Title: Characterization of reactions to laterally-directed perturbations in individuals with chronic stroke

Authors: Alison Schinkel-Ivy, PhD¹, Anthony Aqui, MSc², Cynthia J. Danells, MSc²⁻³, Avril Mansfield, PhD²⁻⁴

Affiliations: ¹School of Physical & Health Education, Nipissing University, 100 College Drive, Box 5002, North Bay, Ontario, Canada P1B 8L7; ²Toronto Rehabilitation Institute–University Health Network, 550 University Ave, Toronto, Ontario, Canada M5G 2A2; ³Department of Physical Therapy, University of Toronto, 500 University Ave, Toronto, Ontario, Canada M5G 1V7; ⁴Evaluative Clinical Sciences, Hurvitz Brain Sciences Research Program, Sunnybrook Research Institute, 2075 Bayview Ave, Toronto, Ontario, Canada M4N 3M5

Corresponding author: Dr. Alison Schinkel-Ivy, Room 201-C, Robert J. Surtees Athletic Centre School of Physical & Health Education, Nipissing University, 100 College Drive, Box 5002, North Bay, Ontario, Canada P1B 8L7; Email: alisons@nipissingu.ca; Phone: 1-705-474-3450 x4561

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Abstract

Background: Reactive balance control is often impaired post-stroke. Studies addressing responses to laterally-directed perturbations in this population are currently lacking; given that stroke-related motor impairments are unilateral, a better understanding of reactive balance responses to these types of perturbations is critical.

Objective: This study aimed to quantify differences in reactive balance control in response to laterally-directed perturbations in individuals with chronic stroke, based on perturbation direction and ability to step with either limb.

Design: Cross-sectional study.

Methods: Individuals with chronic stroke (N=19) were divided into groups representing their ability to step with either limb, based on performance on a reactive balance task in a baseline assessment. The preferred stepping limb was also identified during this assessment. Each participant then underwent a series of laterally-directed perturbations on a motion platform. Behavioural measures were compared between platform direction and group.

Results: Trials with extra steps, step initiation with the preferred limb, and crossover steps were more common with platform motion towards the preferred limb compared to the non-preferred limb; the latter effect was only observed for individuals with an impaired ability to step with either limb. Side-step sequences were more common in those able to step with either limb when the platform moved towards the preferred limb.

Limitations: The participant sample was likely higher functioning than the general population of stroke survivors due to equipment constraints. Additionally, participants may have developed strategies to use the platform’s motion characteristics to aid with balance recovery.

Conclusions: These findings provide an indication of responses to laterally-directed perturbations in individuals with chronic stroke, and may help to inform strategies for improving reactive balance control during stroke rehabilitation.
Introduction

Falls are one of the most common medical complications post-stroke.\textsuperscript{1–3} The ability to execute stepping reactions following a postural perturbation is crucial to prevent falls.\textsuperscript{4–6} Reactive stepping may be particularly challenging post-stroke, given the impaired limb control and/or dyscoordination often experienced by individuals with stroke. For example, individuals with stroke often prefer to initiate reactive stepping exclusively with one limb,\textsuperscript{7} and may be unable to initiate stepping with the non-preferred limb.\textsuperscript{7–9} These impairments in reactive balance control are related to increased falls in individuals with stroke during inpatient rehabilitation\textsuperscript{10} and following discharge from hospital.\textsuperscript{11} While it is becoming more common to assess reactive balance control in clinical practice within this population,\textsuperscript{7,12} emphasis has generally been placed on antero-posterior (AP) perturbations.\textsuperscript{12,13} Investigation of responses to laterally-directed postural perturbations post-stroke are comparatively limited,\textsuperscript{14} despite evidence that balance impairments due to age or pathology are often more marked in this direction.\textsuperscript{15,16}

