chronic stroke survivors show deficits in reactive balance control whether, their ability to prevent a fall is influenced by the direction of perturbation is not known. Therefore, the purpose of this study was to examine the fall risk during forward and backward large magnitude perturbations at same intensity within the community dwelling chronic stroke survivors as compared with healthy controls. We hypothesized that stroke survivors would demonstrate a higher fall risk during backward loss of balance from SLIPS than forward loss of balance from TRIPS resulting from lower stability change from liftoff to touchdown during SLIPS compared with TRIPS (higher change indicating better ability to re-establish balance at touchdown). Further during SLIPS and TRIPS, the stability change in stroke survivors would be lower than healthy controls due to inefficient compensatory step and trunk control.

4.2 Methods

Participants

Community dwelling healthy young adults (n=11), ambulatory chronic stroke survivors with more than 1year post stroke (n=12) and healthy age-matched adults with chronic stroke survivors (n=11) participated in the study. Healthy younger and older adults were screened for any musculoskeletal, neurological or cardiopulmonary disorders. Among stroke survivors, the presence of a hemiparetic stroke was confirmed from the subject's physician prior to enrollment into the study. Stroke survivors with inability to stand independently without any assistance, without cognitive deficits (Montreal Cognitive Assessment score < 26/30) or signs of aphasia

(Mississippi Aphasia Screening Test score < 71%), and subcortical stroke were excluded from the study. Subject demographics are presented in Table 1 and the performance on clinical measures of balance and motor impairment for the stroke survivors is presented in Table 2.

Experimental protocol

All the participants wore a harness and stood on a motorized treadmill, ActiveStep (Simbex, Lebenon, NH). Upon assuming a comfortable stance on the treadmill, all participants experienced a slip-like and a trip-like perturbation in standing position at an unknown time instance. Participants were aware that they may experience either a slip or a trip however, the order of the perturbation was not known. The harness prevented participants' knees from touching the treadmill in case of a fall (Figure 1a). Both SLIPS and TRIPS perturbations were triggered at 16.75 m/s^2 with a displacement of 0.20 m. The displacement and velocity traces of the of perturbation is shown in Figure 1b. Participants were exposed to a single perturbation at each direction and the order of the perturbation direction was randomized. After each perturbation trial the participants stood at a specified position on the treadmill. The perturbations were presented 5 to 20s after the participants assumed a comfortable stance to prevent the predictability of the perturbation onset.

Data collection and analysis

Kinematic data was collected using an eight camera motion capture system with a sampling rate of 120 Hz (Motion Analysis Corporation, Santa Rosa, CA). A load cell connected in series with the harness measured the amount of body weight exerted on the harness during each trial. The load cell data were sampled at 1200 Hz. The Helen Hayes marker set with 29 markers placed on bilateral bony landmarks, head and trunk were used to compute the joint centers and center of mass (Davis et al., 1991). The perturbation onset was identified using a marker placed on the treadmill belt. The raw marker data were low pass filtered using the fourth order Butterworth filter with a cut off frequency of 6Hz. The kinematic variables were computed using custom written algorithms in MATLAB version 2014b (The MathWorks Inc, Nactick, MA).

Outcome variables

Perturbation outcome

Each perturbation outcome was initially classified into a fall or a recovery. The outcome was identified as a fall if the weight exerted on the load cell exceeded 30% of the individual's body weight for more than 1s (F. Yang, Bhatt, & Pai, 2009) and was visually confirmed as definite use of harness to prevent a fall or if the subjects failed to initiate a compensatory step. If the subjects showed a compensatory stepping strategy, it was classified into a forward step, backward step or an aborted step. A forward and a backward step occurred if the stepping limb foot landed anterior and posterior to the non-stepping limb respectively with a complete clearance of the foot off the treadmill belt at liftoff (LO). A compensatory step was classified as an aborted step if the subjects attempted to initiate a step by lifting off the heel followed by an immediate touchdown (TD) without a complete clearance of the foot off the treadmill.

Stability change from liftoff to touchdown

The center of mass state stability was computed as the shortest distance of the instantaneous center of mass (COM) position and velocity relative to the base of support (BOS) from a theoretical threshold for forward and backward loss of balance (Pai & Iqbal, 1999). All the values on the boundary for backward loss of balance (BLOB) represent 0 and the values on the boundary for forward loss of balance (FLOB) represent 1. Thus, stability values less than 0 at any time instance indicates BLOB and the values more than 1 indicate FLOB. The center of mass (COM) position ($X_{COM/BOS}$) and velocity ($\dot{X}_{COM/BOS}$) relative to base of support (BOS) were recorded at liftoff (LO) and touchdown (TD) of the stepping limb for both SLIPS and TRIPS. During SLIPS the heel of the stepping limb formed the most posterior margin of BOS whereas during TRIPS the toe formed the most anterior margin of BOS. Thus, a more anterior (positive) $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ indicated greater stability for SLIPS and lower stability for TRIPS. The difference in stability, $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ from LO to TD of the stepping limb was recorded to measure how stable the individuals were at TD of the stepping limb as compared with the initial loss of balance at LO. A higher value for stability, $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ change i.e. Δstability, $\Delta X_{COM/BOS}$, and $\Delta \dot{X}_{COM/BOS}$ respectively, would therefore indicate a more stable position at TD of the first compensatory step.

Compensatory step and trunk kinematics

The step initiation time was recorded as the time elapsed between the perturbation onset and LO of the stepping limb. The compensatory step length was measured as the excursion of the stepping limb foot from LO to touchdown in the antero-posterior direction. The trunk flexion and extension angles (in degrees) from the vertical orientation were recorded in the sagittal plane at LO and TD. A change in trunk angle from LO to TD during both SLIPS and TRIPS was recorded to examine whether subjects reversed their trunk movement upon compensatory step TD (see Figure 2). A more negative value for trunk angle change (Δtrunk angle) during SLIPS would indicate greater trunk extension at TD as compared with LO. On the other hand, a more positive value for Δtrunk angle during TRIPS would suggest greater trunk flexion at TD than at LO. Finally, peak trunk velocity in the backward and forward directions from perturbation onset to compensatory step TD was recorded measured as sacrum marker velocity in antero-posterior direction.

4.3 Statistical Analysis

To analyze the effect of perturbation type on the proportion of falls, Kruskal–Wallis test for between- group comparisons for SLIPS and TRIPS was employed. Significant main effects were subsequently resolved by the Mann–Whitney U test. To examine the effect of perturbation type on reactive balance response across the three groups a 3 x 2 two-way ANOVA was performed for Δstability change, $\Delta X_{COM/BOS}$, $\Delta \dot{X}_{COM/BOS,}$ step initiation time, compensatory step length and peak trunk velocity with groups (young, age-matched and stroke) and perturbation type (SLIP and TRIP) as independent variables. Significant main effects and interactions were followed up by paired t-tests for differences within groups and independent t-tests for differences between groups. A one-way ANOVA was performed for stability at LO and TD, $X_{COM/BOS}$, $\dot{X}_{COM/BOS}$ at TD, and trunk angle change from LO to TD to compare differences between the groups for individuals SLIPS and TRIPS. Post hoc independent t-tests were performed to resolve the main effects. The statistical significant was set at $p < 0.0.\ 5$. All the statistical analyses were performed using SPSS 24.00 (IBM Inc.)

4.4 Results

All of the subjects showed a backward step, forward step or an aborted step response with or without a fall. During SLIPS, there was a significant difference in incidence of falls between the groups ($\chi^2 = 4.20$, $p < 0.05$) with the incidence being higher in stroke survivors (58.33%) as compared with YA (0%) and AM (0%) groups ($p < 0.05$ for stroke vs. AM and stroke vs. YA). In the presence of TRIPS, the incidence of falls did not differ between the groups $\chi^2 = 1.23$, $p > 0.05$ (16.66% in stroke, 0% in AM and 0% in YA groups) (Figure 3).

There was a significant difference in stability change between SLIPS and TRIPS across the three groups. As compared with SLIPS, the stability change was greater in TRIPS for all the three groups, main effect of perturbation type $F(1, 32) = 434.00$, $p < 0.01$. For both perturbation types the stability change differed between the groups [$F(1, 2) = 12.39$, $p < 0.01$, Figure 4a]. During SLIPS, the stroke group showed the least stability change in comparison with the other two groups ($p < 0.05$ for stroke vs. YA and stroke vs. AM) and the YA group showed highest stability change ($p < 0.05$ for YA vs. AM and stroke). Similarly, during TRIPS there was a linear trend for stability change with the change being least within the stroke group and highest in the YA group, $p < 0.05$ (stroke < AM < YA). The stability change was significantly lower in stroke group than the YA group ($p < 0.05$) with no significant difference between stroke and AM groups ($p > 0.05$) and between AM and YA groups ($p > 0.05$).

The stability change was accompanied by changes in $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ from liftoff to touchdown. The $\Delta X_{COM/BOS}$ differed between the perturbations among the three groups $F(1, 32) = 2.41$, $p < 0.05$ (Figure 4b). All groups showed greater $\Delta X_{COM/BOS}$ during TRIPS as compared with SLIPS ($p < 0.05$ for all groups). During SLIPS, the $\Delta X_{COM/BOS}$ was significantly lower for the stroke group as compared with AM and YA groups ($p < 0.05$ for both comparisons). Further, $\Delta X_{COM/BOS}$ within the AM group was lower than the YA group ($p < 0.05$). For TRIPS, the $\Delta X_{COM/BOS}$ was significantly different between YA and stroke groups ($p > 0.05$). The $\Delta X_{COM/BOS}$ did not differ between the stroke and AM groups ($p > 0.05$) and YA and AM groups ($p > 0.05$). The $\Delta \dot{X}_{COM/BOS}$ did not differ between SLIPS and TRIPS [$F(1, 32) = 1.63$, $p > 0.05$] however, there was a significant difference in $\Delta \dot{X}_{COM/BOS}$ between the groups for both perturbations $F(1, 2) = 4.7$ $p < 0.05$ (Figure 4c). For both perturbation types the stroke group showed lower $\Delta \dot{X}_{COM/BOS}$ compared with YA group ($p < 0.05$). The $\Delta \dot{X}_{COM/BOS}$ was lower in AM versus the YA group ($p < 0.05$ for both perturbations). Although the $\Delta \dot{X}_{COM/BOS}$ within the AM group tended to be greater than stroke group however it did not reach significance level ($p > 0.05$).

