Chyasti, P, Hollands, MA, hollands, K and boonsinsukh, R

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Pornprom Chayasit[a], Kristen Hollands[b], Mark Hollands[c], and Rumpa Boonsinsukh[a]*

[a]*Faculty of Physical Therapy, Srinakharinwirot University, Nakhon Nayok, Thailand;* [b]*School of Health Sciences, University of Salford, Salford, United Kingdom;* [c] *Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, United Kingdom*

*Corresponding author: Rumpa Boonsinsukh, Faculty of Physical Therapy, Srinakharinwirot University, Nakhon Nayok Thailand, Tel: +66 6495000 (ext 27314). Email: rumpa@g.swu.ac.th

Immediate Effect of Voluntary-induced Stepping Response Training on Protective Stepping in Persons with Chronic Stroke: A Randomized Controlled Trial

Abstract (230 words)

Purpose: To compare the immediate effects of voluntary-induced stepping response training (VSR) and DynSTABLE perturbation training (DST) on protective stepping in patients with stroke.

Methods: A randomized controlled trial (registration number: TCTR20170827001) was conducted in 34 patients with chronic stroke who were randomly allocated to the VSR (n=17) or DST (n=17) group. The VSR group was instructed to lean forward to induce protective stepping, while the DST group experienced support surface translation. All participants received one session of training (3 set, 10 minutes for each set with 10-minute rest in between). Step length, step width, number of steps and center of mass (CoM) position during protective stepping were assessed using a computer-assisted rehabilitation environment (CAREN) system prior to and immediately after training. Two-way ANOVA was used to compare between groups and times.

Results: Both types of training resulted in an increase in step width, but step length increased and there was a more positive COM position exhibited following DST ($p<.05$) than following VSR. Single-step incidence increased, whereas multiple-step incidence decreased significantly in both groups. Only participants in the VSR group generated protective stepping with the affected leg in a larger percentage of trials (27%) after training than before training.

Conclusion: Both DST and VSR led to changes in protective stepping parameters after a single session of training. VSR may be a feasible alternative to equipment-based training but requires further study.

Keywords: postural control, balance, rehabilitation, cerebrovascular accident, fall risk

Introduction (4518 words from introduction to conclusion)

Stroke is one of the leading causes of balance disorders, gait deficits, and falls.[1, 2] Persons with stroke have a higher risk of falls following discharge from hospitals than during hospitalization.[3, 4, 5] A previous study in persons with stroke revealed interesting information about near-falls, which is when an individual feels that they are about to fall but does not actually fall. Almost all persons who reported near-falls exhibited recovery responses, including limb movement strategies such as grasping or taking protective steps, to prevent themselves from falling.[6] Protective stepping strategies create a new base of support (BoS) to recapture or decelerate the center of mass (CoM) after the individual experiences a perturbation. Previous studies have demonstrated that some individuals with stroke are unable to perform protective stepping with both limbs or prefer to step with their unaffected leg.[7, 8] Additionally, some individuals required external assistance to respond effectively to perturbations.[7, 8, 9, 10] These findings are important since an impaired ability to take protective steps has been related to an increased fall rate post stroke.[11]

Protective stepping can be practiced with perturbation training using complex instruments (for example, a moveable platform or a cable-release system).[12, 13, 14] Positive effects of perturbation training in response to platform translations have been found in persons with chronic stroke after a single session of slip exposure. After training, the participants had longer protective step lengths, fewer terminating steps and improved stability.[13] Similar results were found in a case study using a cable-release system. A participant with chronic stroke leaned forward with the support of a cable, and the cable was released unpredictably to trigger protective stepping. The results demonstrated that after 6 sessions of training, the participant could respond to a higher magnitude of perturbation without any external assistance.[12] However, the application of these training methods in real clinical practice is limited, as these training paradigms require expensive, large and complex equipment that cannot be readily used in most clinical settings.

With a body position similar to that used in the cable release paradigm, a voluntary-induced stepping response (VSR) can be generated by instructing a participant to voluntarily lean their whole body forward until they feel a loss of balance or a need to take a step. A previous study demonstrated the effectiveness of combined VSR and fast squatting exercises on stability during voluntary arm raises, as there were faster and higher biceps femoris activations and less co-contraction of the leg muscles in people with stroke after training.[15] Given that VSR training facilitates leg movements similar to protective stepping strategies, this training method may be an alternative rehabilitation paradigm to platform translation, which requires complex equipment. Therefore, this study aimed to compare the immediate effects of VSR training and platform perturbation training using platform translation equipment (DynSTABLE, DST) on protective stepping in persons with chronic stroke. DST was selected in this study as a reference training paradigm because it can be used to simulate slip-like situations for participants, and there is evidence that slip-like perturbation training can improve the ability to perform protective stepping in elderly people.[16, 17] DST also includes virtual reality, so sensory feedback and task training parameters can be systematically manipulated. A study reported that the use of virtual reality for locomotion training can promote motor recovery and cortical changes in persons with chronic stroke.[18] We hypothesized that, similar to DST, VSR training can improve the ability to perform protective stepping when individuals respond to surface perturbations, as indicated by increased step lengths or step widths and increased body stability, as measured by positive CoM positions at the first step touch down.