Responses to lateral perturbations in healthy older adults are generally characterized by high frequencies of multiple steps and extra limb reactions (steps or arm movements), as well as foot collisions.\textsuperscript{7,18} With respect to stepping patterns, the most common stepping patterns to increase the base of support in response to laterally-directed perturbations in older adults are: 1) crossover steps, involving placing the limb unloaded by the perturbation (ipsilateral to the direction of platform motion) lateral to the loaded limb; 2) side-step sequences, consisting of a medial step with the unloaded limb followed by a lateral step with the loaded limb; and 3) loaded-leg steps, involving a lateral step with the loaded limb in the direction opposite to the platform motion (Figure 1).\textsuperscript{17,19} A shift in weight-bearing is required for a loaded-leg step and this must occur very quickly to provide the individual with enough time to execute reactive step(s).\textsuperscript{17} Compared to crossover steps, side-step sequences involve a reduced amount of time spent in single support,\textsuperscript{17} and smaller, more rapid steps which may provide more opportunities for corrective adjustments.\textsuperscript{20} Limb collisions are also less frequent with side-step sequences than crossover steps.\textsuperscript{21} Furthermore, in a study of very large postural perturbations, intended to cause a fall to the floor in healthy young adults, the only participants who did not fall executed a side-step sequence,\textsuperscript{22} suggesting that side-step sequences may represent the most effective stepping pattern in response to lateral perturbations among unimpaired individuals. Previous work with individuals with Parkinson’s disease has indicated that side-step sequences may also be effective for this population.\textsuperscript{23} However, in individuals with stroke, the use of this stepping pattern post-stroke may be complicated by the need for effective control of both limbs.

While these studies have provided insight into responses to laterally-directed perturbations in healthy older adults, there is a lack of understanding of responses to these types of perturbations in individuals with stroke. Lateral perturbations impose the additional challenge of avoiding a collision between the swing and stance limbs (particularly for crossover step strategies),\textsuperscript{17} the potential to force use of the more impaired limb in compensatory stepping, and the challenge of compensating for pre-perturbation weight-bearing asymmetry, which affects responses to laterally-directed perturbations.\textsuperscript{14} As such, insight into common characteristics of stepping behaviours in individuals with stroke is needed, to develop improved assessments and rehabilitation programs to target specific deficits in reactive stepping in response to laterally-directed perturbations. De Kam et al.\textsuperscript{14,24} observed that loaded-leg steps were commonly used by individuals with stroke, especially when platform motion was directed towards the non-paretic side. However, the purpose of this previous work was not to characterize reactive stepping strategies post-stroke, and the high prevalence of loaded-leg steps may have been due to the specific protocol employed. Therefore, further work is warranted to investigate stepping characteristics in individuals with stroke.

This study aimed to characterize stepping reactions following laterally-directed perturbations in individuals with chronic stroke, based on perturbation direction and ability to step with either limb. We
hypothesized that crossover and side-step patterns would be more common when platform motion was directed towards the preferred stepping limb, while loaded-leg steps would be prevalent with platform motion towards the non-preferred limb. Furthermore, we hypothesized that individuals able to step with either limb would use more side-step sequences, while crossover steps and loaded-leg steps would be observed more often in those with an impaired ability to step with either limb. We also hypothesized that greater frequencies of trials with extra steps, greater frequency of trials with foot collisions, and greater numbers of extra steps would be observed with platform motion towards the non-preferred limb and in individuals with an impaired ability to step with either limb. Finally, we hypothesized that individuals with an impaired ability to step with either limb would generally step with the preferred limb regardless of platform direction, while those able to step with either limb would differ based on platform direction.

![Figure 1: Schematic of the three primary stepping patterns that increase the base of support in response to laterally-directed perturbations (modified from Maki et al.17). Each diagram represents a perturbation in which the platform shifted to the left underneath the participant. The black footprints represent the limb unloaded by the perturbation; the white footprints represent the limb loaded by the perturbation.](image)

### Methods
**Participants**

Data for the present study were collected as part of a sub-study within a larger multi-site randomized controlled trial (RCT) examining the effect of perturbation-based balance training in individuals with stroke (Clinical Trials registration number: ISRCTN05434601).25 Nineteen community-dwelling individuals (>6 months post-stroke) participated in the sub-study. This sample size is similar to those of other studies examining balance reactions to laterally-directed perturbations in healthy older adults,17,20,21,26 individuals with Parkinson’s disease,23 and individuals with stroke.14
For RCT inclusion, participants had to be able to stand independently for at least 30 s without external support and tolerate a minimum of 10 postural perturbations with a lean-and-release system. Exclusion criteria for the RCT consisted of: height and weight (>2.1 m and/or >150 kg, the limits of the safety harness system); neurological conditions other than stroke that could potentially affect balance control; amputation of the lower extremity; cognitive, language, or communication impairments leading to difficulties with understanding instructions; significant illness, injury, or surgery within the prior 6 months; severe osteoporosis (diagnosis of osteoporosis, plus fracture); diabetes or hypertension that was poorly controlled; contraindications to physical activity, based on the Physical Activity Readiness Questionnaire; current physiotherapy focused on balance and mobility; and/or participation in perturbation training during formal rehabilitation within the prior 12 months. To participate in the sub-study, participants must have undergone a baseline assessment (see Assessments), and been able to ambulate independently for 10 m. All procedures were approved by the institution’s Research Ethics Board. Written informed consent was obtained from all participants prior to data collection.

