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Research Article

The Feasibility of Lateral Externally-Induced Perturbation Training in Fall Prevention after Stroke

Vicki L Gray*, Kelly P Westlake

•Department of Physical Therapy and Rehabilitation Science, School of Medicine, University of Maryland, Baltimore, USA

***Corresponding author:** Vicki L Gray, Department of Physical Therapy and Rehabilitation Science, University of Maryland School of Medicine, Baltimore, USA

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Abstract

Background: Many balance and falls interventions mainly focus on training with voluntarily initiated movements. External perturbation training may be necessary for reducing falls since falls are equally likely to occur from either. **Objectives:** To determine the effects and generalizability of lateral perturbation training on paretic limb stepping after stroke. Whether sensorimotor impairments impact the ability to initiate paretic leg steps. **Methods:** Seventeen individuals >6 months post-stroke participated in a 6-week lateral perturbation training. Percent of paretic leg first steps and step type before and after training during the lateral treadmill and lateral waist-pull perturbation were recorded. Motor recovery and paretic foot cutaneous sensation were assessed. **Results:** Twelve participants (9 male/ 3 female) were recruited from a stroke registry with a mean age of 63.4 years (range 54-72) and completed treadmill perturbation training. They increased the percent of paretic leg steps. After training, fewer medial steps were taken during treadmill perturbations ($P<0.02$), translating to more lateral steps ($P=0.04$) and fewer medial steps ($P=0.01$) during the waist-pull perturbation. Significant correlations were found between foot cutaneous sensation and paretic steps taken during the treadmill perturbation ($r_s=-0.70$, $P=0.01$) and motor recovery ($r_s=0.75$, $P=0.005$) and paretic steps taken during the waist-pull perturbation. **Conclusions:** Transitioning from medial to lateral steps may be a more effective balance recovery strategy. Although, sensorimotor impairments may limit stepping with the paretic leg.

Keywords: Stroke; Stepping; Reactive; Balance; Falls

Introduction

After a stroke, many individuals have residual sensory and motor deficits that negatively impact balance [1] and increase their fall risk [2]. With falls being the most common secondary complication, up to 73% of individuals experience a fall in the first six months after a stroke [3-6]. The consequences of falling can be devastating, resulting in fractures and other fall-related injuries [7,8]. In some cases, individuals develop a fear of falling accompanied by activity avoidance [9]. These behavioral changes can lead to deconditioning, reduced strength, and further declines in balance beyond the stroke-related deficits. Unfortunately, despite the availability of balance interventions, there is currently insufficient evidence to support a fall prevention program in stroke [10,11]. Nevertheless, the American Stroke Association guidelines for stroke rehabilitation continue to recommend formal fall prevention programs during hospitalization [12]. Thus, developing effective interventions in stroke is important.

Current balance and fall prevention programs primarily focus on voluntarily initiated movements [13,14]. Interventions that focus on practicing self-initiated voluntary movements engage feedforward mechanisms relying on cortical and subcortical networks to predict balance disruptions in advance of the movement [15]. However, with these methods on their own, the fall rate remains high regardless of the time since the stroke [2,16]. Evidence suggests falls are equally likely to happen during voluntary self-initiated movements, as during unexpected perturbations to balance [17]. Unexpected balance perturbations require the quick initiation and execution of fall prevention measures (i.e., protective step). These measures generally are based on feedback mechanisms [18,19] involving predominantly brainstem and spinally mediated pathways. Thus, incorporating both aspects of balance perturbations into a rehabilitation program may be necessary to reduce falls after a stroke.

After a stroke, unilateral sensory and motor deficits are common, impairing lateral balance control, which is evident with the doubling of hip fractures, particularly on the paretic side [20]. The muscles (hip abductors/adductors) controlling lateral balance are impaired and take longer to respond, producing less muscle activity, resulting in a prolonged time to re-establish balance stability [19,21-23]. The nature of the unilateral deficits leads to compensations in which less weight is distributed toward the paretic limb in standing [24,25], and walking [26]. The reluctance or inability to transfer weight onto the paretic limb decreases the limits of stability on the paretic side (i.e., distance one can lean before losing their balance) [27]. As a result, protective steps used to re-establish balance are initiated at smaller perturbations than healthy controls [19,28]. Given the unilateral deficits and unwillingness to use the paretic limb, directly training lateral balance control may be necessary. Not all balance disturbances may allow for an initial non-paretic response. Without training the paretic limb, a response with the non-paretic limb could be inappropriate and potentially detrimental to recovering balance successfully [29].