Materials and methods

Study design

A two-armed, parallel-design randomized controlled trial was conducted in participants with chronic stroke at a neuro-rehabilitation center from September 2017 to July 2018. This study was a part of a larger study that assessed both the immediate and retention effects of VSR training and was registered in the Thai Clinical Trials Registry [URL http://www.clinicaltrials.in.th/].

Sample size

Sample size was estimated with data from our pilot study of 10 persons with stroke using G*Power 3.1. Effect sizes were calculated from the variance explained by the interaction effect of the protective step length (f = 0.19). The alpha was set at 0.05, the power was set at 80%, and the correlation between the pre- and posttests was set at 0.8, resulting in the need for 26 participants. A 30% attrition rate was added for each group, resulting in a total estimated sample size of 34 participants (17 per group).

Participants

Individuals were recruited to participate in the study if they experienced a stroke more than 6 months prior, were medically stable, were able to stand independently without an orthotic device and were able to walk independently with or without cane for at least 6 meters. The exclusion criteria were individuals who 1) underwent perturbation testing and/or training within the past year; 2) had a neurological condition other than stroke, 3) had cardiovascular disorders (e.g., uncontrolled hypertension, or acute deep vein thrombosis), or 4) had musculoskeletal problems that prevent stepping. The study was approved by the institutional review board prior to the beginning of the study. Informed consent was given by each participant prior to inclusion.

Procedures

Demographic information regarding the participants' age, sex, weight, height, stroke duration, hemiplegic side, fall history, and fear of falling were collected via self-report. Cognitive function was assessed by the Mini-Mental State Examination (MMSE),[19] balance confidence was assessed by the Activities-specific Balance Confidence scale (ABC),[20] recovery after stroke was assessed by the Fugl-Meyer Assessment of lower extremity motor (FMA-LE)[21] and sensation subscale, and functional muscle strength was assessed by the Five Times Sit-to-Stand Test (FTSST).[22] The clinical test for protective stepping comprised the compensatory stepping tasks (items 16-18) of the Balance Evaluation System Test.[23, 24] A participant could receive a score of 0 (inability to step) to 3 (perform one large step) for each item. The Timed Up and Go (TUG) test and Dynamic Gait Index (DGI) were also administered to assess balance during walking and turning.[25] Fall history within the past 12 months was recorded, and a "faller" was defined as a person who reported falling at least once in the past 12 months.[26] The fear of falling was identified by asking the question, are you afraid of falling?

Protective stepping assessment

To examine the immediate effect of training on protective stepping, the participants experienced unpredicted platform movements at two consecutive events (baseline and an immediate assessment after training). The computer-assisted rehabilitation environment (CAREN, Motekforce Link, Amsterdam, The Netherlands) system that consists of a movable computer-driven 2 m-diameter platform was used to simulate slip-like situations.[27] Perturbations were delivered by rapidly moving the platform backward (acceleration of 4

m/s^2 with acceleration and deceleration periods lasting 300 ms each) to elicit a forward fall of the participants while they were standing on the platform. The onset of the platform perturbations varied during each trial to reduce the participants' ability to anticipate the perturbations. The participants wore a safety harness and stood barefoot a foot's width apart on an A3 paper that was taped on the top of the moveable platform to standardize the preferred foot position. The verbal instruction "try to put equal weight on each leg" was given to each participant to minimize the influence of pre-perturbation loads on stepping performance. The safety harness was set so that the participants had sufficient space to take steps without their hands and knees touching the platform. Platform perturbations were delivered for 10 trials both before and immediately after training. The participants were instructed to act naturally to recover their balance, and no instructions were given regarding which leg they should step with. Each participant underwent a practice trial with a platform perturbation to reduce behaviors related to being startled.

Thirty-nine retroreflective markers were adhered to the participants according to the full-body plug-in gait marker set, including four markers on the long toe and fifth metatarsal, to compute the COM position.[28, 29] Three additional markers were placed on the platform to calculate the onset of movement during the perturbation trials. Full-body marker trajectories were recorded using a ten-camera VICON motion capture system (VICON Motion Systems Ltd, Oxford, United Kingdom). Kinematic data were computed using the plug-in gait model. Two video cameras were used to record all testing events for each participant.

The participants were randomly allocated to either the voluntary-induced stepping response (VSR) or DynSTABLE perturbation training (DST) group using stratified randomization with a 1:1 allocation ratio. Stratified randomization was performed using the FMA-LE cut-off score (>14.5 score classified as high function), as recommended by a previous study [30], to obtain balanced groups in terms of stroke severity. The randomization sequence was computer generated and operated by an internet randomization service (www.rando.la). This web-based randomization tool provided unpredictable sequences by simply generating randomized results for each individual after the participant's code and FMA-LE score were determined; therefore, selection bias was alleviated. As the randomization, allocation, intervention and assessment steps were performed by one researcher (an experienced physical therapist), the intervention allocation results could not be completely concealed, and the researcher could not be blinded to the assessment and treatment results. However, the outcome measures were objective assessments, so the risk of assessor bias was limited.

