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Timing of reactive stepping among individuals with sub-acute stroke: effects of 'single-task' and 'dual-task' conditions

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Abstract

Performance decrements in balance tasks are often observed when a secondary cognitive task is performed simultaneously. This study aimed to determine whether increased cognitive load resulted in altered reactive stepping in individuals with sub-acute stroke, compared to a reactive stepping trial with no secondary task. The secondary purpose was to determine whether differences existed between the first usual-response trial, subsequent usual-response trials, and the dual-task condition. Individuals with sub-acute stroke were exposed to external perturbations to elicit reactive steps. Perturbations were performed under a usual-response (single-task) and dual-task condition. Measures of step timing and number of steps were based

on force plate and video data, respectively; these measures were compared between the usual-response and dual-task trials, and between the first usual-response trial, later usual-response trials (trials 2–5) and a dual-task trial. A longer time of unloading onset and greater number of steps were identified for the first usual-response trial compared to later usual-response trials. No significant differences were identified between usual-response and dual-task trials. Although improvements were observed from the first to subsequent usual-response lean-and-release trials, performance then tended to decrease with the introduction of the dual-task condition. These findings suggest that when introduced after usual-response trials, the dual-task trial may represent the first trial of a new condition, which may be beneficial in reducing the potential for adaptation that may occur after multiple repetitions of a reactive stepping task. Therefore, these findings may lend support to the introduction of a new condition (i.e. a dual-task trial) in addition to usual-response trials when assessing reactive balance in individuals with stroke.

Keywords: Health sciences, Medicine

1. Introduction

Increased falls risk has been identified in individuals with stroke [1], which may be due at least in part to the disturbances in balance, postural responses, and perception caused by the stroke [2]. Balance ability may be further impaired by the simultaneous performance of a secondary cognitive task in addition to a balance task [3, 4], specifically one that incorporates processes related to attention, perception, memory, decision making, or voluntary movement [5]. This effect is thought to be due to a limited capacity for information processing resources, such that when attention-demanding tasks (e.g., both balance and cognitive tasks) are performed simultaneously, there will be competition between the two, which may result in interference with one or both tasks [4, 6]. Central processing characteristics and attentional capacity have been identified as factors limiting balance performance during these types of dual-task situations [7]. Therefore, in addition to balance impairments, reduced cognitive function and/or compromised attentional resources associated with the stroke may further contribute to falls risk [8].

The addition of a cognitive task to a voluntary postural control task has generally been observed to lead to decrements in performance of the postural task in individuals with stroke. For example, during quiet standing, two previous studies have found that the implementation of a cognitive task (memorization and recall) resulted in reduced sway [9, 10], while another study identified greater velocity of the centre of pressure and greater weight bearing asymmetry when a verbal arithmetic task was performed [11]. The discrepancies in these findings may have been due to the type of cognitive task and whether the task was articulated or non-articulated [12]. Dual-task

conditions also contribute to reduced velocity during walking [9], as well as increased step reaction time and time to foot contact during voluntary forward and backward stepping in individuals with stroke [7]. While these types of voluntary balance activities are important for balance and mobility function post-stroke, good reactive balance control is essential to regaining stability following a loss of balance [6] and reducing falls risk for individuals with stroke [13]. Due to the rapid onset and high movement speeds required during these types of movements [14, 15], reactive balance control is often difficult for this population, and the addition of a cognitive task may impose further challenges. Furthermore, reactive stepping may impose a greater demand for cognitive resources compared to balance reactions that do not require changing the size of the base of support [5]. Consequently, further study of these types of scenarios (reactive stepping task plus cognitive task) is warranted.

The effects of dual-task scenarios on reactive balance tasks have been examined in healthy young, healthy older, and balance-impaired older adults [16, 17, 18]. Overall, the addition of a cognitive task generally results in decrements in performance of reactive balance tasks. Specifically, under dual-task conditions, increases in centre of pressure excursion have been identified during feet-in-place reactions in healthy young adults [16], as have decreased postural stability, decreased compensatory step length, and slowed reaction time in healthy young adults during reactive stepping [17]. Furthermore, in healthy older adults, execution of anticipatory postural adjustments following an external perturbation (prior to the stepping response) has been found to be impaired with the addition of a dual task, with reductions in both duration and amplitude of the adjustment [18]. Alterations in the timing of the stepping response have also been identified under dual-task conditions in this population, including decreased foot-off and foot-contact times, and delayed step onset times [18]. While it is generally accepted that impaired reactive balance performance results from the simultaneous performance of a cognitive task, to the authors' knowledge, an investigation of how reactive stepping is altered in individuals with sub-acute stroke when a cognitive task is performed concurrently has not yet been conducted.

Therefore, this study aimed to determine whether increased cognitive load, imposed through a dual-task paradigm, resulted in altered reactive stepping in individuals with sub-acute stroke, compared to a reactive stepping trial with no secondary task. The secondary purpose was to determine whether differences existed between the first usual-response trial, subsequent usual-response trials, and the dual-task condition. It was hypothesized that decrements in performance would be observed during the dual-task condition compared to the usual-response trials, with delayed unloading onset and time to unloading (foot-off time – unloading onset); decreased swing time; and an increase in the number of reactive steps during the dual-task condition compared to the usual-response trials.

