Journal of NeuroEngineering and Rehabilitation

RESEARCH

Open Access

Is lateral external perturbation training more beneficial for protective stepping responses than voluntary stepping training in stroke? A pilot randomized control study

Marcel B. Lanza[1], Masahiro Fujimoto[2], Larry Magder[3], Sandy McCombe-Waller[1], Mark W. Rogers[1] and Vicki L. Gray[1*]

Abstract

The study examined whether lateral perturbation training could improve stepping performance and balance in individuals post-stroke. Thirty-one participants with hemiparesis were randomly allocated to PERT (external perturbation) or VOL (voluntary stepping) step training. The PERT and VOL group consisted of 80 step trials predominantly in the lateral direction, with a small proportion of steps in the anterior/posterior direction. Outcome measures based on step type (medial and lateral) included step initiation time, step length, step clearance, step velocity during an induced waist pull perturbation and voluntary step, and clinical balance assessments. The PERT group initiated a lateral step faster with the non-paretic leg during the induced waist pull perturbation step ($P=0.044$) than the VOL group after training. Both groups improved the non-paretic step length and step velocity during lateral steps. During the voluntary steps, the PERT group significantly initiated a voluntary step faster. No significant changes were observed in the paretic leg. Both groups significantly improved on the Community Balance & Mobility Scale and Activities Specific Balance Confidence Scale. Overall, we demonstrated that an exercise to improve stepping performance with external perturbations might provide more benefits in protective stepping responses than training with voluntary steps for individuals with a stroke.

Trial registration

The study was retrospectively registered at ClincalTrials.gov (NCT06638476).

Keywords Falls, Hemiparesis, Exercise, Induced step, Voluntary step

*Correspondence:
Vicki L. Gray
vicki.gray@som.umaryland.edu
[1]Department of Physical Therapy and Rehabilitation Science, University of Maryland School of Medicine, 100 Penn Street, Baltimore, MD 21201, USA
[2]Health and Medical Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Takamatsu, Kagawa, Japan
[3]Department of Epidemiology and Public Health, University of Maryland School of Medicine, Baltimore, MD, USA

Introduction

Seven million Americans who have experienced a stroke have residual sensorimotor deficits [1] and long-term disability [2]. These deficits negatively impact independent balance and mobility [2, 3], leading to a high fall rate [4, 5]. Falls are the most common secondary complication regardless of the time since a stroke [6–9]. Falls can be devastating, leading to fall-related injuries, a fear of falling [10], and limited mobility [11]. Many interventions such as weight shifting, visual feedback, virtual reality, and task-oriented training target poor balance after a stroke [12–17], but improvements in balance do not translate to a reduction in falls [18]. The interventions primarily focus on self-initiated movements that challenge balance rather than training responses to externally derived perturbations that act on the body through slips, trips, or pushes. Both may be important for fall prevention since falls are equally as likely to result from either after a stroke [19]. Incorporating both forms of balance training into stroke rehabilitation may be essential for reducing falls.

Despite the concerns with safety and the method of delivering external perturbations, there is evidence of increased acceptability of using perturbations as an intervention for individuals following a stroke [20]. The repeated exposure to external perturbations has led to some benefits, including an increased protective stepping threshold (i.e., the lowest perturbation magnitude that induces a protective step) [21], fewer steps used to recover balance [22], and an increased incidence of lateral steps [21]. The limitations in the current literature are that many studies create an imbalance in the anterior or posterior perturbations (i.e., slips and trips), with less information regarding perturbations directed laterally, which may be essential to train after stroke.

Balance instability in the lateral direction is vital after stroke since sensorimotor deficits are commonly unilateral and lead to compensatory strategies that reduce limb loading on the paretic side while standing [23, 24] and walking [25]. Also, the high number of hip fractures on the paretic limb indicates a vulnerability of lateral balance problems in this population [26]. The muscles (e.g., hip abductors/adductors) that control mediolateral balance are impaired with a delayed initiation time and reduced magnitude in muscle activity [27–29], resulting in a slower walking speed [25], a prolonged time to initiate a protective step [30], and a longer time to stabilize balance [27–29]. Lateral balance may be crucial to reducing falls, so interventions targeting balance in this plane would be necessary for this population. Therefore, the aim of this pilot study was to determine whether lateral perturbation training would improve the stepping performance of steps initiated voluntarily or in response to lateral external perturbation compared to voluntary step training in community-dwelling individuals with chronic stroke. The secondary aim was to determine if there would be more significant improvements in clinical balance measures in the perturbation training group.

Methods

Participants

Thirty participants with hemiparesis more than six months after a stroke were enrolled from November 2013 to June 2017 and ended after enrollment numbers were met. The number was based on 80% power to detect an effect size of 1.1 or greater, where the effect size was the difference between the two groups with respect to the mean changes in step initiation time and first step length for the voluntary and reactive steps. The calculation was based on a 2-sided t-test and alpha of 0.05-level. Participants were included if they were 50 years of age or older, ambulated independently 10 m with or without an assistive device, and could stand unsupported for 5 min. The exclusion criteria were medical conditions significantly impacting their ability to walk beyond the effects of the stroke, or that precluded their ability to exercise. Using an ankle foot orthosis (AFO) was not an exclusion criterion; users kept them on during testing and training. However, the inability to ambulate without an assistive device (cane) was an exclusion criterion. Informed consent to participate in the study was obtained from all participants enrolled, and the University of Maryland, Baltimore Institutional Review Board approved the study protocol.