Training protocol

Voluntary-induced stepping response (VSR) was produced by instructing the participants to lean their whole body forward without bending at the hip and knee until they felt a loss of balance and then took a step. The participants were asked to perform VSR training for up to 10 minutes at a time by alternately stepping with their unaffected and affected legs, and periods of rest (approximately 10 minutes) were provided between trials, as needed. For participants who could not perform VSR training, manual guidance from a therapist (by moving the pelvis forward) was given to facilitate the participant in moving correctly during the demonstration. A maximum of 3 sessions lasting 10 minutes each were performed by all participants.

DynSTABLE perturbation training (DST) is a mode of training in the dynamic stability and balance learning environment (DynSTABLE) instrument (Motekforce Link, Amsterdam, The Netherlands). DynSTABLE includes a set of training applications in which real-time feedback is provided in challenging physical, visual and cognitive environments; the system comprises three screens with projectors, an audio system, and a 2 degree-offreedom moveable platform. Perturbations were introduced randomly by translating the movable platform in 4 directions (anterior, posterior, right, left).[16, 17] During training, the participants were asked to stand with their feet apart in a comfortable position, watch the virtual screen in front of them which displayed a ball moving in several directions to induce platform movement, and act naturally when recovering their balance. The visual feedback regarding the direction of platform movement was given to the participants. The training was conducted in the same way for the same period of time as it was for VSR training (figure 1). The perturbation difficulty was programmed to gradually increase from level 1 to 10 (acceleration = 9.8 m/s^2) within a session. The gradual increase in acceleration resulted in a shift from participants using feet-in-place to stepping responses.

Prior to VSR training or DST, all participants performed warm-up exercises for 7 minutes, including lower extremity muscle stretching, weight shifting practice, and voluntary forward stepping 10 times with each leg. They also performed leg stretching after training for 3 minutes as a cool down. During both training sessions, the researcher stood beside the participants to give them individual instructions and for their safety.

[Figure 1 near here]

Data analysis

The primary outcomes, including step length, step width and COM position at the 1st stepping foot touchdown measured pre- and posttest, were calculated and analyzed using MATLAB software (MathWorks, Inc., Natick, Massachusetts). Step length and step width were defined as the distance between the heels of the supporting and stepping limbs at the point of stepping foot touchdown in the anteroposterior and mediolateral directions, respectively. Step length and width were normalized by the stepping leg length and multiplied by 100 to determine the percentages of the stepping leg length. Foot touchdown was the first moment at which the difference between the vertical position of stepping limb's heel or toe (depending on which part of the foot touched the ground first) and floor marker were within 2 SD of the resting baseline value.

The CoM position at foot touchdown was computed from the kinematic data relative to the stepping limb's heel marker in the anterior direction. A more negative CoM position indicates that the COM was located forward of the stepping limb's heel at foot touchdown and may suggest greater instability in the forward direction. In contrast, a more positive CoM position indicates a better ability to resist forward instability at stepping foot touchdown (figure 2).

[Figure 2 near here]

The secondary outcomes included the number of protective steps per trial, which leg was selected as the stepping leg, how often the participants grasped the handrails, and how often they lost balance (needed to be caught by the harness). If the participants took multiple steps, only the stepping leg used in the first step was considered the stepping leg. The secondary outcomes were recorded in real time for each trial and verified with the video recorded files. The affected and unaffected step lengths and widths were analyzed separately to determine whether the amount of improvement differed between the legs. The frequency of the secondary outcomes was obtained from every single trial during the pre- or post-test, resulting in a total of 170 trials (17 participants x 10 trials) for each training method.

Statistical analysis

Descriptive statistics were used to describe the subject characteristics. The mean of the 10 trials for each participant with respect to step length, step width, and CoM position were used for statistical analysis. Independent t-tests and Mann-Whitney U tests (for nonparametric data) were used to compare the subject characteristics between groups. Mixed analysis of variance (2x2) was used to determine the effect of VSR training and DST on protective stepping at baseline and posttest, and the Bonferroni comparison test was then used to resolve significant interactions. The number of stepping responses, choice of the stepping leg, number of times the participant grasped the handrails per trial, and number of times the participant lost balance per trial were reported as the frequency and percentage of all trials in each of the groups. Chi-square and McNemar tests were used to compare the percent differences between groups and between the pre- and posttests, respectively. All statistical analyses were performed using IBM SPSS statistics version 24 (IBM Corporation, Armonk, New York) with a significance level of 0.05. Effect sizes were calculated using Cohen’s d based on the following criteria: 0.2 = small; 0.5 = medium and 0.8 = large.[31]

Results

Of the thirty-six participants who were recruited, two were excluded due to a limited ability to stand independently for longer than 5 minutes or discontinued before baseline testing. Thirty-four participants were assessed at baseline and randomly allocated to either the VSR or DST group (figure 1). One of the participants in the DST group was unavailable for the posttest; thus, the data from the remaining 33 participants were used for analysis. There were no significant differences between the VSR and DST groups in age, weight, height, sex, hemiplegic side, fall history, or number of persons with a fear of falling. However, stroke duration was significantly longer in the DST group. Cognitive and memory performance, balance confidence level, motor performance, leg sensation, functional leg muscle strength, balance ability while walking and turning, protective balance performance, and walking mobility did not differ between groups (Table 1).

