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A single session of trip-specific training modifies trunk control following treadmill induced balance perturbations in stroke survivors

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Abstract

Background—Individuals with stroke are at significant risk of falling. Trip-specific training is a targeted training approach that has been shown to reduce falls in older adults and amputees by enhancing the compensatory stepping response required to prevent a fall. Still, individuals with stroke have unique deficits (e.g. spasticity) which draws into question if this type of training will be effective for this population.

Objective—Evaluate if a single session of trip-specific training can modify the compensatory stepping response (trunk movement, step length/duration, reaction time) of individuals with chronic stroke.

Methods—Sixteen individuals with unilateral chronic stroke participated in a single session of trip-specific training consisting of 15 treadmill perturbations. A falls assessment consisting of 3 perturbations was completed before and after training. Recovery step kinematics measured during the pre- and post-test were compared using a repeated measures design. Furthermore, Fallers (those who experienced at least one fall during the pre- or post-test) were compared to Non-fallers.

Results—Trip-specific training decreased trunk movement post perturbation. Specifically following training, Trunk flexion was 48 and 19 percent smaller on the small and medium perturbations at the end of the first compensatory step. Fallers (9 out of 16 subjects) post-training

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CONFLICTS OF INTEREST STATEMENT

The University of Illinois at Chicago owns a patent on some technology used in the ActiveStep system and consequently there is an institutional conflict of interest.

Mark D. Grabiner is an inventor of the ActiveStep system but has no conflicts of interest to declare with regard to the present study.

resembled Non-Fallers pre-training. Specifically, Trunk flexion at the completion of the first step during small and medium perturbations was not different between Fallers post-training and Non-Fallers pre-training. Still enthusiasm was tempered because Trunk flexion at the largest perturbation (where most falls occurred) was not changed and therefore total falls were not reduced as a result of this training.

Significance—Our results indicate that trip-specific training modifies the dynamic falls response immediately following trip-like treadmill perturbations. However, the incidence of falls was not reduced with a single training session. Further study of the implications and length of the observed intervention effect are warranted.

Keywords

Balance; Stroke; Dynamic fall response; Trips; Biomechanics

INTRODUCTION

In 2000, falls among older adults cost the US healthcare system 19 billion dollars [1]. This number ballooned 63% to 31 billion dollars in only 15 years [2]. From 2001 to 2008, falls increased 50% [3] and with a growing elderly population [2] so too are associated health care costs [4,5]. Individuals with stroke are 1.77 times more likely to fall compared to unimpaired older adults [6] making falls the most common medical complication after stroke [7]. There is a clear need for effective fall prevention programs for this vulnerable population.

Trip-specific training is a targeted training approach that reduces falls in older adults and amputees [8–10]. During trip-specific training, trainees are exposed to treadmill perturbations in a controlled setting where injuries are not possible. Treadmill perturbations simulate over-ground trips [11] allowing trainees to practice responding to conditions that occur during community trips. Trips are targeted because they represent one of the most significant causes of falls in older adults and individuals with stroke [12,13]. Trip-specific training reduces the fall-risk of older women in the laboratory by 83.2% [8] and in the community by 50% compared to control groups [14]. Trip-specific training accomplishes this rapidly in 4 hours over 2 weeks [14].

Contrast trip-specific training with exercise fall prevention programs. Exercise-based interventions (e.g. tai chi) have garnered attention in recent years due to their success in decreasing falls in older adults [15]. In group exercise programs, individuals attend one-hour sessions, 2–3 times a week, for at least 12 weeks [6,16,17]. Exercise-based interventions work by targeting factors associated with falls (e.g. muscle strength) [15]. These programs are effective at fall reduction, reducing falls 17% [15] *but* these programs are not as effective in individuals with stroke [18,19]. This raises the question if trip-specific training will be effective in individuals with stroke.

The ability to arrest and reverse the motion of the trunk after a trip is one of the most sensitive measurements to predict fall outcomes in the laboratory in young adults, older adults, and individuals with stroke [8,10,11,20,21]. For example, Fallers have significantly larger trunk flexion and velocity compared to Non-Fallers at the completion of the first recovery step [8,20]. Individuals with stroke are distinctive from older adults *but* they fall for similar reasons [20]. Falls in individuals with stroke can be characterized by larger trunk flexion velocities [20]. The objective of this study was to evaluate if a single session of trip-specific training can modify the compensatory stepping response (trunk movement, step length/duration, reaction time) of individuals with chronic stroke. We hypothesized that a single session of trip-specific training would modify the compensatory stepping response by reducing trunk flexion and velocity at the completion of the first recovery step similar to our previous results in older women [8].

