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Training Rapid Stepping Responses in an Individual With Stroke

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Background and Purpose. Compensatory stepping reactions are important responses to prevent a fall following a postural perturbation. People with hemiparesis following a stroke show delayed initiation and execution of stepping reactions and often are found to be unable to initiate these steps with the more-affected limb. This case report describes a targeted training program involving repeated postural perturbations to improve control of compensatory stepping in an individual with stroke.

Case Description. Compensatory stepping reactions of a 68-year-old man were examined 52 days after left hemorrhagic stroke. He required assistance to prevent a fall in all trials administered during his initial examination because he showed weight-bearing asymmetry (with more weight borne on the more-affected right side), was unable to initiate stepping with the right leg (despite blocking of the left leg in some trials), and demonstrated delayed response times. The patient completed 6 perturbation training sessions (30–60 minutes per session) that aimed to improve preperturbation weight-bearing symmetry, to encourage stepping with the right limb, and to reduce step initiation and completion times.

Outcomes. Improved efficacy of compensatory stepping reactions with training and reduced reliance on assistance to prevent falling were observed. Improvements were noted in preperturbation asymmetry and step timing. Blocking the left foot was effective in encouraging stepping with the more-affected right foot.

Discussion. This case report demonstrates potential short-term adaptations in compensatory stepping reactions following perturbation training in an individual with stroke. Future work should investigate the links between improved compensatory step characteristics and fall risk in this vulnerable population.



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Stroke often results in impaired postural control, which is associated with a high incidence of falls, reduced willingness to walk independently, and reduced overall activity.^{1–3} Previous research has revealed the essential role of “compensatory” reactive balance control for maintaining balance.⁴ Although falls can be initiated by external factors (eg, a slip, trip, or nudge), the capacity to recapture balance and prevent falling is fundamentally determined by the effectiveness of compensatory balance reactions.⁴ In particular, change-in-support reactions, involving rapid compensatory stepping and grasping reactions that increase the size of the base of support, are essential to prevent falling.⁵ These are not reactions of last resort but are commonly the preferred response to maintain balance following a postural perturbation.^{5,6}

Successful change-in-support reactions depend upon high speed of execution combined with accurate limb placement.⁵ These characteristics create tremendous demands on individuals poststroke, making the control of such reactions difficult.^{7,8} In particular, when faced with a situation requiring a compensatory step, individuals with stroke-related hemiparesis are presented with a unique challenge: one that requires reliance on the more-affected limb, either for generating the muscle force and power required to step rapidly or for accepting full body weight during a step with the less-affected limb. Individuals with stroke are more likely to initiate compensatory steps with the less-affected limb than with the more-affected limb.^{8,9} They also show delayed time to initiate and execute compensatory steps, increased use of multistep reactions, and altered anticipatory control prior to step initiation compared with people who are healthy.⁸

Due to training specificity,¹⁰ optimal rehabilitation strategies for improving control of compensatory stepping reactions should include postural perturbations. Simply practicing voluntarily initiated steps that do not have the same speed and stability requirements as compensatory steps likely will not lead to great improvements in reactive balance control.¹¹ To this end, recent research has examined the potential for perturbation training to improve control of compensatory stepping reactions.^{12,13} Jöbges et al¹³ used manually delivered, multidirectional perturbations in training and demonstrated increased step length and faster step initiation in response to “backward-fall” perturbations following training in participants with Parkinson disease. These adaptations were retained after 2 months. In a randomized controlled trial including older adults who were healthy, Mansfield et al¹² reported greater reductions in the frequency of multistep reactions and collisions between the swing and stance limbs in response to mediolateral perturbations following a 6-week moving-platform-based perturbation training program compared with a control group. These perturbation training programs focused on the specific challenges to reactive balance control experienced by the target populations.¹¹ Challenges to reactive balance control and subsequent treatment strategies are likely to be highly variable within the stroke population and dependent upon stroke-related sensorimotor and cognitive

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Table 1.
Clinical Balance, Gait, and Motor Impairment Scores^a