[Table 1 near here]

Step kinematics

Step width and step length at baseline were not significantly different between groups (figure 3A and 3D). The overall step width (figure 3D) was wider in both groups after training ($p<0.05$, 95% CI 1.46 to 4.56, Cohen's d = 0.31). The interaction effect ($p<0.01$) suggested that the overall step length (figure 3A) was longer after training only in the DST group ($p<0.001$, 95% CI 3.12 to 7.87, Cohen's d = 0.54). No significant changes were found in the unaffected step length after either training method, but when a participant used the affected leg to step, a significantly longer step length post training was found in both groups ($p<0.01$, 95% CI 2.4 to 10.23, Cohen's d = 0.51) (figure 3C).

[Figure 3 near here]

Center of mass

There was no difference in the CoM position at baseline between the DST and VSR groups (figure 4), but the significant interaction between the time and training group ($p=0.02$) indicated that the CoM position, relative to the stepping limb's heel of mostly the unaffected leg, improved only after training in the DST group ($p<0.01$, 95% CI, 13.94 to 48.79, Cohen's d = 0.48), by shifting from negative to positive values post training. In the VSR group, the CoM positions were positive during both pre- and post-training, suggesting that the VSR group was able to maintain the CoM in the appropriate position before training; hence, no improvement was found.

[Figure 4 near here]

Secondary outcomes

The secondary outcomes are presented in Table 2. Due to some technical errors that occurred at baseline and posttest, not all trials could be included in the analysis. As a result, at baseline, 168 trials from the VSR group and 168 trials from the DST group were analyzed, while 163 posttest trials from the VSR group and 154 posttest trials from the DST group were included in the analysis. There were significant differences in the number of protective steps, choice of the protective stepping leg and handrail grasping occurrences between groups pre- and posttest. After training, the frequency of trials with a single step increased by 16.3% of the trials in the VSR group ($p=0.002$) and 13.1% of the trials in the DST group ($p<0.001$). Only the VSR training group showed significant changes in the choice of the protective stepping leg; there was a significant increase in the use of the affected leg and a significant decrease in the use of the unaffected leg after training compared with before training ($p<0.001$). Although both groups showed a decrease in handrail grasping occurrences after training compared with before training, a significant reduction was found only in the VSR group ($p<0.001$). No changes in the number of times the participant lost his or her balance were found after VSR or DST compared with before training.

[Table 2 near here]

Discussion

This study is the first to examine the immediate effect of voluntary-induced stepping response (VSR) training on protective stepping responses in persons with chronic stroke. We hypothesized that VSR training can improve the ability to perform protective stepping in the same way as training with a complicated platform translation instrument can. The findings partially supported our hypothesis given that step length of the affected limb, step width and percentage of trials in which the participants took a single step, but not the COM position, improved on both types of training. Moreover, improvement of other outcome variables varied depending on the type of training. The participants in the DST group demonstrated a longer step length and a positive CoM position that was larger in magnitude after training compared with before training, whereas the participants in the VSR training group showed a higher percentage of trials in which they used the affected leg to step and a reduction in the need to grasp the handrails.

DST in this study encouraged the practice of a feet in-place strategy, i.e., ankle and hip strategies, for maintaining balance during platform perturbations. However, the perturbations in our DST protocol gradually increased in difficulty from level 1 to 10 to trigger protective stepping responses. This training protocol revealed improvements in protective stepping in terms of a larger step length and better control of the CoM during the posttest in the DST group. The improvements in protective stepping following DST were in line with the results from a recent study on instrument perturbation training in persons with chronic stroke for 5 weeks, where the percentage of trials in which the subjects took a single step during forward perturbations significantly increased.[32] Even though the period of training was shorter in our study than in the previous study, these results demonstrated that DST is effective and can improve protective stepping poststroke.