At present, it is unclear whether lateral external perturbation training improves the ability to recover balance. More importantly, whether the improvements generalize to other mechanisms used to induce external perturbations. Therefore, the purpose of this single group pre-post design was to examine the effects of lateral perturbation training on paretic limb stepping and whether the improvements would generalize to a lateral waist-pull perturbation and reduce falls in community-dwelling individuals with chronic stroke. A secondary aim was to understand whether sensory and motor impairments interfere with the ability to initiate a first step with the paretic leg in response to a lateral perturbation.

Methods

Participants

Individuals >50 years of age with hemiparesis from a stroke that occurred at least six months prior to study participation were recruited. The eligibility criteria included the ability to stand 5 minutes independently without support and the ability to walk 3 meters with or without a gait aid. The exclusion criteria included those individuals with neurological conditions other than a stroke or a medical condition that precluded their ability to exercise. The participants were recruited from a stroke registry in Baltimore, MD, in the United States. The study was approved by the University of Maryland School of Medicine Institutional Review Board, and all participants provided written informed consent before participation.

Training

Training consisted of external perturbations to standing balance induced by a computer-controlled treadmill (ActiveStep®, Simbex, Lebanon, NH) directed laterally. Training occurred for 45 minutes three times a week for six weeks (18 sessions). An assessment during the first training session determined the starting perturbation magnitude. The assessment began at the lowest perturbation level and progressed to the next level until the step threshold was determined. The step threshold, defined as the lowest perturbation level that a protective step was used to recover balance, was the level used to start training. The levels were based on velocity and displacement (Figure 1). As the perturbation level increased in velocity, the acceleration and deceleration phase changed (Table 1). In order to reduce the participant anticipating the impending perturbation, the perturbation was varied by three parameters: velocity (three velocities within one level), perturbation direction (paretic, non-paretic), and time delay at the start of the trial (range 0.5–1.75s). 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.

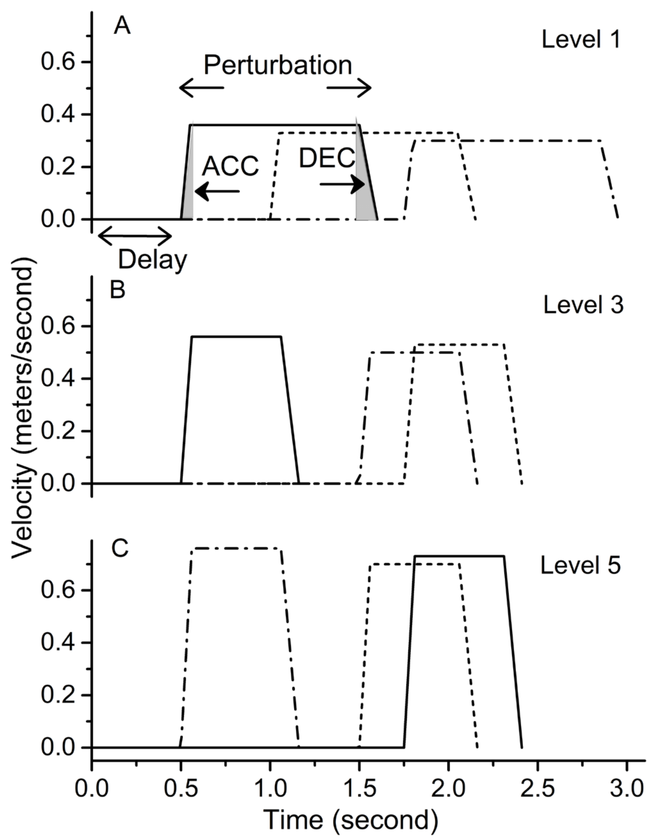

Figure 1: Select perturbation profiles used for the treadmill perturbation training, Level 1 (A), Level 3 (B), and Level 5 (C).

Each perturbation level has three different perturbation profiles (solid line, dashed line, dash-dotted line) varied by velocity and delay (onset of perturbation). Panel A, the delay was the time before the start of the trial (range 0.5 - 1.75 seconds) and the perturbation phases, including the acceleration phase (ACC) perturbation at a constant velocity, was the displacement and deceleration phase (DEC). The velocity and delay was the varying component of the perturbation profile within levels and among levels.