Compensatory step kinematics for slips and trips

The step initiation time differed between the three groups [main effect of group $F(1, 2) = 5.93$, $p < 0.05$] with no significant effect of perturbation type [$F(1, 32) = 1.27$, $p < 0.05$] (Figure 5a). For SLIPS, the step initiation time was significantly longer in stroke group as compared with the AM ($p < 0.05$) and YA ($p < 0.05$) groups however, it did not differ between AM and YA groups ($p > 0.05$). There was no difference in step initiation times between the groups for TRIPS ($p > 0.05$) for all comparisons. The compensatory step length differed between the groups with regards to perturbation type [group x perturbation interaction $F(1, 32) = 7.28$, $p < 0.05$] (Figure 5b). The stroke group significantly increased compensatory step length during TRIPS as compared with SLIPS ($p < 0.05$) whereas the AM and YA groups did not a differ in step lengths between perturbations ($p > 0.05$ for both groups). During SLIPS, the stroke group showed shorter step length (stroke < AM and stroke < YA groups, $p < 0.05$). Further, there was no difference in step length between the AM and YA groups ($p > 0.05$). During TRIPS however, the step length did not differ between the groups ($p > 0.05$ for all comparisons).

A mean negative change in trunk angle was observed for SLIPS from liftoff to touchdown (TD minus LO) among all groups (Figure 5c). There was no significant main effect of group with regards to this change $F (2, 32) = 0.64$, $p > 0.05$. For TRIPS however, a significant difference in trunk angle change was observed between the groups $F (2, 32) = 4.38$, $p < 0.05$. A mean negative change in trunk angle from liftoff to touchdown (TD minus LO) was observed among the YA and AM groups (YA vs. AM, $p > 0.05$). The stroke group showed a positive change in trunk angle which was greater than the other two groups (stroke > YA, and stroke > AM, $p < 0.05$, Figure 4c). Further, the peak trunk velocities in forward direction during TRIPS and in backward direction during SLIPS differed among the three groups with a significant main effect of perturbation type $F (1, 31) = 25.40$, $p < 0.05$ and main effect of group $F (2, 31) = 3.57$, $p < 0.05$ (Figure 5d). The peak trunk velocities for all the groups were lower for TRIPS than for SLIPS ($p < 0.01$). Further, the peak trunk velocities were higher among the stroke survivors as compared with the YA and AM groups for TRIPS perturbations ($p < 0.05$ for both comparisons).

4.5 Discussion

The purpose of current study was to compare the postural stability and fall risk to forward and backward large magnitude perturbations inducing SLIPS and TRIPS respectively in individuals with and without (young and older adults) a hemiparetic stroke. Our results suggest that regardless of aging or neurological impairments from stroke, individuals demonstrate lower fall risk indicated by higher stability change from liftoff to touchdown during TRIPS as compared with SLIPS at same perturbation intensity (displacement and acceleration). Consequently, the stability change between all the groups was more pronounced for SLIPS with lower stability change among stroke survivors than both age-matched and younger adults, and lower stability change in age-matched adults than younger adults.

The COM state stability is influenced by both instantaneous COM position and velocity relative to the BOS and thus provides a robust measure of balance during dynamic postural tasks (Bhatt, Wening, & Pai, 2006b; Pai & Iqbal, 1999). During SLIPS, it is essential that the stability changes from a posterior state (negative value) at liftoff to a more anterior state (positive value) at touchdown as BOS is re-established after initiating a compensatory step. The opposite is true for a TRIPS wherein stability changes from an anterior state (positive value) at liftoff to a posterior state (less positive or negative) at touchdown. It is conceivable that a greater change in stability from liftoff to touchdown would be suggestive of a more stable posture at touchdown. Consequently, we observed that the stability change (Δstability) from liftoff to touchdown was greater for TRIPS than SLIPS for all the groups. The difference in Δstability between the two perturbations occurred largely through higher $\Delta X_{COM/BOS}$ during TRIPS than SLIPS across all of the groups with a modest contribution of $\Delta \dot{X}_{COM/BOS}$ as observed in our previous studies (P. Patel & Bhatt, 2015; Salot et al., 2016). These findings suggest that all individuals, regardless of aging or balance deficits due to stroke, are more stable while recovering balance from TRIPS as compared with SLIPS at the completion of the first compensatory step. A rapid, large compensatory step is crucial in catching the COM well within the BOS and generate sufficient ground reactive force to reverse the trunk movement (Maki & McIlroy, 1997a). At the same time, controlling trunk excursion and velocity assists in reducing the impact of loss of balance (Grabiner et al., 2008; Hsiao-Wecksler, 2008). The younger and older adults achieved a higher Δstability during TRIPS without any differences in compensatory step length or step initiation time. Considering that there was a greater change in $\Delta X_{COM/BOS}$ during TRIPS despite no difference in step length between the perturbations, it possible that the differences in Δstability during SLIPS and TRIPS likely stems from differences in the ability to arrest trunk rotation in healthy adults.

With regards to SLIPS and TRIPS, it is essential to reverse or limit trunk excursion in the direction of balance loss after the BOS has been re-established. In our study, although the healthy adults reversed trunk flexion from liftoff to touchdown (negative change in trunk flexion from LO to TD, see figure 2b and 4c) during TRIPS, they were unable to do so during SLIPS (negative change in trunk extension from LO to TD, figure 2a and 4c), attributing to a greater $\Delta X_{COM/BOS}$ during TRIPS. Peak trunk velocity is an important predictor of falls during loss of balance in either of the directions (Crenshaw, Rosenblatt, Hurt, & Grabiner, 2012; Grabiner et al., 2008; Parijat & Lockhart, 2012).The differences in ability to arrest trunk movement during SLIPS versus TRIPS could be explained by greater peak trunk velocities induced by slips than trips contributing towards difficulty in decelerating the trunk movement in the backward direction. So it can be argued that a greater trunk control along with a longer step length would be most essential to generate a ground reaction force sufficient to decelerate the trunk during SLIPS as compared with TRIPS.

Our findings are in line with the study by Tan et al. (2006) which examined the impact velocity on wrists during forward and backward falls. The authors observed that the impact on wrist while falling backwards is greater than that while falling forwards from tether release perturbations (Tan, Eng, Robinovitch, & Warnick, 2006). It is therefore possible that backward fall prevention would involve offsetting a larger impact of balance loss through protective mechanisms. Another study observed that the maximum lean angle thresholds from which younger and older adults can recover balance with a single step was 22% greater for forward leans than backward leans with the compensatory steps being shorter for maximum backward leans which suggests greater tolerance for recovery from perturbations inducing forward loss of balance than backward balance loss (Carbonneau & Smeesters, 2014). This study to our knowledge is the first to directly compare recovery responses to both of these opposing perturbations and its results corroborate previous study findings supporting the view that recovering balance from backward balance loss is more challenging (Carbonneau & Smeesters, 2014; Hsiao & Robinovitch, 1998b).

It can be noted that balance recovery from SLIPS is inherently more difficult as observed in younger adults who did not present with any neurological condition or aging related decline in neuromuscular function. The Δstability during SLIPS was also lower in older adults than the younger adults as compared with TRIPS which suggests that even aging related changes in sensorimotor function seems to affect recovery during SLIPS more than TRIPS. Given the implicit demands of recovery from SLIPS, recovering balance during large SLIP-like perturbations may be even more challenging among chronic stroke survivors in face stroke-related deficits in balance function.

Despite motor and balance deficits, stroke survivors showed greater Δstability during TRIPS than SLIPS, similar to healthy older and younger adults. This could be explained predominantly by a greater $\Delta X_{COM/BOS}$ from liftoff to touchdown during TRIPS. Unlike the healthy controls, greater $\Delta X_{COM/BOS}$ could be attributed to an increase in compensatory step length in TRIPS versus SLIPS allowing greater BOS for COM excursion. Stroke survivors also attempted to reduce the step initiation time during trips which means that these individuals could initiate a step before COM was further anterior to the edge of BOS and thus providing a better chance of balance recovery. Nevertheless, stroke survivors were less stable at touchdown during SLIPS and TRIPS compared with younger and older adults (see table 2).

While stroke survivors could increase step length during TRIPS they showed higher peak trunk flexion velocity and deficits in ability to revert the trunk flexion at touchdown. Considering that it is more challenging to recover balance by controlling trunk kinematics (position & velocity) rather than modulating the BOS (Han, Betker, Szturm, & Moussavi, 2006), it is likely that despite a longer compensatory step during TRIPS, the stability at touchdown in stroke survivors tend to be lower than older and younger adults. In addition to poor trunk control during SLIPS, the stroke survivors were unable to offset the effect of backward balance loss by increasing the compensatory step length, observed by significantly shorter step length compared with the other two groups. Such deficits in balance control could explain lower stability and higher incidence of falls during SLIPS compared with healthy controls.