VSR is a type of internal perturbation training, as participants need to lean forward with their whole body to voluntarily induce forward instability and generate a protective step. Our results demonstrated that VSR training can improve protective responses by increasing step width, increasing the frequency of using a single step, increasing the frequency of using the affected leg to step with a larger step length, and decreasing the frequency of grasping the handrails. The increase in step width may not necessarily indicate an improvement of ability to perform protective stepping, as increased step width could also be the result from an increase in loading of the unaffected limb. However, the improvement in other secondary outcomes, such as increasing the frequency of using the affected leg to step with a larger step length and decreasing the frequency of grasping the handrails, could be clearly used to indicate the improvement of protective responses in clinic. A significant increase in the frequency of using the affected leg was only found after VSR training but not after DST. This result may be due to the specific VSR training protocol introduced in this study, where the participants were trained to use both the affected and unaffected legs to step. We also demonstrated that VSR training did not lead to a significantly larger step length and better control of the CoM, as observed with the DST. The level of protective balance performance and frequency of balance loss at baseline may be responsible for this discrepancy. The participants in the VSR training group tended to have higher protective balance performance, as measured by the BESTest (score of 6.9 ± 4.2) and CoM position at baseline (positive value), than those in the DST group (score of 4.4 ± 3.8 and negative CoM position), even though the differences in BESTest score and CoM position between groups did not reach significance. In addition, there were differences in the frequency of loss of balance between the VSR and DST during pretest (1.2% versus 10.1% of trials) which may also suggest different protective stepping ability between groups at baseline.

Improvement in the protective stepping response after short periods of VSR training has not been reported elsewhere. A possible explanation for the improvement in protective stepping in response to perturbations after short periods of VSR training in this study may be that the training was task-specific. Task-specific training is a type of neuromotor intervention in which muscles are trained to function for a particular action.[33] This type of training emphasizes goal-directed tasks, mass practice and the repetition of skills for regaining functional abilities by using either undamaged areas or recruiting supplementary areas of the brain.[34] A systematic review and meta-analysis of task-specific training for upper limb function in persons with subacute and chronic stroke revealed changes in the sensorimotor cortex, as measured with TMS, fMRI, PET, and SPECT at pre- and posttest, with standardized effect size of 0.84.[35] VSR training can be considered task-specific training for protective stepping, as the participants received many repetitions (201±40 repetitions) of protective stepping with both the affected and unaffected legs. In addition, there is evidence of cortical involvement during the late phase of automatic postural responses[36], and protective stepping may be controlled by the cortex in that phase.[37] These findings, coupled with our own findings, introduce the possibility that VSR training may facilitate the cortical components of protective stepping, resulting in improvements in protective responses under external perturbations.

The VSR training protocol in our study is novel. We found only one study that utilized training using internal perturbation coupling with manual external perturbations.[38] Internal perturbations were induced by using agility tasks such as kicking a soccer ball, and manual external perturbations were induced by a therapist asserting a pushing or pulling force on the patients. In this study, protective stepping performance was measured by the reactive subscale of the mini-BESTest, which mainly focused on the number of protective steps taken, step length, and stability after the responses. The reactive subscale scores of the mini-BESTest increased after training with the procedure when compared with conventional therapy. However, due to the combined type of perturbation training, it was not clear whether the improvement in the protective stepping response observed in the study was attributable to the practice of internal or manual perturbations or the combined effect of both practices.

Several important issues must be considered prior to applying VSR training in clinics. First, only participants with chronic stroke who could stand and walk independently and had low BESTest item scores of 16-18 were recruited. Thus, improvement after training can be expected in persons who have these characteristics, so these should be set as criteria for selecting persons with stroke for VSR training. Second, therapists should train protective stepping repetitively using both the affected and unaffected legs. This process will facilitate successful protective stepping under different constraints. For the participants who could not perform VSR training, we found that adding 2-3 repetitions of manual guidance by moving the pelvis forward during the demonstration was useful in facilitating the understanding of the VSR movement. All persons with stroke should wear a safety harness around the waist, and therapists should stand beside them throughout the VSR training period for safety.

Despite careful randomization, the stroke duration of the participants was longer in the DST group than in the VSR group, which is a common problem for small RCTs. However, this should not confound our results, as the FMA-LE, FMA sensory, FTSST, TUG and DGI scores did not significantly differ between groups at baseline; thus, the levels of motor recovery, muscle strength, walking and general balance ability may be similar between groups. Nevertheless, future studies should be conducted to explore the effects of time since stroke on responses to VSR training. VSR training is unidirectional (forward direction only), and the changes in postural response variables observed after VSR training in this study may not be observed after training in other directions. Furthermore, our study investigated only the immediate effects of VSR; whether the improvement in protective stepping will be retained for a longer period is uncertain. Therefore, additional studies need to be conducted to determine the effectiveness of long-term VSR training programs on motor learning, retention and/or transferability in persons with stroke.

In conclusion, 50 minutes of VSR training can be administered to improve individuals' ability to perform protective stepping after stroke to an extent similar to DST. Both types of training can increase protective stepping performance by increasing the step width, affected step length, and frequency of trials using a single protective step. VSR training can also increase the ability to step with the affected limb and reduce the handrail grasping frequency, while DST can increase the step length and magnitude of the positive CoM position at the step touchdown.

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Declaration of Interest

The authors report no conflicts of interest.

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Table 1 Subject characteristics at the baseline assessment.