2. Materials and methods

2.1. Participants

This study consisted of a retrospective, cross-sectional design, with secondary analysis of data from individuals admitted to an in-patient stroke rehabilitation program at a rehabilitation hospital. As part of the in-patient stroke rehabilitation program, clinical assessments of reactive balance control were included as routine care during individuals' stay, conducted by one of four on-site physiotherapists [19]. However, components of the assessment may not have been conducted for every individual (at the physiotherapists' discretion). The purpose of the assessment was to aid physiotherapists in developing treatment programs for each individual. All procedures were approved by the institution's Research Ethics Board with a waiver of patient consent approved for the purpose of the review.

For data to be included in the present analysis, individuals must have completed at least two trials of unconstrained, or 'usual-response', reactive stepping, as well as one trial of reactive stepping under a dual-task condition (see Section 2.2). These trials must also have met specific criteria related to perturbation magnitude (see Section 2.3). Of 512 individuals admitted to the in-patient stroke rehabilitation unit during the review period (spanning 3 years), 70 were included in the analysis (13.7%) (Fig. 1). The reactive balance component is among the most difficult of the clinical assessment. Potential reasons for the low participation rate for this component include: individuals' anxiety or refusal of the reactive stepping component; low physical activity tolerance; pain or a musculoskeletal disorder that may have been exacerbated by the reactive stepping component; and/or other health or medical factors [19]. Individuals may also have been unable or reluctant to lean forward to complete the test. In addition, some individuals may have attempted the reactive stepping component but were unable to perform the specified number of trials or meet the criteria related to perturbation magnitude.

2.2. Assessments

Hospital charts were used to gather information relating to participants' sex, age, stroke date, and affected side of the body. Furthermore, scores for the National Institutes of Health Stroke Scale [20], Chedoke-McMaster Stroke Assessment [21], Berg Balance Scale [22], and Montreal Cognitive Assessment (MoCA) [23] were extracted, where available, in order to quantify stroke severity, motor impairment, balance capacity, and cognitive impairment, respectively. Demographic and stroke-related characteristics for the study sample are presented in Table 1.

Reactive stepping was assessed using a lean-and-release method [13, 19, 24, 25, 26], within a single session. Participants wore their usual flat closed-toe footwear and ankle-foot orthoses, if prescribed [27], and were outfitted with a safety harness
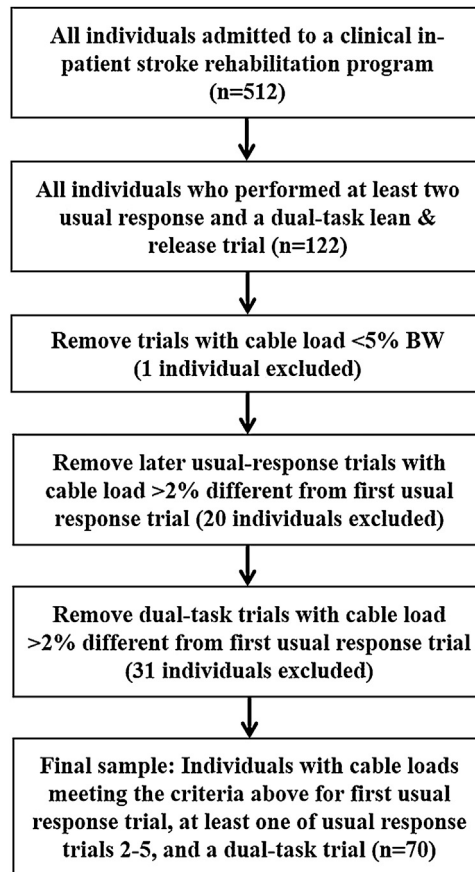
Fig. 1. Procedure used to identify participants for inclusion in the data analysis, based on the cable load from usual response trial 1, at least one of usual response trials 2–5, and the dual-task trial.

attached to an overhead track, which acted to prevent a fall to the floor in the event of a failure to recover balance following the perturbation. A release cable was clipped to the back of the safety harness, as well as to an attachment point on the wall behind the participant. A load cell located in series with the cable measured the proportion of participants' body weight (BW) supported by the cable. Participants stood with one foot positioned on each of two adjacent force plates (Advanced Mechanical Technology, Inc., Watertown, USA) in a standardized position [28]. A third force plate was positioned directly in front of the initial two force plates, in order to capture force information from the first reactive step. Force plate data were sampled at 256 Hz [25, 29]. Participants were asked to lean forward, such that the cable supported approximately 8–10% BW. Once this target level was achieved, an investigator released the cable at an unexpected time. Upon the removal of support from the release cable, participants started to fall forwards, and were required to take at least one step to regain their balance. A cable load of approximately 8%BW has been observed to elicit at least one step during most

Table 1. Demographic- and stroke-related information for the study sample, taken at the date of the assessment. Values are presented as either mean (standard deviation (SD)) or as number of participants (% of participants).

Characteristic	Number of participants	Mean (SD) or number (%)
Sex (number (%))	70	
Male		54 (77.1)
Female		16 (22.9)
Age (years)	70	65.4 (13.4)
Time since stroke (days)	70	23.6 (16.7)
More-affected side of the body (number (%))	70	
Right		38 (54.3)
Left		27 (38.6)
Both		4 (5.7)
Neither		1 (1.4)
National Institutes of Health Stroke Scale (score out of 42)	56	2.9 (2.3)
Chedoke-McMaster Stroke Assessment (leg score out of 7, more-affected side)	63	4.8 (1.1)
Chedoke-McMaster Stroke Assessment (foot score out of 7, more-affected side)	63	4.4 (1.2)
Berg Balance Scale (score out of 56)	70	38.7 (14.4)
Montreal Cognitive Assessment (score out of 30)	19	20.6 (6.4)

lean-and-release trials (98.5% of all trials) in individuals admitted to in-patient stroke rehabilitation [19]. All trials were videotaped for further off-line analysis.