Assessments
Baseline assessment
Demographic data were collected via self-report, and included age, sex, date of stroke, and affected side of the body. Stroke severity, motor impairment, and functional balance were assessed using the National Institutes of Health Stroke Scale (NIHSS), the Chedoke-McMaster Stroke Assessment (CMSA; affected leg and foot), and the Berg Balance Scale (BBS), respectively. These descriptors were used to characterize the study sample (Table 1).

Table 1: Demographic and stroke-related descriptors of the participant groups. Continuous descriptors are presented as mean (standard deviation), while nominal descriptors are presented as number (% of group). EU: encouraged-use.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>EU-impaired group (impaired ability to step with both limbs (n=8))</th>
<th>EU-capable group (ability to step with both limbs (n=11))</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>64.1 (10.4)</td>
<td>62.8 (9.1)</td>
<td>0.74</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6 (75.0%)</td>
<td>7 (63.6%)</td>
<td>0.60</td>
</tr>
<tr>
<td>Female</td>
<td>2 (25.0%)</td>
<td>4 (36.4%)</td>
<td></td>
</tr>
<tr>
<td>Time post-stroke (years)</td>
<td>3.5 (3.0)</td>
<td>4.7 (4.4)</td>
<td>0.49</td>
</tr>
<tr>
<td>Affected side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>4 (50.0%)</td>
<td>5 (45.5%)</td>
<td>0.85</td>
</tr>
<tr>
<td>Right</td>
<td>4 (50.0%)</td>
<td>6 (54.5%)</td>
<td></td>
</tr>
<tr>
<td>Agreement between affected and preferred side?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>4 (50.0%)</td>
<td>4 (36.4%)</td>
<td>0.55</td>
</tr>
<tr>
<td>No</td>
<td>4 (50.0%)</td>
<td>7 (63.6%)</td>
<td></td>
</tr>
<tr>
<td>National Institutes of Health Stroke Scale score</td>
<td>5.1 (3.9)</td>
<td>2.7 (2.1)</td>
<td>0.09</td>
</tr>
<tr>
<td>Chedoke-McMaster Stroke Assessment leg score</td>
<td>5.3 (1.2)</td>
<td>6.0 (1.0)</td>
<td>0.24</td>
</tr>
<tr>
<td>Chedoke-McMaster Stroke Assessment foot score</td>
<td>4.6 (1.4)</td>
<td>5.4 (1.3)</td>
<td>0.40</td>
</tr>
<tr>
<td>Berg Balance Scale score</td>
<td>51.4 (7.6)</td>
<td>54.0 (2.6)</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Assessment of reactive balance control using a lean-and-release paradigm was also included in this session. Participants were outfitted with a safety harness attached by a cable to an overhead track.
second cable connected the back of the harness to a support beam mounted on the wall behind the participant. The participant stood in front of the support beam with the feet in a standardized position,\textsuperscript{31} and leaned forward so the cable supported approximately 10\% of body weight (measured by a load cell in series with the cable). This load level is sufficient to evoke at least one step following the perturbation.\textsuperscript{12} Once the target load level was achieved, the cable was released at an unpredictable time by an investigator. Following cable release, participants executed balance reactions to arrest their forward motion.

Five trials were performed in which no instructions were given regarding the limb to be used to initiate stepping (‘usual-response’). The limb used to initiate stepping on each trial was recorded. The preferred limb was designated as the limb used to initiate stepping on 3+ trials. Five trials were then performed in which the preferred limb was physically blocked by an investigator using his/her foot, to encourage step initiation with the non-preferred limb (‘encouraged-use’; EU).\textsuperscript{7,11,32} Participants were classified into two groups based on EU performance.\textsuperscript{32} Participants that appropriately stepped with the non-preferred limb on all EU trials\textsuperscript{32} were classified into a ‘EU-capable’ group, indicating an ability to step with either limb. Participants requiring external assistance, an attempted step with the preferred limb, or a slide step with the non-preferred limb on at least one EU trial\textsuperscript{32} were classified into a ‘EU-impaired’ group, indicating an impaired ability to step with either limb.