	VSR (n=17)	DST (n=17)
Age (y)	66.5(10.3)	68.0(10.9)
Weight (kg)	83.7(11.8)	77.9(14.4)
Height (cm)	173.9(9.6)	173.0(6.6)
Sex (M)†	14(82.4)	14(82.4)
Stroke duration (y, range)	5.1(10.2) (0.6 - 44)	6.4(4.9)* (0.8 – 16.8)
Hemiplegic side (Rt.)†	10(58.8)	10(58.8)
Faller†	9(52.9)	4(23.5)
FoF (Yes)†	9(52.9)	6(35.3)
MMSE (/30)	28.0(2.5)	28.5(2.2)
ABC (/100%)	66.5(21.9)	72.2(17.1)
FMA-LE (/34)	25.2(7.0)	25.9(7.2)
FMA-sensory (/12)	10.9(1.4)	10.8(1.0)
FTSST (s)	18.6(9.6)	22.2(12.3)
TUG (s)	22.2(16.2)	18.9(6.9)
Item 16-18 BESTest (/12)	6.9(4.2)	4.4(3.8)
DGI (/24)	18.1(4.8)	17.3(4.3)

Note: Values are the mean (SD); *significant difference between groups with $p < 0.05$. †Categorical data are in n (%); Abbreviations: M = male, FOF = fear of falling, A/U/O = affected side/unaffected side/other, MMSE = Mini-Mental State Examination, ABC = Activities-specific Balance Confidence Scale, FMA = Fugl-Meyer Assessment, FTSST = Five Times Sit-to-Stand Test, TUG = Timed Up and Go, BESTest = Balance Evaluation System Test, VSR = voluntary-induced stepping response, DST = DynSTABLE perturbation training

Table 2 Frequency of stepping responses, at which each leg was selected the first protective step, of grasping events, and of loss of balance events.

		VSR		DST	
		Pretest N(%)	**Posttest N(%)**	**Pretest N(%)**	**Posttest N(%)**
Number of protective steps	No step	0 (0)	0 (0)	35 (20.8)	31 (20.1)
	1 step	120 (71.4)	143 (87.7)*	68 (40.5)	98 (63.6)**
	Multiple steps	48 (28.6)	20 (12.3)*	65 (38.7)	25 (16.2)**
Choice of protective stepping leg	No step	0 (0)	0 (0)	35 (20.8)	31 (20.1)
	Affected leg	34 (20.2)	44 (27)**	48 (28.6)	42 (27.3)
	Unaffected leg	134 (79.8)	119 (73)**	85 (50.6)	81 (52.6)
Grasping events	No	117 (69.6)	128 (78.5)**	84 (50)	97 (63)
	Grasp	51 (30.4)	35 (21.5)**	84 (50)	57(37)
Loss of Balance events	No	166 (98.8%)	163 (100%)	151 (89.9%)	141 (91.6%)
	Loss balance	2 (1.2%)	0 (0%)	17 (10.1%)	13 (8.4%)

Note: *significant difference between pre- and posttest within a group (p<0.01) and ** (p<0.001).