Up to five trials were performed without any constraints on stepping responses (usual-response trials; single-task condition). One trial was then performed under a dual-task condition, to increase the cognitive load. The order of the trials was consistent across all participants. While obtaining the target load on the release cable and while waiting for the cable release, participants were asked to perform a cognitive task simultaneously. Depending on the level of stroke-related cognitive-communicative impairment and the presence of language barriers, the dual task consisted of counting backwards by intervals of seven or three, or a naming task (i.e., listing names beginning with a specific letter). The wide range of abilities and impairments of individuals entering into the rehabilitation program necessitated the use of multiple dual tasks to tailor the difficulty and nature of the task to each individual; a very simple task would not have provided a sufficient challenge to those with high cognitive functioning, while a more difficult task would have prevented those with low cognitive functioning and/or language barriers from participating. Accuracy on the dual task was not recorded. Individuals were not instructed to continue counting throughout the perturbation and reactive response in order to prioritize the balance task over the cognitive task (as the balance task was the main focus of the assessment), and to address the ability to switch attention from one task to the other. However, it was ensured that individuals did continue the dual task until the cable was released; if the dual task was stopped prior to the cable release, the test was terminated and repeated.

2.3. Data processing and analysis

For each of the usual-response trials, the average cable load (%BW) over the 1 s prior to release was determined. The procedures outlined in Fig. 1 were then used to identify participants for inclusion in the analysis. For inclusion, the cable load for participants' first usual response trial had to be >5%BW; and at least one of the remaining usual-response trials (trials 2–5) as well as the dual-task trial had to have a cable load >5%BW, and within ±2% of the first usual-response trial. This ensured that cable loads were similar within the usual-response trials, and between the usual-response and dual-task trials.

Outcome measures for each included trial were then determined from the force plate data. Signals were low-pass filtered at 10 Hz with a dual-pass, fourth-order Butterworth filter [25, 29]. The following outcome measures were then determined from the filtered force data [24] (Fig. 2): time of unloading onset of the stepping limb (time of the peak vertical force under the stepping limb, prior to foot-off; expressed relative to perturbation onset); time to foot-off of the first step (time when one of the force plates measured a vertical force <1%BW; expressed relative
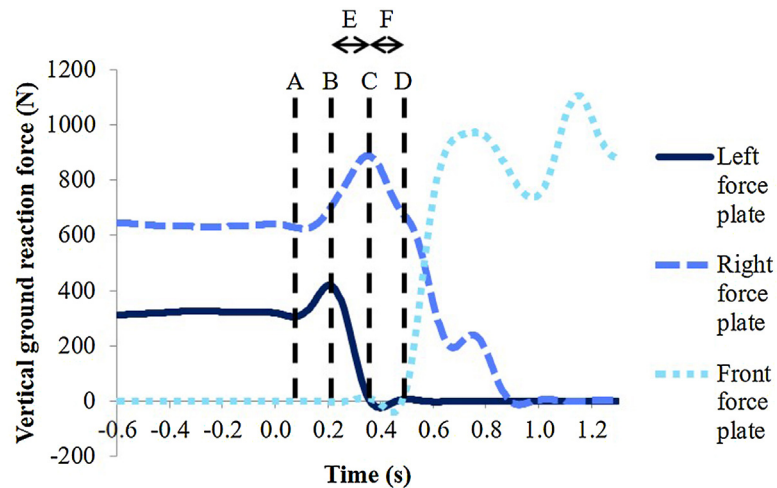
Fig. 2. Time series of typical vertical ground reaction forces during a lean-and-release trial, with perturbation onset occurring at 0.0 s. Participants began the trial by standing on the adjacent left and right force plates, and generally stepped forward onto the third force plate positioned in front of the other two plates. A: perturbation onset; B: time of unloading onset of the stepping limb; C: time of foot-off of the first step; D: time of foot contact of the first step; E: time to unload the stepping limb; F: swing time.

to perturbation onset); time to unload the stepping limb (time to foot-off of the first step − unloading onset); time to foot contact of the first step (time when the front force plate measured a vertical force of >1%BW; expressed relative to perturbation onset); and swing time of the first step (time of foot contact of the first step − time of foot-off of the first step). In addition, the number of steps taken in response to each perturbation was determined from the video recordings. Dependent variables in the analysis were: unloading onset, time to unload, swing time, and number of steps, while the independent variable was the type of trial. Repeated-measures analyses of variance (ANOVA) with two levels for the type of trial (usual-response compared to dual-task) were used for the initial purpose; repeated-measures ANOVAs for the secondary purpose consisted of three levels for the type of trial (usual-response trial 1, usual-response trials 2–5, and the dual-task trial). For the usual-response trials, the mean of each outcome measure was determined for all trials that met the criteria for inclusion stated above. Post-hoc comparisons were performed using pairwise comparisons with a Bonferroni correction. In addition, a preliminary analysis of relationships between cognitive impairment and the cost of the dual-task condition was conducted. For the 19 individuals for whom MoCA scores were available, dual-task cost was calculated relative to usual-response trial 1 and to usual-response trials 2–5, using Eq. 1 [30]. Spearman correlations were used to investigate relationships between MoCA scores and the dual-task costs. Alpha was initially set at 0.05 and adjusted using the Holm-Bonferroni method [31].

$$\frac{(usual\ response\ measure - dual\ task\ measure)}{usual\ response\ measure} * 100 \qquad (1)$$