Only two groups have investigated the efficacy of a training program that included perturbations (i.e. subjects being pushed/pulled in a controlled manner) delivered to individuals with stroke [22–24]. We extend their results by 1) evaluating the independent effects of trip-specific training on kinematic quantification of compensatory stepping responses (e.g. trunk kinematics, step length) of individuals with chronic stroke, 2) evaluating the effects of trip-specific training on center of mass (COM) stability measures, and 3) evaluating the effects of trip-specific training on subjects classified as Fallers and Non-fallers to determine whether falling prior to training influenced the results of the training.

METHODS

Participants

Sixteen subjects with unilateral chronic stroke participated in this study (Table 1). Eligibility criteria were: 1) ability to stand and walk independently for 5 minutes, 2) no musculoskeletal injury or surgery in the past year and 3) no history of dizziness or fainting in the past year. This study was approved by Rehabilitation Institute of Chicago (RIC), Northwestern University, and University of Illinois at Chicago’s (UIC) Institutional Review Boards. All subjects provided written informed consent.

Protocol

Subject characteristics and stroke information were recorded. PASE (Physical Activity Scale for the Elderly) [25], Fall Efficacy Scale – International (FES-I) [26], and Fall history questionnaires were completed. Balance and functional mobility were assessed using Berg Balance Scale, 10 m walk test, and 5 times sit-to-stand (Table 1). Stance Asymmetry was represented as the ratio of the weight borne on the non-paretic leg to the weight borne on the paretic leg over a 20-second period during which the subject stood quietly with a self-selected stance width and each foot on separate force plates (AMTI, Watertown, MA).

During the experiment, subjects received perturbations while standing on a dual-belt, stepper motor driven, and computer-controlled treadmill (ActiveStep™, Simbex, Lebanon, NH). Perturbations of varying amplitude were delivered in both anterior and posterior directions whereby a stepping response was required to prevent a fall. Subjects were instructed to stand with self-selected stance width on the treadmill and “do what is necessary to prevent falling” as the treadmill belt rapidly moves in an unexpected direction. Subjects were fitted with a ceiling-mounted safety harness to prevent their hands and knees from contacting the treadmill belts if they were unsuccessful to regain balance following a perturbation.

Subjects completed both a pre- and post-test as well as a single session of perturbation training. Training consisted of 15 posteriorly-directed perturbations (relative to the direction the subject was facing) during which the treadmill belts followed a trapezoidal velocity profile of moderate magnitude (displacement: 0.22 m, constant velocity: 0.56 m/s, acceleration and deceleration: 13.89 and −13.89 m/s^2). Posteriorly-directed perturbations elicit recovery kinematics that closely mimic those following an over-ground trip [11]. Posteriorly-directed perturbations require a forward stepping response to avoid a fall. The pre- and post-tests consisted of the same 6 perturbations – 3 posteriorly-directed and 3 anteriorly-directed perturbations. The direction of the perturbation was randomized to reduce the likelihood of anticipating the perturbation. Posteriorly-directed perturbations were designed using three different trapezoidal kinematic profiles (Small (level 1): 0.22m, 0.26 m/s, 6.5 and −6.5 m/s^2; Medium (level 2): 0.29 m, 0.64 m/s, 15.9 and −15.9 m/s^2; Large (level 3): 0.76 m, 1.3 m/s, 12.9 and 12.9 m/s^2). Displacement, constant velocity, acceleration and deceleration of anteriorly-directed perturbations ranged from 0.04 to 0.14 m, −0.6 to −1.2 m/s, −10 and 10 m/s^2. The direction of the perturbation was randomized but the magnitude was sequenced from small to large.

Data collection and analysis

Twenty-two passive-reflective markers were placed over specific upper and lower extremity and trunk landmarks using a modified Helen Hayes marker set [27]. The three-dimensional positions of markers were tracked by an 8-camera motion capture system (Motion Analysis Co., Santa Rosa, CA) operating at 120 Hz. Markers trajectories were filtered using a 4th order Butterworth with a cutoff frequency 6Hz (Cortex 2.5.2, Motion Analysis Co., Santa Rosa, CA). Kinematics were calculated from markers position using custom software (MATLAB, Mathworks, Natick, MA).

Dependent variables were Reaction time, Step duration, Step length, Trunk flexion and velocity, Dx, and Margin of stability (MOS). All variables are defined in Table 2 (Fig. 1). Variables were calculated at initiation (step_start: SS) and completion (step_end: SE) of the first recovery step. SS (i.e. toe off) was detected by visually detecting the first movement of the toe marker in the vertical direction. SE (foot contact) was detected by visually detecting the moment when either toe or heel marker vertical velocity reaches to zero (i.e. foot has contacted the treadmill). Whichever marker (i.e. toe or heel marker) that reaches zero velocity first is used to determine the SE.