Experimental protocol

Participants attended one visit before training (base) and a second visit within one week after training (post). The visit consisted of a lateral stepping assessment (induced steps with a waist-pull perturbation and voluntarily initiated steps) and a clinical evaluation of balance and sensorimotor deficits. During the lateral stepping assessment, a safety harness fitted on the participants ensured safety during the testing. However, the harness only provided support if they could not recover their balance. They stood on two adjacent force platforms (Advanced Mechanical Technology Inc., Watertown, MA, USA) in their comfortable stance width. A study team member visually monitored the ground reaction forces to ensure symmetrical weight-bearing before the start of the trial. Individuals with difficulty bearing weight equally on their limbs were trained to use strategies for bearing weight symmetrically. A lateral waist-pull perturbation system generated the externally induced steps [31]. Twenty-four trials randomly presented pulled the participant off balance laterally in the paretic or non-paretic direction. The perturbation consisted of four magnitudes known to induce stepping in older adults [32, 33] and individuals after a stroke [34]. The magnitudes varied based on velocity, ranging from 18.0 to 45 cm/s, and displacement, ranging from 8.6 to 19.3 cm. Instructions given to the participants were to "respond naturally and, if necessary, prevent yourself from falling." From the 24 stepping trials, a balance tolerance limit (BTL), defined as the perturbation magnitude where balance recovery transitioned from single-step recovery to multiple-step recovery, was determined for each participant for the paretic and non-paretic pull [33]. The established BTL level from the baseline testing was the perturbation magnitude used for the baseline and post-testing trials which were included in the analyses. The first step at BTL was categorized into three step types: lateral step, where the passively loaded leg, due to the perturbation, moves sideways in the direction of the pull; crossover step, whereby the passively unloaded leg moves toward and beyond the loaded leg in front (crossfront) or behind the body (crossback); and a medial step was when the unloaded leg moves toward and not beyond the loaded leg [33].

A pole with a horizontal bar containing three lights was positioned 2 m anterior to the participant for the lateral voluntary steps. The light on the right end of the horizontal bar indicated a right step, and the left side was a left step. Besides indicating the leg to step, the light indicated when to step. The instructions were to "step as fast as possible when you see the light cue." The participants completed ten trials randomly presented, five with the paretic and five with the non-paretic leg.

The ground reaction forces were collected for 7 s during the stepping assessment and sampled at 600 Hz. Reflective markers were placed on the body according to Eames et al. [35] and kinematic data were recorded for 7 s at a sampling rate of 120 Hz, using a 10-camera motion analysis system (Vicon, Oxford, UK).

Clinical assessment

Balance and balance confidence were assessed at two time points, base and post-training. Balance was assessed with the Community Balance & Mobility Scale, a valid and reliable measure for individuals after stroke [36] that evaluates tasks necessary for community ambulators. The Activities-Specific Balance Confidence Scale (ABC) is a self-reported measure of balance confidence used in several studies of community-dwelling individuals following a stroke [37, 38]. Other clinical measures characterized the level of motor recovery and cutaneous sensation. The Chedoke-McMaster Stroke Assessment was used to assess the level of motor recovery of the leg and foot [39]. The stages of motor recovery are graded from 1 to 7, with 7 classified as normal and 1 as flaccid. Cutaneous sensation was assessed on the plantar surface of the foot with a series of Semmes-Weinstein monofilaments, ranging from 1.65 to 6.65, with the lowest value representing normal cutaneous sensation [40]. The assessor was not blinded to the group assignment.

Training

Participants were randomly assigned to either the lateral external perturbation group (PERT) or the lateral voluntary step training (VOL) group. A randomized list was generated by MATLAB and the participants were assigned to the group by the PI. In order to control for potential differences in their level of motor recovery, randomization was stratified based on the level of motor recovery (high motor recovery > 9 and low motor recovery ≤ 9) assessed by the CMSA leg and foot subscale. The value was found to distinguish between those with decreased synergist patterns and weight-bearing symmetry from those with movement characteristics of synergist patterns and weight-bearing asymmetry [23]. Each group trained three times a week for six weeks for a total of 18 sessions. The participants were attached to an overhead safety harness system during the training sessions. The PERT group was exposed to 80 externally induced steps to standing balance each session through a computer-controlled treadmill (ActiveStep®, Simbex, Lebanon, NH). The trials were randomly presented based on velocity, perturbation direction, and time delay at the start of the trial. Seven levels changed based on velocity (range 30–96 cm/s) and displacement (range 32–58 cm). Each level had three velocities with three perturbation magnitudes in each level ranging from a velocity of 30–96 cm/s and a displacement of 32–58 cm. A detailed description of the training parameters has been published previously [41]. The training was advanced to the next level when 90% of the trials were classified as a successful recovery of balance, defined as not requiring external assistance from a person or harness. The VOL group performed 80 step trials (40 paretic, 40 non-paretic), including an equal number of crossover (front and back) and lateral steps, emphasizing moving outside the base of support, step length, and speed of stepping and completed in blocks of paretic and non-paretic steps. Although most of the training was a laterally directed step, 20% of the trials were in the anterior-posterior directions. The trials were blocked into lateral, which was always the first part of the training session, preceded by anterior-posterior trials. No manual assistance was provided during the training unless the participant could not recover balance. Assistance was provided to return to a stable position during these trials.

Data analysis

The time from the onset of the light cue or the lateral waist-pull perturbation to the first step liftoff from the ground reaction force of the stepping leg was defined as the step initiation time. The first step characteristics of