3. Results

There were no significant differences in cable load between the usual-response and dual-task trials ($p = 0.37$), nor were there differences in any of the outcome measures ($p > 0.15$; Table 2). Therefore, the remainder of the paper will refer to the secondary analyses (usual-response trial 1, usual-response trials 2–5, and the dual-task trial). Perturbation magnitudes did not differ significantly between the three trial types (mean (standard deviation) of 8.7%BW (2.2), 8.8%BW (2.2), and 8.6%BW (2.3) for usual-response trial 1, usual-response trials 2–5, and the dual-task trial, respectively; $F_{2,138} = 0.44$, $p = 0.65$). Significant differences between conditions were identified for the time of unloading onset ($F_{2,134} = 7.68$, $p = 0.001$) and the number of steps taken after the perturbation ($F_{2,132} = 5.99$, $p = 0.003$), but not for the time to unload the stepping limb ($F_{2,134} = 0.81$, $p = 0.45$) or swing time ($F_{2,110} = 2.98$, $p = 0.055$; Fig. 3, Table 3). For both the time of unloading onset and the number of steps, post-hoc testing revealed significant differences between usual-response trial 1 and usual-response trials 2–5, such that longer times of unloading onset and greater numbers of steps were observed for usual-response trial 1. No significant differences were identified between either type of usual-response condition and the dual-task condition. There was a negative correlation between dual-task cost (relative to usual-response trial 1) for time to unload and MoCA scores; however, this correlation was not statistically significant ($p = 0.030$; Fig. 4, Fig. 5).

4. Discussion

It was hypothesized that participants would exhibit delayed time of unloading onset and time to unloading; decreased swing time; and an increase in the number of

Table 2. Number of participants and mean (standard deviation) for each outcome measure for all usual-response trials compared to the dual-task trials. None of the comparisons were significant (corrected alpha = 0.013).

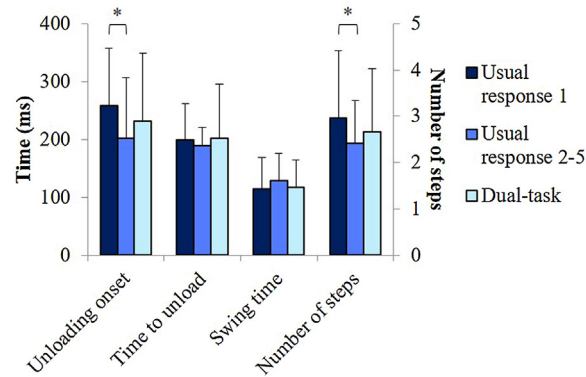| Outcome measure	N	All usual-response trials	Dual-task trials
Unloading onset (ms)	68	219.78 (91.55)	231.60 (117.97)
Time to unload (ms)	68	191.91 (34.14)	202.06 (93.04)
Swing time (ms)	62	120.34 (43.38)	113.84 (47.40)
Number of steps	68	2.6 (0.9)	2.7 (1.4)

Fig. 3. Mean (SD) outcome measures, compared between usual response trial 1, usual response trials 2–5 (average of eligible trials), and the dual-task trial. The time of unloading onset, time to unloading, and swing time are read off the left-hand axis, and the number of steps is read off the right-hand axis. *Significant after Holm-Bonferroni correction; corrected alpha = 0.013.

reactive steps in the dual-task condition compared to the first and subsequent usual-response trials. Significant delays in the time of unloading onset, and increases in the number of steps, were observed in the first usual-response trial compared to the subsequent usual-response trials. However, no significant changes in response were identified between the dual-task trial and either the first or subsequent usual-response trials.

The improvements in timing responses with the later usual-response trials (2–5) compared to the first usual-response trial arose primarily from the period between the time of the perturbation to the beginning of the response (onset of unloading). The delayed response during the first usual-response trial implies that the centre of mass moved further towards or outside the base of support before the response was initiated following cable release, compared to the later usual-response trials. This delay may also have potentially contributed to the increased number of steps. During a reactive stepping response, there is a range of foot placements that enable the base of support to encompass the centre of mass following the step [32]. If the

Table 3. Number of participants and mean (standard deviation) for each outcome measure for usual-response trial 1, usual-response trials 2–5, and the dual-task trials. *Significant after Holm-Bonferroni correction; corrected alpha = 0.013.