Level	Velocity (cm/s)	Displacement (cm)	Acceleration (cm/s^2)	Deceleration (cm/s^2)
1	30.0 – 36.0	32.0-34.0	600.0-720.0	300.0-340.0
2	40.0 – 46.0	34.0-34.5	800.0-920.0	400.0-460.0
3	50.0 – 56.0	34.0-35.0	1000.0-1120.0	500.0-560.0
4	60.0 – 66.0	36.0-38.0	1200.0-1320.0	600.0-660.0
5	70.0 – 76.0	35.0-38.0	1167.0-1267.0	700.0-760.0
6	80.0 – 86.0	40.0-42.0	1333.0-1433.0	800.0-860.0
7	90.0 – 96.0	54.0-58.0	1500.0-1600.0	900.0-960.0

Table 1: Range of training parameters at each level for the Active Step.

Each training session consisted of a maximum of 80 perturbations, with the number of trials in each direction (paretic, non-paretic) being equal. The perturbations were predominantly induced in the lateral direction, though 20% were in the anterior-posterior direction.

Treadmill perturbation assessment

For training sessions 1 and 18, the randomized lateral perturbation trials were used for analysis. The participants had their standing balance perturbed by translating the treadmill in the right or left direction. The perturbation treadmill has a unique biomechanical feature, whereby the treadmill moves the base of support outside the body's center of mass. The perturbation passively loads the leg of which the perturbation is directed, requiring unloading the passively loaded leg to take a lateral step. Alternatively, the passively unloaded leg could initiate stepping towards the loaded leg (medial step) or crossover step (crossover step) by stepping in front or behind the loaded leg. The percent of paretic limb steps taken was calculated by dividing the number of trials the paretic limb was used as the first recovery step by the total number of lateral perturbation trials and multiplying by 100 for each participant. The step type (medial, lateral, crossover) taken with the paretic leg was recorded for each session. For each step type, a percentage was calculated by dividing the number of each step type (medial, lateral, crossover) by the total number of lateral perturbation trials multiplying by 100 for each participant.

Lateral waist-pull perturbation

The participants were exposed to 18 lateral waist-pull perturbation trials that perturbed standing balance using a custom-built motor-driven waist-pull device [30]. The lateral waist-pull perturbations were performed before (baseline) and within one week after training (post). The trials consisted of three pulls to the paretic and three non-paretic side pulls at three perturbation magnitudes. The perturbation direction of the waist-pull presented randomly contained perturbation magnitudes based on velocity (v) and displacement (d) as follows: Level 1 v=27.0 cm/s d=12.1 cm, Level 2 v=36.0 cm/s d=15.7 cm, and Level 3 v=45cm/s d=19.3 cm (Figure 2). Based on previous studies, the levels chosen are known to induce stepping responses in older adults [31,32] and individuals after stroke [33]. Verbal instructions to all participants were to "respond naturally and, if necessary, prevent yourself from falling." Similar to the treadmill perturbation, the lateral waist-pull has a unique biomechanical feature. The perturbation passively loads the leg used to take a lateral step, except the lateral waist-pull moves the center of mass outside the base of support.