It is argued that behavioral goals have a crucial role in development of motor patterns (Grasso, Bianchi, & Lacquaniti, 1998). Frequent practice of a movement pattern could facilitate stimulation of the associated sensorimotor pathways, thereby strengthening the motor programs for that specific movement (Hodgson, Roy, de Leon, Dobkin, & Edgerton, 1994; Karni et al., 1995; Nudo, 2013). Given that the majority of functional activities, including locomotion involve movement in a forward direction, it is possible that such repetitive stimulation of the associated motor pattern could assist in developing greater balance control during forward stepping contributing towards greater Δstability during TRIPS versus SLIPS. Post-stroke improving locomotor function is one of the primary goals and focuses on forward walking (Hollands, Pelton, Tyson, Hollands, & van Vliet, 2012; Hornby et al., 2011; Nadeau, Duclos, Bouyer, & Richards, 2011). Further, walking within the community encourages some gait adaptations to changes in walking surfaces, transitioning between walking surfaces and to different visual conditions providing some flexibility within the learned behavior. Although stroke survivors might not acquire the same level of gait adaptability as healthy adults (Balasubramanian, Neptune, & Kautz, 2009; Chen, Patten, Kothari, & Zajac, 2005), meeting functional demands in everyday activities involve forward walking. All the stroke survivors in our study were community ambulators. Thus, a repetitive practice of forward stepping movements could have facilitated selection of the appropriate motor program culminating in a large forward compensatory step in response to TRIPS leading to a higher stability upon TRIPS than SLIPS.

We conclude that reactive balance control to large perturbations varies with regards to the perturbation direction with the stability being lower during SLIPS than TRIPS when the perturbation intensities are similar. Although aging and presence of neurological impairments may predispose individuals to a higher fall risk during sudden disturbances, the likelihood of backward falls seems higher than that of forward falls, particularly in chronic stroke survivors. Post stroke balance and rehabilitation is often targeted towards intentional balance training and/or locomotor (Jung, Kim, Chung, & Hwang, 2014; Lubetzky-Vilnai & Kartin, 2010; Srivastava, Taly, Gupta, Kumar, & Murali, 2009; Yatar & Yildirim, 2015). Our results suggest that reactive balance assessment and training might be crucial for fall prevention in chronic phases of recovery when a large proportion of stroke survivors achieve community ambulation and therefore are predisposed to environmental falls. As stroke survivors show a higher fall risk for both perturbation types, reactive balance training may require higher dosage or more number of trials than that in healthy adults with an emphasis on compensatory stepping and trunk control.

4.6 Tables and figures

Table 1. Mean (standard deviation) of subject demographics. There was no significant difference in age, height and weight between the age-match and stroke groups.

Variable	Young (n = 11)	Age-Match (n = 11)	Stroke (n = 12)
Age (years)	24.63 ± 3.9	58.08 ± 5.80	60.75 ± 5.78
Sex (M/F)	5/6	5/6	4/8
Height (m)	1.69 ± 0.88	1.68 ± 0.88	1.65 ± 0.96
Weight (lbs)	145.63 ± 23.70	166.3 ± 39.35	169.9 ± 25.07

Table 2. Demographics and clinical outcome measures scores for individuals with stroke.

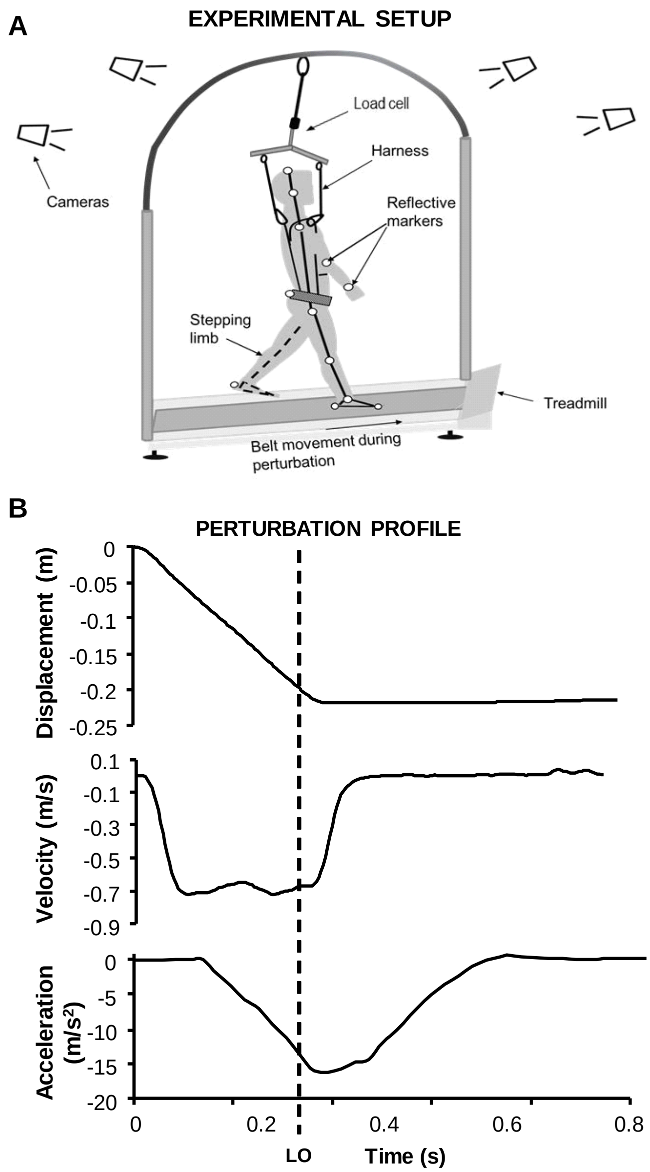
Variable	Mean (SD)
Age (years)	60.75 (5.78)
Type of stroke (ischemic/ hemorrhagic)	7/5
Time since stroke (years)	9.2 (5.14)
Chedoke McMaster Stroke Assessment for lower extremity (/7)	
Leg	4.1 (1.04)
Foot	3.00 (1.61)
Berg BalanceScale (/56)	41.36 (7.28)
Timed Up and Go test (seconds)	15.92 (6.02)

Table 3. Mean (±SD) differences between young adults, age-matched adults and chronic stroke survivors.

Group	Stability at LO		Stability at TD		$X_{COM/BOS}$ at TD		$\dot{X}_{COM/BOS}$ at TD		P_{group}
	SLIP	TRIP	SLIP	TRIP	SLIP	TRIP	SLIP	TRIP	
Young	-0.234±0.12	1.22±0.07	0.349±0.19	-0.325±0.07	0.804±0.34	-0.687±0.16	0.001±0.02	-0.005±0.02	< 0.01
Age-match	-0.201±0.07	1.27±0.14	0.204±0.16[a, c]	-0.166±0.09[a]	0.507±0.34[a, c]	-0.451±0.19	-0.069±0.04[a]	0.059±0.02[a]	< 0.01
Stroke	-0.167±0.07	1.24±0.10	0.004±0.20[a, b]	-0.140±0.13[a]	0.22±0.44[a, b]	-0.451±0.28	-0.073±0.04[a]	0.082±0.03[a]	< 0.01

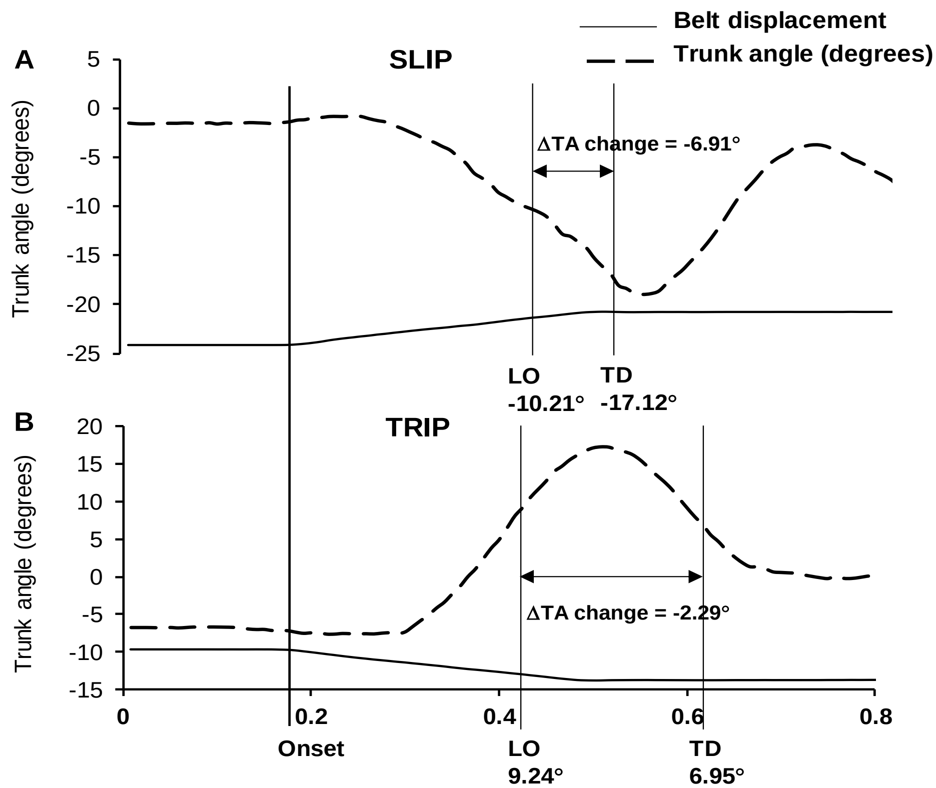
LO = liftoff, TD = touchdown; [a] significant difference compared to young adults, [b] significant difference compared to age-matched adults, [c] significant difference compared to chronic stroke survivors.

Figure 1.