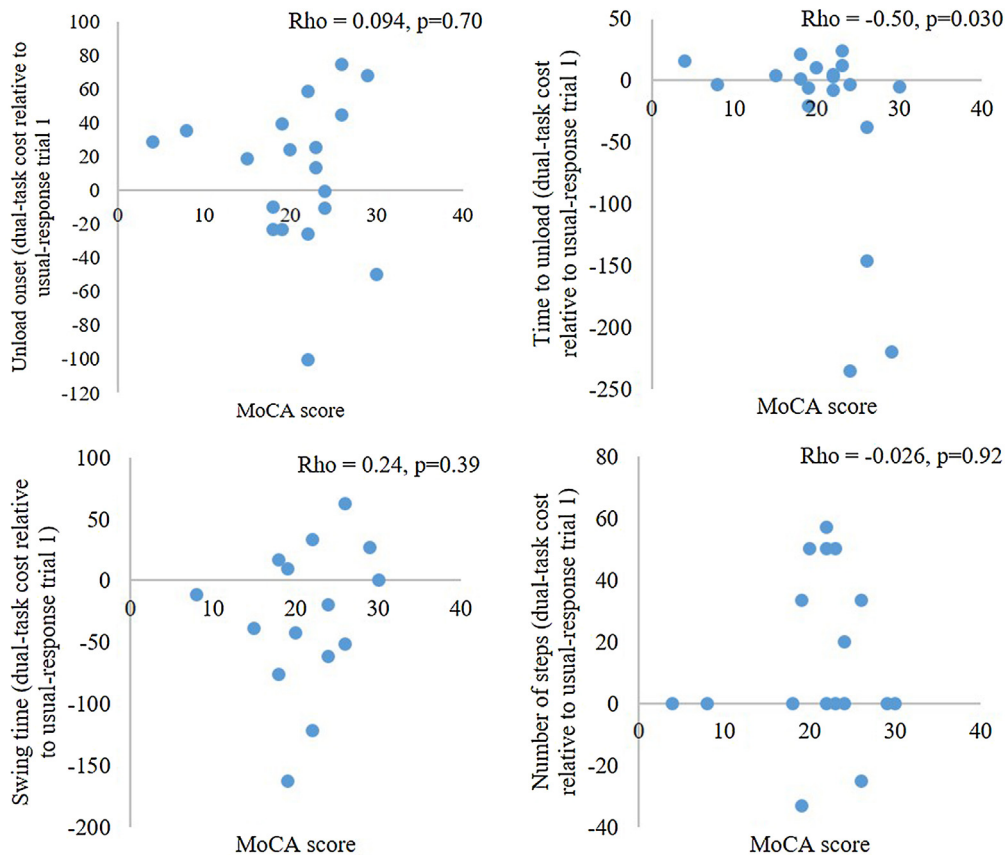| Outcome measure	N	Usual-response trial 1	Usual-response trials 2-5	Dual-task trials
Unloading onset (ms)*	68	258.41 (99.15)	201.63 (105.60)	231.60 (117.97)
Time to unload (ms)	68	199.21 (62.55)	189.40 (31.73)	202.06 (93.04)
Swing time (ms)	56	113.91 (54.61)	128.60 (46.85)	117.11 (46.92)
Number of steps (ms)*	57	3.0 (1.4)	2.4 (0.9)	2.7 (1.4)

Fig. 4. Spearman coefficients and *p*-values for Montreal Cognitive Assessment (MoCA) scores and dual-task costs for each of the outcome measures, relative to usual-response trial 1. The Holm-Bonferroni corrected alpha was 0.0063.

individual's response is delayed, as in the first usual-response trial, it would be more difficult for them to move their foot during the step in order to reach a sufficient foot placement to regain stability; thereby requiring additional steps in the first usual-response trial relative to the later usual-response trials. These findings are consistent with patterns identified by past work when comparing responses to support-surface perturbations in healthy young adults, in that the response to the first perturbation tended to elicit larger displacement of the centre of mass [33, 34], higher occurrence of stepping [35], and a greater number or length of steps before stability was regained [35]. Therefore, it may be beneficial to include the first trial of reactive stepping in analyses of reactive balance control, as responses to these trials may provide insight into pathophysiological mechanisms associated with accidental falls during everyday life [36].

While no significant differences were identified between the dual-task trial and either the first or subsequent usual-response trials, there were non-significant decrements in performance from usual-response trials 2–5 to the dual task trial.
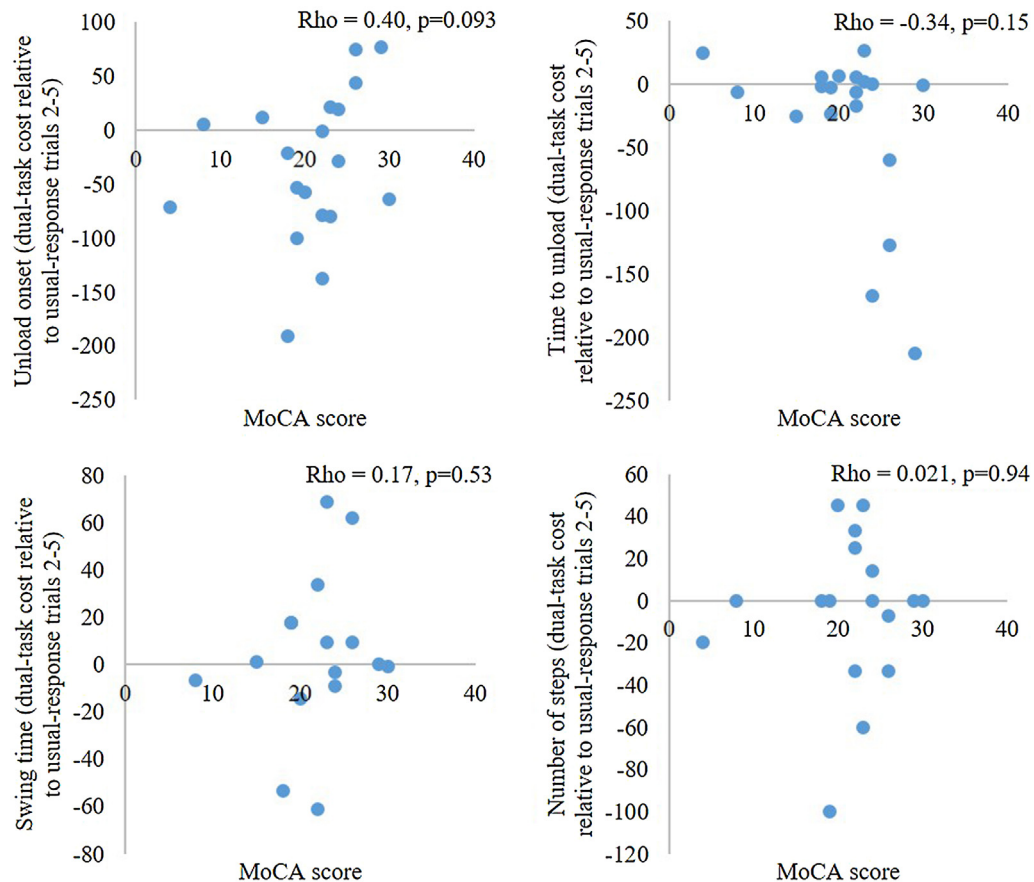
Fig. 5. Spearman coefficients and *p*-values for Montreal Cognitive Assessment (MoCA) scores and dual-task costs for each of the outcome measures, relative to usual-response trials 2–5. The Holm-Bonferroni corrected alpha was 0.0063.