All pre- and post-test trials were classified as either a “fall” or “recovery”. If the subject became unambiguously supported by the harness following a perturbation, the trial was considered a fall.

Statistics

To evaluate the influences of a single-session trip-specific training on the effectiveness of recovery attempts following treadmill perturbations, a pre- and post-test comparison of all the dependent variables was conducted. Based on our hypothesis, we expected that trunk flexion angle and velocity would be significantly reduced after training similar to our previous results in older women [8]. A generalized linear mixed-effects model (GLMM) [28] was used with condition (pre-test/post-test) and perturbation level (1–3) as the independent variables and the aforementioned dependent variables (e.g. trunk kinematics). Subjects were treated as a random factor. Post-hoc comparisons were conducted using Tukey HSD test.

In a secondary analysis, Fallers (i.e. those who experienced at least one fall during the pre- or post-test) and Non-fallers (i.e. subjects who never fell during the experiment) were compared. Pre-test trials of Fallers and Non-fallers were compared to post-test trials. Furthermore, post-test trials for Fallers were compared to pre-test trials for Non-fallers. The same statistical analyses described above were conducted with pre-test and post-test, perturbation level (1–3) and Faller/Non-faller as the independent variables and the same dependent variables.

Fallers and Non-fallers were compared in subject characteristics and clinical scores (Table 1) using independent t-tests. All statistical analyses were conducted using R (R Development Core Team, 2006) with a significance level of $p < 0.05$.

RESULTS

A total of 17 falls were recorded of which 15 occurred following the level 3 perturbation. Nine subjects who fell at least once were classified as Fallers. Nine falls occurred during the pre-test and 8 falls occurred during the post-test. Seven of the 9 Fallers fell during both pre- and post-test. Only 2 Fallers who fell in pre-test avoided falling in post-test. Differences of subject characteristics and clinical scores between Fallers and Non-fallers were not significant (all $P>0.05$; Table 1).

A majority of subjects used the non-paretic limb consistently through the experiment but a handful of subjects used the paretic limb or modified their strategy during the training. Thirteen subjects always initiated recovery steps with their non-paretic limb. Three subjects (2 Fallers and 1 Non-faller) used both the paretic and non-paretic legs to initiate recovery steps across different levels and conditions. During pre-training on levels 1 and 2, none of the subjects initiated a stepping response with paretic leg. During post-training, 2 (level 1) and 3 (level 2) subjects initiated the recovery step with their paretic limb. Finally, at level 3, 2 subjects used the paretic limb during both pre- and post-tests.

Pre-test vs. post-test for all subjects

The trip-specific training was associated with reduced post-perturbation Trunk flexion following level 1 and level 2 perturbations (Fig. 2). At level 1, post-test Trunk flexion at SS was 34 percent smaller than that of the pretest ($F_{1,73}=6.03$, $P=0.016$). Post-test Trunk flexion at SE was 48 percent smaller than that of the pretest ($F_{1,73}=19.91$, $P<0.0001$). At level 2, the post-test Trunk flexion velocity at SS decreased 20 percent compared to pre-test ($F_{1,73}=8.05$, $P=0.006$). Finally, post-test Trunk flexion at SE decreased 19 percent compared to the pre-test ($F_{1,73}=9.33$, $P=0.003$). The post-training differences in Trunk flexion velocity at SE, Reaction time, Step duration, Step length, Dx and MOS were not significant (all levels; all $P>0.05$).

Pre-test vs. post-test within Faller and Non-faller groups

Fallers showed more differences pre and post-test than Non-fallers (Fig. 3). At level 1 post-test, Fallers showed a reduction of 38 percent in Trunk flexion at SS compared to the pre-test ($F_{1,68}=5.92$, $P=0.017$). Fallers post-test Trunk flexion at SE decreased 54 percent compared to the pretest ($F_{1,68}=20.90$, $P<0.0001$). Moreover, the post-test Dx at SS increased more than 100 percent ($F_{1,68}=11.15$, $P=0.0013$). At level 2, Fallers posttest Trunk flexion at SE decreased 20 percent ($F_{1,68}=7.01$, $P=0.0097$) and Step duration was 33 percent larger in post-test trials compared to the pretest ($F_{1,68}=4.04$, $P=0.048$). The post-training differences in Trunk flexion velocity, reaction time, Dx at SE, MOS, and step length for Fallers were not significant (all levels; all $P>0.05$).