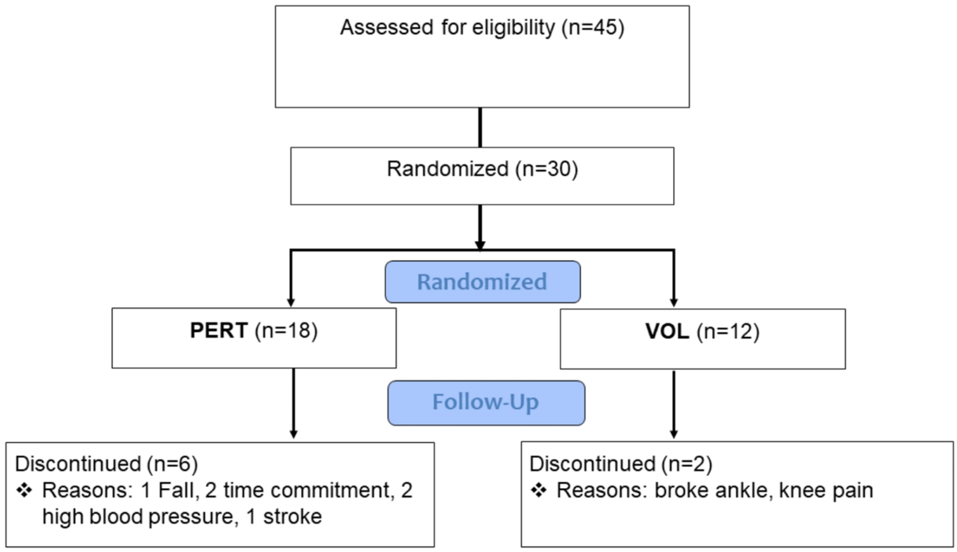

Fig. 1 Flow chart of participants in the study

step length, step clearance, and step velocity were identified from the ankle marker. Global step length was calculated as the square root of the sum of squares of the anteroposterior and mediolateral displacement, and step clearance was calculated as the maximum vertical displacement, and both were normalized to body height and expressed as a percent. The step velocity was calculated by dividing the global step length by the step duration. The first step characteristics for the lateral waist-pull perturbation were calculated for the steps at BTL for the paretic and non-paretic limbs for each participant.

Statistics

The step characteristics of step initiation time, first step length and clearance, and step velocity were compared between base and post for the PERT and VOL group for the lateral waist-pull perturbation steps. Only participants who had a particular type of step (i.e., lateral) at both time points were included in the analysis for each step type. The effects of training on the lateral voluntary step were determined by a longitudinal regression model, including a random effect for individuals, and the analysis was performed separately for the paretic and non-paretic steps for the PERT and VOL groups. The waist-pull perturbation steps were then divided into steps initiated with the paretic and non-paretic leg, and a longitudinal regression model included a random effect for individuals was used to determine the effects of training on the leg used, and step type and step characteristics for the paretic and non-paretic steps for the PERT and VOL group. The effects of training on the CB&M and ABC were assessed with two-way repeated measures ANOVA with a between factor (time x group), and *post hoc* comparisons were conducted using Bonferroni *post hoc* tests.

Table 1 Demographics and clinical measures of the perturbation and voluntary training group

Variable	Perturbation Training Group *n* = 18	Voluntary Training Group *n* = 12
Age	62.5 (7.1)	61.9 (7.9)
Sex, % male	77.7%	41.6%
Time post stroke, mean (range) years	6.9 (3.2–19.3)	10.7 (3.9–48.2)
Fallers, %	28%	23%
Side of paresis, % left	77.7%	41.6%
Body mass index, kg/m^2	31.3 (6.2)	28.8 (7.5)
Chedoke McMaster Stroke Assessment (Foot + Leg subscale, / 14)	8.1 (2.7)	9.5 (2.2)
Cutaneous sensation -paretic foot, median (range)	4.31 (2.36–6.65)	4.00 (2.83–6.65)
Cane user, %	38.9%	50.0%
Ankle foot orthoses, %	27.8%	41.7%

For all tests, the significance level was set as $p = 0.05$. Effect sizes were calculated as the difference between the groups with respect to change divided by an estimate of the standard deviation of changes and classified as follows: <0.20= "trivial"; 0.20–0.49= "small"; 0.50–0.79= "moderate"; or ≥0.80= "large".

Results

There were 30 participants randomized, 18 in the PERT group and 12 in the VOL group, with 22 participants who completed training (Fig. 1). The number of participants in the two groups differed due to the unexpectedly high number of individuals randomized with lower motor recovery (73%). The clinical and demographic information for the groups is in Table 1. Only 5 participants

Table 2 Paretic leg estimated mean change in step characteristics over time by treatment group for lateral waist pull perturbation by medial and lateral steps

Variable	Perturbation Training Group		Voluntary Training Group		P-value for difference in change between groups	Effect size [3]
	Mean Change	P-value for change	Mean Change	P-value for change		
Medial Steps[1]						
Onset time (milliseconds)	21.67	0.64	26.56	0.4	0.93	-0.05
Step Clearance (% of height)	-0.0026	0.61	-0.0023	0.51	0.96	-0.04
Step Length (% of height)	-0.0056	0.86	0.02	0.35	0.49	-0.6
Step Velocity (m/s)	0.0274	0.72	0.0491	0.34	0.8	-0.17
Lateral Steps[2]						
Onset time (milliseconds)	-2.2	0.96	-95.88	0.1	0.12	0.29
Step Clearance (% of height)	0.0053	0.18	0.0034	0.55	0.75	0.25
Step Length (% of height)	0.0195	0.4	0.0155	0.67	0.92	0.06
Step Velocity (m/s)	0.0439	0.34	0.0541	0.45	0.9	-0.11

[1]Perturbation Group, based on 11 individuals of whom 2 had at least one medial step at both time points; Voluntary Group, based on 9 individuals of whom 6 had at least one medial step at both time points.

[2]Perturbation Group, based on 6 individuals of whom 3 had at least one lateral step at both time points; Voluntary Group, based on 5 individuals of whom only 1 had at least one lateral step at both time points.

[3]Difference in the mean change between groups divided by an estimate of the SD of change (based on the pooled estimate from those who had observations at both time points).