Measure	Admission (31 Days Poststroke)	First Examination (52 Days Poststroke)	Discharge (79 Days Poststroke)
Functional Independence Measure			
Total score (maximum=126)	23	NA	93
Motor score (maximum=91)	15	NA	73
Chedoke-McMaster Stroke Assessment ¹⁸ (maximum score=7)			
Leg (right, left)	4, 4	NA	5, 7
Foot (right, left)	5, 4	NA	6, 7
Berg Balance Scale (maximum score=56) ¹⁷	10	34	40
Level of functional ambulation	Moderate-maximal assist of 1–2 people	Walking with close supervision (no aid)	Independent walking indoors (no aid)
Preferred walking speed (m/s)	NA	0.51	0.66
Quiet stance symmetry (% body weight borne on the right limb)	75	69	60

^a Admission scores were taken at admission to rehabilitation; the first examination was the first time that perturbation tests were completed. NA=not assessed.

impairments.⁸ The purpose of this case report is to describe a targeted perturbation training program for treatment of impaired compensatory stepping in an individual with stroke.

Patient History and Systems Review

The patient was a 68-year-old, right-handed man (weight=81 kg, height=180 cm) admitted to the Toronto Rehabilitation Institute 31 days after a hemorrhagic stroke affecting his left frontal, parietal, and occipital lobes. Prior to his stroke, he was a semiretired professional living at home with his spouse. He had no significant medical history and was not taking prescription medications prior to the current stroke. Computed tomography scans revealed an old right cerebellar stroke that had not been detected previously. He was prescribed citalopram, clobazam, and phenytoin.

The patient’s goals upon admission to rehabilitation were to be able to walk and perform self-care activities (dress, toilet, bathe) independently. He also hoped to be able to return to golfing after discharge. The patient reported at least one fall while in

acute care; however, he was not able to accurately recall the number of falls experienced or the causes of the falls. At admission to the Toronto Rehabilitation Institute, he was classified as being at high risk for falling using the STRATIFY tool.¹⁴

The patient’s Mini-Mental State Examination¹⁵ score was 17/30. Use of many standardized outcome measures was impeded by communication and cognitive deficits. The collective examinations of the interprofessional team revealed the patient had moderate to severe communication impairments, with characteristics consistent with fluent aphasia and mild dementia. He exhibited short-term memory deficits, impaired organizational skills, and difficulty generating specific, sequenced movements with instruction. He also revealed significant right-side inattention, with decreased scanning to the right. In quiet standing, he bore more weight on the right (more-affected) side (Tab. 1). Sensation was grossly intact, and the patient exhibited active, isolated movements of all limbs but with mild weakness of the right hip musculature. Clinical balance and motor

impairment scores are displayed in Table 1.

The patient progressed and, approximately 21 days after admission to the rehabilitation unit, was deemed by his physical therapist to be able to walk with supervision indoors. He was not able to use a walking aid safely because frequent right lower-limb collisions with the aid were observed. His walking pattern was characterized by a forward-flexed shuffling gait; the right step often was shorter in length, with decreased clearance during swing when not attending to it. More-detailed assessment of the patient’s dynamic balance responses occurred at that time, as outlined below.

Examination of Dynamic Balance Responses

Despite the importance of reactive balance control to maintaining stability, conventional clinical balance outcome measures focus on static postures or voluntary movements.¹⁶ The clinical examination of reactive balance control is not currently standard practice, primarily due to lack of adequate safety measures (eg, harness), lack of technology to deliver

controlled perturbations, and lack of technology to measure responses with sufficient precision. The Balance Mobility and Falls Clinic at the Toronto Rehabilitation Institute is a research and clinical care partnership that was established to address this gap in practice. This clinic provides examination of quiet standing balance, dynamic balance control during walking, and perturbation-evoked compensatory balance reactions in patients with stroke by combining technology (eg, forceplates, pressure mats, accelerometers) with conventional clinical measures (eg, Berg Balance Scale,¹⁷ Chedoke-McMaster Stroke Assessment¹⁸).