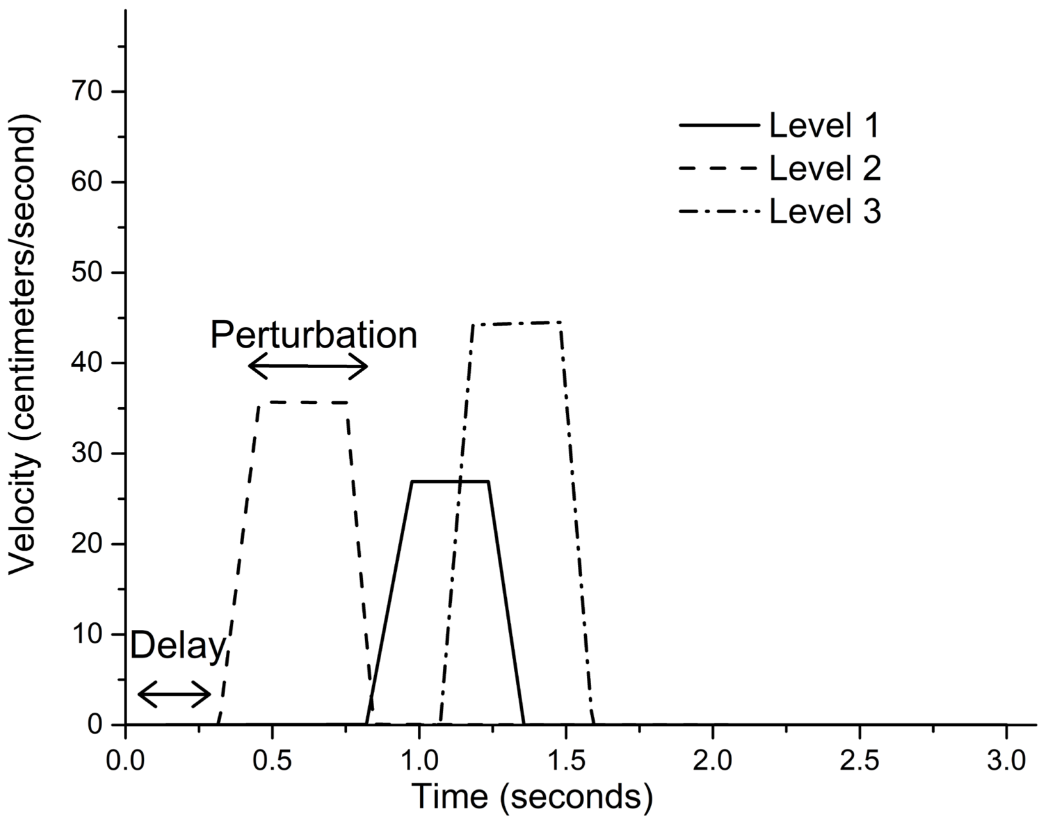

Figure 2: Waist-pull perturbation profiles for baseline and post-training assessment for Level 1 (solid line), Level 2 (dashed line), and Level 3 (dash-dotted line). The delay was the time before the start of the trial.

Participants wore a safety harness and stood in their comfortable stance width on two adjacent force platforms (Advanced Mechanical Technology Inc., Watertown, MA, USA). Before starting each trial, the weight distribution beneath each limb was controlled by visually monitoring the ground reaction forces obtained from each force plate (recorded for 7 s and sampled at 600 Hz). If necessary, participants received verbal cues to shift their weight, so there was an even distribution of weight under each leg. Kinematic data recorded with a 10-camera motion analysis system (Vicon, Oxford, UK) captured data from a reflective marker affixed bilaterally over the lateral malleoli (recorded for 7s and sampled at 120Hz). The percent of paretic leg use for the first recovery step, whether lateral, crossover, or medial, and the percent of paretic leg use for lateral steps alone were recorded and later verified by the kinematic and kinetic data.

For training and testing assessments, the participants wore their shoes during all sessions.

Clinical tests

Clinical tests were conducted at baseline and immediately following training on the same day as the lateral waist-pull perturbations. The Activities-specific Balance Confidence (ABC), a validated measure of self-reported balance confidence in individuals after stroke [34]. The ABC measures balance confidence during tasks in the home and outside the home. The participant rates their confidence on 16 tasks from 0% (no confident) to 100% (very confident). The mean score is considered the total score, and a higher score indicates a higher level of balance confidence. The Timed Up and Go (TUG) is a valid and reliable measure to assess dynamic balance after stroke [35]. Participants sat in a chair, with their back resting on the chair and arms on the armrests. They were instructed to walk 3 m (to a line on the floor) at a comfortable speed, turn around, walk back to the chair, and sit down in the chair. Motor recovery assessed by the Chedoke McMaster Stroke Assessment (CMSA) (leg and foot subscales) is graded from one to seven, with seven being normal and one being flaccid [36]. Cutaneous sensation of the plantar aspect of the foot was assessed by a series of Semmes-Weinstein monofilaments, ranging from 1.65-6.65, with the lowest value representing normal cutaneous sensation [37]. Peak isokinetic joint torques of the non-paretic and paretic side were measured in 5 trials at 30º/s using the Biodex System Pro4 (Biodex Medical Systems, NY, USA) for ankle dorsiflexion and plantarflexion and hip abduction and adduction. The torque values were normalized by body weight by body height. Falls were reported retrospectively for the six months prior to enrollment. The participants were contacted once a month after training finished to track the number of falls for six months after completing training. Falls, defined as an event that resulted in a person coming to rest inadvertently on the ground or floor or a lower level, were retrospectively recorded for the six months to prior enrollment for each participant [38].