\textbf{Reactive balance control assessment}

In a separate session that occurred between 1 and 11 days after the baseline assessment, participants underwent a detailed reactive balance control assessment with a motorized moving platform (Figure 2). The 6 m-by-3 m platform consisted of an X-Y mechanism with two rail assemblies per axis and one servo-motor, bearing wheels, and toothed timing belt for each rail, allowing it to be controlled to move suddenly in any direction in the transverse plane. Four 1.5 m-by-1.5 m force plates (Advanced Mechanical Technology, Inc., Watertown, Massachusetts) were embedded in the platform to measure ground reaction forces. Platform motion was controlled by a custom Matlab-Simulink program (The Mathworks, Inc., Natick, USA). Participants wore a safety harness attached to a gantry on an overhead track during all trials to prevent a fall to the floor in case of an inability to recover balance. The assessment involved three 30 s quiet standing trials with the feet in a standardized position,\textsuperscript{31} followed by four perturbations in the anterior, posterior, left, and right directions, presented in an unpredictable order. Only the laterally-directed perturbation trials were included in the present analysis. The platform motion profile was 300 ms acceleration and 300 ms deceleration.\textsuperscript{17} Four additional ‘catch’ trials (one per direction) with a different motion profile (200 ms acceleration, 400 ms constant velocity, 200 ms deceleration) were interspersed within the experimental trials, to minimize adaptation to the standard motion profile.\textsuperscript{17} Rest breaks were provided when requested.

The waveform used for the first trial in each lateral direction had an acceleration of 2.0 m/s\textsuperscript{2} (peak velocity: 0.6 m/s, total displacement: 0.18 m).\textsuperscript{33,34} Based on procedures developed prior to data collection, we observed participant responses to these initial perturbations, and adjusted the perturbation magnitude for the remaining trials if necessary. If the perturbations did not consistently evoke stepping, we used a waveform with peak acceleration of 3.0 m/s\textsuperscript{2} (peak velocity: 0.9 m/s, total displacement: 0.27 m); or if the perturbation was too challenging with a concern for participant safety, we used a waveform with peak acceleration of 1.0 m/s\textsuperscript{2} (peak velocity: 0.3 m/s, total displacement: 0.09 m).

Perturbation trials began with participants placing their feet in a standardized position, with each foot on a different force plate.\textsuperscript{31} Once participants indicated that they were ready, the platform motion program was initiated by an investigator after a random interval, with the platform moving 5 s later. Participants were instructed to do whatever they needed to regain balance. All trials were video-recorded and analyzed offline.
**Data processing**

Vertical ground reaction forces from the quiet standing and perturbation trials were low-pass filtered with a dual-pass Butterworth filter (cutoff frequency: 10 Hz). Due to the effect of pre-perturbation weight bearing asymmetry on stepping responses, the mean percent of body weight (%BW) on each limb during each quiet standing trial, and during the 100 ms prior to platform motion for the perturbation trials, were determined. The mean loading and mean standard deviation and range of loading on the preferred limb were determined for the quiet standing trials and perturbation trials in each direction.

![Image](image.png)

**Figure 2:** The moving platform, with a participant standing in the starting position prior to a perturbation.

From the video data, frequencies of stepping patterns used for the initial stepping reaction (crossover steps, side-step sequences, loaded-leg steps, other stepping patterns) were identified for each platform direction within each participant. The frequency of trials with extra steps subsequent to the initial stepping reaction was also determined. Extra steps were any steps additional to that required for the selected stepping pattern; side-step sequences required two steps, while all other patterns required one step. The average number of extra steps, frequency of foot collisions, and limb used to initiate stepping for each trial (preferred or non-preferred; more %BW or less %BW, determined from the weight-bearing asymmetry analysis) were also determined for each trial.