Although non-significant, these trends were consistent with those identified in healthy young, healthy older, and balance-impaired older adults [16, 17, 18]. When examining the responses from the three types of trials, the general trends were for performance to improve from the first usual-response trial to the later usual-response trials, and then to worsen from the later usual-response trials to the dual-task trial (i.e. return to baseline levels, or the first usual-response trial, after the introduction of the dual-task condition). As the first usual-response trial was the first trial of one experimental condition, the findings suggest that when introduced after usual-response trials, the dual-task trial may represent the first trial of a new condition. This may be beneficial in reducing the potential for motor adaptation that may occur after repeated exposure to usual-response lean-and-release trials, which may confound results of clinical assessments performed over time [32]. Therefore, these findings may lend support for the introduction of a new condition (i.e. a dual-task trial) after usual-response trials (i.e., single-task) when assessing reactive balance control over repeated trials in individuals with stroke. This may

also have utility in developing treatment programs for individuals post-stroke; introducing a dual task to reactive stepping tasks may provide an additional challenge, such that individuals may continue to improve their performance as opposed to experiencing a plateau in performance. As dual task conditions are often experienced during daily life, training with this paradigm may also help to prepare individuals for a return to the community post-rehabilitation.

The lack of differences between the usual-response and dual-task conditions may have been due in part to heterogeneity within the participant sample with respect to their ability to successfully perform the dual-task condition, although this was addressed to an extent by tailoring the difficulty of the task to individuals' abilities and impairments during the assessment. Variation in cognitive capacity or functioning may have influenced individuals' ability to perform the dual-task condition. However, MoCA scores were not quantified for all individuals, potentially contributing to the lack of significant relationships identified between MOCA scores and any of the dual-task cost measures. For the 19 individuals for whom MoCA scores were collected, the average score was 20.6/30, which is below the cut-off for 'normal' cognitive functioning ($\geq$26/30) [23] and suggests some cognitive impairment in this sample. Therefore, the potential for categorizing individuals with stroke with respect to their performance during dual tasks, as well as their level of cognitive functioning or impairment, may represent a future direction for investigation that would have utility for informing care for this population. Furthermore, previous work has indicated that MoCA scores improve over time post-stroke [37], suggesting that cognitive impairment may resolve as individuals progress to the chronic stage of stroke; future work may also seek to identify changes in performance as MoCA scores improve post-stroke.

From a clinical perspective, a dual-task trial may also be beneficial as the addition of a cognitive task may increase the sensitivity of the test to identify either cognitive or balance impairments, and may potentially reveal altered postural control strategies that are not necessarily evident under a single-task condition [38]. As there are no existing clinical assessments of reactive balance control under dual-task conditions, these findings highlight the potential utility of adding the cognitive task to the reactive balance task. Furthermore, the dual-task paradigm provides an easy-to-implement test requiring no additional equipment or space, making it feasible for a clinical setting. Should the lean-and-release paradigm not be feasible due to equipment, budget, or space constraints, a potential alternative may be to incorporate a dual task into a simple reactive balance assessment such as the Mini-BESTest [39], which requires no specialized equipment (although the step timing measures of the current study would not necessarily be available, and analysis would be limited to behavioural responses). A dual-task test is ecologically relevant, as many activities in everyday life are characterized by multi-tasking between postural and cognitive tasks [38, 40]. The dual-task

condition may also have clinical implications with respect to falls risk. Delayed stepping responses following lean-and-release perturbations have been related to increased fall rates during in-patient stroke rehabilitation [24] and after discharge into the community [13]. As such, it is possible that the delays observed during the dual-task condition may also contribute to falls risk for individuals with stroke, both in rehabilitation and upon return to community living. Therefore, the ability to assess cognitive interference during postural tasks, and to subsequently design treatments that address these deficits, may have considerable value for post-stroke rehabilitation programs.

Cognitive tasks involved in dual-task paradigms may either be articulated or non-verbal. Although both types of cognitive tasks may be encountered in everyday life, the cognitive tasks performed by the participants in the present analysis were always articulated to ensure that participants were cognitively engaged in the task. In previous studies with samples of young healthy participants, dual-task effects on postural control (quiet standing) differed when the cognitive task was articulated or non-articulated [12, 41]. However, these studies focused on quiet standing, such as measures related to centre of pressure, as opposed to the gross stepping responses required during lean-and-release tasks. Additionally, the use of a secondary motor task (as opposed to cognitive), such as sequential finger tapping, may also demonstrate a greater dual-task effect. As such, it may be warranted to determine in future work whether the type of secondary task affects responses and outcome measures during reactive stepping tasks.