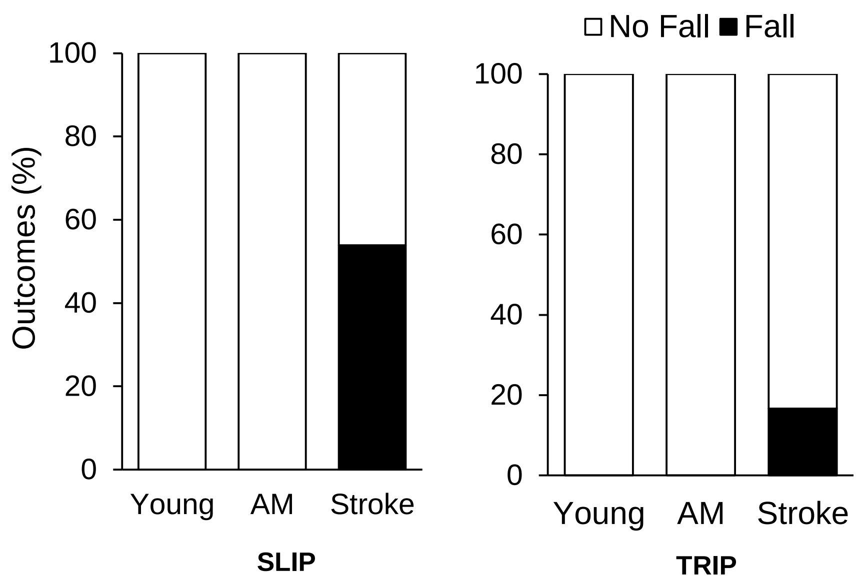
a) Schematic representation of the experimental setup where individuals where exposed to SLIPS and TRIPS like perturbations in standing position and b) displacement, velocity and acceleration profiles of the perturbation intensity for SLIP perturbation. The perturbation profile was reversed to induce TRIPS through backward belt displacement keeping the displacement, velocity and acceleration the same as SLIPS. Zero seconds represents the time of perturbation onset and the vertical line represents compensatory step liftoff (LO) of a representative participant.

Figure 2.



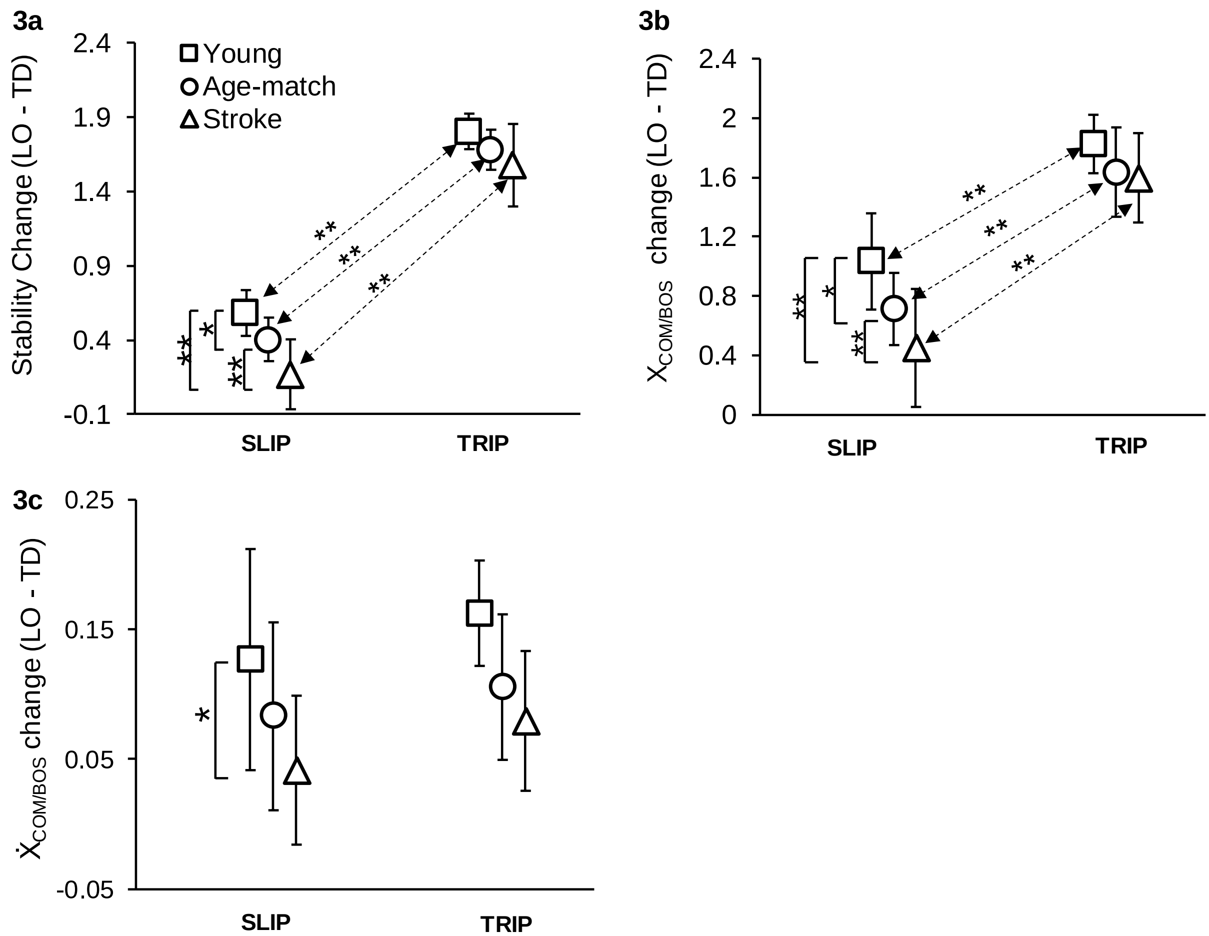
Time series of trunk angle (dotted line) during a) SLIPS and b) TRIPS of a representative participant. Negative trunk angle values indicate trunk extension and positive trunk angle values indicate trunk flexion. Trunk angles a liftoff (LO) and touchdown (TD) during both perturbations are shown. The change in trunk angle (TA change) from LO to TD was calculated at TA at TD minus TA at LO. During SLIPS a negative value for TA change would indicate more trunk extension at TD than at LO. During TRIPS a negative value for TA change would indicate more trunk flexion at LO than at TD.

Figure 3.



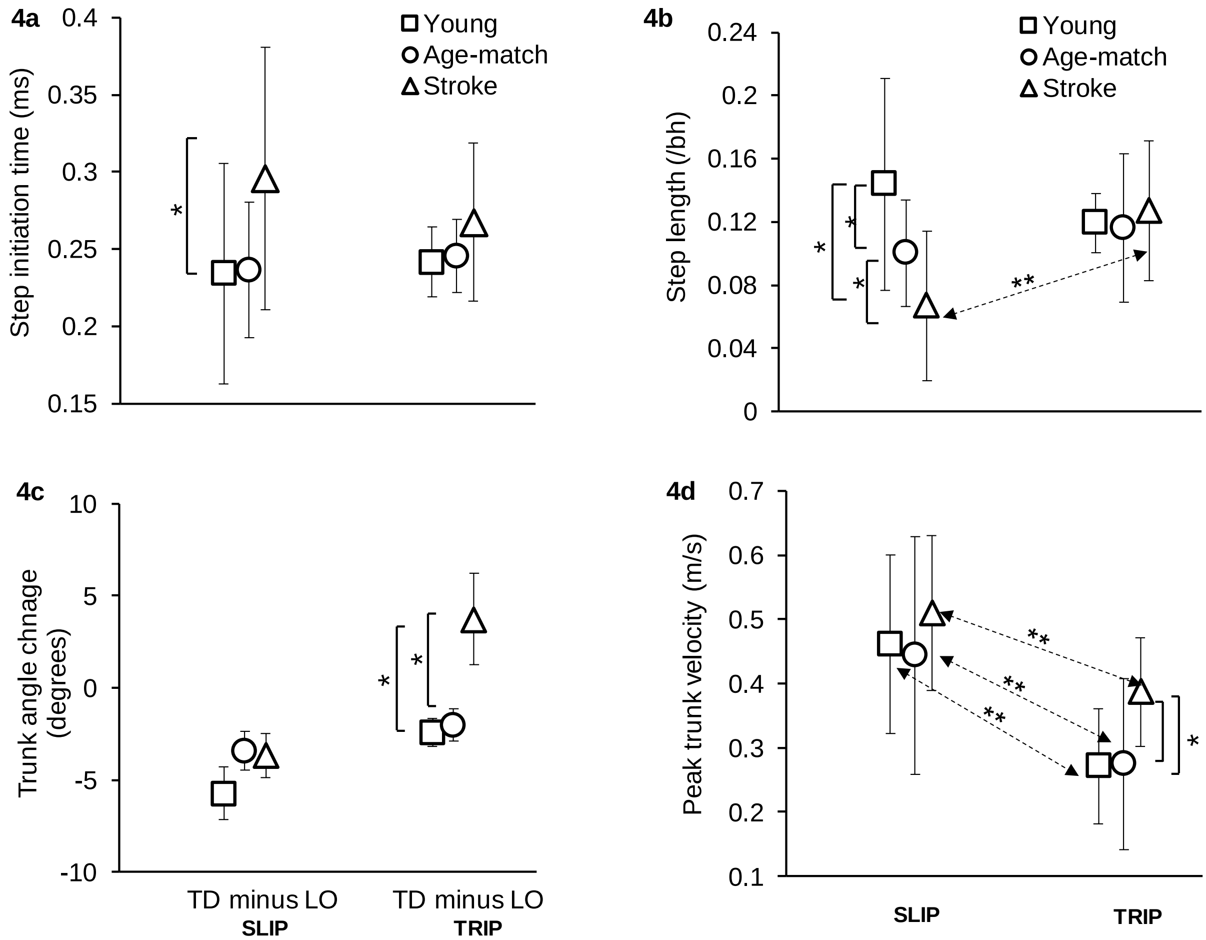
Proportion of falls and no falls between the groups for SLIP and TRIPS. Significant difference in incidence of falls between young adults, age-matched adults (AM) and chronic stroke survivors for SLIPS ($p < 0.05$). An individual was said to have had a fall if the weight exterted on the harness exceeded > 30% of the body weight for > 1s with a definite use of harness for recovering balance on visual inspectection.