A “lean-and-release” postural perturbation system was used to evaluate control of compensatory stepping (Fig. 1). Using this system, the patient stood in a standardized foot position (heel centers 17 cm apart, 14° between the long axes of the feet¹⁹) and leaned forward with 5% to 10% of his body weight supported by a cable attached to the wall. For reference, a lean of 11% of body weight corresponds to an ankle angle of approximately 9 degrees from vertical.²⁰ At an unexpected time, the cable was released, the patient started to fall forward, and a compensatory step was required to maintain stability. This perturbation mechanism has been used in research and offers several advantages.^{21,22} The setup is simple, with minimal equipment and a small footprint, allowing for ease of clinical application. The magnitude of postural perturbation is determined by controlling the amount of body weight supported by the cable prior to release, allowing for control of variability of perturbation characteristics. Additionally, lean-and-release perturbations expose impairments in the timing of stepping reactions that may not be revealed with other perturbation mechanisms.^{21,23} Such perturbation techniques are not

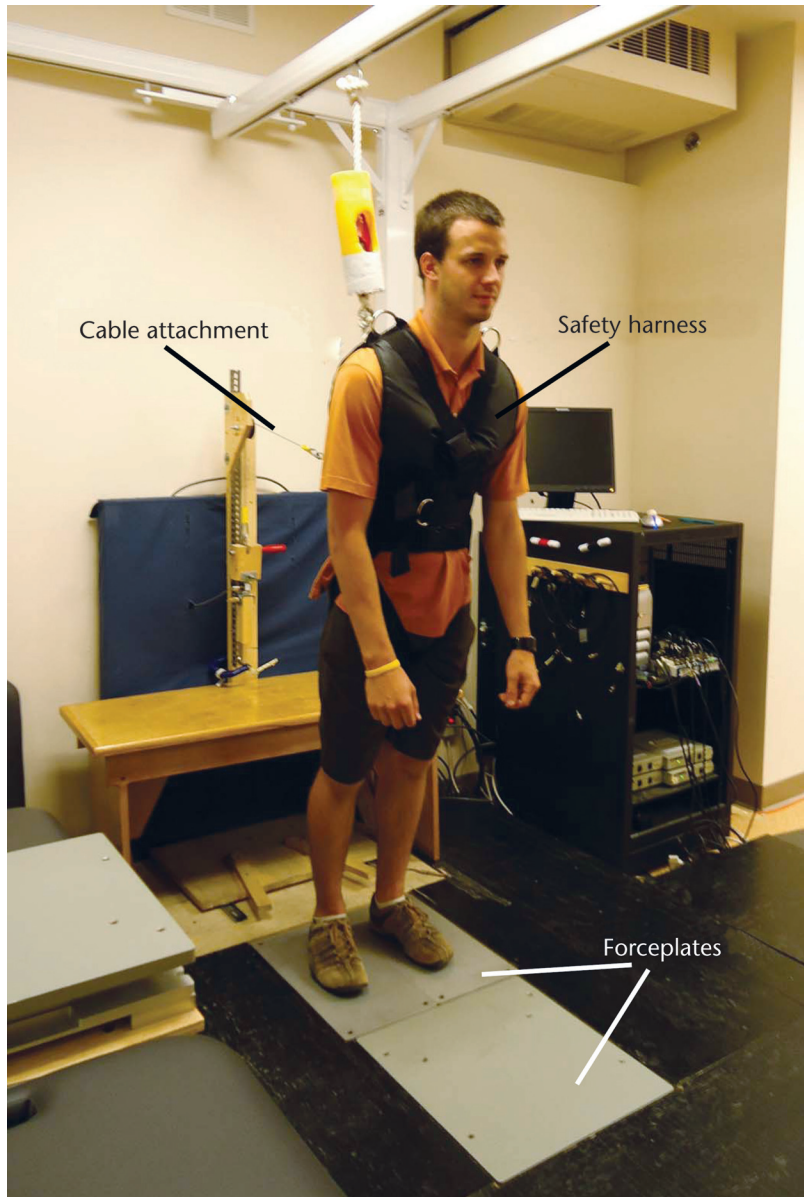


Figure 1.