**Data analysis**

Continuous demographic and stroke-related descriptors were compared between the EU-capable and EU-impaired groups using independent T-tests (age, time post-stroke), Chi-square tests (sex, affected side, agreement between affected and preferred side), and Mann-Whitney U tests (NIHSS, CMSA, BBS). The mean %BW on the preferred limb, and the standard deviation and range of %BW, were compared between quiet standing and pre-perturbation quiet standing using one-way analyses of variance, with Bonferroni corrections for post-hoc testing.
The frequency of trials with extra steps, frequency of foot collisions, frequency of step initiation with the preferred limb, and the average number of extra steps were compared between platform direction (preferred/non-preferred) and group (EU-capable/EU-impaired) using two-way mixed analyses of variance. Bonferroni corrections were used for post-hoc testing. The frequencies of stepping patterns were compared between platform directions within groups (Wilcoxon signed-rank tests), and between groups within platform directions (Mann-Whitney U tests). The likelihood of stepping with the limb with the higher %BW, based on the platform direction, group, and the amount of body weight borne on the preferred limb, was determined using multiple logistic regression with generalized estimating equations and repeated measures. An autoregressive correlation structure was assumed to account for order effects. For all analyses, alpha was 0.05.

**Results**

There were no differences in demographic or stroke-related characteristics between groups (Table 1). All but two participants experienced the 2.0 m/s² magnitude perturbations during the reactive balance control assessment; one participant each required the 1.0 m/s² and 3.0 m/s² magnitude perturbations. The standard deviation and range of loading on the preferred limb differed significantly between quiet standing and the perturbation trials, with higher standard deviations and ranges during the perturbation trials; the mean load did not differ significantly between quiet standing and the perturbation trials (Table 2).

**Table 2:** Comparison of participants’ mean, standard deviation, and range of load on the preferred limb (measured in % body weight (BW)) between quiet standing trials, trials with platform motion to the preferred side, and trials with platform motion to the non-preferred side. Values presented are means (standard deviations). Reported p-values are from analyses of variance comparing the mean, standard deviation, and range of load between quiet standing and the two platform directions. *Significantly different from quiet standing following Bonferroni correction.

<table>
<thead>
<tr>
<th></th>
<th>Quiet standing</th>
<th>Platform motion to preferred side</th>
<th>Platform motion to non-preferred side</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load on the preferred limb (%BW)</td>
<td>49.4 (5.4)</td>
<td>47.9 (5.1)</td>
<td>47.7 (5.6)</td>
<td>0.089</td>
</tr>
<tr>
<td>Standard deviation of load on the preferred limb (%BW)</td>
<td>1.8 (1.1)</td>
<td>3.5 (1.4)*</td>
<td>3.0 (2.0)</td>
<td>0.002</td>
</tr>
<tr>
<td>Range of load on the preferred limb (%BW)</td>
<td>3.2 (2.1)</td>
<td>7.8 (3.1)*</td>
<td>6.8 (4.7)*</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

A total of 151 perturbation trials were analyzed for this study (one participant only performed three trials in the non-preferred direction). Crossover steps were observed for 53/151 trials (35%); side-step sequences for 42/151 trials (28%); and loaded-leg steps for 15/151 trials (10%). Other stepping patterns were observed in 41/151 trials (27%) and consisted of aborted crossovers, in which the initial limb trajectory suggested a crossover but the final placement was either directly in forward or backward of the starting position (11/41); counter-displacement steps, with a small lateral step using the limb unloaded by the perturbation (24/41); foot lifts and/or steps in which the strategy was unclear (5/41); and a single medial step (1/41). When pre-perturbation %BW on the preferred limb was controlled for, neither platform direction nor group significantly predicted the likelihood of stepping with the more-loaded limb (p=0.13 and p=0.66, respectively).
Table 3: Mean (standard deviation) frequencies for outcome measures analyzed using mixed analyses of variance (ANOVA), along with the results of each effect examined in the ANOVA.

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>EU-impaired group; motion towards preferred limb</th>
<th>EU-impaired group; motion towards non-preferred limb</th>
<th>EU-capable group; motion towards preferred limb</th>
<th>EU-capable group; motion towards non-preferred limb</th>
<th>Main effect of direction</th>
<th>Main effect of group</th>
<th>Interaction of direction and group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of trials with extra steps</td>
<td>75.0 (29.9)</td>
<td>34.4 (44.2)</td>
<td>47.7 (39.5)</td>
<td>31.8 (27.6)</td>
<td>F(1,17)=16.4, p=0.001*</td>
<td>F(1,17)=0.99, p=0.33</td>
<td>F(1,17)=3.15, p=0.094</td>
</tr>
<tr>
<td>Average number of extra steps</td>
<td>1.3 (0.7)</td>
<td>0.8 (1.1)</td>
<td>0.5 (0.4)</td>
<td>0.6 (0.7)</td>
<td>F(1,17)=0.99, p=0.33</td>
<td>F(1,17)=3.22, p=0.091</td>
<td>F(1,17)=1.77, p=0.20</td>
</tr>
<tr>
<td>Frequency of trials initiated with the preferred limb</td>
<td>90.6 (18.6)</td>
<td>15.6 (35.2)</td>
<td>90.9 (23.1)</td>
<td>15.9 (35.8)</td>
<td>F(1,17)=50.6, p&lt;0.001*</td>
<td>F(1,17)=0.00, p=0.97</td>
<td>F(1,17)=0.00, p&lt;0.99</td>
</tr>
<tr>
<td>Frequency of trials with foot collisions</td>
<td>12.5 (26.7)</td>
<td>0 (0)</td>
<td>22.7 (32.5)</td>
<td>18.2 (35.5)</td>
<td>F(1,17)=0.74, p=0.40</td>
<td>F(1,17)=2.51, p=0.13</td>
<td>F(1,17)=0.16, p=0.69</td>
</tr>
</tbody>
</table>