Figure 4.



Mean (±SD) differences in a) stability change from liftoff (LO) to touchdown (TD), b) change in center of mass position relative to base of support ($X_{COM/BOS}$) and c) change in center of mass velocity relative to base of support ($\dot{X}_{COM/BOS}$) between the three groups, young adults, age-matched adults and chronic stroke survivors for SLIPS and TRIPS. The $X_{COM/BOS}$ was normalized to the individual's foot length and $\dot{X}_{COM/BOS}$ was normalized to a dimensionless fraction of square root of gravity (g) and body height (h). Significant differences are indicated by $^{**}p < 0.01$ and $^{*}p < 0.05$.

Figure 5



Mean (±SD) differences in a) step initiation time (ms), b) compensatory step length normalized by body height (bh) and c) change in trunk angle from liftoff to touchdown and d) peak trunk velocity between the three groups, young adults, age-matched adults and chronic stroke survivors for SLIPS and TRIPS. Significant differences are indicated by **p < 0.01 and *p < 0.05.

Chapter 5 – Effect of motor tasks on CMI in individuals aging with and without stroke

5.1 Introduction

A dual-task paradigm has been widely used to understand the attentional demands of balance and locomotor tasks. The view that maintaining stability during upright postural tasks may involve attentional resources stems from several empirical findings showing that the performance on the postural and/or cognitive task declines when the two are performed simultaneously (Brown, Shumway-Cook, & Woollacott, 1999a)(Melzer, Goldring, Melzer, Green, & Tzedek, 2010) (Li et al., 2001; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002). This is referred to as cognitive-motor interference (CMI) (Plummer et al., 2013). These findings can be interpreted in the light of two main frameworks - “capacity sharing” and “bottleneck” theories which assume that the central resources/ capacity is limited resulting in a processing delays when two tasks requiring similar neural pathways are performed concurrently.

While there is evidence suggesting that balance and locomotor tasks are attentionally demanding, the innate demands of the motor task itself could affect the performance in a dual-tasking situation. For example, attentional demands for reaching from a standing position involving voluntary action however, limited movement across different body segments on a stable base of support (BOS), could differ from the demands of walking involving movement across several body segments through a changing BOS. Further, attentional demands may vary depending on threat perceived and the level of experience/skill to perform a specific task. Thus, maintaining balance while walking on an even surface could incur lower attention demand than that while catching balancing during sudden disturbance causing slip or a trip. Limited studies have examined the differential attentional needs of balance activities. One study by Lajoie et al

(Lajoie, Teasdale, Bard, & Fleury, 1993) demonstrated longer reaction times to an auditory stimulus during static standing as compared with static sitting suggesting postural tasks with greater balance demands also needs greater attentional resources.

As such, cognitive load during balance tasks also affects younger and older adults differently. Sparrow et al. (2002) demonstrated that older adults have greater reaction times to a visual task while walking or greater decline in gait speed while performing a memory recall task as compared with younger adults (Li et al., 2001; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002). A direct injury to the central nervous system such as a stroke, Parkinson's disease or multiple sclerosis resulting in both motor and cognitive impairments also seems to affect dual-tasking ability as these individuals need to maintain balance in the face of reduced neural resources and sensorimotor impairments (Canning, Ada, & Paul, 2006; Kizony, Levin, Hughey, Perez, & Fung, 2010). Cognitive and motor deficits occur with aging and neurological conditions. As presence of cognitive deficits affect motor abilities, it is essential to understand attentional demands of different balance tasks involving intentional and reactive balance in individuals aging with and without neurological conditions as well.

Therefore, the purpose of this study is to examine the influence of a single higher cognitive (working memory) task while concurrently performing three different dynamic postural tasks – limits of stability (intentional balance), compensatory stepping during large magnitude backward perturbations (reactive balance) and walking across healthy younger adults, older adults and older chronic stroke survivors. Motor and cognitive cost of performing the three postural tasks under dual-task conditions were measured. Based on the attentional demands incurred by the postural tasks, the motor, cognitive or both the costs will differ across the three balance tasks within all the groups. Further, motor and cognitive costs of performing the balance tasks would be greater among stroke survivors as compared with healthy adults.

5.2 Methods

Participants

Healthy young adults (18-30 years, N = 36), community dwelling chronic stroke survivors (50-70 years, N =36) and age-matched healthy adults (50-70 years, N = 36) participated in the study. The information about type of stroke was obtained from subjects' physicians. Stroke survivors were included if they satisfied the following criteria 1) ability to walk 10 m with a speed of ≥ 0.58 m/s without any assistive device i.e., least limited and unlimited community ambulators and 2) intact cognitive function determined by score of ≥ 26/30 on Montreal Cognitive Assessment scale. This test focuses on different aspects of cognitive functions such as orientation, attention, recall, working memory, and language and the stroke survivors were excluded in presence of any other acute or chronic medical conditions. Table 1 shows subject demographics for all the participants. Performance on measures of balance – Berg Balance Scale, motor impairments – Chedoke McMaster Stroke Assessment and physical activity levels using Rapid Assessment of Physical Activity was assessed for stroke survivors (Table 2). The healthy adults were excluded if they presented with any acute or chronic musculoskeletal, neurological and cardiopulmonary conditions. In addition to stroke survivors, younger and age-matched healthy controls were included to examine the effect of both aging and chronic stroke on CMI. The CMI pattern was assessed for all subjects performing one of the three different balance tasks. A schematic representation of the three balance tasks is shown in Figure 1.

Intentional balance assessment

Intentional balance was assessed using the limits of stability test (LOS) by NeuroCom SMART Equitest for computed dynamic posturography. The subjects donned a harness and stood on the platform placing their feet on the force plates. The subjects' center of pressure vector was projected on the screen in front of them in the form of a figure, known as "avatar". The subjects attained the initial position to maintain the avatar in the center of the screen. Upon receiving an auditory cue, subjects moved towards the target in the forward direction as fast as possible. Subjects are asked to reach as close to the target as possible and hold the avatar in that position until the second auditory cue was heard while refraining from stepping or holding onto the surrounding box. After receiving a single familiarization trial, all the subjects performed this task in single-task and dual-task conditions.

Outcome**:** The maximum excursion of the center of pressure (MXE) in the forward direction was recorded (Au-Yeung, Hui-Chan, & Tang, 2009). This indicates the maximum distance up to which the individual can shift his/her center of mass outside the base of support without initiating a step, reflecting the individual's limits of stability in the forward direction.

Reactive Balance Assessment

The subjects were exposed to trip-like perturbations from standing position on a motorized treadmill, ActiveStep (Simbex, Lebenon, NH). Initially subjects assumed a comfortable stance on the treadmill with their feet shoulder width apart. A harness donned prevented the participants' knees from touching the treadmill in case of a fall. Prior to the testing session, the participants were presented with a familiarization trial wherein they were instructed to execute a natural response to recover their balance upon a sudden backward trip-like perturbation. The familiarization trial was presented to acquaint the participants with testing procedure. Following familiarization, perturbations were triggered at 16.75 m/s^2 with a displacement of 20 cm.

Data collection and analysis

An eight camera motion capture system with a sampling rate of 120 Hz recorded full body kinematics (Motion Analysis Corporation, Santa Rosa, CA). The Helen Hayes marker set with 29 markers placed on bilateral bony landmarks, head and trunk was used to compute the joint centers and center of mass (COM) (Davis et al., 1991). An additional marker was placed on the treadmill belt to identify the instant of perturbation onset. The raw marker data were low pass filtered using the fourth order Butterworth filter with a cut off frequency of 6Hz. The kinematic variables were computed using custom written algorithms in MATLAB version 2014b (The MathWorks Inc, Nactick, MA).

Outcome: The center of mass (COM) position was recorded relative to the anterior margin of the base of support (BOS) at touchdown of the stepping limb in the anteroposterior direction ($X_{COM/BOS}$) and normalized to the individual's foot length. A more positive $X_{COM/BOS}$ would indicate greater instability in the forward direction.

Gait Assessment

Gait parameters were recorded using an electronic mat GaitRite (CIR Systems, Inc., Sparta, NJ). It consists of sensors embedded into 12 x 2 feet mat which measures spatial and temporal gait parameters via the accompanying GaitRite software (GaitRite Gold, Version 3.2). To record the steady state walking pattern, subjects began walking about 1 meter before stepping on the mat and continued walking about 2 meters beyond the mat. Gait velocity was measured while the subjects walked on the mat and was defined as the distance walked in the walking time for that specific trial (Al-Yahya et al., 2011).

Cognitive task

Subjects performed a mental arithmetic or serial subtraction task involving counting backwards from a specific two-digit number by a given single-digit number. The number of correct responses over a period of 30s were recorded while standing (single-task) and while performing the balance tasks (dual-task).