The only significant difference found between pre- and post-tests of Non-fallers was a 24 percent reduction in post-test Trunk flexion velocity at SS at level 2 trials ($F_{1,68}=5.17$, $P=0.026$). Non-fallers demonstrated trends toward smaller Trunk flexion at SE in posttest trials at level 1 ($F_{1,68}=2.84$, $P=0.096$) and level 2 ($F_{1,68}=3.13$, $P=0.08$) that did not reach significance. No differences were observed in Reaction time, Step duration, Step length, Trunk flexion velocity at SE, Dx and MOS at any levels (all $P>0.05$).

Non-fallers vs. Fallers before and after training

Fallers exhibited a 65 percent larger level 1 ($F_{1,68}=4.99$, $P=0.028$) and a 38 percent larger level 2 ($F_{1,68}=5.38$, $P=0.023$) Trunk flexion at SE compared to Non-fallers (Fig. 4). Fallers also had a 290 percent larger level 2 ($F_{1,68}=6.38$, $P=0.014$) and a 434 percent larger level 3 Trunk flexion velocity at SE compared to Non-Fallers. Finally at level 3, Fallers showed 184 percent smaller Dx at SE ($F_{1,68}=12.06$, $P=0.0008$) and 34 percent smaller Step length ($F_{1,68}=10.24$, $P=0.002$) compared to Non-fallers during the pre-test.

While Fallers showed differences prior to training, after training Fallers resembled pretest Non-Fallers. Trunk flexion at SE did not differ between post-test Fallers and pre-test Non-Fallers at level 1 ($F_{1,68}=0.50$, $P=0.48$) and level 2 ($F_{1,68}=0.41$, $P=0.52$). No differences were found between the groups in Trunk flexion velocity at SE at level 2 ($F_{1,68}=1.54$, $P=0.22$). No differences were found between the groups in Step duration, Reaction time and any other variables at SS (all levels; all $P>0.05$). Still, differences between the groups emerged at level 3. Trunk flexion velocity of Fallers was larger ($F_{1,68}=6.10$, $P=0.016$), Dx at SE was smaller ($F_{1,68}=7.18$, $P=0.009$), and Step length was smaller ($F_{1,68}=7.56$, $P=0.007$) compared to Non-fallers at level 3.

DISCUSSION

The objective of this study was to evaluate if a single session of trip-specific training can modify the compensatory stepping response (trunk movement, step length/duration, reaction time) of individuals with chronic stroke. We hypothesized that a single session of trip-specific training would modify the compensatory stepping response by reducing trunk flexion and velocity at the completion of the first recovery step similar to our previous results in older women [8]. We found that the single-session trip-specific training protocol modified trunk control in all subjects with Fallers showing the most changes with their kinematics after training resembling those of Non-fallers pre-test.

Despite these notable changes, no significant differences were found at the largest perturbation (level 3) – where most falls occurred. Further, only 22 percent (2 out of 9) of Fallers fell less often on the post-test compared to the pre-test. Thus, while significant modifications were found in a single session, indicating that this may be a viable option in individuals with stroke, additional questions are now raised. For example, what is the upper limit of perturbation from which an individual with stroke can learn to recover? For how long is the modified performance retained? Are falls in the community reduced by this training? Perhaps of greatest immediate interest is the extent to which the presently reported results are reproducible.

A single session of trip-specific training modified trunk control as measured by trunk flexion; however, trunk flexion velocity was less sensitive to trip-specific training. While no differences in trunk flexion velocity were reported pre- and post-training, trunk flexion velocity was modified when Fallers post-training were compared to Non-fallers pre-training suggesting this metric is being modified in Fallers but may not reach statistical significance due to 1) the short duration of training and 2) small sample size of this pilot study. Our previous work in older women showed both trunk flexion and velocity improvements [8]. However, these studies were larger (52 subjects) and each subject received at least 120 perturbations over 4–10 sessions. With this in mind, it is of significance that this study demonstrated modifications in trunk control in only a single session of 15 trials in a more challenging population. Still, future work should extend and replicate this work in a larger pool of subjects to determine if trunk flexion velocity and other important dependent variables (e.g. Reaction time, Step length, Step duration, Dx) can be modified.