Table 3 Non-paretic leg estimated mean change in step characteristics over time by treatment group for lateral waist pull perturbation by medial and lateral steps

Variable	Perturbation Training Group		Voluntary Training Group		P-value for difference in change between groups	Effect size [3]
	Mean Change	P-value for change	Mean Change	P-value for change		
Medial Steps[1]						
Onset time (milliseconds)	-60.91	0.16	-45.05	0.23	0.77	-0.08
Step Clearance (% of height)	-0.0021	0.6	-0.0021	0.55	0.99	0
Step Length (% of height)	0.0026	0.8	0.0061	0.52	0.79	-0.08
Step Velocity (m/s)	0.0023	0.92	0.0227	0.57	0.73	-0.1
Lateral Steps[2]						
Onset time (milliseconds)	-89.55	***0.0051***	-3.3	0.93	***0.044***	-0.66
Step Clearance (% of height)	0.0089	***0.0017***	0.0057	0.1	0.43	0.18
Step Length (% of height)	0.0271	***0.0024***	0.0311	***0.0095***	0.77	-0.09
Step Velocity (m/s)	0.046	***0.026***	0.091	***0.0019***	0.18	-0.44

[1]Perturbation Training Group, based on 13 individuals, 6 had at least one medial step at both time points; Voluntary Training Group, based on 9 individuals, 8 had at least one medial step at both time points.

[2]Perturbation Training Group, based on 12 individuals, 7 had at least one lateral step at both time points; Voluntary Training Group, based on 9 individuals, 3 had at least one lateral step at both time points.

[3]Difference in the mean change between groups divided by an estimate of the SD of change (based on the pooled estimate from those who had observations at both time points).

(PERT=2, VOL=3) took crossover steps at both testing sessions. Hence, the analysis focused on lateral and medial steps.

Lateral waist pull perturbation

Paretic steps For the paretic leg, 79.3% of the steps were medial, and 20.7% were lateral steps at baseline. Post-training, 37% of the steps were medial steps, and 63% were lateral steps. There was a significant increase in the number of paretic lateral steps in the PERT group (0.048) and a trend for lateral steps to increase in the VOL group ($P=0.088$). There was no significant difference from baseline to post-intervention between ($P\geq0.12$) or within groups ($P\geq0.10$) for the medial or lateral step measure (Table 2).

Non-paretic steps No significant between or within-group differences in the medial step measure were found (Table 3). There was a significant difference between groups in the lateral step onset time, with the PERT group initiating the step faster than the VOL group after training ($P=0.044$; ES= -0.66; Table 3). The PERT group also had a within-group difference (baseline to post-intervention) in the lateral step with a faster step initiation time ($P=0.0051$), larger step clearance ($P=0.0017$), larger step length ($P=0.0024$), and faster step velocity ($P=0.026$) after training (Table 3). There was a within-group difference in the VOL group in the lateral step with a larger step length ($P=0.0095$) and faster step velocity ($P=0.0019$) after training (Table 3).

Lateral voluntary step

Paretic leg There were no significant changes between or within the paretic leg after training for either group. However, there was a trend for an increased step velocity in the PERT group from baseline to post-intervention ($P=0.084$; Table 4).

Table 4 Paretic and non-paretic estimated mean change in various measures over time, by treatment group for voluntary steps

Variable	Perturbation Training Group		Voluntary Training Group		P-value for difference in change between groups	Effect size [1]
	Mean Change	P-value for change	Mean Change	P-value for change		
Paretic Side						
Onset time (milliseconds)	-58.2	0.27	-26.5	0.64	0.68	-0.4
Step Clearance (% of height)	0.0016	0.52	0.0019	0.49	0.94	-0.03
Step Length (% of height)	0.0211	0.1	0.0226	0.1	0.93	-0.03
Step Velocity (m/s)	0.0384	0.084	0.0331	0.16	0.86	0.07
Non-Paretic Side						
Onset time (milliseconds)	-90.41	***0.041***	-49.05	0.29	0.5	-0.28
Step Clearance (% of height)	0.0027	0.28	0.0017	0.52	0.78	0.11
Step Length (% of height)	0.0153	0.15	0.014	0.23	0.93	0.04
Step Velocity (m/s)	0.035	0.059	0.0303	0.13	0.85	0.15

[1]Difference in the mean change between groups divided by an estimate of the SD of change (based on the pooled estimate from those who had observations at both time points).

Non-paretic leg The PERT group presented a within-group difference for the step onset time after training ($P=0.041$; Table 4). There was also a trend to execute a step faster (step velocity) for the PERT group after training ($P=0.059$; Table 4).

Clinical measures

The CB&M scale showed a main effect of time ($P<0.001$) with an increase after training in the PERT (base 33.0±17.5, post 37.0±18.9; $P=0.06$) and VOL (base 31.0±11.0, post 37.1±9.4; $P<0.001$) group, but no differences between groups. There was also a main effect of time ($P<0.001$) with a significant increase in the ABC in the PERT (base 76.1±10.2, post 84.1±10.8, $P=0.005$) and VOL (base 76.5±12.7, post 83.2±9.5, $P=0.022$) groups after training, with no differences between groups.

Discussion

The pilot study compared the effects of lateral perturbation-induced step training and lateral voluntary step training on protective stepping performance in chronic stroke. During the lateral waist pull perturbation, we found that the lateral step with the non-paretic leg resulted in a significantly faster step initiation time after training in the PERT group than in the VOL group. In the PERT group, training also significantly improved step length, step clearance, and step velocity when the non-paretic leg took the first step. Similarly, the VOL group had increases in step length and step velocity for the non-paretic lateral step. No changes were observed for the medial step or the paretic leg for either group. Although there were no changes in the paretic stepping performance, the number of paretic lateral steps increased after training. Surprisingly, fewer changes were detected during the voluntary step, with only a trend for the non-paretic leg to initiate a step faster in the PERT training group. For the medial step, there was no change for either group, which may be limited in the ability to demonstrate improvements given the limited distance the foot can move toward the supporting leg. Finally, both training groups significantly improved in the Community Balance & Mobility Scale and Activities Specific Balance. An exercise to improve stepping performance with external perturbations might provide more benefits than training with voluntary steps. However, the interventions had similar effects on clinical balance measures.