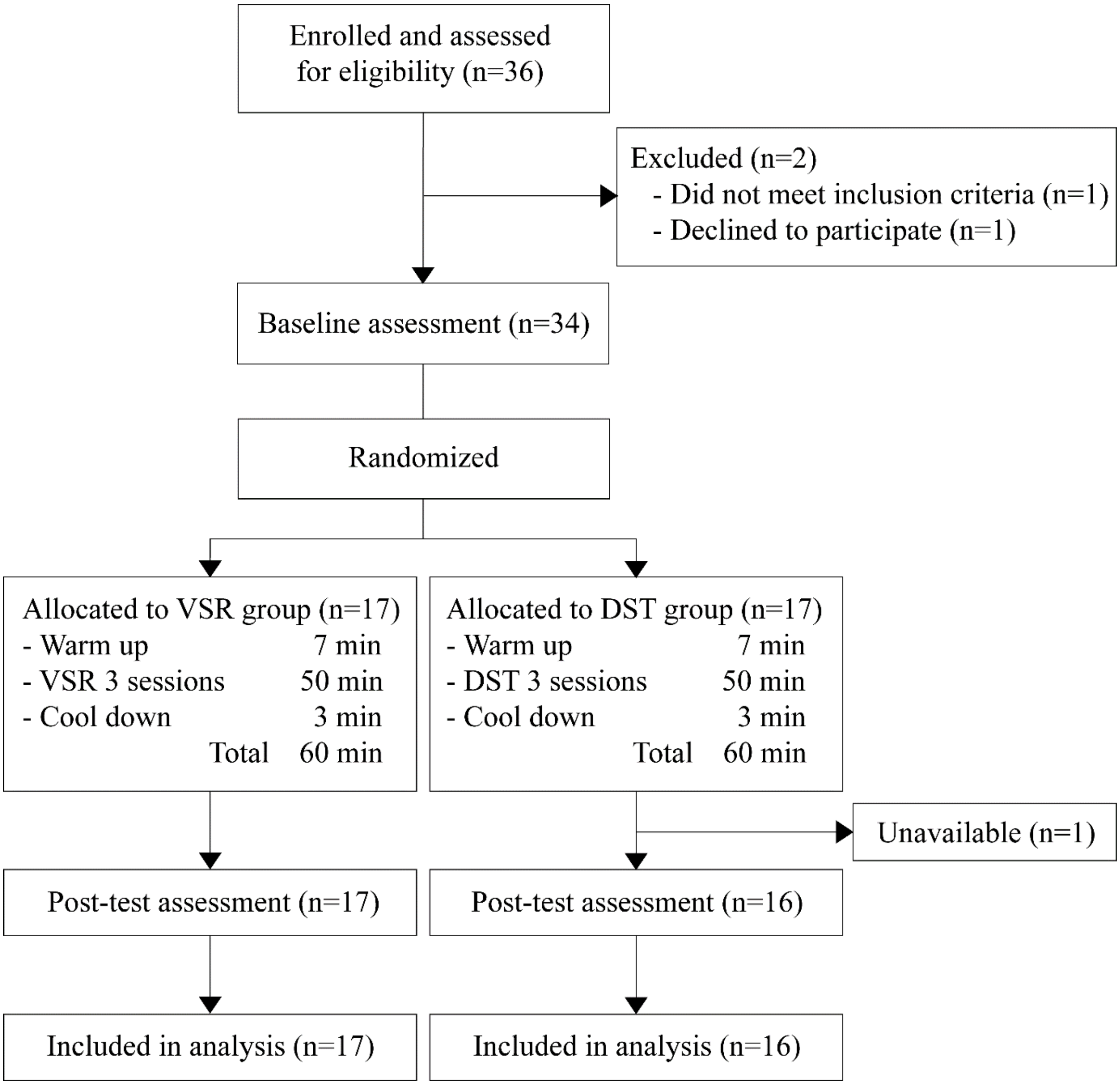
Figure legends

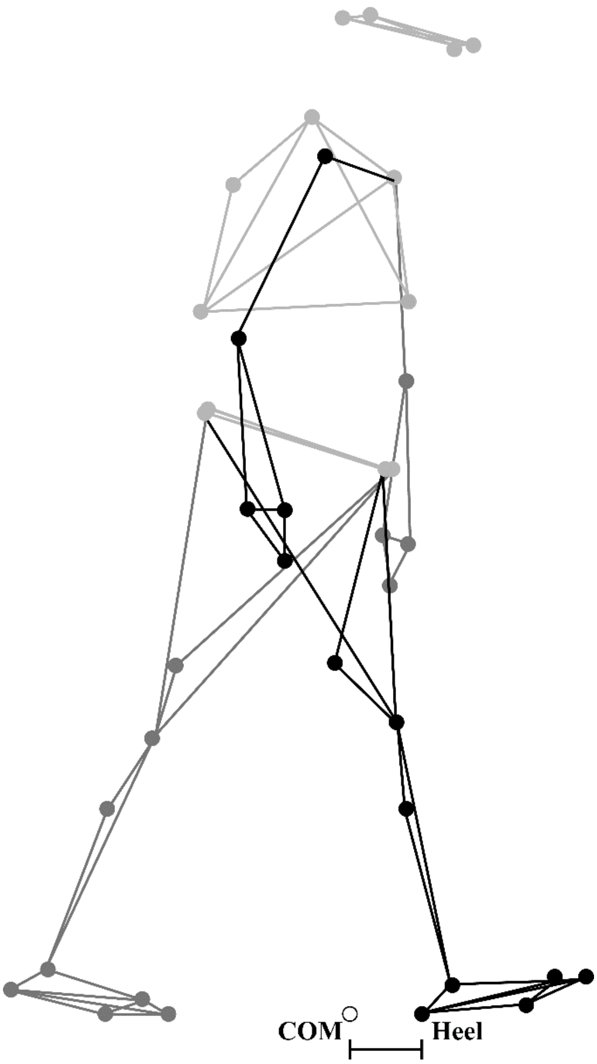
Figure 1 Flow diagram of participant enrolment. VSR refers to voluntary-induced stepping response training, and DST refers to DynSTABLE perturbation training.