Experimental protocol

Subjects first received standardized instructions on how to perform the cognitive task followed by one familiarization trial. Subjects then performed a single trial of the cognitive task in standing position. This was by followed by random allocation of the subjects to evaluate dual-tasking function on one of the three balance tasks i.e. either the LOS, gait or reactive balance tasks. Within each of the groups the balance task was performed in single-task i.e. performing the balance task without the cognitive task and dual-task conditions. The duration of each trial was 10-30s depending upon type of balance task.

a. Limits of Stability (LOS): For this task, subjects were required to shift their center of pressure (COP) in the forward direction upon hearing an auditory cue. After a familiarization trial, the subjects performed the LOS task in isolation followed by performing the LOS tasks concurrently with the serial subtraction task. In the dual-task condition, subjects initiated the balance and serial subtraction task simultaneously upon hearing the auditory cue.

b. Gait: Subjects initially walked for three trials at preferred walking speed followed by another block of three trials in the dual-task condition wherein the subjects began the serial subtraction walking tasks simultaneously.
c. Reactive balance task (RB): After being exposed to a familiarization trial with trip-like forward perturbation, subjects were exposed to a single trip in absence of a cognitive task (single-task). Subjects then performed the balance task in dual-task condition.

For the LOS and reactive balance tasks, half of the subject performed balance tasks in the single-task condition prior to the dual-task and the other half of the subjects performed trials in the reverse order. While performing the gait task, single-task and dual-task trials were delivered in a randomized order which was identical for all the subjects.

Motor Cost

The effect of dual-tasking on both balance and cognitive parameters was assessed by comparing the absolute values for all balance, gait and cognitive variables between single- and dual-task conditions. To compare the effect of dual-tasking across the balance tasks between the three groups, the motor and cognitive dual-task cost was measured using following the formula (Kelly et al., 2010)

$$[(\text{Single-task} — \text{Dual-task})/\text{Single-task}] *100$$

Higher cost indicated reduced performance on the individual balance task under dual-task condition, and a negative cost indicated improved performance in the dual-task condition. The differential challenge of the balance tasks was determined based upon the motor cost under the respective dual-task conditions.

5.3 Statistical Analysis

To analyze the effect of dual-tasking across the different balance tasks, between the groups, 3 x 2 two-way repeated measures ANOVA was performed for motor and cognitive costs with the balance tasks (reactive balance, gait and LOS) as within-groups factor and groups (young, age-match adults and stroke) as the between group factor. The significant interactions and main effects were resolved by independent t-tests. Further, independent t-tests were performed to examine the difference between motor and cognitive costs for each balance task within each group. The alpha level was set at $p < 0.05$. All the analyses were performed using SPSS 24.00 (IBM. Inc)

5.4 Results

Effect of dual-tasking on motor task

The effect of dual-tasking on motor costs varied as a function of the type of balance task across the three groups showing a significant group x task interaction [$F (4, 66) = 2.73$, $p < 0.05$, Figure 2a]. Within the groups the motor costs differed across the tasks [$F (2, 66) = 4.57$, $p = 0.05$]. The younger adults and older adults showed a trend towards greater motor costs for the RB and gait tasks as compared with the LOS task. The motor cost for the LOS tasks was significantly lower as compared with the other two tasks for younger adults ($p < 0.05$ for LOS vs. RB and for $p < 0.01$ LOS vs. gait]. Within the age-matched adults, the motor cost tended to be lower for LOS tasks as compared with the other two tasks ($p < 0.05$ for LOS vs. RB and LOS vs. gait). Within the stroke group however, the motor cost showed a trend towards higher motor cost during the LOS task as compared with other two tasks however, there was no significant difference in motor cost between the three tasks. There was a significant main effect of groups for the motor cost, [$F (2, 33) = 16.20$ $p = 0.00$, Figure 2a]. For the RB task, the motor cost was significantly greater in the age-match and stroke groups in comparison with the young adults (p

= 0.01 for age-match vs. young, p = 0.01 for stroke vs. young) however, there was no difference in motor cost between the age-matched adults and stroke survivors ($p > 0.05$). Similarly, for gait task the motor cost was significantly lower in younger adults than the other two groups (p = 0.02 for young vs. age-match and p = 0.04 for young vs. stroke). There was no difference in motor cost for gait between stroke and age-matched adults ($p > 0.05$). For the LOS task, the motor cost was significantly different between all three groups – young adults < age-matched adults (p = 0.00), age-matched adults < stroke survivors (p = 0.00) and young adults < stroke survivors (p = 0.00).

With regards to the cognitive cost, there was a significant main effect of group [$F(2, 3) = 3.31$, $p < 0.05$, Figure 2b]. While the cognitive costs were not significantly different between the tasks within each of the groups [no main effect of task $F(2, 66) = 1.09$, $p > 0.05$]. There was no difference in cognitive cost for RB task between the groups ($p > 0.05$). The cognitive cost for gait task was greater among age-matched adults and stroke survivors as compared with younger adults ($p < 0.05$). For the LOS task as well, the cognitive cost was higher in stroke survivors and age-match adults than younger adults ($p < 0.05$ for both comparisons).

Further, a comparison of motor and cognitive costs for each of the tasks among all groups showed significantly greater cognitive cost for reactive balance task (p = 0.03) and LOS (p = 0.00) tasks among the younger adults with no significant difference between the costs for gait task ($p > 0.05$) (Figure 3a-c). The age-matched adults and stroke survivors showed a higher cognitive cost for LOS (p = 0.00 for age-match, p = 0.01 for stroke) however no difference between motor and cognitive costs for the RB and gait tasks (Figures 3d-i).

5.5 Discussion.

This study aimed to examine the whether the CMI pattern differed with regards to the type of balance task and effect of aging with and without a stroke on CMI pattern across the motor tasks. As hypothesized, the type of balance task influenced the CMI pattern. Further, chronic stroke had some effect on the CMI pattern. Generally, the age-matched adults and chronic stroke survivors showed higher motor costs for all three tasks however, marked differences between all three groups were observed predominantly for the LOS task. A decline in cognitive in performance was also observed among all the groups.

CMI across balance tasks in healthy nervous system

The effect of dual-tasking differed between the motor tasks in both younger adults, such that the motor cost for RB and gait tasks were similar and greater than the LOS task. The differences in motor costs may arise from the neural processes involved in movement control and biomechanical demands of the tasks itself. The intentional movements are believed to be controlled primarily by the supplementary motor area which is involved in movement planning and posture control (Jahanshahi et al., 1995). Although gait and reactive balance tasks could be controlled by the central pattern generators in brainstem and spinal cord, a descending influence of cortical centers via cerebellum facilitates modulation of these postural tasks (Beloozerova, Sirota, Orlovsky, & Deliagina, 2005a; Morton & Bastian, 2004; J. F. Yang & Gorassini, 2006). Further, walking and compensatory stepping tasks require coordinated movements between trunk and lower extremities to maintain balance over changing BOS. On the contrary, a voluntary reaching task as LOS, involves maintaining balance on a constant BOS requiring control of only the upper body segment. Considering the involvement of cortical areas during less complex voluntary task, it is possible that individuals could explicitly allocate attention to maintain the stability on the LOS task. The neural processes modulating tasks that pose greater threat to stability are likely interfered to a greater extent by concurrent working memory tasks resulting in higher motor costs. These findings are in line with a previous study that showed the attentional demands of postural tasks progressively increased from sitting, standing to walking observed by an increase in reaction time on an auditory task (Lajoie et al., 1993).

Dual-tasking often results in a trade-off of attentional resources between motor and cognitive tasks and it is possible to minimize the cost of performing either of the tasks in presence of explicit instruction (Remaud, Boyas, Lajoie, & Bilodeau, 2013; Yogev-Seligmann et al., 2010). We observed implicit prioritization of motor tasks during RB and LOS as the cognitive cost was considerably higher than motor cost for these tasks (see figures 3a & 3c). It suggests that younger adults attempted to trade off the performance on the cognitive task to achieve stability during momentary balance loss whether voluntary (LOS) or involuntary (RB). During gait task however, the two costs were similar indicating a mutual cognitive-motor interference (figure 3b). Considering that walking is a continuous task, individuals likely attempt to allocate equal attentional resources to both motor and working memory tasks affecting performance on both the tasks equally.

Effect of aging on CMI across balance tasks

Similar to young adults, age-matched older adults also showed modulation in attentional demands with higher motor cost during less stable RB and gait tasks than LOS task. However, the effect of aging was evident by higher motor costs for all balance tasks and higher cognitive cost for the gait and LOS tasks in this population (Boisgontier et al., 2013). With normal aging process, there is a decline in balance control due as reduced proprioceptive function, impaired synergistic contraction of muscles contributing to greater co-activation of muscles and delayed postural reflexes (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Maki & McIlroy, 1996; Nardone, Siliotto, Grasso, & Schieppati, 1995) as well as reduced cognitive functions like working memory and information processing speed (Morcom, Good, Frackowiak, & Rugg, 2003; Park & Reuter-Lorenz, 2009), the cognitive functions deemed crucial for balance control (Yogev-Seligmann, Hausdorff, & Giladi, 2008). Considering reduced central capacity with aging alongside declining neuromuscular function could possibly limit greater allocation of attentional resources to motor tasks, contributing to a higher motor costs as seen in our study (Pashler, 1994b). Unlike young adults, age-matched adults prioritized motor task only during the LOS task (figure 3f) as seen in previous studies (Bhatt, Subramaniam, & Varghese, 2016). They were unable to do so during the RB task which in fact posed higher threat to balance than the LOS task. The decline in central capacity with aging also appears to interfere with the ability prioritize motor task when the relative demands of the balance task are greater.