The release-from-lean perturbation setup. The patient (not pictured) wore the cable-attachment harness, which was connected to a cable attached to the wall. The patient leaned, such that a portion of his body weight was supported by the cable. A load cell in series with the cable attachment recorded the amount of the patient’s body weight that was supported by the cable prior to the perturbation. A pin was pulled, releasing the cable and causing the patient to fall forward. Forceplates beneath the patient’s feet recorded ground reaction forces following the perturbation and provided information on unloading, foot-off, and foot-contact times. The patient also wore a safety harness that was attached to an overhead support structure to prevent a fall to the floor in the event of a failed attempt to recover balance.

intended to mimic the mechanisms of real-world postural perturbations but rather are used to reveal the capacity to respond to a challenging external postural perturbation by evoking rapid compensatory stepping reactions.

The following characteristics of compensatory steps were examined: use of external assistance to prevent a fall to the floor (ie, “failed” balance recovery), limb used to initiate the stepping response, and time to initiate and complete the first step. We also examined preperturbation lean magnitude and asymmetry as confounders to responses. Tests were video recorded and reviewed to confirm initial stepping limb and whether harness or therapist assistance was required to prevent a fall to the floor.

Three forceplates* embedded in the surface upon which the patient stood during perturbation tests measured ground reaction forces (Fig. 1) and were used to determine preperturbation stance loading symmetry and unloading onset, foot-off, and foot-contact times (Fig. 2). *Preper-turbation stance loading symmetry* was defined as the percentage of body weight borne on the right leg averaged over 1 second prior to the perturbation. *Preper-turbation cable load* was monitored using a load cell† in series with the cable attachment. *Perturbation onset time* was the time when the load cell recorded less than 1 N of force. All other timing measurements were calculated relative to perturbation onset time. *Unloading onset time* was the time, prior to foot-off, when the peak vertical force was recorded under the stepping foot. *Foot-off time* was the time when vertical force

recorded by the forceplate under the stepping foot was less than 1% of body weight. *Foot-contact time* was the time after foot-off when vertical force recorded either by the forceplate under the stepping foot or the front forceplate was greater than 1% of body weight. A “slide” step was a step with limited foot clearance and was defined by forward-directed motion of the foot, evident on the video recording, without completely unloading the forceplate. Forceplate and load cell data were sampled at 256 Hz and stored for offline processing.

The outcome measures were quantitative and unaffected by rater reliability. Two previous studies in groups of participants without stroke repeated perturbation testing over time with no balance training between test sessions and provide evidence for stability of step timing measures with repeated testing. One study showed no change in compensatory step foot-off time in response to cable pull perturbations after 1 week in individuals with Parkinson disease.¹³ The other study included older adults who were healthy and showed a small decrease (<30 milliseconds) in foot-off time in response to surface translation perturbations with repeated testing over 6 weeks.¹² Another study supports the repeatability of testing of reactive balance control poststroke. This study used an observational scale to rate responses to cable pull perturbations in individuals with stroke and showed acceptable reliability of the rating scale when at least 2 trials were averaged (intraclass correlation coefficients >.83).⁷

The patient completed lean-and-release tests at the Balance Mobility and Falls Clinic 21 days after admission (ie, 52 days poststroke). Nine postural perturbation trials were completed in the first examination: 3 were “preferred response” trials

(ie, no constraint or additional task), 3 included a cognitive task (backward counting), and 3 were “encouraged use” trials (ie, blocking of the less-affected limb with the therapist’s hand placed approximately 5 cm in front of the shin). The cognitive task was used to expose problems executing compensatory steps under attention-demanding situations, whereas the encouraged-use condition exposed control of right-limb compensatory steps. This protocol is part of a routine care at the Toronto Rehabilitation Institute and was repeated immediately prior to discharge from rehabilitation (79 days poststroke).