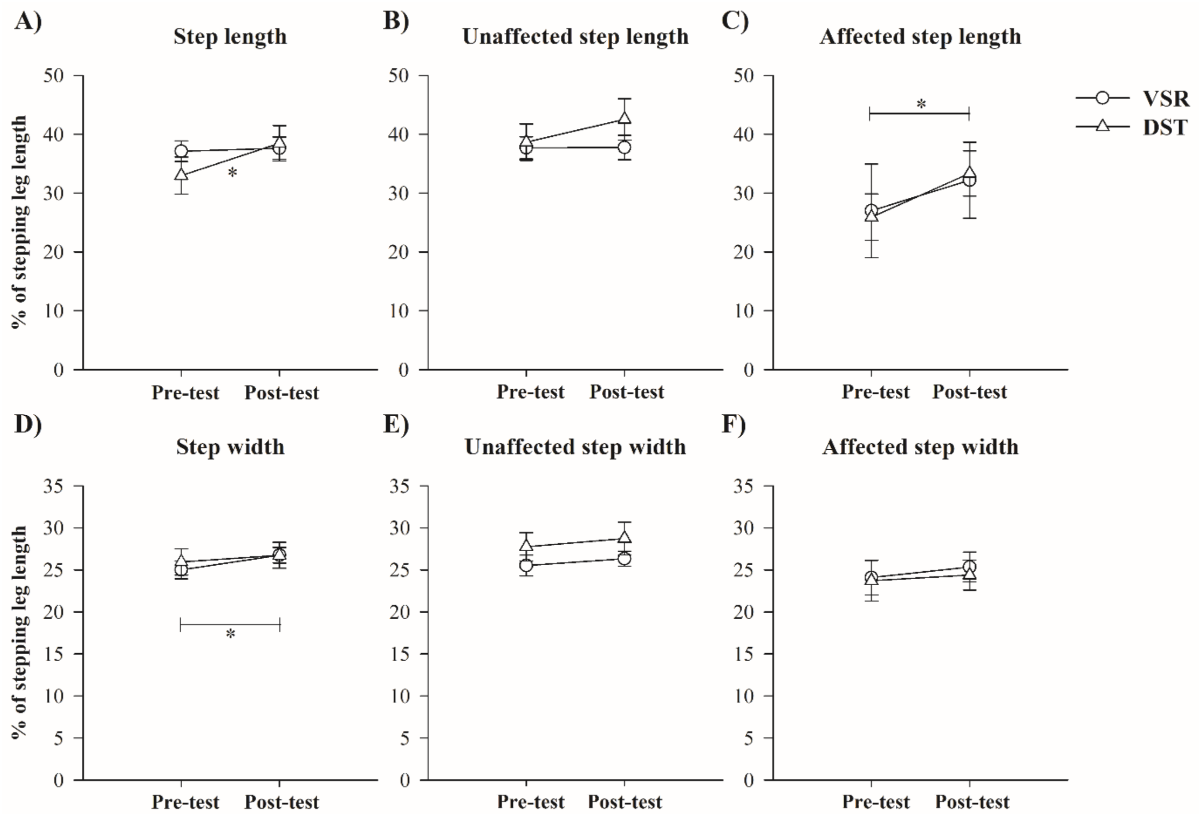
Figure 2 Center of mass (CoM) position relative to the stepping leg at foot touchdown. The stepping side is shown in black, the stance side is shown in dark gray, and the head and trunk are shown in light gray. The filled circles represent markers. The open circle shows the location of the body's CoM projected to the floor.

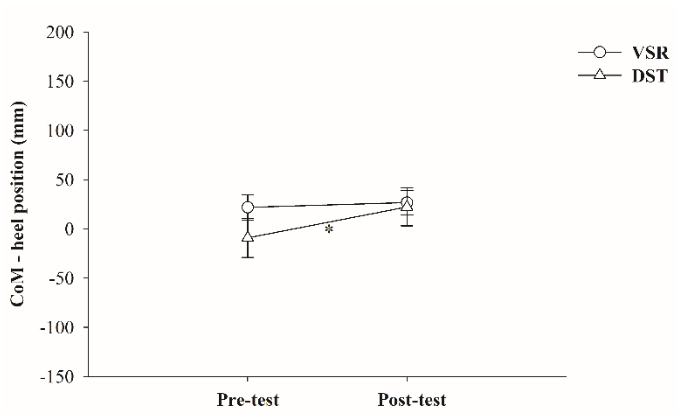
Figure 3 Step length, step width, and standard errors of the stepping leg in the first step for both legs (A and D), only the unaffected leg (B and E) and only the affected leg (C and F). VSR refers to voluntary-induced stepping response training, and DST refers to DynSTABLE perturbation training. $*p<0.05$.

Figure 4 Center of mass (CoM) position and standard error relative to the stepping limb's heel at the 1st foot touchdown at pre- and posttest in the VSR and DST groups. VSR refers to voluntary-induced stepping response training, and DST refers to DynSTABLE perturbation training. $*p<0.05$.


Enrolled and assessed for eligibility (n=36)
Excluded (n=2)
- Did not meet inclusion criteria (n=1)
- Declined to participate (n=1)
Baseline assessment (n=34)
Randomized
Allocated to VSR group (n=17)
- Warm up 7 min
- VSR 3 sessions 50 min
- Cool down 3 min
Total 60 min
Allocated to DST group (n=17)
- Warm up 7 min
- DST 3 sessions 50 min
- Cool down 3 min
Total 60 min
Unavailable (n=1)
Post-test assessment (n=17)
Post-test assessment (n=16)
Included in analysis (n=17)
Included in analysis (n=16)


COM
Heel


A)
Step length
B)
Unaffected step length
C)
Affected step length
D)
Step width
E)
Unaffected step width
F)
Affected step width
% of stepping leg length
Pre-test
Post-test
*
VSR
DST


CoM - heel position (mm)
Pre-test
Post-test
*
VSR
DST