Does Perturbation-Based Balance Training Improve Control of Reactive Stepping in Individuals with Chronic Stroke?

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Background: Although perturbation-based balance training (PBT) may be effective in improving reactive balance control and/or reducing fall risk in individuals with stroke, the characteristics of reactive balance responses that improve following PBT have not yet been identified. This study aimed to determine if reactive stepping characteristics and timing in response to support-surface perturbations improved to a greater extent following PBT, compared to traditional balance training. *Materials and methods:* This study represents a substudy of a multisite randomized controlled trial. Sixteen individuals with chronic stroke were randomly assigned to either perturbation-based or traditional balance training, and underwent 6-weeks of training as a part of the randomized controlled trial. Responses to support-surface perturbation were evaluated pre- and post-training, and 6-months post-training. Reactive stepping characteristics and timing were compared between sessions within each group, and between groups at post-training and 6-months post-training while controlling for each measure at the pre-training session. *Results:* The frequency of extra steps in response to perturbations decreased from pre-training to post-training for the PBT group, but not for the control group. *Conclusions:* Improvements in reactive balance control were identified after PBT in individuals with chronic stroke. Findings provide insight into the mechanism by which PBT improves reactive balance control poststroke, and support the use of PBT in balance rehabilitation programs poststroke.

Key Words: Stroke—reactive balance control—reactive stepping—perturbation-based balance training

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Introduction

The risk of falling and subsequent injury is twice that for individuals with stroke compared to age-matched controls.[1] The ability to execute balance reactions is critical to maintaining stability following a loss of balance.[2] Change-in-support reactions (reactions that increase base-of-support size), including reactive stepping, are crucial for preventing falls.[3] However, these responses are often impaired with stroke. Individuals with stroke tend to exhibit multistep responses, delayed time to initiate and/or complete stepping, and strong preferences for initiating reactive stepping with 1 limb, often with complete inabil-

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ity to initiate stepping with the opposite limb.[4-7] Several of these characteristics of reactive stepping have been related to increased falls in individuals with stroke during inpatient rehabilitation[8] and following discharge from rehabilitation.[9]

While traditional balance training (TBT), focused on maintaining stability during voluntary movement, prevents falls in older adults, these programs do not reduce fall rates in individuals with stroke.[10,11] Perturbation-based balance training (PBT) focuses on practicing responses to instability,[12] aiming to improve reactive balance control and reduce fall risk. In older adults, PBT reduces the frequency of multistep reactions and foot collisions,[13] and reaction time to auditory stimuli.[14] A case study identified improved reactive step timing and ability to step with the nonpreferred stepping limb after PBT in an individual with subacute stroke.[6] Collectively, these findings indicate that PBT may improve reactive stepping characteristics poststroke, but this has not yet been explored in individuals with chronic stroke.

Preliminary evidence suggests potential for PBT to improve reactive balance control among individuals with chronic stroke.[15] Accordingly, reactive stepping characteristics that improve following PBT must be identified. Identifying the means by which improvements occur will further our understanding of reactive balance control in individuals with stroke, and potentially help to further refine PBT for clinical implementation. Therefore, we aimed to determine whether reactive stepping characteristics (frequencies of extra steps, lateral steps, stepping with the more affected limb, foot collisions) and timing (foot-off time, swing time) in response to support-surface perturbations improved following 6-weeks of PBT. We expected improvements following PBT (fewer trials requiring extra steps or lateral steps, greater frequency of stepping with the more affected limb, fewer foot collisions, faster foot-off time, longer swing time), with greater improvements following PBT compared to TBT.

Materials and Methods

Participants

Participants in this analysis (N = 16; Fig 1) were a subset of participants enrolled in a multisite randomized controlled trial (RCT; clinical trials registration number: ISRCTN05434601)[15] examining the effects of PBT on falls in individuals with chronic stroke (>6-months poststroke) for up to 1-year post-training. The trial protocol and results of the full trial have been previously published.[12,15] The full study took place from April 2014 to August 2017 (enrolment from April 2014 to August 2016, with 1-year follow-up). Participants were enrolled by a blinded research assistant. Inclusion criteria for the larger study were: able to stand independently for at least 30 seconds without external support; and tolerate at least 10 postural perturbations with a lean-and-release system.[12,15] Briefly, exclusion criteria for the larger study were: height/weight (limited by the safety harness system; >2.1 m and/or >150 kg), medical (eg, Parkinson's disease, lower extremity amputation, severe osteoporosis) or poorly controlled (eg, diabetes, hypertension) conditions that may have confounded study results; impairments that affected participants' understanding of instructions; current physiotherapy or balance training; and recent PBT in formal rehabilitation. These criteria have been detailed previously.[12,15]