Participants were not instructed with regards to accuracy of the dual task; they were not instructed to continue performing the task once the perturbation was initiated; and the priority placed on the cognitive task by participants was not quantified. The lack of control of the cognitive task constitutes a limitation of the study, as greater emphasis on these characteristics may have highlighted differences between the usual-response and dual-task conditions. However, within the context of the clinical assessment, these measures would have been exceedingly difficult to obtain. Therefore, it may be important in future work to address whether greater changes in reactive stepping than in the present study are also observed with additional emphasis placed on accuracy, and/or while continuing to perform the cognitive task throughout the reactive response.

Several additional methodological limitations were present in the study. Two types of usual-response trials (trial 1, trials 2–5) were included to provide an indication of improvements in performance with multiple trials, and how the changes in performance during the dual-task trial related to usual-response trials at the first exposure and after several repetitions. However, outcome measures from the subsequent usual-response trials (trials 2–5) were determined as an average of those trials, as opposed to the first usual-response trial or the dual-task trial,

potentially resulting in more stable measures for usual response trials 2–5. Perturbation magnitudes were controlled as closely as possible during collection. However, some participants were unable to achieve or maintain the desired cable load, resulting in a large number of individuals being excluded due to insufficient or dissimilar cable loads across trials. Furthermore, individuals were tested in their own footwear, and shoe stiffness was not controlled, potentially affecting reactive stepping behaviours. Because the lean-and-release trials were collected as part of a routine assessment for a clinical stroke rehabilitation program, the order of the trials was kept consistent across all individuals, as opposed to counter-balancing the order of the conditions. However, this enabled an investigation of how performance changed across multiple trials of a novel task and subsequently with an increase in cognitive load, which may also be useful for the design of assessment and rehabilitation post-stroke.

5. Conclusion

No significant effects of the dual-task condition on reactive stepping responses were identified, although a longer time of unloading onset and greater number of steps were identified for the first usual-response trial compared to later trials. However, reactive stepping during the dual-task trial exhibited a trend to return to baseline performance (the first usual-response trial). As the first usual-response trial was the first trial of an experimental condition, the findings suggest that exposure to the dual-task trial represented the first trial of a new experimental condition, and would thus likely reduce the potential for motor adaptation resulting from multiple exposures to usual-response trials that may occur in an assessment setting. Therefore, these findings may lend support to the use of dual-task trials following multiple repetitions of usual-response or single-task trials when assessing reactive balance in individuals with stroke.

Declarations

Author contribution statement

Alison Schinkel-Ivy: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Andrew H. Huntley: Analyzed and interpreted the data; Wrote the paper.

Elizabeth L. Innessa: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Avril Mansfield: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

[1] L. Jørgensen, T. Engstad, B.K. Jacobson, Higher incidence of falls in long-term stroke survivors than in population controls: depressive symptoms predict falls after stroke, Stroke 33 (2002) 542–547.

[2] L. Nyberg, Y. Gustafson, Patient falls in stroke rehabilitation: A challenge to rehabilitation strategies, Stroke 26 (5) (1995) 838–842.

[3] S.G. Brauer, M. Woollacott, A. Shumway-Cook, The influence of a concurrent task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders, Gait Posture 15 (2002) 83–93.

[4] C.E. Little, M. Woollacott, Effect of attentional interference on balance recovery in older adults, Exp. Brain Res. 232 (2014) 2049–2060.

[5] B.E. Maki, W.E. McIlroy, Cognitive demands and corticol control of human balance-recovery reactions, J. Neural Transm. 114 (10) (2007) 1279–1296.

[6] C.E. Little, M. Woollacott, EEG measures reveal dual-task interference in postural performance in young adults, Exp. Brain Res. 233 (2015) 27–37.

[7] I. Melzer, I. Tzedek, M. Or, et al., Speed of voluntary stepping in chronic stroke survivors under single- and dual-task conditions: A case-control study, Arch. Phys. Med. Rehabil. 90 (2009) 927–933.

[8] S. Subramaniam, C.W.-Y. Hui-Chan, T. Bhatt, Effect of dual tasking on intentional vs. reactive balance control in people with hemiparetic stroke, J. Neurophysiol. 112 (2014) 1152–1158.

[9] D. Hyndman, A. Ashburn, L. Yardley, et al., Interference between balance, gait and cognitive task performance among people with stroke living in the community, Disabil. Rehabil. 28 (13-14) (2006) 849–856.

[10] D. Hyndman, R.M. Pickering, A. Ashburn, Reduced sway during dual task balance performance among people with stroke at 6 and 12 months after discharge from hospital, Neurorehabil. Neural Repair 23 (8) (2009) 847–854.

[11] M. de Haart, A.C. Geurts, S.C. Huidekoper, et al., Recovery of standing balance in postacute stroke patients: A rehabilitation cohort study, Arch. Phys. Med. Rehabil. 85 (6) (2004) 886–895.

[12] L. Yardley, M. Gardner, A. Leadbetter, et al., Effect of articulatory and mental tasks on postural control, Neuroreport 10 (1999) 215–219.

[13] A. Mansfield, J.S. Wong, W.E. McIlroy, et al., Do measures of reactive balance control predict falls in people with stroke returning to the community? Physiotherapy 101 (4) (2015) 373–380.

[14] W.E. McIlroy, B.E. Maki, Influence of destabilization on the temporal characteristics of 'volitional' stepping, J. Mot. Behav. 28 (1996) 28–34.