Table 4: Mean (standard deviation) frequencies for outcome measures analyzed using Wilcoxon signed-rank tests (to compare measures between platform directions within groups) and Mann-Whitney U tests (to compare measures between groups within platform directions).

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>EU-impaired group; motion towards preferred limb</th>
<th>EU-impaired group; motion towards non-preferred limb</th>
<th>EU-capable group; motion towards preferred limb</th>
<th>EU-capable group; motion towards non-preferred limb</th>
<th>Main effect of direction</th>
<th>Main effect of group</th>
<th>Within motion towards the preferred limb</th>
<th>Within motion towards the non-preferred limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of crossover steps</td>
<td>59.4 (40.0)</td>
<td>15.6 (29.7)</td>
<td>43.2 (38.9)</td>
<td>22.7 (32.5)</td>
<td>T=0.00, Z=-2.23, p=0.026*</td>
<td>U=33.50, Z=-0.906, p=0.37</td>
<td>U=39.00, Z=-0.503, p=0.62</td>
<td></td>
</tr>
<tr>
<td>Frequency of side-step sequences</td>
<td>3.1 (8.8)</td>
<td>18.8 (34.7)</td>
<td>34.1 (40.7)</td>
<td>45.5 (38.4)</td>
<td>T=3.00, Z=-1.34, p=0.18</td>
<td>U=23.50, Z=-1.96, p=0.063</td>
<td>U=22.50, Z=-1.86, p=0.063</td>
<td></td>
</tr>
<tr>
<td>Frequency of loaded leg steps</td>
<td>9.4 (18.6)</td>
<td>12.5 (35.4)</td>
<td>4.5 (15.1)</td>
<td>15.9 (35.8)</td>
<td>T=2.00, Z=-0.45, p=0.66</td>
<td>U=37.50, Z=-0.85, p=0.40</td>
<td>U=42.00, Z=-0.26, p=0.80</td>
<td></td>
</tr>
<tr>
<td>Frequency of other stepping patterns</td>
<td>28.1 (28.2)</td>
<td>53.1 (45.2)</td>
<td>18.2 (31.8)</td>
<td>15.9 (32.2)</td>
<td>T=27.00, Z=-1.27, p=0.20</td>
<td>U=32.50, Z=-1.03, p=0.30</td>
<td>U=21.5, Z=-2.02, p=0.043*</td>
<td></td>
</tr>
</tbody>
</table>
A significant main effect of direction was identified for frequencies of trials with extra steps ($F_{1,17}=16.49$, $p=0.001$), step initiation with the preferred limb ($F_{1,17}=50.62$, $p<0.001$), and crossover steps (within the EU-impaired group; $T=0.00$, $z=-2.23$, $p=0.026$). For each of these comparisons, greater frequencies were observed with platform motion towards the preferred limb, compared to the non-preferred limb (Tables 3–4). A significant main effect of group was identified for side-step sequences during platform motion towards the preferred limb, with the EU-capable group using this stepping pattern more often ($U=23.50$, $z=-1.96$, $p<0.050$). Conversely, a significant effect of group was observed for other stepping patterns during platform motion towards the non-preferred limb, in that the EU-impaired group exhibited these stepping patterns more frequently ($U=21.5$, $z=-2.02$, $p=0.043$). No significant effects were identified for the frequency of loaded-leg steps or foot collisions (present in 22/151 trials (15%)), or the average number of extra steps (associated $p$-values>0.062 for all of these comparisons).