Statistical Analyses

All statistical analyses were conducted using SPSS (SPSS, Chicago, IL, USA). Mann-Whitney *U* and chi-square tests were performed to determine whether the clinical characteristics of those that completed training and those that withdrew differed. The comparison between pre and post-training was performed on those that completed training. The number of steps taken with the paretic limb and the step type (medial, lateral, crossover) was calculated as a percent of total steps for each participant for the treadmill and waist-pull perturbations. Pre-post comparisons were made between session 1 (or baseline), and session 18 (or post-training) for the percent of paretic limb steps taken and step type (medial, lateral, crossover) during the treadmill perturbation and waist-pull perturbation using the Wilcoxon signed ranked test. Paired two-tailed *t*-tests were performed to compare the scores of the ABC and TUG times from baseline to post-training. A McNemar's test was performed to determine whether the proportion of fallers declined after training. Spearman's correlation coefficients assessed the relationship between percent of paretic limb steps (taken during the first training session and baseline waist-pull assessment), motor recovery (i.e., CMSA score), and cutaneous sensation of the paretic foot. The level of significance was set at an alpha of 0.05.

Results

Seventeen participants were enrolled, five dropped out before they completed the training. The average number of sessions completed from those that dropped out was 5.4 sessions (range 0-14). The 12 participants that remained in the study completed 100% of the training sessions. The attrition rate was 29%, with the participants that withdrew tended to be younger (P=0.09), had fewer years post-stroke (P=0.019), and had a better motor recovery score on the CMSA (P=0.04) compared to those who did not withdraw (Table 2). The reasons cited for study withdrawal were changes in personal schedules that no longer permitted time to commit to the study (3) and new medical conditions unrelated to the training (2). The proportion of fallers declined from 41.7% before training to 16.7% in the six months after training, although these declines were not significantly different (P=0.25).

	Completed N=12	Dropped out N=5	*P*-value
Age (years), mean (range)	63.3 (54-72)	58.6 (53-62)	0.09
Sex (Number of Male/Female) [a]	9/3	3/2	0.65
Body mass index	32.7 (6.6)	28.6 (4.2)	0.29
Post-stroke (years)	8.6 (4.7)	3.5 (2.0)	0.02*
Chedoke McMaster Stroke Assessment leg+foot subscale (/14)	7.6 (2.6)	9.6 (3.4)	0.04*
Cutaneous Sensation[b]	4.24 (2.36-6.65)	4.31 (2.83-5.18)	0.87
Timed Up and Go (seconds)	15.5 (8.1)	11.1 (2.6)	0.21
Activities Specific Balance Confidence Scale (/100)	77.1 (10.8)	75.9 (14.4)	0.72
Ankle Dorsiflexors (peak torque (wt x ht)	0.056 (0.55)	0.12 (0.070)	0.051
Ankle Plantarflexors (peak torque (wt x ht)	0.069 (0.068)	0.22 (0.18)	0.021
Hip Abductors (peak torque (wt x ht)	0.24 (0.11)	0.37 (0.20)	0.25

Hip Adductors (peak torque (wt x ht)	0.21 (0.12)	0.30 (0.17)	0.25
Fallers[c] (%)	41.7%	20.0%	0.39
Values expressed as mean ± standard deviation unless indicated [a]Values are presented as number [b]Values are presented as median (minimum-maximum) [c]Fallers are defined as individuals who reported at least one fall in the past six months.			

Table 2: Participant demographics and clinical characteristics.

Treadmill perturbation training: There was no significant difference in the mean percent of paretic limb steps taken in the first session compared to the last training session (Start, 45.8 ± 14.3 %; End, 41.0 ± 21.9%, P=0.93). There was a significant decline in medial steps (P=0.02) in the last session of training. There was a tendency for the number of lateral steps taken to increase (P=0.1); however, these findings were not statistically significant (Figure 3).

Lateral waist-pull perturbation: There was no significant difference in the mean percent of paretic limb steps at baseline and post-training (baseline 38.2 ± 22.0 %; post-training 26.2 ± 25.6.%, P=0.1). There was a significant decline in the percentage of medial steps (Figure 3; P=0.01, ES=0.61), while the percent of lateral steps increased (P=0.04, ES=0.66) after training. There was no change in the number of crossover steps (P=0.7). For the non-paretic leg, there was a significant decline in the medial step (P=0.009, ES=0.75) and an increase in lateral steps (P=0.02, ES=0.68). The crossover steps were not significantly different after training (P=0.07).

Clinical measures: The mean ABC score was significantly improved (baseline 77.1 ± 10.8; post-training 84.5 ± 10.9, P=0.01; ES=0.68), whereas TUG mean times were not significantly different between baseline and post-training (baseline 15.5 ± 8.1 seconds; post-training 15.9 ± 8.1seconds, P=0.7).