Following participation in a baseline assessment (see Procedures) at RCT inclusion, appropriate participants (ie, meeting the inclusion criteria below) were invited to undertake additional assessments on a motion platform prior to and after PBT, as well as 6-months post-training. Sample size was calculated based on data from the first 8 participants and the dependent measure frequency of multistep reactions postperturbation (later modified to frequency of extra steps, to better account for the number of steps required for various stepping patterns). Only appropriate participants who were enrolled from January 2015 to August 2016 were invited to participate; these participants were primarily recruited from 1 of the 2 RCT sites. The additional inclusion criteria for the motion platform component of the study were: having undergone a baseline assessment (see Procedures); and the ability to walk independently for 10 m without a gait aid.[16] The latter criterion was necessary as no loose objects could be on the platform while it was operating as a safety precaution. Participants also had to be willing to undertake these additional assessments (some invited participants declined the assessments; Fig 1). All procedures were approved by the institutions' Research Ethics Boards. Written informed consent was obtained from all participants prior to data collection.

Instrumentation

A motorized moving platform was used to evoke balance reactions in response to standardized perturbations in 4 directions (anterior, posterior, left, right).[16] The platform was 6 m-by-3 m in size and made up of an X-Y mechanism with 2 rail assemblies/axis and 1 servo-motor, bearing wheels, and toothed timing belt for each rail, allowing the platform to move rapidly in any horizontal direction. A custom Matlab-Simulink program (The Mathworks, Inc., Natick, MA) controlled the platform's motion. If a participant was unable to recover balance, a fall to the floor was prevented by a safety harness attached by a cable to an overhead gantry system with an in-series load cell (Durham Instruments, Toronto, Canada); the harness was worn by participants whenever they were on the platform. All trials were video recorded, and a triaxial accelerometer (Dytran Instruments, Inc., Chatsworth, LA) located at 1 end of the platform measured platform acceleration. The surface of the middle of the platform was