**Discussion**

This study aimed to quantify differences in reactive balance control following laterally-directed perturbations in individuals with chronic stroke, based on perturbation direction and ability to step with either limb. Significant differences between platform directions were identified for the frequency of trials with extra steps and step initiation with the preferred limb, although these did not support our hypotheses that greater frequencies would be observed with platform motion towards the non-preferred limb. However, our hypotheses that crossover steps would be more common with platform motion towards the preferred limb, and that side-step sequences would be more common in the EU-capable group, were supported. There were no differences in the frequency of loaded-leg steps or foot collisions, or the average number of extra steps. Neither platform direction nor group predicted the likelihood of stepping with the more-loaded limb.

Frequencies of the different stepping characteristics were comparable to those reported for healthy older adults for both waist-pull and support-surface perturbations, although more foot collisions were found in the present study compared to both Maki et al. and Yungher et al. (6% and 1.6% of trials, respectively), and a higher number of crossover- and loaded-leg steps compared to Maki et al. (13% and 1% of trials, respectively). The higher numbers of crossover- and loaded-leg steps may potentially be due to the tendency for individuals with stroke to only step with the preferred limb; while higher frequencies of foot collisions may be due to the increased use of crossover steps, and/or a decreased ability to control limb trajectory post-stroke. The frequency of loaded-leg steps, as well as the difference in frequency based on the direction of the perturbation, was much smaller than those identified by De Kam et al. A variety of methodological differences may have accounted for the discrepancy, including a different motion profile for the platform (300 ms acceleration, 500 ms constant velocity, and 300 ms deceleration; versus 300 ms acceleration and 300 ms deceleration for this study).

In the EU-impaired group, crossover steps were observed more frequently with platform motion towards the preferred limb. The perturbation would have unloaded the preferred limb, facilitating initial stepping with that limb. With a crossover step, the step initiation limb is primarily responsible for extending the base of support under the center of mass, while in a side-step sequence, the second stepping limb is the primary contributor. A successful crossover step with the preferred limb could provide sufficient movement of the base of support to contain the centre of mass without requiring additional steps with the non-preferred limb. Consequently, this strategy may have been used with platform motion towards the preferred limb with the intention that the single step would be sufficient. Conversely, platform motion towards the non-preferred limb would have encouraged stepping with the non-preferred limb. In this scenario, crossover steps may have been disregarded in favour of less
demanding stepping patterns\textsuperscript{17,19} or those initiated with the preferred limb (i.e., there were more trials (although non-significant) with loaded-leg steps with platform motion towards the non-preferred limb).

Extra steps were more prevalent with platform motion towards the preferred limb, contrary to our hypothesis. The increased use of crossover steps with this platform direction may have resulted in the greater need for additional steps, agreeing with the results of Maki et al.\textsuperscript{17} These patterns may have been selected with the intention of taking only a single step. In practice, however, crossover stepping patterns are demanding and difficult to control,\textsuperscript{17} such that the minimum number of steps may not have been sufficient to regain stability, thereby requiring additional steps and contributing to the greater frequency of trials with extra steps with platform motion towards the preferred limb.

With platform motion towards the preferred limb, side-step sequences were more frequently executed by the EU-capable group than the EU-impaired group, supporting our hypothesis. The groups were based on individuals’ ability to initiate stepping with either limb. These functional differences may account for the EU-capable group’s increased use of side-steps, as side-step sequences require steps with both limbs. Although side-step sequences are potentially the most effective stepping pattern for recovery from laterally-directed perturbations in healthy young adults\textsuperscript{22} and individuals with Parkinson’s disease,\textsuperscript{23} the EU-impaired group commonly selected other stepping patterns. This may be cause for concern for individuals unable to step with either limb, as side-step sequences may be the only stepping pattern that prevents falling after large-magnitude perturbations.\textsuperscript{22} Together with the present findings, these results suggest that side-step sequences are a more effective strategy to recover balance following lateral perturbations, supporting the notion that side-step sequences should be trained in falls-prevention balance training programs.\textsuperscript{36}

The frequency of initiating stepping with the preferred limb was greater with platform motion towards that limb, relative to the non-preferred limb. Conversely, when responding to antero-posterior perturbations, participants generally showed a clear preference for stepping with one limb. These findings may suggest that for laterally-directed perturbations, the direction of the perturbation, rather than the preferred limb, is more important in determining the initial stepping limb. Therefore, lateral perturbations directed towards the non-preferred limb may provide a means of training stepping with that limb during rehabilitation of reactive balance post-stroke, especially for individuals who experience difficulty with stepping with the non-preferred limb in antero-posterior perturbations.