Trip-specific training as a viable fall-prevention strategy

While previous work has demonstrated the potential of trip-specific training in healthy older adults, the present work aimed to assess the efficacy of trip-specific training in individuals with stroke. Previous work indicates trip-specific training [8,14] and slip-specific training [29] are viable fall-prevention interventions that can effectively reduce fall-risk in older adults even in a single session and in individuals with Parkinson’s disease [30]. Moreover, the effectiveness of compensatory stepping response required to recover from falling, as measured by trunk control, is enhanced by trip-specific training [8]. Still, individuals with stroke may have neuromuscular deficits such as muscle weakness, spasticity/flaccidity, and abnormal muscle synergies [31] as well as diminished capacity for motor learning [32] that may limit the effectiveness of trip-specific training unless those deficits are addressed by the training. To our knowledge, only two groups have evaluated the effects of a training program that included postural perturbations on falls and stepping response of individuals with stroke [22–24]. Mansfield et al., 2018 engaged individuals with stroke in a 6-week trip-specific training protocol. They found that fall outcomes in the community were not statistically different between individuals exposed to trip-specific training and the control group. Still, differences were observed in reactive balance clinical testing (BEST-reactive) which were

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still present 12 months post-training. Our results support this report in that we see modification of the compensatory stepping response (decreased trunk movement) but not a decrease in laboratory-induced falls. This indicates that the traditional dosing of trip-specific training may need to be modified, lengthened, or used in conjunction with other fall prevention strategies to yield a decrease in fall outcomes. Still, Mansfield et al., 2018 and this report indicate that the reactive response during a fall can be modified in individuals with stroke and in relatively short duration (1 session/6 weeks) warranting further evaluation.

In summary, we have shown that 1) a single-session trip-specific training can modify trunk control in individuals with stroke following large postural perturbations that simulate a trip during locomotion 2) Fallers are particularly responsive to this type of training – even resembling Non-fallers' pre-test results.

Limitations and future directions

The present work represents a preliminary study that requires further study to determine its reproducibility and validate its use. First, we only evaluated short-term effects of training. Additional training is needed to modify responses to their natural limit as well as enhance retention, which we did not evaluate. Second, our subjects were ambulatory individuals with stroke with high Berg balance scores (Table 1). Future work should evaluate the safety and efficacy of this type of training in more severely impaired individuals. Third, no modifications were found on level 3 perturbations, where most experimental falls occurred. It is unclear if this lack of effectiveness is due to 1) limitations related to individuals with stroke (e.g. muscle weakness), 2) our specific protocol (e.g. training occurred on medium-sized perturbations of a single level), and/or 3) a combination of both. We found modifications on level 1 and 2, which is the similar size we trained the subjects. In the future, larger perturbations should be utilized to determine if further modifications can be seen during more challenging fall protocols. Alternatively, further practice on mid-size perturbations may prove effective given a longer, multiple-session protocol. Future work should probe how protocol shifts enhance the effectiveness of trip-specific training. Finally, our current study evaluated only anterior-posterior perturbations and did not consider upper extremity movements. We chose posteriorly-directed perturbations because they have been shown to resemble the mechanics of over-ground trips [11]. However, individuals with stroke can fall due to numerous reasons and other types of perturbations should be evaluated. In addition, upper extremity reaching movements are an important strategy used by older adults and patient populations [33,34]. Therefore, future studies should also evaluate if training affects these movements.

Conclusion

A single session (15 trials) of trip-specific training modifies trunk control in individuals with stroke. While dynamic falls response required to prevent a fall following a trip-like perturbation was modified, the incidence of falls was not reduced in a single training session. Replication and further study with an extended version of the presently described trip-specific training protocol is warranted to investigate whether the trunk control modifications can lead to reduced incidence of falls in stroke population.

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Highlights

- Trip-specific training, which reduces older adult falls, is evaluated post-stroke.
- Trip-specific training modifies the ability to arrest and reverse the trunk.
- Still, total falls were not decreased suggesting additional sessions are needed.
- Trip-specific training warrants further study to determine if it can prevent falls.