In the first examination, the patient took multiple short steps that were ineffective for recapturing balance following all perturbations and used either the harness or assistance from physical therapists to prevent a fall. He had weight-bearing asymmetry, with 69% to 80% of body weight borne on the affected right side, and markedly delayed response timing (unloading time=355–638 milliseconds, foot-off time=530–925 milliseconds, foot-contact time=595–1,177 milliseconds). Despite blocking the left limb, the patient initiated steps with the left foot in 2 of the 3 encouraged-use trials. There were no marked differences in performance in the cognitive task condition compared with the preferred response condition.

Clinical Impression

In sum, this patient had a history of falls, had progressed to be able to walk with supervision, but had persistent deficits limiting his goal of safe and independent walking. From clinical examination, we felt that the patient’s impaired cognition, mild right lower limb weakness, and right-side inattention, resulting in intermittent decreased clearance of the right lower limb, contributed to

* Advanced Medical Technology Inc, 176 Waltham St, Watertown, MA 02472-4800.

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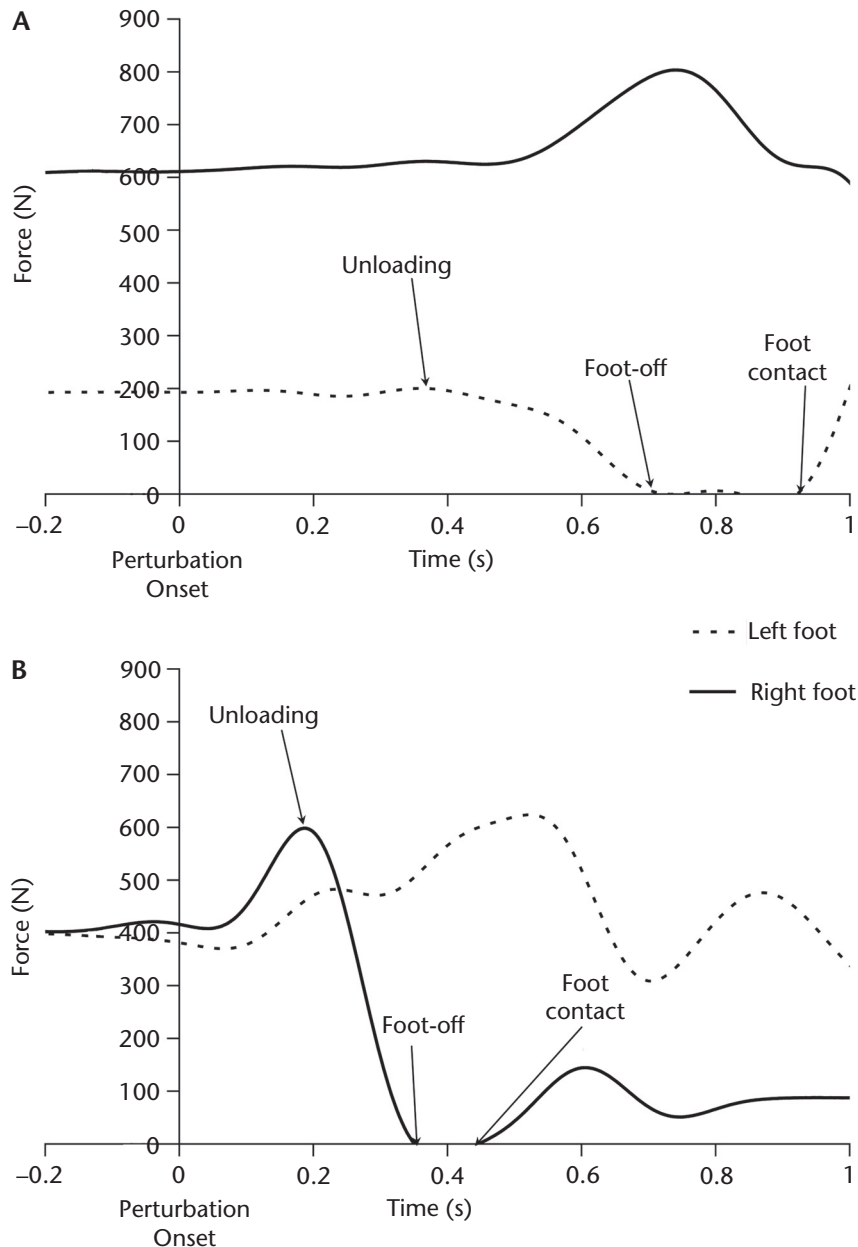