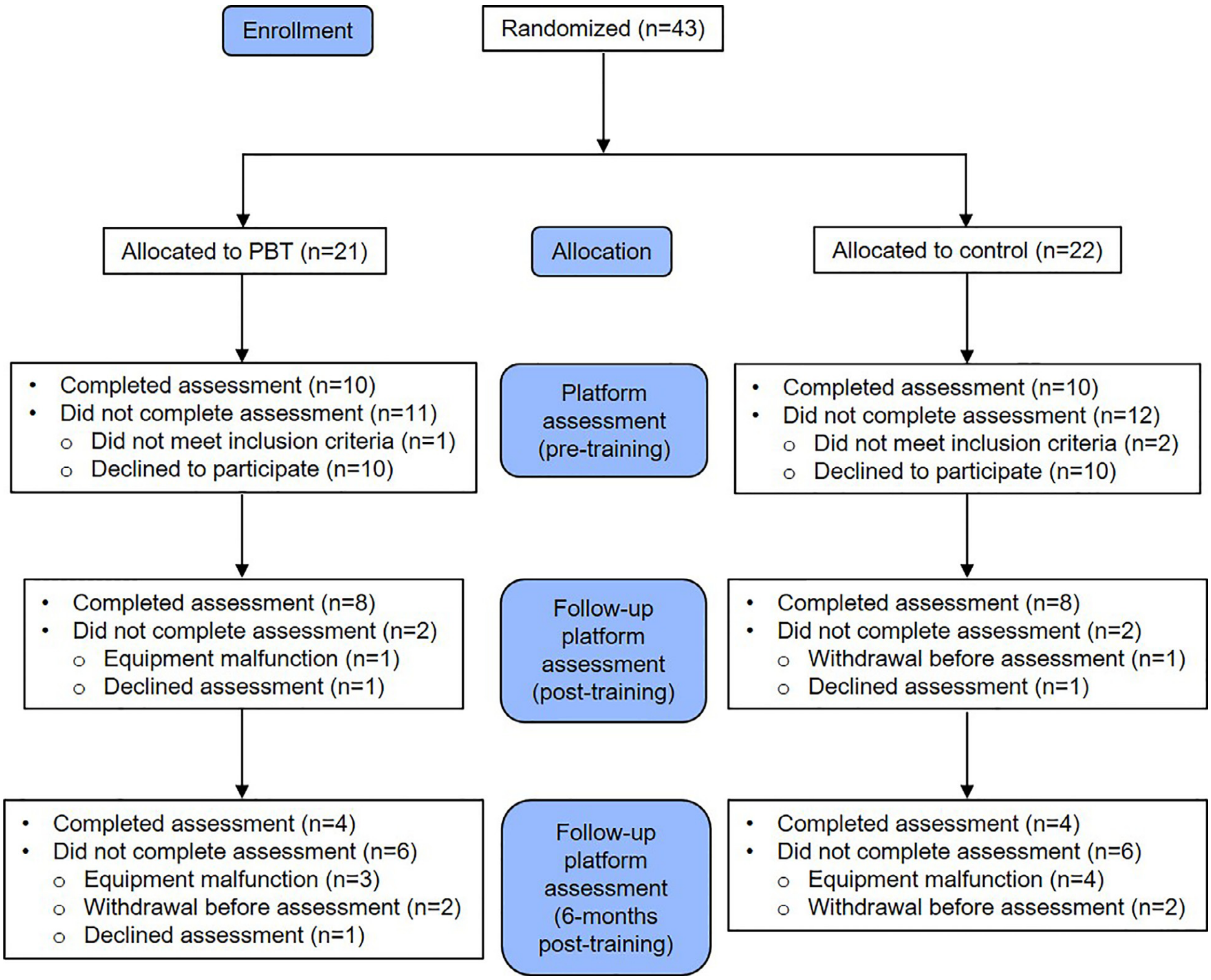

Figure 1. *Participant flow through the study, for both the perturbation-based balance training (PBT) and traditional balance training (TBT; control) groups. All participants had already been enrolled into the larger RCT and randomized into a training group; those included in the diagram represent only those appropriate participants (ie, meeting the additional inclusion criteria for the motion platform assessments) who were enrolled in the larger RCT from January 2015 to August 2016.*

made up of four 1.5 m-by-1.5 m embedded force plates (Advanced Mechanical Technology, Inc., Watertown, MA), used to measure ground reaction forces. Force plate data were sampled at 250 Hz. Electromyography data were also recorded for several bilateral lower extremity muscles, with the intention of investigating muscle onset timing. However, due to missing electromyography data for a large number of trials for various reasons (the muscle activity burst occurring after foot-off; no apparent activity; or excessive activity or noise interfering with the ability to determine onset time), we decided not to include electromyography data in the analysis.

Procedures

Following enrolment in the larger RCT, participants attended a baseline assessment. During this session, demographic descriptors (age, sex, date of stroke, and affected side of the body) were collected by self-report, and height and weight were measured. Observational rating scales and questionnaires were used to assess stroke severity (National Institutes of Health Stroke Scale),[17] motor impairment (Chedoke-McMaster Stroke Assessment (affected leg and foot)),[18] functional balance and mobility (Berg Balance Scale;[19] Mini Balance Evaluation Systems Test;[20] timed up & go),[21] balance confidence (Activities-Specific Balance Confidence Scale),[22] physical activity (Physical Activity Scale for Individuals with Physical Disabilities),[23] and participation (Subjective Index of Physical and Social Outcome).[24] During this assessment, 10 lean-and-release trials[4,25] were performed. In the first 5 trials, no specific instructions were provided with regards to the limb used to initiate stepping. The limb used to initiate stepping in the majority of the trials was designated the preferred stepping limb. For the subsequent 5 trials, participants were encouraged to use the nonpreferred stepping limb, through physical blocking of the preferred limb by an investigator.[4,12,26] The number of failed responses (use of external assistance during any trial, or stepping with the preferred limb during the later 5 trials) was used for the blocked stratified randomization of participants into the training groups.[12,15]