Effect of stroke on CMI across balance tasks

Unlike healthy adults (younger and older), the stroke survivors failed to show a specific trend for the motor cost. The motor costs were similar for all three tasks within this group. Stroke survivors perhaps demonstrate a disproportionate ability to divide attention between motor and cognitive tasks compared with healthy age-match controls. Although it is well-known that there is a decline in dual-task function post-stroke (Baetens et al., 2013; Bowen et al., 2001; Cockburn et al., 2003; Plummer-D'Amato et al., 2008; Regnaux et al., 2005) (Melzer et al., 2010), most studies have reported CMI during a single motor task such as gait, quiet standing or voluntary stepping. Furthermore, no study thus far has examined CMI during compensatory stepping from large perturbations which is impaired in this population (Mansfield et al., Salot et al.,). Hyndman et al. (2006) compared the CMI during quite standing and walking and observed that a concurrent cognitive task affected on walking speed but not the anteoposterior sway during standing suggesting that a simple task like standing may not be affected by a cognitive task among chronic stroke survivors (Hyndman, Ashburn, Yardley, & Stack, 2006). Similarly, we observed a decline in both motor and cognitive performance on all the motor tasks focused on dynamic balance. The fact that all dynamic balance tasks incurred equal attentional resources regardless of the differential postural challenge, it is possible that the ability to flexibly allocate attention to postural task remains affected in chronic phases of stroke.

In comparison with age-matched adults, the motor cost was greater for the LOS task whereas the costs were comparable between the groups for gait and RB task. As stroke affects higher cortical areas which predominantly influence movement control during voluntary balance tasks, a cortical injury during stroke could possibly affect the ability to allocate attention to carry out voluntary tasks under cognitive loads. This may explain a higher motor cost for the voluntary, LOS task in stroke survivors as compared with the age-matched controls despite implicit prioritization of the motor task (see figure 3i) (Bhatt et al., 2016). Considering that the stroke survivors in this study were in chronic phase of recovery (at least 3 years post stroke), it may be difficult to conclude that the CMI observed in this population may be directly due the stroke-related pathology (Canning et al., 2006).

The similarities in motor and cognitive costs between age-match controls and chronic stroke survivors during RB and gait tasks could be potentially related to motor recovery and continued community ambulation in the chronic phase post-stroke. During community ambulation, the demand for dual-tasking ability is significant. Independent mobility in different community settings (e.g. grocery stores, hospitals, school, post office, gym etc.) may perhaps facilitate gains in balance or assist in developing compensatory strategies. The severity of motor impairment is negatively associated with community mobility and balance (Knorr, Brouwer, & Garland, 2010). The stroke survivors in our study showed only mild to moderate levels of motor impairment (CMSA leg score 3-6/7), were community ambulators and were involved in light to moderate levels of physical activity on daily basis (RAPA1 score 4-6/7). This could possibly explain similar dual-task function in stroke survivors and age-match healthy controls. Very few studies have investigated the CMI in chronic stroke survivors with their healthy counterparts. Two studies compared effect of dual-tasking in ambulatory older stroke survivors with > 3 years post stroke with healthy controls (Canning et al., 2006; Pohl et al., 2011). These studies also reported a similar decline in gait velocity and cadence in older chronic stroke survivors and healthy adults in dual-task condition suggesting that dual-task deficits in chronic stroke survivors may be in part due to aging.

Dual-tasking is increasingly incorporated in clinical settings for both assessment and training. At the rehabilitation level, our findings emphasize the importance of including balance activities with different postural demands or challenge for people aging with and without a cerebral injury from stroke. Given some degree of similarity in CMI between older healthy individuals and stroke survivors, it is possible that stroke survivors show similar gains in dual-tasking ability with training. This study extends the literature related to CMI by demonstrating the attentional demands of balance tasks that may pose differential threat to stability among healthy younger adult and adults aging with and without a stroke. Although in the chronic stage, stroke survivors may show some similar CMI as their healthy counterparts for more complex balance tasks, these individuals lack the ability to regulate the allocation of attentional resources based on type of balance tasks.

5.6 Tables and figures

Table 1.

Mean (standard deviation) of subject demographics. There was no significant difference in age, height and weight between the young, age-match and stroke groups.

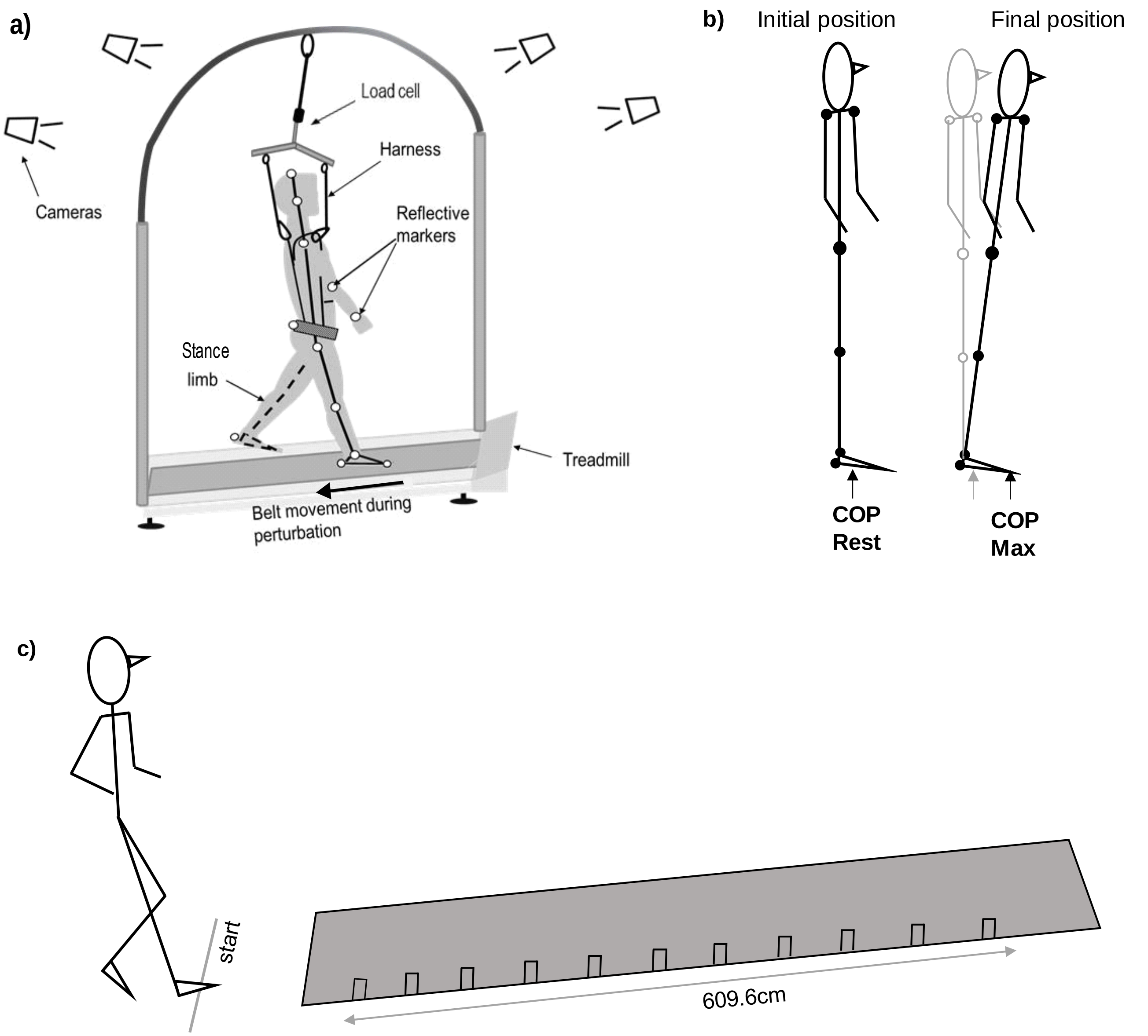
Variable	Young (n = 36)	Age-Match (n = 36)	Stroke (n = 36)
Age (years)	22.20 ± 2.04	62.50 ± 4.77	58.66 ± 6.41
Height (m)	1.64 ± 0.37	1.67 ± 1.05	1.77 ± 0.97
Weight (lbs)	146.33 ± 29.74	188.33 ± 39.35	169.9 ± 25.07

Table 2.

Demographics and clinical outcome measures scores for chronic stroke survivors.

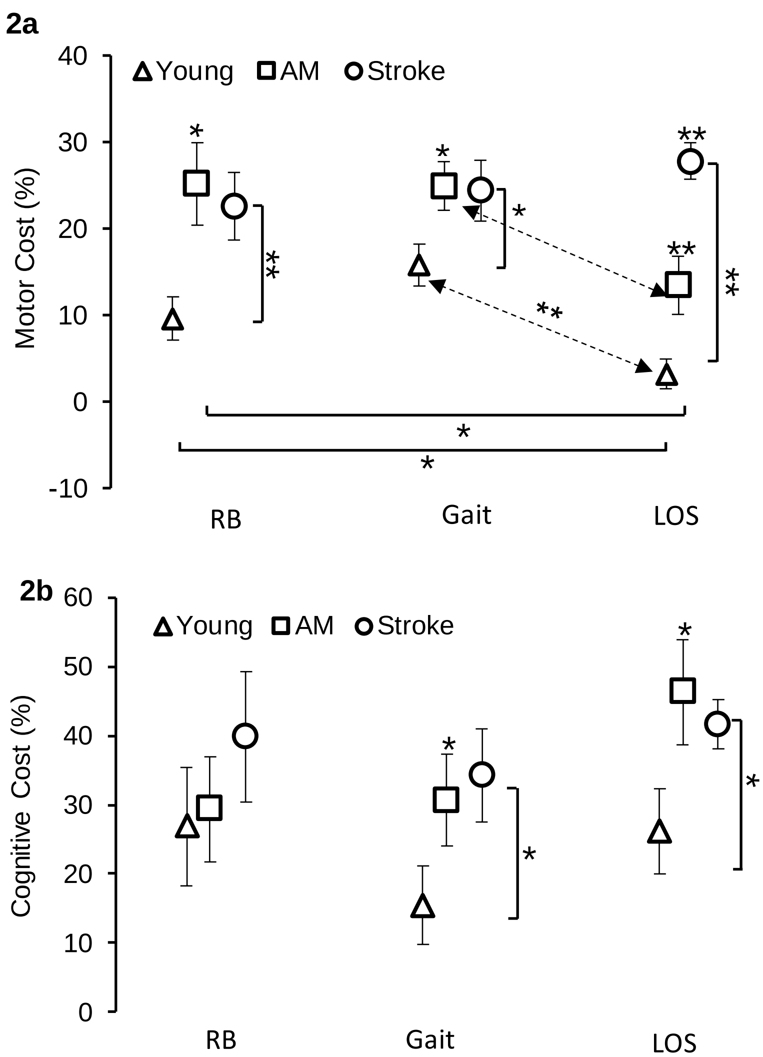
Variable	Mean (SD)
Age (years)	58.66 (6.41)
Time since stroke (years)	9.2 (5.14)
Chedoke McMaster Stroke Assessment for lower extremity	
Leg (/7)	4.85 (1.08)
Foot (/7)	3.10 (1.83)
Berg balance scale (/56)	41.36 (7.28)

Figure 1.