[15] W.H. Gage, K.F. Zabjek, S.W. Hill, et al., Parallels in control of voluntary and perturbation-evoked reach-to-grasp movements: EMG and kinematics, Exp. Brain Res. 181 (2007) 627–637.

[16] R.G. Norrie, B.E. Maki, W.R. Staines, et al., The time course of attention shifts following perturbation of upright stance, Exp. Brain Res. 146 (2002) 315–321.

[17] P.J. Patel, T. Bhatt, Attentional demands of perturbation evoked compensatory stepping responses: Examining cognitive-motor interference to large magnitude forward perturbations, J. Mot. Behav. 47 (3) (2015) 201–210.

[18] J.L. Zettel, W.E. McIlroy, B.E. Maki, Effect of competing attentional demands on perturbation-evoked stepping reactions and associated gaze behavior in young and older adults, J. Gerontol. 63A (12) (2008) 1370–1379.

[19] E.L. Inness, A. Mansfield, L. Biasin, et al., Clinical implementation of a reactive balance control assessment in a sub-acute stroke patient population using a 'lean-and-release' methodology, Gait Posture 41 (2015) 529–534.

[20] T. Brott, H.P. Adams, C.P. Olinger, et al., Measurements of acute cerebral infarction: a clinical examination, Stroke 20 (7) (1989) 864–870.

[21] C. Gowland, P. Stratford, M. Ward, et al., Measuring physical impairment and disability with the Chedoke-McMaster Stroke Assessment, Stroke 24 (1993) 58–63.

[22] K. Berg, S. Wood-Dauphinee, J.I. Williams, The balance scale: reliability assessment with elderly residents and patients with an acute stroke, Scand. J. Rehab. Med. 27 (1995) 27–36.

[23] Z.S. Nasreddine, N.A. Phillips, V. Bédirian, et al., The Montreal cognitive assessment (MoCA): a brief screening tool for mild cognitive impairment, J. Am. Geriatr. Soc. 53 (2005) 695–699.

[24] A. Mansfield, E.L. Inness, J.S. Wong, et al., Is impaired control of reactive stepping related to falls during inpatient stroke rehabilitation? Neurorehabil. Neural Repair 27 (6) (2013) 526–533.

[25] A. Schinkel-Ivy, E.L. Inness, A. Mansfield, Relationships between fear of falling, balance confidence, and control of balance, gait, and reactive stepping in individuals with sub-acute stroke, Gait Posture 43 (1) (2016) 154–159.

[26] A. Schinkel-Ivy, J.C. Singer, E.L. Inness, et al., Do quiet standing centre of pressure measures within specific frequencies differ based on ability to recover balance in individuals with stroke? Clin. Neurophysiol. 127 (2016) 2463–2471.

[27] E.L. Inness, A. Mansfield, B. Lakhani, et al., Impaired reactive stepping among patients ready for discharge from inpatient stroke rehabilitation, Phys. Ther. 94 (2014) 1755–1764.

[28] W.E. McIlroy, B.E. Maki, Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing, Clin. Biomech. 12 (1) (1997) 66–70.

[29] J. Hendrickson, K.K. Patterson, E.L. Inness, et al., Relationship between asymmetry of quiet standing balance control and walking post-stroke, Gait Posture 39 (1) (2014) 177–181.

[30] F. Hamilton, L. Rochester, L. Paul, et al., Walking and talking: An investigation of cognitive-motor dual tasking in multiple sclerosis, Mult. Scler. 15 (10) (2009) 1215–1227.

[31] S. Holm, A simple sequentially rejective multiple test procedure, Scand. J. Statist. 6 (1979) 65–70.

[32] B.E. Maki, W.E. McIlroy, The role of limb movements in maintaining upright stance: the change-in-support strategy, Phys. Ther. 77 (1997) 488–507.

[33] L.B.O. Nijhuis, J.H.J. Allum, G.F. Borm, et al., Directional sensitivity of first trial reactions in human balance control, J. Neurophysiol. 101 (2009) 2802–2814.

[34] K.-S. Tang, Movement patterns underlying first trial responses in human balance corrections, Neuroscience 225 (2012) 140–151.

[35] W.E. McIlroy, B.E. Maki, Adaptive changes to compensatory stepping responses, Gait Posture 3 (1995) 43–50.

[36] J.H.J. Allum, K.-S. Tang, M.G. Carpenter, et al., Review of first trial responses in balance control: Influence of vestibular loss and Parkinson's disease, Hum. Mov. Sci. 30 (2011) 279–295.

[37] L. Sivakumar, M. Kate, T. Jeerakathil, et al., Serial Montreal Cognitive Assessments demonstrate reversible cognitive impairment in patients with acute transient ischemic attack and minor stroke, Stroke 45 (2014) 1709–1715.

[38] L. Bensoussan, J.M. Viton, M. Schieppati, et al., Changes in postural control in hemiplegic patients after stroke performing a dual task, Arch. Phys. Med. Rehabil. 88 (8) (2007) 1009–1015.

[39] F. Franchignoni, F. Horak, M. Godi, et al., Using psychometric techniques to improve the Balance Evaluation Systems Test: The Mini-BESTest, J. Rehabil. Med. 42 (2010) 323–331.

[40] F. Mersmann, S. Bohm, S. Bierbaum, et al., Young and old adults prioritize dynamic stability control following gait perturbations when performing a concurrent cognitive task, Gait Posture 37 (2013) 373–377.

[41] M.C. Dault, L. Yardley, J.S. Frank, Does articulation contribute to modifications of postural control during dual-task paradigms? Cogn. Brain Res. 16 (2003) 434–440.