A second data collection session (PRE) was undertaken following the baseline assessment (range: 1-11 days) for participants who agreed to undergo the motion platform assessment.[16] Following instrumentation, participants stood on the platform and experienced 4 perturbations (1/direction) to familiarize them with the platform motion (these trials were not included in the analysis). The platform motion profile for these familiarization trials was 300 ms acceleration and 300 ms deceleration.[27] For posterior and lateral perturbations, the peak platform acceleration was 2.0 m/s^2 (peak velocity: .6 m/s, total displacement: .18 m); for anterior perturbations, the peak platform acceleration was 1.5 m/s^2 (peak velocity: .45 m/s, total displacement: .14 m).[16,28,29] Using procedures established prior to data collection, the perturbation magnitudes were either kept the same or adjusted prior to the experimental trials.[16] If the perturbation magnitude was too small to consistently evoke stepping, the peak accelerations were increased (posterior/lateral: peak acceleration: 3.0 m/s^2, peak velocity: .9 m/s, total displacement: .27 m; anterior: peak acceleration: 2.0 m/s^2, peak velocity: .6 m/s, total displacement: .18 m); or if the perturbation magnitude was too large such that there was a concern for participant safety, the peak accelerations were decreased (posterior/lateral: peak acceleration: 1.0 m/s^2, peak velocity: .3 m/s, total displacement: .09 m; anterior: peak acceleration: .7 m/s^2, peak velocity: .22 m/s, total displacement: .07 m).[16] Three experimental trials in each direction were then performed at the magnitudes determined from the familiarization trials, using the same platform motion profile. Additionally, 4 "catch" trials (1/direction) were included throughout the experimental trials, to minimize adaptation to the platform motion profile; the waveform for these trials consisted of 200 ms acceleration, 400 ms constant velocity, and 200 ms deceleration.[27] Only the experimental trials (3/direction) were included in the analysis.

All perturbation trials began with 1 foot on each of 2 force plates in a standardized position.[30] Participants provided verbal confirmation that they were ready for the trial, at which time the platform control program was initiated by an investigator after a random interval. Platform motion began 5 seconds later. Rest breaks were offered throughout the collection session, and participants could request additional breaks if needed.

Following the PRE session, participants then underwent 6-weeks of training (two 1-hour sessions/week) on a one-on-one basis with a trained, licensed physiotherapist, in 1 of 2 training programs: PBT or TBT (control group).[12,15] Participants were assigned to training programs using stratified blocked randomization (stratification factors: rehabilitation hospital site, frequency of failed responses during the baseline lean-and-release assessment)[12,15] with allocation concealment; the principal investigator generated the random allocation sequence via computer, and assigned participants to interventions. Research assistants involved with data collection were blinded to participants' groups. The training programs are detailed elsewhere.[12,15] Briefly, a general guideline was developed for each training program, although each participant's program was individualized to address specific balance control impairments. TBT focused on maintaining postural stability during voluntary movement, while PBT used both internal (eg, kicking a soccer ball) and external (eg, push or pull) perturbations with the intent of training balance reactions following balance loss. Following the 6-week training period, the PRE session was repeated (POST) for the 16 participants (8/group) included in the final analysis. Eight participants (4/group) were tested again at 6-months post-training (6MO). POST and 6MO sessions were not conducted for the remaining participants due to equipment malfunction (POST n = 1; 6MO n = 7), withdrawal from the study (POST n = 1; 6MO n = 4), or participants declining the assessment (POST n = 2; 6MO n = 1). While baseline assessment and training were administered at 2 rehabilitation hospitals, the motion platform assessments were conducted at 1 hospital where the motion platform was located. Motion platform assessments were conducted by investigators or research assistants blinded to participants' groups. Harms and unintended effects for the full participant cohort are reported in the primary paper for the RCT.[15]

Data Processing

Video data from the platform assessments were used to identify the number of steps, direction of stepping, limb used to initiate stepping, occurrence of foot collisions, and stepping patterns (eg, crossover steps, side-step sequences, loaded-leg steps)[27] in response to each perturbation. The minimum number of steps required for each stepping response was determined based on the stepping pattern.[27] This value was subtracted from the number of steps to determine the number of extra steps. For anterior- or posterior-directed perturbations, the number of steps taken in either lateral direction was identified. The frequencies of trials with extra steps, trials with lateral steps, trials with stepping initiated with the more affected limb, and trials with foot collisions were then determined.[16]