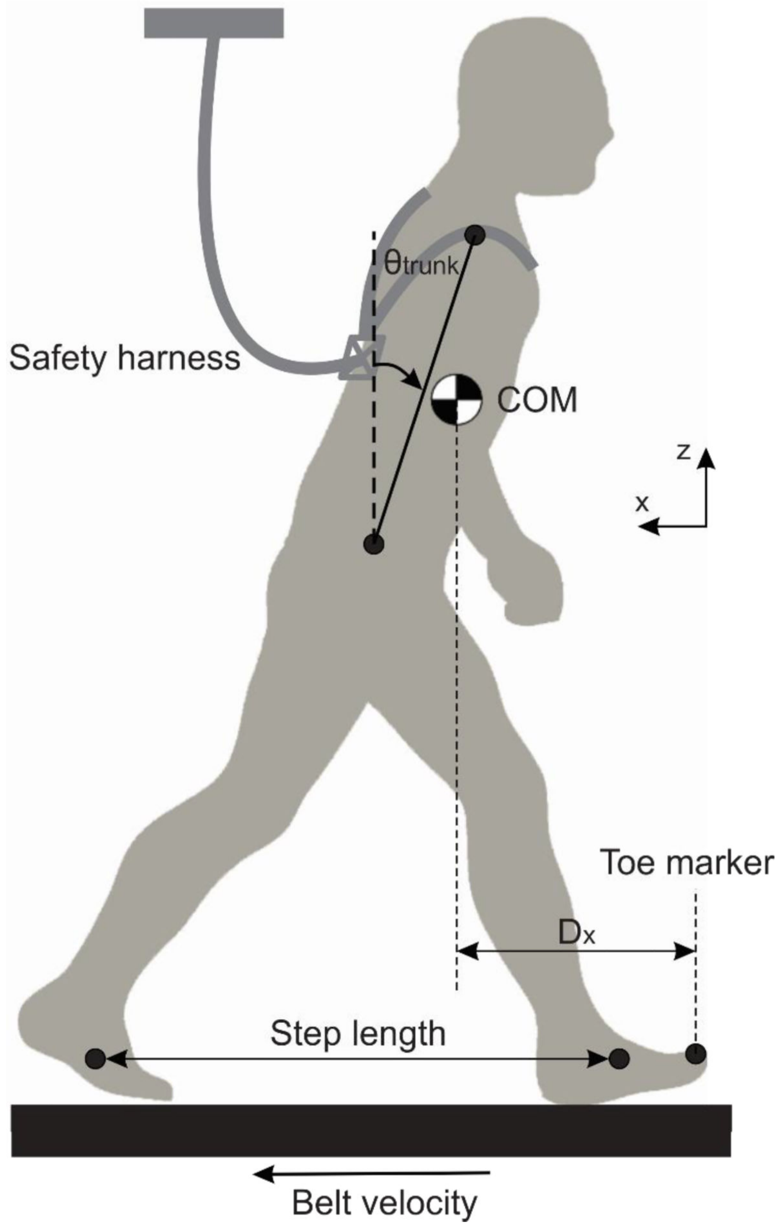

Figure 1: Kinematic and stability measures.

Figure depicts a positive Trunk flexion angle, Center of mass (COM) position, positive Dx, and Step length.

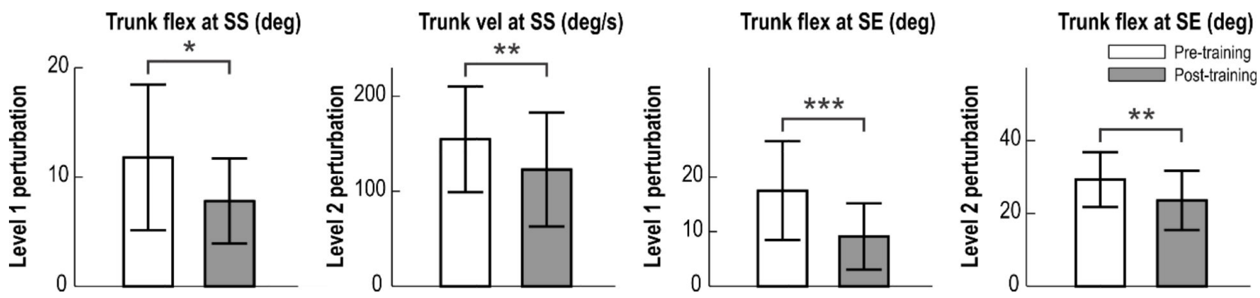

Figure 2: Pre-test vs. post-test trials comparisons for all subjects.

Figure represents significant differences between pre-test and post-test trials on different levels of perturbation. Subjects showed modified trunk control by showing reduced Trunk flexion and velocity at level 1 and 2 after trip-specific training. Error bars represent ± standard deviation. * = P-value < 0.05, ** = P-value < 0.01, *** = P-value < 0.001.