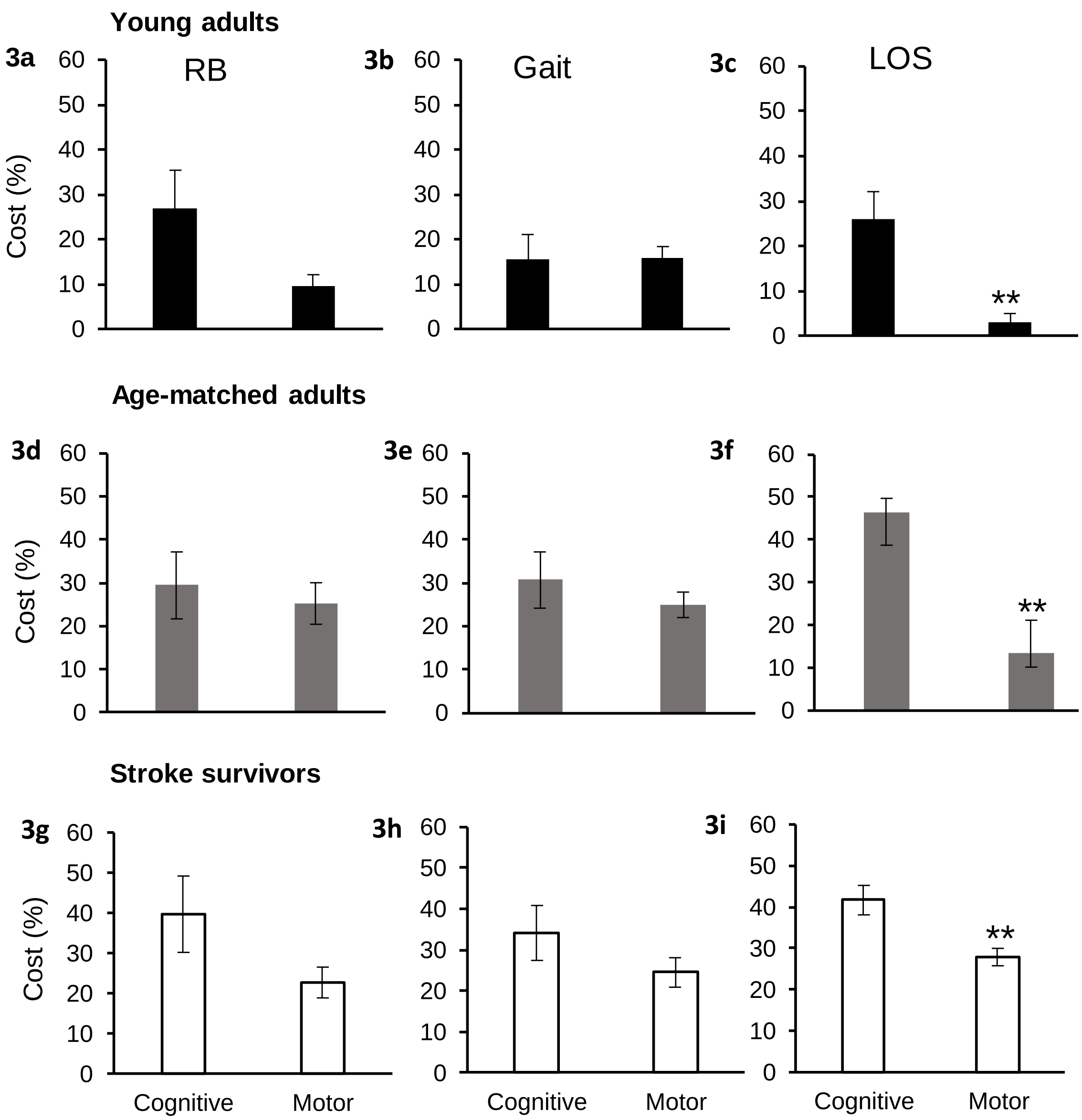
Schematic representation of the three motor tasks – a) reactive balance (RB), b) limits of stability in the forward direction, c) gait. For the RB, subjects experienced a trip-like perturbation that evoked a compensatory stepping response. The center of mass position relative to base of support ($X_{COM/BOS}$) was recoded at compensatory step touchdown. During the gait task subjects walked on the GaitRite mat at preferred walking speed and the velocity was measured. The limits of stability (intentional balance task) required subjects to lean forward upon hearing an auditory cue. The maximum center of pressure (COP) excursion from the resting position (MXE) was recorded.

Figure 2.



Differences in means (± SE) a) motor cost and b) cognitive cost across the balance tasks, RB = reactive balance, LOS = limits of stability between young adults, age-matched (AM) adults and stroke survivors. Significant within and between group differences are indicated by * $p < 0.05$ and ** $p < 0.01$.

Figure 3.



Comparison of motor and cognitive costs for each of the balance tasks (RB = Reactive balance, LOS = Limits of stability) within young adults (a-c), age-matched adults (2-f) and stroke survivors (g-i). * indicates $p < 0.05$ and ** indicates $p < 0.01$

Conclusion and future directions

While dual-tasking, the central goal of the nervous system i.e. stability might be achieved by differential allocation of attentional resources depending on demands of the tasks and the individual's capabilities. This dissertation facilitates the understanding of attentional demands of balance tasks by examining cognitive motor interference (CMI) in healthy young adults and then by examining the effect of aging and chronic stroke on CMI.

Within the healthy non-aging nervous system, the CMI of walking differs with regards to the type of higher cognitive task. Results suggests an overlap in the cortical centers involve in walking and visuomotor, working memory, and executive functions. Nevertheless, younger adults may prefer to prioritize less practiced or more challenging cognitive tasks such as an executive function task while walking. Cognitive-motor interference is also influenced by walking speed such that slow walking could facilitate performance on more complex cognitive tasks and thus could be used as a strategy to voluntarily allocate attention to the secondary task while dual-tasking (Chapter 1). Moreover, performing a working memory tasks negatively affects postural stability during large slip-like perturbations resulting in a mutual cognitive and motor interference within young adults. Thus, compensatory stepping evoked by large perturbations which induce falls may possibly involve some degree of modulation from higher cortical centers (Chapter 3). Furthermore, perturbations evoking backward (SLIPS) rather than forward (TRIPS) loss of balance may pose higher fall risk as individuals can achieve higher stability during TRIPS than SLIPS through greater forward trunk control (Chapter 4). It is likely that balance recovery from SLIPS may require greater attentional resources than from TRIPS however differential challenge of these perturbations was examined in only single-task condition. Lastly, the attentional demands of motor tasks are influenced by the type of motor task as well.

In particular, postural tasks that are perceived more unstable such as walking or compensatory stepping possibly require higher attention than tasks perceived to be more stable like a voluntary forward leaning (Chapter 5).

Cognitive-motor interference pattern among chronic stroke survivors who present with residual sensorimotor deficits seem to be altered as compared with young adults (Chapter 2). Chronic stroke survivors demonstrate greater interference during working memory tasks leading to a greater motor and cognitive cost of dual-task walking than younger adults. Further, chapter 4 demonstrated that these individuals pose a higher risk of falls during SLIPS than TRIPS however, postural stability during SLIPS is significantly lower in chronic stroke survivors than healthy young and older adults. The decline in dual-tasking ability in chronic phases of stroke could be influenced by both aging and stroke related deficits. Therefore, chapter 5 demonstrates that the ability to modulate attentional resources to the motor task based on perceived threat to stability is impaired in older chronic stroke survivors compared with age-matched controls. Yet, continued community involvement and physical activity in chronic phases stages may promote some degree of motor and cognitive recovery resulting in similar attentional demands for motor tasks like walking and reactive balance as age-matched controls.

While current studies demonstrate that attentional control of postural tasks is influenced by the type of cognitive task, type of motor task and with neurological conditions, future studies could focus on identifying the neural mechanisms that underlie the control of motor and cognitive tasks in dual-task situations. Particularly to isolate the mechanisms between those aging with and without stroke considering some degree of overlap in dual-task function in these populations.

Ability to divide attention during several motor tasks is important to perform tasks safely, promote mobility and confidence when functioning in challenging environments. Another direction for future studies would be examine whether explicit prioritization of either motor or cognitive tasks is affected with task complexity and with neurological conditions. Future studies should also examine the efficacy of dual-task training balance and locomotor training in reducing cognitive motor interference among older healthy adults and post neurological conditions. Considering higher fall risk in stroke survivors in response to sudden perturbations, balance rehabilitation must also focus on inclusion of reactive balance training to lower fall risk.

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