Accelerometer and force plate data were processed using a custom Matlab program (The Mathworks, Inc., Natick, MA). Data were low-pass filtered with a dual-pass, second-order Butterworth filter (cut-off frequency: 10 Hz).[31,32] The onset of platform motion for each trial was identified using accelerometer signals in the direction of motion, defined when the acceleration exceeded .1 m/s^2. The times of foot-off and foot-contact for the initial stepping limb were determined from the force plate data, defined as the first point after perturbation onset when there was less than 1% body weight and greater than 5% body weight, respectively, on the force plate under the stepping limb.[6,8] The foot-off and foot-contact times were then used to calculate swing time (foot-contact time−foot-off time). The perturbation onset, foot-off, and foot-contact times were verified manually by a research assistant and corrected if necessary. Research assistants involved with data processing were blinded to participants' groups.

Data Analysis

Continuous demographic and stroke-related descriptors were tested for normality using Shapiro-Wilk tests. Descriptors were compared between groups using independent *t* tests (continuous, normally-distributed variables), Wilcoxon rank-sum tests (ordinal or non-normal continuous variables), or Fisher's exact test (nominal variables).

The frequency of extra steps, frequency of stepping with the more affected limb, and foot-off time were analyzed for all perturbation directions. The frequency of lateral steps was analyzed for anterior and posterior perturbations, as an indication of mediolateral balance control during these trials. Similarly, swing time was only analyzed for anterior or posterior perturbations, as the swing limb often contacted the stance limb force plate in response to laterally-directed perturbations, and so foot contact time could not be determined for these trials. Frequency of foot collisions was only analyzed for laterally-directed perturbations, as collisions would not be expected for anterior or posterior perturbations.

All continuous dependent measures at POST and 6MO were tested for normality using Shapiro-Wilk tests. Dependent measures were compared between PRE and POST (n = 8/group) and between PRE and 6MO (n = 4/group) for each group, using paired *t* tests (continuous, normally-distributed variables) or Wilcoxon signed-rank tests (ordinal or non-normal continuous variables). Analyses of covariance were used to identify differences between the groups at POST and 6MO, using the PRE values for each measure as the covariate. Alpha was .05.

Results

There were no significant between-group differences for age, sex, height, weight, time poststroke, affected side of the body, or stroke-related descriptors (Table 1). The frequency of trials with extra steps significantly differed between PRE and POST for the PBT group (Wilcoxon signed rank S = −18, *P* = .008; Table 2). From PRE to POST, the mean (standard deviation) frequency of trials with extra steps decreased from 42% (30%) of trials to 20% (17%) of trials in the PBT group. Within the TBT group, there were no significant changes between PRE and POST, or between PRE and 6MO (*P* > .05; Table 3). None of the measures differed between groups at either POST or 6MO when controlling for PRE values (*P* > .05; Table 4).

Discussion

We aimed to evaluate changes in reactive stepping characteristics and timing measures in response to support-surface perturbations following PBT. Our findings supported our hypothesis with respect to the effects of training on the frequency of extra steps, with reductions from PRE to POST for the PBT group. There were no significant effects for frequencies of lateral steps, stepping with the more affected limb, or foot collisions, nor for foot-off time or swing time. These findings provide insight into the characteristics of reactive stepping that improve following PBT. Findings also provide evidence for the clinical implications of PBT, a feasible and cost-effective intervention,[33] for individuals with chronic stroke. Our analysis of all participants involved in this RCT found greater improvements in reactive balance control following PBT compared to TBT,[15] assessed using the Mini-Balance Evaluation Systems Test reactive subscale.[20] The current study extends the results of Mansfield et al[15] by providing insight into how the overall outcome of improved reactive balance control is facilitated by PBT. As such, this study supports the implementation of PBT into rehabilitation training programs for improving reactive balance control poststroke.