The PERT group demonstrated more improvements in stepping performance during the lateral waist-pull perturbation with the non-paretic leg than the VOL group. As one would expect, the PERT group showed more improvements in stepping performance based on the principle of training specificity, where adaptations are based on the components of the exercise performed (i.e., frequency, mode, and/or duration) [42]. The PERT group received training in repetitive exposure to external perturbations, which likely influenced the improvements in stepping performance in this group. However, the same principle of training specificity did not occur with the paretic leg since there was no difference between or within groups after training. Interestingly, the step velocity and length emphasized during the VOL group training transferred to the stepping performance during the waist-pull perturbation. More concerning was the lack of improvements in the voluntary steps in the VOL group, which would be expected based on training specificity. It may result from the unwillingness or reluctance to risk a loss of balance during a voluntary step test [43]. Therefore, the step training without perturbations, as performed in the present study, may not be as effective for overcoming the concerns of falling when moving the center of mass outside of the base of support.

When the paretic leg initiated the first step during the lateral waist-pull perturbation, neither group demonstrated improvement in this study. Previous research showed that individuals after a stroke tend to initiate a step with the non-paretic leg more frequently than the paretic leg [44, 45]. In this study, the potentially fewer steps with the paretic limb may have limited the training effects for the paretic limb. An induced waist-pull system that requires fast-stepping responses might be a limitation with training paretic limb responses. Individuals after a stroke might feel safer performing a step with the non-paretic leg since they have better control of this leg. In a previous study, when individuals after a stroke had their non-paretic leg blocked and were exposed to an induced forward loss of balance, they still tried to step with the non-paretic leg even though it potentially put them at an even greater risk of falling [44]. Thus, more extended training periods may be necessary to improve confidence in using the paretic leg more often.

Stepping characteristics scaled to the temporal and spatial displacement of the body's center of mass are essential for balance recovery. Previous work has demonstrated that individuals after stroke take smaller steps [30, 46, 47], have a reduced step clearance [30] and are slower to initiate a step [30, 47] compared to controls. Impaired stepping characteristics can distinguish fallers from non-fallers, with fallers being slower to initiate a step with the paretic and non-paretic leg than individuals who do not fall [48]. In contrast, one study showed no difference in step length and step initiation between individuals after a stroke at different fall thresholds (low vs. medium vs. high) [49]. Thus, step characteristics may be important for balance recovery and avoiding falls [50]. In this study, the PERT group improved when the non-paretic leg initiated the first step during the lateral waist-pull perturbation. Understanding the underlying mechanisms contributing to a slower step initiation may be crucial to reducing falls in this population. Finally, even though we did not show any changes in the paretic leg stepping performance, there was an increase in the number of lateral steps in the PERT group and a trend in the VOL Group. The shift in step types with the paretic limb may be just as important as the step characteristics, though further research would be necessary to understand the impacts on balance recovery and falls.

After a stroke, there are limitations in the ability to generate fast movements with the paretic limb, as evidenced by the inability to increase torque as velocity increases [51–53]. It may be expected that voluntary training might improve voluntary step performance, particularly emphasizing speed of movement. However, even though the training in the VOL group focused on speed of movement, this did not translate into faster voluntary choice reaction steps for the paretic or non-paretic leg. Nonetheless, the PERT group initiated the voluntary step quicker with the non-paretic leg during the voluntary choice reaction step after the perturbation training. Previous studies showed that training volume, intensity, and/or frequency [54–56] play an important role in training adaptations. It is clear the training characteristics of the VOL training used here were not sufficient to induce the necessary adaptations to improve step performance even though the speed of movement and step length were focused on during the training. It was expected training with exercises emphasizing speed in the VOL group would show improvements. We previously found that after a single session of isokinetic isolated joint movements, velocity increased in ankle dorsiflexion and knee extension of the paretic limb [57]. Similar to our study, improvements in movement speed were only found in the non-paretic leg during a single session of self-induced steps [58]. Yet, this was not the case in the present study. The control of standing balance may limit the ability of the paretic limb to generate quicker movements than if performed in sitting. The PERT group demonstrated a quicker non-paretic step initiation time which appears to improve the compensatory strategy by enhancing the non-paretic stepping performance rather than directly improving the impaired stepping performance of the paretic limb. In order to improve the impair stepping performance of the paretic limb it may be necessary to minimize the compensatory action through forced paretic limb use.

Clinical balance outcome measures

Interestingly, both training groups improved their performance during the clinical assessments. Similarly, other studies found no difference when comparing perturbation training to conventional physical therapy, with both groups demonstrating an improved performance on clinical balance outcome measures, such as the mini-BEST, Timed Up and Go Test, and Berg Balance Scale [49, 59, 60]. However, it is intriguing that the VOL group still increased its performance during the clinical assessment with no increase in stepping performance during the voluntary steps. This may indicate that an isolated single voluntary step test performed as quickly as possible may capture different aspects of balance than measured in the balance outcome measures. The step test placed an emphasis on speed, where most balance measures are a self-paced task. Most balance outcome measures evaluate self-initiated and self-paced voluntary movements and do not test balance control in response to external balance perturbations or movements that require quick responses. Given the importance of external perturbations to balance control and falls, clinical tests that include components to assess reactive balance control, such as the Mini-BESTest, are essential and might provide more accurate information about the individual's ability to recover balance during unexpected situations. Alternatively, the choice reaction step test for the voluntary test used in this study may require other mechanisms that are impaired but not addressed in this study, such as cognitive deficits that limit planning and choice to initiate a step that was not targeted in the voluntary training.