Correlations of paretic limb use and clinical measures: There was a statistically significant negative correlation between the paretic foot cutaneous sensation and the percent of paretic limb steps in the first treadmill training session (r_s = -0.70, P=0.01). In contrast, the percent of paretic limb first steps during the baseline lateral waist-pull perturbation was correlated with the CMSA leg and foot motor recovery score (r_s = 0.75, P=0.005) (Figure 4).

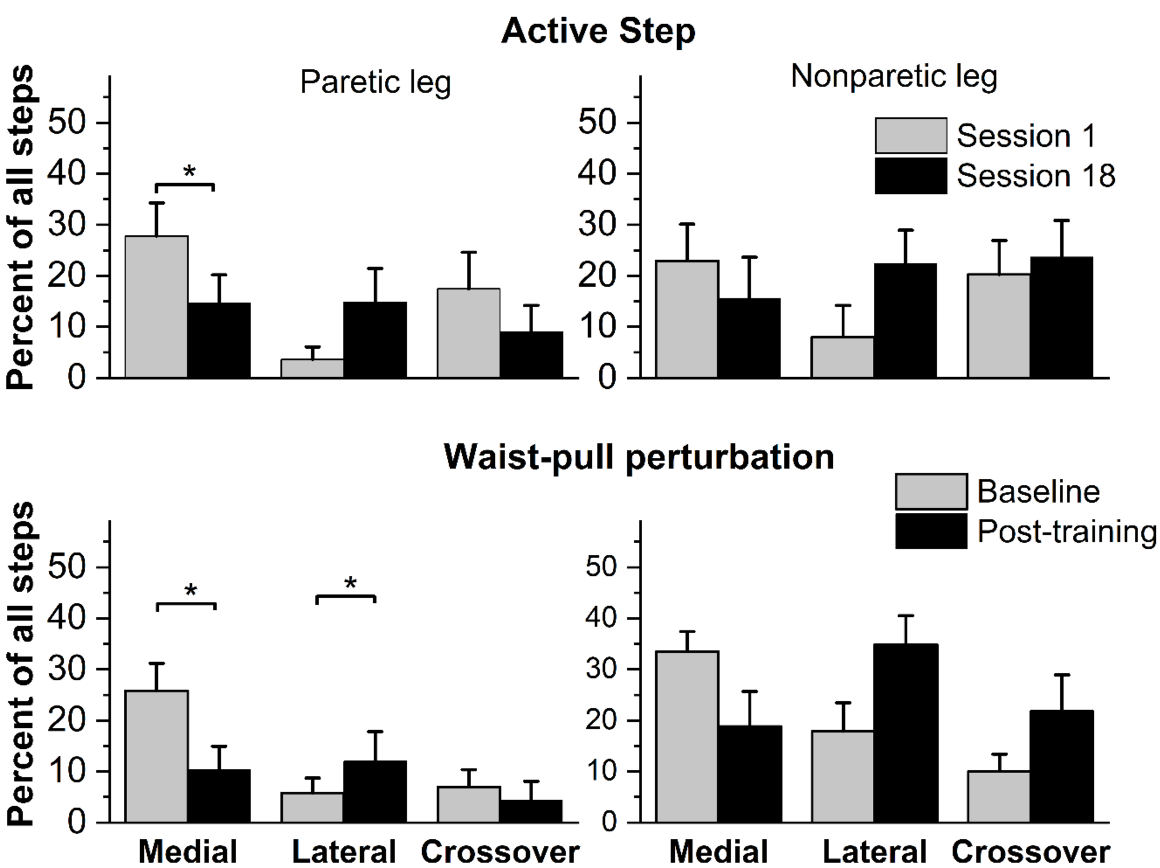

Figure 3: The percent of step type of the paretic and non-paretic leg during the treadmill perturbation and the waist-pull perturbation at session 1/ baseline (light gray bar) and session 18/post-training (black bar). Lateral steps (loaded steps) taken are in the same direction as the pull, where the medial and crossover steps (unloaded steps) the pull direction is opposite to the stepping leg (i.e., paretic medial step results from a non-paretic pull). Values are the mean and standard deviation of all participants. Value for each participant is calculated based on the percent of all their trials. *P<0.05, Wilcoxon Signed Ranks test.