A significant reduction in the frequency of extra steps was identified for the PBT group (but not the TBT group) at POST, indicating that PBT was successful in improving control of stepping reactions as extra steps beyond the minimum were required less often. Additional reactive steps beyond the minimum required for balance recovery may indicate that the initial step(s) was/were not sufficient to regain stability; that is, the new base-of-support resulting from the minimum number of steps was not sufficient to arrest motion of the body's center-of-mass.[27] That the PBT group required extra steps less often may suggest that PBT improved stepping response effectiveness, as these individuals were more often able to control the center-of-mass with the minimum number of steps post-training. The mechanism(s) by which the effectiveness of stepping responses improves remain(s) to be investigated. It is possible that mechanisms of improvement in stepping response effectiveness may differ between individuals with stroke, due to the wide variability in levels and types of impairment experienced by each individual. Functionally, a better ability to regain balance following a perturbation may reduce the risk of falling in response to the perturbation, and may also better prepare an individual for any subsequent perturbation.

Psychological factors may have contributed to the reduced frequency of extra steps, specifically familiarity

Table 1. *Demographic and stroke-related descriptors and observational rating scale/questionnaire results for the perturbation-based balance training (PBT) and traditional balance training (TBT) groups*

Descriptors	PBT	TBT	*P* value
Age (years)	66.1 (8.3) Range: 51-78	60.3 (8.9) Range: 43-72	.20
Sex (male/female)	6/2	6/2	>.99
Height (m)	1.71 (.07)	1.67 (.09)	.30
Weight (kg)	78.34 (9.20)	7.33 (.56)	.16
Time post stroke (years)	3.6 (2.9) Range: .5-9.0	5.4 (5.0) Range: .5-14.4	.71
Affected side of the body (left/right)	6/2	5/3	>.99
National Institutes of Health Stroke Scale score (/42)	3.9 (4.2) Range: 1-13	4.0 (2.4) Range: 0-8	.43
Chedoke-McMaster Stroke Assessment leg score (more affected side) (/7)	5.8 (1.4) Range: 3-7	5.3 (.7) Range: 5-7	.20
Chedoke-McMaster Stroke Assessment foot score (more affected side) (/7)	5.1 (1.6) Range: 2-7	4.5 (.9) Range: 3-6	.21
Berg Balance Scale score (/56)	52.5 (7.7) Range: 34-56	52.4 (3.1) Range: 48-56	.21
Mini-Balance Evaluation Systems Test score (/28)	20.6 (4.5) Range: 11-25	19.3 (2.9) Range: 14-23	.25
Timed up & go time (s)	13.8 (10.0) Range: 5.6-34.3	13.9 (5.3) Range: 8.7-24.8	.43
Activities-Specific Balance Confidence Scale score (/100)	87.8 (11.3) Range: 65-100	70.5 (24.9) Range: 34.4-96.3	.19
Physical Activity Scale for Individuals with Physical Disabilities score	9.7 (5.1) Range: 5.1-20.9	11.3 (6.3) Range: .8-20.9	.49
Subjective Index of Physical and Social Outcome score (/40)	30.4 (7.5) Range: 19-40	26.5 (9.9) Range: 11-39	.53

Continuous variables are presented as means (standard deviation). *P* values represent comparisons between groups by either independent *t* tests (age, height, weight), Fisher's exact test (sex, affected side of the body), or Wilcoxon rank-sum tests (all remaining measures).

Table 2. *Comparison of reactive stepping characteristics between pre-training (PRE) and post-training (POST), and between pre-training and 6-months post-training (6MO), within the perturbation-based balance training group*

Measure	PRE n = 8	POST	*P* value	PRE n = 4	6MO	*P* value
Frequency of extra steps (proportion of trials)	.42 (.30)	.20 (.17)	.008*	.33 (.18)	.04 (.08)	.13
Frequency of lateral steps (proportion of trials)	.25 (.27)	.13 (.17)	.13	.25 (.29)	.00 (.00)	.25
Frequency of stepping with the more affected limb (proportion of trials)	.38 (.26)	.35 (.29)	.88	.25 (.20)	.27 (.22)	.50
Frequency of foot collisions (proportion of trials)	.17 (.20)	.02 (.06)	.25	.08 (.17)	.00 (.00)	>.99
Step timing (ms)						
Foot-off time	346 (37)	363 (63)	.34	343 (40)	354 (24)	.38
Swing time	147 (33)	145 (18)	.79	141 (41)	134 (51)	.72

Values presented are means (standard deviation). *P* values represent comparisons between time points (PRE and POST, PRE and 6MO) within the group. *$P < .05$.