Study limitations, strengths, and recommendations

We demonstrated for the first time that lateral step training of induced perturbations might provide greater improvements in step characteristics for balance recovery than voluntary step training in individuals post-stroke. However, caution should be taken with these results. The changes were demonstrated only during the perturbation stepping responses, and they did not improve during voluntary steps, which is vital for overcoming an obstacle and/or stair ascending/descending. Thus, it is still unknown whether the training interventions used in the present study would improve step performance in different situations, such as during walking, compared to what we evaluated in this study. However, we expect the control of the center of mass-base of support relationship during a loss of balance will be similar while standing as in motion. Future research to examine the transferability of transfers would be necessary to verify. Furthermore, the lack of improvement when using voluntary step training is a concern. Future studies should try different voluntary stepping configurations to identify optimum training parameters to improve step performance. The laboratory-based perturbation system limits the translation of the findings into a home-based environment. Moreover, we could not determine which factors were related to the performance improvement we identified in the present study (e.g., neuromuscular activation rate of force production, among others). Hence, further investigation is warranted to identify factors contributing to the stepping performance. Finally, the number of lateral steps the participants took limited the analysis for comparing the lateral steps. We did not find differences in the number of lateral steps from the first to the last training session [41]. The ability to take a lateral step is a significant limitation that should be considered when training with lateral perturbations in stroke. Methods encouraging lateral steps, particularly with the paretic limb, would be necessary to improve stepping responses to lateral perturbations.

Conclusions

In conclusion, we demonstrated that individuals after a stroke, whether trained with lateral perturbations or voluntary steps, can improve the non-paretic step length and step velocity during external balance perturbations. Thus, when speed and step length are emphasized, there is a potential for transferring voluntary lateral step training improvements to the stepping performance in response to external lateral perturbations. However, only the external perturbation training group demonstrated a faster step initiation time with the non-paretic leg. More importantly, neither group demonstrated changes in the voluntary step performance or when initiating a step with the paretic limb in either stepping assessment. Thus, understanding the mechanisms contributing to this impaired performance may be necessary for developing interventions to improve the performance during the voluntary steps, especially for the paretic leg.

Acknowledgements

VLG, MWR, MF, and SMW contributed to the conceptualization and methodology. VLG, SMW and MF were responsible for data collection. MBL, LM, and VLG conducted the data analysis and statistics. MWR, and SMW contributed to supervising the study. All authors wrote, reviewed, and approved the final manuscript.

Author contributions

VLG, MWR, and SMW contributed to the conceptualization and methodology. VLG and MF were responsible for data collection. MBL, MF, LM, and VLG conducted the data analysis and statistics. MWR, and SMW contributed to supervising de study. All authors wrote, reviewed, and approved the final manuscript.

Funding

This study was developed under a grant from the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR) (H133P100014, H133F140027). NIDILRR is a center within the Administration for Community Living (ACL), Department of Health and Human Services (HHS). The contents of this publication do not necessarily represent the policy of NIDILRR, ACL, HHS, and you should not assume endorsement by the federal government. This study was also supported by the American Heart Association (14CRP19880025) and The National Institute on Aging Claude D. Pepper Older Americans Independence Center (P30-AG028747).

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The Ethics Committee of the University of Maryland Baltimore approved all protocols. All participants provided written confirmed consent according to the Declaration of Helsinki

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 19 February 2024 / Accepted: 21 October 2024
Published online: 05 November 2024

References

1. Centers for Disease C, Prevention. Prevalence of stroke–United States, 2006–2010. MMWR Morb Mortal Wkly Rep. 2012;61(20):379–82.
2. Benjamin EJ, Blaha MJ, Chiuve SE, et al. Heart Disease and Stroke Statistics-2017 update: a Report from the American Heart Association. Circulation. 2017;135(10):e146–603. https://doi.org/10.1161/CIR.0000000000000485.
3. Garland SJ, Gray VL, Knorr S. Muscle activation patterns and postural control following stroke. Motor Control. 2009;13(4). https://doi.org/10.1123/mcj.13.4.387.
4. Friedman SM, Munoz B, West SK, Rubin GS, Fried LP. Falls and fear of falling: which comes first? A longitudinal prediction model suggests strategies for primary and secondary prevention. J Am Geriatr Soc. 2002;50(8):1329–35. https://doi.org/10.1046/j.1532-5415.2002.50352.x.
5. Yardley L, Smith H. A prospective study of the relationship between feared consequences of falling and avoidance of activity in community-living older people. Gerontologist. 2002;42(1):17–23. https://doi.org/10.1093/geront/42.1.17.