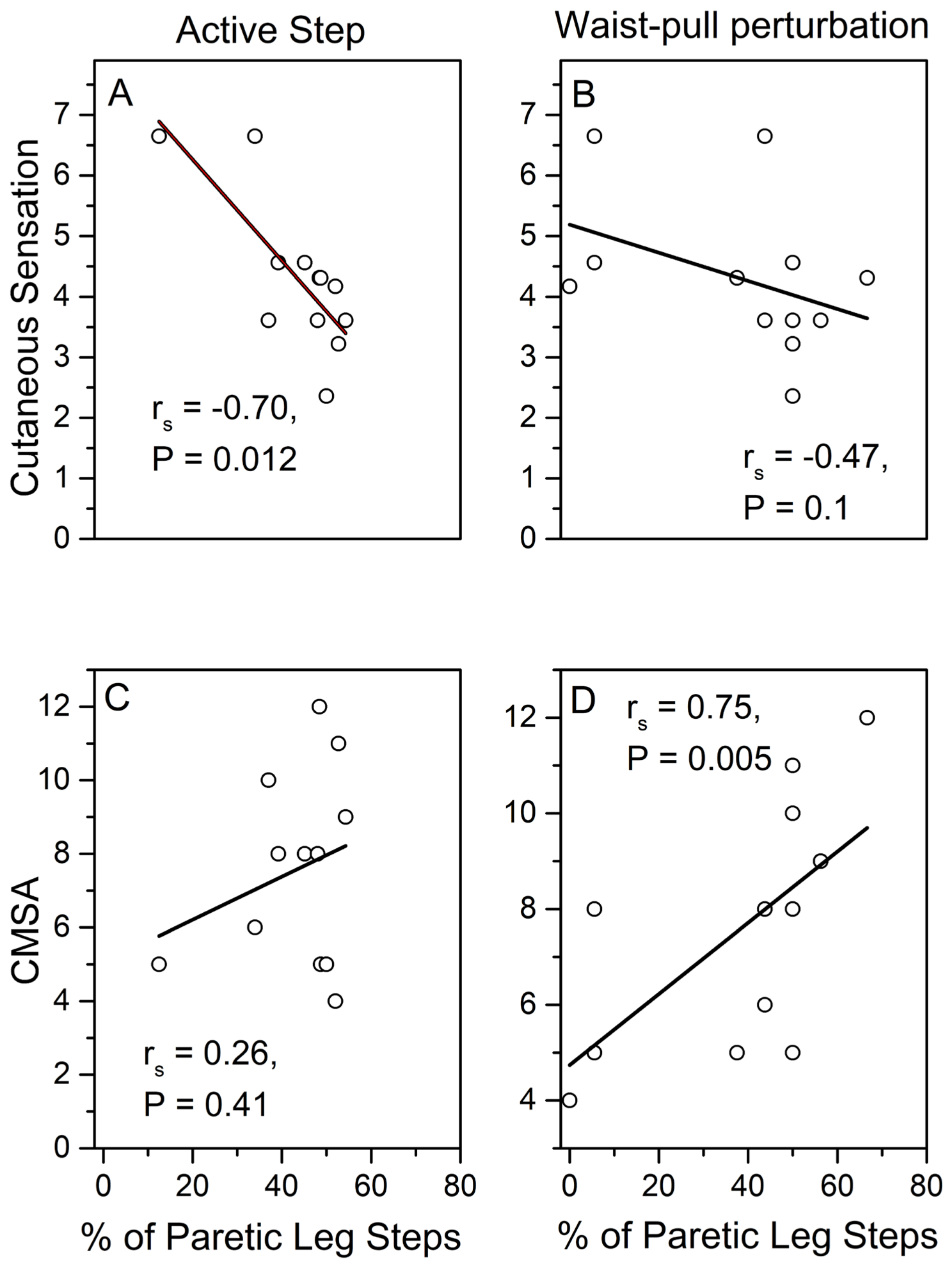

Figure 4: Relationships between the cutaneous sensation of the plantar aspect of the foot and percent of paretic limb steps during the first training session (Active Step) (A) and during baseline testing (lateral waist-pull perturbation) (B), and between Chedoke McMaster Stroke Assessment (CMSA) leg-foot subscale and percent of paretic limb protective step in the first training session (Active Step) (C) and during baseline testing (lateral waist-pull perturbation) (D).

Discussion

The study highlights the feasibility of lateral perturbation training following stroke. Although the attrition rate was ~30%, the individuals who withdrew cited the time commitment of the intervention rather than the intervention itself as a reason for withdrawing. Nevertheless, it may be essential to determine the minimum training parameters needed for improving protecting stepping responses since younger individuals may be less likely to engage when the time commitment is three times a week. Previous findings in older adults report improved responses after a single perturbation session that was retained after twelve months [39,40]. Further exploration of the training parameters in persons following stroke would be necessary for developing an intervention.