Table 3. *Comparison of reactive stepping characteristics between pre-training (PRE) and post-training (POST), and between pre-training and 6-months post-training (6MO), within the traditional balance training group*

Measure	PRE n = 8	POST	*P* value	PRE n = 4	6MO	*P* value
Frequency of extra steps (proportion of trials)	.46 (.33)	.30 (.19)	.09	.38 (.28)	.29 (.25)	.38
Frequency of lateral steps (proportion of trials)	.15 (.24)	.10 (.15)	.75	.083 (.17)	.083 (.17)	n/a
Frequency of stepping with the more affected limb (proportion of trials)	.31 (.18)	.19 (.12)	.06	.33 (.26)	.23 (.17)	.38
Frequency of foot collisions (proportion of trials)	.06 (.18)	.04 (.12)	>.99	.13 (.25)	.00 (.00)	>.99
Step timing (ms)						
Foot-off time	369 (43)	383 (56)	.27	386 (41)	382 (57)	.77
Swing time	155 (24)	160 (24)	.74	156 (36)	151 (8)	.83

Values presented are means (standard deviation). *P* values represent comparisons between time points (PRE and POST, PRE and 6MO) within the group. *$P < .05$.

Table 4. *Comparison of reactive stepping characteristics between groups at post-training (POST) and 6-months post-training (6MO), using pre-training values for each measure as covariates.*

Measure	POST (n = 16)			6MO (n = 8)		
	PBT	TBT	*P* value	PBT	TBT	*P* value
Frequency of extra steps (proportion of trials)	.21 [.14, .28]	.27 [.22, .37]	.063	.05 [−.14, .24]	.28 [.09, .47]	.09
Frequency of lateral steps (proportion of trials)	.11 [.001, .21]	.12 [.020, .23]	.78	−.021 [−.17, .13]	.10 [−.045, .25]	.20
Frequency of stepping with the more affected limb (proportion of trials)	.33 [.21, .45]	.22 [.10, .33]	.33	.30 [.18, .42]	.20 [.08, .32]	.29
Frequency of foot collisions (proportion of trials)	.02 [−.05, .10]	.04 [−.04, .12]	>.99	.00 [.00]	.00 [.00]	n/a
Step timing (ms)						
Foot-off time	376 [343, 409]	370 [337, 404]	.81	373 [340, 406]	362 [329, 395]	.59
Swing time	145 [128, 162]	160 [143, 176]	.20	137 [92, 183]	148 [102, 193]	.70

Values presented are least square means (adjusted for the pre-training value as a covariate) and 95% confidence intervals in parentheses. *P* values represent comparisons between groups using analysis of covariance. *$P < .05$.

with support-surface perturbations and the resulting reduction in anxiety. Past experience and expectations are used by the central nervous system to modulate postural responses.[34] Gaining a greater amount of experience with balance recovery in response to external perturbations, as in PBT, may have allowed for a stronger influence of these prior experiences and expectations on reactive stepping.[35] As both groups exhibited reductions in the frequency of extra steps (although only significant for the PBT group), these factors may be at least partially responsible for this finding.

Study Limitations

Due to the nature of the motion platform, only RCT participants able to walk independently were invited to take part in the motion platform assessment. This criterion may have resulted in a relatively high-functioning sample of individuals with stroke for this study, potentially contributing to a ceiling effect for some measures; generalizability to the broader population of individuals with stroke may also be limited. Furthermore, we focused on chronic stroke. While stroke recovery can continue for years,[36] individuals who begin rehabilitation sooner after stroke tend to experience greater gains.[37,38] Therefore, PBT for individuals with subacute stroke may elicit greater reactive stepping improvements.

Conclusions

This study identified reduced frequency of trials with extra steps from pre-training to post-training following PBT in individuals with chronic stroke. Reactive balance control improvements may have been facilitated by PBT in individuals with chronic stroke. These findings provide insight into characteristics of reactive balance responses that are improved following PBT, and suggest that the incorporation of PBT into rehabilitation training programs may be beneficial for improving reactive balance control poststroke.

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Supplementary Materials

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