6. Batchelor FA, Mackintosh SF, Said CM, Hill KD. Falls after stroke. Int J Stroke. 2012;7(6):482–90. https://doi.org/10.1111/j.1747-4949.2012.00796.x.
7. Persson CU, Hansson PO, Sunnerhagen KS. Clinical tests performed in acute stroke identify the risk of falling during the first year: postural stroke study in Gothenburg (POSTGOT). J Rehabil Med. 2011;43(4):348–53. https://doi.org/10.2340/16501977-0677.
8. Weerdesteyn V, de Niet M, van Duijnhoven HJ, Geurts AC. Falls in individuals with stroke. J Rehabil Res Dev. 2008;45(8):1195–213.
9. Lim JY, Jung SH, Kim WS, Paik NJ. Incidence and risk factors of poststroke falls after discharge from inpatient rehabilitation. PM R. 2012;4(12):945–53. https://doi.org/10.1016/j.pmrj.2012.07.005.
10. Watanabe Y. Fear of falling among stroke survivors after discharge from inpatient rehabilitation. Int J Rehabil Res. 2005;28(2):149–52.
11. Munford D, Gunn H. What are the perceptions and experiences of falls amongst people with stroke who live in the community? Disabil Rehabil. 2020;42(5):722–9. https://doi.org/10.1080/09638288.2018.1510047.
12. Salbach NM, Mayo NE, Wood-Dauphinee S, Hanley JA, Richards CL, Côté R. A task-orientated intervention enhances walking distance and speed in the first year post stroke: a randomized controlled trial. Clin Rehabil. 2004;18(5):509–19. https://doi.org/10.1191/0269215504cr763oa.
13. Cho KH, Lee KJ, Song CH. Virtual-reality balance training with a video-game system improves dynamic balance in chronic stroke patients. Tohoku J Exp Med. 2012;228(1):69–74. https://doi.org/10.1620/tjem.228.69.
14. Kim JH, Jang SH, Kim CS, Jung JH, You JH. Use of virtual reality to Enhance Balance and Ambulation in Chronic Stroke: a Double-Blind, randomized controlled study. Am J Phys Med Rehabil. 2009;88(9):693–701. https://doi.org/10.1097/PHM.0b013e3181b33350.
15. Van Peppen R, Kortsmit M, Lindeman E, Kwakkel G, Effects of visual, feedback therapy on postural control in bilateral standing after stroke. A systematic review. J Rehabil Med. 2006;38(1):3–9. https://doi.org/10.1080/16501970500344902.
16. De Haart M, Geurts AC, Dault MC, Nienhuis B, Duysens J. Restoration of weight-shifting capacity in patients with postacute stroke: a rehabilitation cohort study. Arch Phys Med Rehabil. 2005;86(4):755–62. https://doi.org/10.1016/j.apmr.2004.10.010.
17. Andersson P, Franzén E. Effects of weight-shift training on walking ability, ambulation, and weight distribution in individuals with chronic stroke: a pilot study. Top Stroke Rehabil. 2015;22(6):437–43. https://doi.org/10.1179/1074935715Z.00000000052.
18. Taylor-Piliae RE, Hoke TM, Hepworth JT, Latt LD, Najafi B, Coull BM. Effect of Tai Chi on physical function, fall rates and quality of life among older stroke survivors. Arch Phys Med Rehabil. 2014;95(5):816–24. https://doi.org/10.1016/j.apmr.2014.01.001.
19. Mansfield A, Inness EL, Wong JS, Fraser JE, McIlroy WE. Is impaired control of reactive stepping related to falls during inpatient stroke rehabilitation? Neurorehabilit Neural Repair. 2013;27(6):526–33. https://doi.org/10.1177/1545968313478486.
20. Pigman J, Reisman DS, Pohlig RT, Wright TR, Crenshaw JR. The development and feasibility of treadmill-induced fall recovery training applied to individuals with chronic stroke. BMC Neurol. 2019;19(1):102.
21. Van Duijnhoven HJR, Roelofs JMB, Den Boer JJ, et al. Perturbation-based balance training to improve step quality in the chronic phase after stroke: a proof-of-concept study. Front Neurol. 2018;9:1–12. https://doi.org/10.3389/fneur.2018.00980.
22. Schinkel-Ivy A, Huntley AH, Aqui A, Mansfield A. Does perturbation-based balance training improve control of reactive stepping in individuals with chronic stroke? J Stroke Cerebrovasc Dis. 2019;28(4):935–43. https://doi.org/10.1016/j.jstrokecerebrovasdis.2018.12.011.
23. Gray VL, Juren LM, Ivanova TD, Garland SJ. Retraining postural responses with exercises emphasizing speed poststroke. Phys Ther. 2012;92(7):924–34. https://doi.org/10.2522/ptj.20110432.
24. Roerdink M, Geurts AC, de Haart M, Beek PJ. On the relative contribution of the paretic leg to the control of posture after stroke. Neurorehabil Neural Repair. 2009;23(3):267–74. https://doi.org/10.1177/1545968308323928.
25. Hsiao H, Gray VL, Creath RA, Binder-Macleod SA, Rogers MW. Control of lateral weight transfer is associated with walking speed in individuals post-stroke. J Biomech. 2017;60. https://doi.org/10.1016/j.jbiomech.2017.06.021.
26. Andersson AG, Seiger A, Appelros P. Hip fractures in persons with stroke. Stroke Res Treat. 2013;2013:954279. https://doi.org/10.1155/2013/954279.
27. Kirker SG, Simpson DS, Jenner JR, Wing AM. Stepping before standing: hip muscle function in stepping and standing balance after stroke. J Neurol Neurosurg Psychiatry. 2000;68(4):458–64.
28. Hedman LD, Rogers MW, Pai YC, Hanke TA. Electromyographic analysis of postural responses during standing leg flexion in adults with hemiparesis. Electroencephalogr Clin Neurophysiol. 1997;105(2):149–55.
29. Holt RR, Simpson D, Jenner JR, Kirker SGB. Ground reaction force after a sideways push as a measure of balance in recovery from stroke. Clin Rehabil. 2000;2155(00):88–95.
30. Gray VL, Yang C, ling, Fujimoto M, McCombe Waller S, Rogers MW. Stepping characteristics during externally induced lateral reactive and voluntary steps in chronic stroke. Gait Posture. 2019;71:198–204. https://doi.org/10.1016/j.gaitpost.2019.05.001.
31. Pidcoe PE, Rogers MW. A closed-loop stepper motor waist-pull system for inducing protective stepping in humans. J Biomech. 1998;31(4):377–81. https://doi.org/10.1016/S0021-9290(98)00017-7.
32. Hilliard MJ, Martinez KM, Janssen I, et al. Lateral balance factors predict future falls in community-living older adults. Arch Phys Med Rehabil. 2008;89(9):1708–13. https://doi.org/10.1016/j.apmr.2008.01.023.
33. Yungher DA, Morgia J, Bair WN, et al. Short-term changes in protective stepping for lateral balance recovery in older adults. Clin Biomech (Bristol Avon). 2012;27(2):151–7. https://doi.org/10.1016/j.clinbiomech.2011.09.003.
34. Martinez KM, Mille ML, Zhang Y, Rogers MW. Stepping in persons poststroke: comparison of voluntary and perturbation-induced responses. Arch Phys Med Rehabil. 2013;94(12):2425–32. https://doi.org/10.1016/j.apmr.2013.06.030.
35. Eames M, Cosgrove A, Baker R. Comparing methods of estimating the total body centre of mass in three-dimensions in normal and pathological gaits. Hum Mov Sci. 1999;18:637–46. https://doi.org/10.1016/S0167-9457(99)00022-6.
36. Knorr S, Brouwer B, Garland SJ. Validity of the community balance and mobility scale in community-dwelling persons after stroke. Arch Phys Med Rehabil. 2010;91(6):890–6. https://doi.org/10.1016/j.apmr.2010.02.010.
37. Salbach NM, Mayo NE, Robichaud-Ekstrand S, Hanley JA, Richards CL, Wood-Dauphinee S. Balance self-efficacy and its relevance to physical function and perceived health status after stroke. Arch Phys Med Rehabil. 2006;87(3):364–70. https://doi.org/10.1016/j.apmr.2005.11.017.
38. Pang MY, Eng JJ. Determinants of improvement in walking capacity among individuals with chronic stroke following a multi-dimensional exercise program. J Rehabil Med. 2008;40(4):284–90. https://doi.org/10.2340/16501977-0166.
39. Gowland C, Stratford P, Ward M, et al. Measuring physical impairment and disability with the Chedoke-McMaster Stroke Assessment. Stroke. 1993;24(1):58–63.
40. Roll R, Kavounoudias A, Roll JP. Cutaneous afferents from human plantar sole contribute to body posture awareness. NeuroReport. 2002;13(15):1957–61.
41. Gray V, Westlake K. The feasibility of lateral externally-Induced perturbation training in fall Prevention after Stroke. Int J Cerebrovasc Dis Stroke. 2024;7(1). https://doi.org/10.29011/2688-8734.100174.
42. Hawley JA. Specificity of training adaptation: time for a rethink? Perspectives. J Physiol. 2008;586(1):1–2. https://doi.org/10.1113/jphysiol.2007.147397.
43. Dettmann MA, Linder MT, Sepic SB. Relationships among walking performance, postural stability, and functional assessments of the hemiplegic patient. Am J Phys Med. 1987;66(2):77–90.
44. Mansfield A, Inness EL, Lakhani B, McIlroy WE. Determinants of limb preference for initiating compensatory stepping poststroke. Arch Phys Med Rehabil. 2012;93(7):1179–84. https://doi.org/10.1016/j.apmr.2012.02.006.
45. Lakhani B, Mansfield A, Inness EL, McIlroy WE. Compensatory stepping responses in individuals with stroke: a pilot study. Physiother Theory Pract. 2011;27(4):299–309. https://doi.org/10.3109/09593985.2010.501848.
46. Handelzalts S, Steinberg-Henn F, Levy S, Shani G, Soroker N, Melzer I. Insufficient balance recovery following unannounced external perturbations in persons with stroke. Neurorehabil Neural Repair. 2019;33(9):730–9. https://doi.org/10.1177/1545968319862565.
47. Salot P, Patel P, Bhatt T. Reactive balance in individuals with chronic stroke: biomechanical factors related to Perturbation-Induced Backward falling. Phys Ther. 2016;96(3):338–47. https://doi.org/10.2522/ptj.20150197.
48. Gray VL, Fujimoto M, Rogers MW. Lateral perturbation-Induced and Voluntary Stepping in fallers and nonfallers after Stroke. Phys Ther. 2020;100(9):1557–67. https://doi.org/10.1093/ptj/pzaa109.
49. Handelzalts S, Kenner-Furman M, Gray G, Soroker N, Shani G, Melzer I. Effects of perturbation-based balance training in subacute persons with stroke: a randomized controlled trial. Neurorehabilit Neural Repair. 2019;33(3):213–24. https://doi.org/10.1177/1545968319829453.