All the participants tolerated the 80 trials for each session and completed 18 sessions of reactive training. However, barriers to adherence and participation in the program were removed with the exclusion criteria, which required individuals to be community ambulators. The attrition rate was fairly high compared to other exercise intervention studies that report attrition values of less than 15%. We do not know whether the participants dropped due to the lack of benefits they perceived from the intervention. Further investigations of the acceptability of the intervention may be necessary for understanding the high attrition rate.

The paretic limb use before training found in this study is similar to values from other studies [33,41,42]. However, we did not see any changes in the number of times the paretic limb was used as a first recovery step after training. The negative correlation of paretic foot cutaneous sensation and the number of the paretic leg steps in the first treadmill perturbation session may indicate the importance of foot cutaneous sensation for signaling balance instability when translating the base of support. Thus stepping with the paretic limb, especially with sensory impairments, could impose constraints for using the paretic limb. In contrast, the level of motor recovery was associated with paretic limb steps during the waist-pull perturbation. A previous study found a similar relationship between motor recovery and preferred stepping limb [29]. Individuals with a higher motor recovery were more likely to step with the paretic limb when placed in a lean position and released in the forward direction [29]. Although, in our study, the foot cutaneous sensation may not be as important during the waist-pull perturbation since the belt attached to the waist may provide somatosensory input to signal imbalance. Facilitating sensorimotor interaction in the lesioned motor system is essential for motor recovery [43], and may be necessary for improving feedback responses. Repetitive sensory input can enhance motor cortical plasticity indicating the significant impact sensory training can have on facilitating motor recovery [44]. Although the evidence mainly focuses on passive sensory interventions with less evidence of active sensory training [45]. The exploration of sensory strategies in conjunction with the perturbation may improve responses to perturbation training.

Although there was no increase in paretic limb use, there was a shift in step types taken. There was a decline in medial steps with the paretic leg during the treadmill and waist-pull perturbations, with an increased number of paretic leg lateral steps during the waist-pull perturbation. Thus the improvements from the treadmill perturbations transferred to the waist-pull perturbation indicating there may be a generalization. Indeed, a lateral step may be considered a more stable strategy for balance recovery [46-48], since the base of support increases. Medial steps are problematic since the medially directed step towards the stance leg reduces the base of support and potentially decreases stability, thereby necessitating a second recovery step to stabilize the body. The significant increase in lateral steps was only observed during the waist-pull perturbation and not the treadmill perturbation. Other mechanisms, such as foot cutaneous sensation, may limit the ability to modify stepping behaviors during the treadmill perturbation compared to the waist-pull perturbation. In a study by Perry et al. [49], temporarily impairing foot cutaneous sensation in healthy subjects resulted in a transition from lateral to medial/crossover step during platform translations. As discussed earlier, the sensory input at the waist may provide earlier information on the impending imbalance during the waist-pull than the treadmill perturbation. Thus, shifting from a medial to lateral step may be constrained in those who have impaired cutaneous foot sensation.

Many well-established interventions, such as lateral weight shifting and gait training [50], have improved balance responses controlled in a feedforward manner. In contrast, few have reduced the number of falls in stroke [50,51]. Studies of perturbation training after stroke do not find an improved balance when assessed with commonly used clinical outcome measures (i.e., Berg Balance Scale, TUG) [52-54], similar to our lack of improvements in the TUG. However, similar to our study, we found a significant increase in balance confidence [52,55]. The lack of improvements in the TUG may be limited by the domain assessed. The TUG involves voluntarily initiated movements that do not capture the effects of perturbation training that is more of a feedback mechanism to balance control. Therefore, it is crucial and necessary to develop clinical measures that assess external balance perturbations.

Study Limitations

Among the study limitations is the small sample size. Thus, a larger sample size and a comparison group of current clinical practice are necessary to establish the effectiveness of the intervention. Also, this is a single group pre-post design, which does not establish whether the intervention is superior to current clinical practice. Although unpredictable in timing and direction, the perturbations used in this study were not unexpected, and participants were aware of an impending perturbation. In this regard, the perturbation paradigm used here is not an exact replication of real-world balance perturbations. However, falls occur when the center of mass moves outside the base of support, and we examined the mechanism of control when this occurs.

In conclusion, the individuals after stroke tolerated the perturbation training. The ability to emphasize the use of the paretic limb was challenging for some participants, especially those with sensorimotor deficits of the lower extremity. Future research is necessary as part of a larger clinical trial to optimize and individualize perturbation training paradigms to prevent falls after stroke.

Declaration of Interest: The authors report no conflict of interest.

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