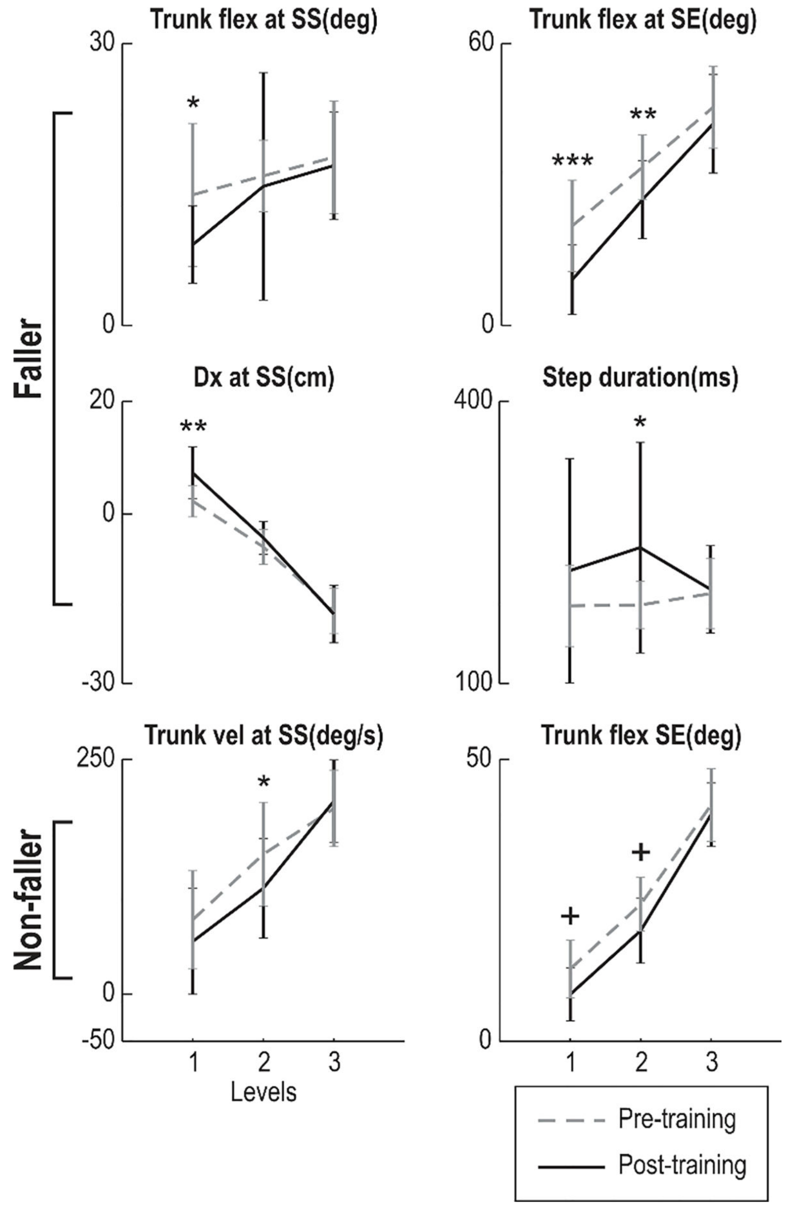

Figure 3: Pre-test vs. post-test trials comparisons for Fallers and Non-fallers.

Pretest and post-test trials were compared across all different levels of perturbation in Faller and Non-faller groups separately. Recovery attempts of Fallers showed to be influenced by trip-specific training to a greater extent. Error bars represent ± standard deviation. + = P-value < 0.1; * = P-value < 0.05, ** = P-value < 0.01, *** = P-value < 0.001.