The groups in the present study were determined based on individuals’ function during a lean-and-release encouraged-use condition,\textsuperscript{32} as opposed to lesion location or other medical criterion. EU-impaired individuals, as defined in this paper, are at increased risk for falls in daily life.\textsuperscript{11} No differences between groups were observed for any of the demographic or stroke-related characteristics, agreeing with Schinkel-Ivy et al.,\textsuperscript{32} who found that groups distinguished based on performance during encouraged-use trials only differed based on CMSA foot scores, but not in sex, age, NIHSS, time since stroke, or more-affected side of the body. Performance during the encouraged-use trials attempts to assess the ability to step with either limb, and impairments in stepping with the non-preferred limb.\textsuperscript{32} These specific characteristics may not necessarily be evident in the clinical assessments reported in this study, which focus on voluntary as opposed to reactive movements. This provides support for assessing individuals with stroke based on the function of the movement system, as opposed to specific medical criteria. Specifically, the inclusion of an assessment of reactive stepping ability with the non-preferred limb may be warranted in order to identify limb-specific impairments that may not be identified with most clinical assessments.

While not a primary focus for the present study, weight-bearing asymmetry prior to perturbations differed from quiet standing, with less symmetrical and more variable weight-bearing during perturbation trials. This agrees with previous work comparing participants’ load on the paretic limb in quiet standing versus perturbation trials.\textsuperscript{9} It is possible that the increased variability in weight-
bearing during perturbation trials may have been used as an anticipatory strategy for the upcoming perturbation.

While reactive balance assessment is becoming more commonly used in clinical practice, perturbations are typically restricted to the antero-posterior direction. As stroke-related impairments commonly manifest unilaterally, responses to laterally-directed perturbations provide additional insight into reactive balance strategies in this population. As such, laterally-directed perturbations (e.g., as in the Balance Evaluation Systems Test) may be useful for reactive balance assessment post-stroke in order to identify deficits in lateral stepping (e.g., use of crossover or loaded-leg steps, as opposed to side-step sequences). Incorporating lateral perturbations would be associated with challenges such as reducing predictability of the perturbation direction and limb pre-loading due to leaning. If these issues can be addressed, the inclusion of lateral perturbations in reactive balance assessments may help to focus rehabilitation programs on patient-specific deficits in order to improve lateral stepping post-stroke. Previous studies have designed perturbation-based balance training programs for older adults based on knowledge of common age-related impairments in reactive stepping. Therefore, the results of this study could be used to inform stroke-specific perturbation-based balance training programs. For example, training strategies may include emphasizing stepping with both limbs, training stepping with the non-preferred limb, or training more effective stepping patterns (i.e., side-step sequences) following lateral perturbations.

Several limitations were present in the study. The sample size for this study was relatively small (N=19), though similar to previous studies examining balance reactions to laterally-directed perturbations in healthy older adults, individuals with Parkinson’s disease, and individuals with stroke. Due to platform design, we were unable to have a ‘spotter’ stand close to participants and, for safety reasons, a gait aid could not be on the platform, even between trials. Consequently, the study sample was likely higher functioning than the general population of chronic stroke survivors. Although an attempt was made to control for adaptation to the platform’s motion profile by imposing ‘catch’ trials, participants may have developed strategies to use the platform’s motion characteristics, such as the deceleration phase, to help regain balance. Alternating with additional motion profiles may have reduced such adaptation, but would have increased the number of trials required and potentially increased participant fatigue. Lastly, while information regarding lesion location was not collected as part of this study, future research may aim to quantify the relationship between lesion location and specific stepping characteristics.

In conclusion, this study aimed to characterize responses to laterally-directed perturbations in individuals with chronic stroke. Trials with extra steps, step initiation with the preferred limb, and crossover steps (in the EU-impaired group) were more common with platform motion towards the preferred limb. Side-step sequences were more common in the EU-capable group than the EU-impaired group with platform motion towards the preferred limb. The findings provide insight into reactive balance control strategies following laterally-directed perturbations for individuals with chronic stroke, and suggest that laterally-directed perturbations may be valuable in reactive balance assessment post-stroke. These findings may provide an indication of possible avenues for improving treatment programs to train reactive balance control post-stroke and potentially reduce the risk of lateral falls.

Conflict of interest
None.

References