50. Okubo Y, Schoene D, Caetano MJ, et al. Stepping impairment and falls in older adults: a systematic review and meta-analysis of volitional and reactive step tests. Ageing Res Rev. 2021;66:101238. https://doi.org/10.1016/j.arr.2020.101238.
51. Bohannon RW. Relative decreases in knee extension Torque with increased knee extension velocities in stroke patients with Hemiparesis. Phys Ther. 1987;67(8):1218–20. https://doi.org/10.1093/ptj/67.8.1218.
52. Da Vies JM, Mayston MJ, Newham DJ. Electrical and mechanical output of the knee muscles during isometric and isokinetic activity in stroke and healthy adults. Disabil Rehabil. 1996;18(2):83–90. https://doi.org/10.3109/09638289609166022.
53. Lum PS, Patten C, Kothari D, Yap R. Effects of velocity on maximal torque production in poststroke hemiparesis. Muscle Nerve. 2004;30(6):732–42. https://doi.org/10.1002/mus.20157.
54. Colquhoun RJ, Gai CM, Aguilar D, et al. Training volume, not frequency, indicative of maximal strength adaptations to Resistance Training. J Strength Conditioning Res. 2018;32(5):1207–13. https://doi.org/10.1519/JSC.0000000000002414.
55. Mangine GT, Hoffman JR, Gonzalez AM, et al. The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. Physiol Rep. 2015;3(8):e12472. https://doi.org/10.14814/phy2.12472.
56. Wernbom M, Augustsson J, Thomeé R. The influence of frequency, intensity, volume and Mode of Strength Training on whole muscle cross-sectional area in humans. Sports Med. 2007;37(3):225–64. https://doi.org/10.2165/00007256-200737030-00004.
57. Gray VL, Ivanova TD, Garland SJ. A single session of open kinetic chain movements emphasizing speed improves speed of movement and modifies postural control in stroke. Physiother Theory Pract. 2016;32(2):113–23. https://doi.org/10.3109/09593985.2015.1110848.
58. Gray VL, Ivanova TD, Garland SJ. Effects of fast functional Exercise on muscle activity after stroke. Neurorehabil Neural Repair. 2012;26(8):968–75. https://doi.org/10.1177/1545968312437944.
59. Kumar C, Pathan N. Effectiveness of manual perturbation exercises in improving balance, function and mobility in stroke patients: a randomized controlled trial. J Novel Physiotherapies. 2016;6(2):1000284. https://doi.org/10.4172/2165-7025.1000284.
60. Mansfield A, Aqui A, Danells CJ, et al. Does perturbation-based balance training prevent falls among individuals with chronic stroke? A randomised controlled trial. BMJ Open. 2018;8(8):1–12. https://doi.org/10.1136/bmjopen-2018-021510.

Publisher's note