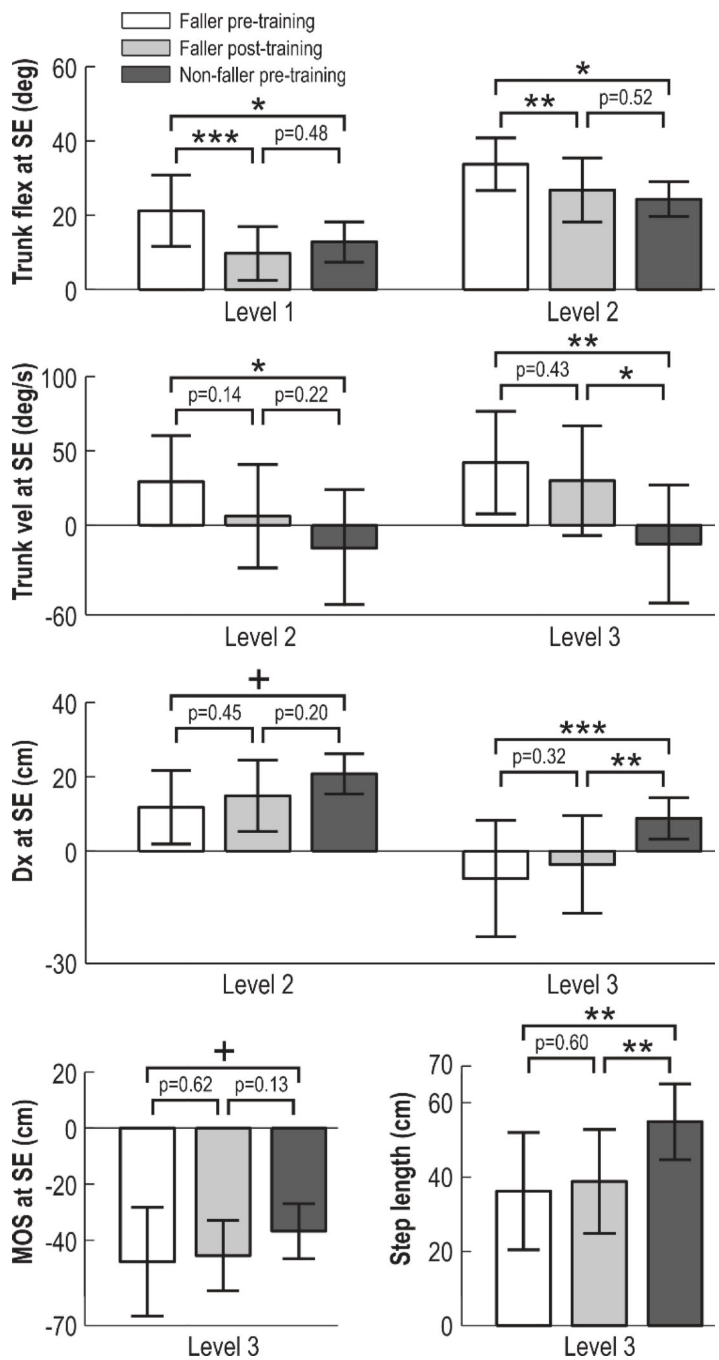

Figure 4: Post-test trials for Fallers vs. pre-test trials for Non-fallers Comparisons.

Before training, there were several differences in kinematics of the recovery attempts of Fallers and Non-fallers across all different levels. Recovery attempts of Fallers after training at level 1 and 2 were not different from the recovery attempts of Non-fallers before training. At level 3, recovery attempts of Fallers were not significantly influenced by the training and remained different from Non-fallers' recovery attempts prior to training. Error bars represent

± standard deviation. + = P-value < 0.1; * = P-value < 0.05, ** = P-value < 0.01, *** = P-value < 0.001.

Table 1:

Subject characteristics and clinical scores for Fallers vs. Non-fallers.

Fallers: those who experienced at least one fall (unambiguously supported by the harness) following a perturbation during pre- or post-test. Non-fallers: those who never fell during the experiment.

Variable	Faller (n=9) mean (SD) or n	Non-faller (n=7) mean (SD) or n	P-value
Subject characteristics			
Gender (M/F)	6/3	7/0	
Age (year)	60.8 (11.1)	57.7 (6.5)	0.53
BMI (kg/m2)	28.9 (4.0)	28.0 (6.3)	0.73
Hemiparetic side (R/L)	8/1	5/2	
Dominant leg before stroke (R/L/unknown)	6/3/0	6/0/1	
Time since stroke (year)	9.7 (6.1)	7.0 (3.3)	0.32
Stroke type (ischemic/hemorrhagic/unknown)	5/4/0	5/1/1	
Clinical scores			
Berg balance	49.6 (4.5)	52.9 (2.8)	0.11
5 times sit to stand (s)	23.5 (12.7)	22.1 (11.7)	0.82
10 m walk (comfortable pace) (s)	7.0 (1.0)	6.8 (2.2)	0.81
10 m walk (fast) (s)	5.0 (1.3)	5.0 (1.2)	0.97
PASE	134.1 (61.7)	156.2 (78.2)	0.54
Fall Efficacy Scale - International (FES-I)	29.4 (8.9)	23.6 (6.6)	0.17
Stance Asymmetry	1.15 (0.53)	1.00 (0.21)	0.50

Abbreviations: PASE Physical Activity Scale for the Elderly, M male, F female, R right, L left

Table 2:

Dependent variables and their definitions.

The limb that initiated the first recovery step was labeled as the stepping limb and the contralateral limb was labeled as the base limb. Margin of stability (MOS) was adopted from Hof et al., 2005 [35].

Dependent variables	Definition
Reaction time	Time from perturbation onset to SS.
Step duration	Time from SS to SE.
Step length	Anteroposterior distance between the centers of stepping foot segment and base foot at SE.
Trunk flexion	Sagittal plane angle of the line connecting the center of the pelvis to the midpoint of the line connecting the shoulder markers relative to the initial position of the trunk at perturbation onset. Positive values representing a forward trunk tilt.
Trunk flexion velocity	Time derivative of the Trunk flexion.
Dx	Anteroposterior distance between vertical projection of center of mass (COM) position and the edge of the base of support (stepping leg toe marker) with positive values indicating COM to be within the boundary of the base of support (dynamically stable).
Margin of stability (MOS)	A dynamic stability measure calculated using both anteroposterior position and velocity of COM relative to the edge of the base of support with positive values representing dynamically stable and negative values indicating dynamically unstable conditions.

Abbreviations: SS: step_start, SE: step_end, COM: center of mass, MOS: Margin of stability.