Figure 2.

Ground reaction forces during 2 trials: (A) data recorded from the first trial in the first examination, and (B) data recorded during a biofeedback trial at the end of training session 1. Unloading, foot-off, and foot-contact times are marked. Perturbation-onset time was the time when the load cell recorded less than 1 N of force, which is at 0 seconds in both graphs. All other timing measurements were calculated relative to perturbation-onset time. Unloading onset time was the time, prior to foot-off, when the peak vertical force was recorded under the stepping foot. Foot-off time was the time when the vertical force recorded by the forceplate under the stepping foot was less than 1% of body weight. Foot-contact time was the time after foot-off when the vertical force recorded either by the forceplate under the stepping foot or the front forceplate was greater than 1% of body weight. In the first examination (panel A), stance-loading asymmetry was evident, with more weight on the right limb. Time taken to complete the stepping response was delayed, largely owing to a delay in the time taken to initiate unloading of the swing limb. This was evident in little change in the ground reaction force under the left foot until 400 to 600 milliseconds after perturbation. Training in session 1 focused on improved stance-loading symmetry (by providing feedback prior to the perturbation) and encouraging use of the right limb for stepping. The trial illustrated in panel B, which was a biofeedback trial, shows near-symmetrical stance loading and reduced time to initiate unloading of the swing limb. Improved symmetry and reduced loading on the right limb may have contributed to the increased likelihood of initiating stepping with that limb.

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Table 2.
Trials Completed During Examination and Training Sessions^a

Session	Tasks	No. of Trials
First examination	Preferred response	3
	Cognitive task	3
	Encouraged use	3
Training session 1	Biofeedback and encouraged use	5
	Biofeedback	10
Training session 2	Preferred response	6
	Encouraged use	11
Training session 3	Preferred response	7
	Biofeedback	4
	Encouraged use	5
Training session 4	Preferred response	15
	Biofeedback	5
	Encouraged use	5
Training session 5	Preferred response	5
	Instructed right-foot step	5
Training session 6	Preferred response	4
	Biofeedback	5
	Instructed right-foot step	2
	Encouraged use	5
	Cognitive task	5
	Obstacle clearance	6
Discharge	Preferred response	3
	Cognitive task	3
	Encouraged use	3

^a Preferred response: there was no instruction on how to respond, and there was no extra constraint on response. Cognitive task: The patient was given a cognitive task to perform prior to the perturbation; in examination, this task was backward counting, and in training, this task was listing words beginning with a letter. Encouraged-use: initiation of the stepping response with the right foot was encouraged by blocking the left foot with the therapist's hand. Biofeedback: preperturbation stance loading symmetry was encouraged by providing visual feedback of weight bearing through the right limb prior to the perturbation. Instructed right-foot step: the patient was instructed to initiate stepping with the right foot. Obstacle clearance: a cane was placed in front of the patient's feet, and he was instructed to step over it following the perturbation to regain his balance.

his becoming unstable when walking. Additionally, we felt that this patient's impaired responses to *regain* stability (ie, deficits in stepping reactions revealed by the perturbation examination) contributed to his elevated fall risk. Specifically, these deficits included delayed stepping reactions and an inability or unwillingness to initiate stepping with the right (more-affected) limb that was possibly exacerbated by stance asymmetry, with the right

lower limb being more heavily loaded than the left lower limb.

We believed that this patient would benefit from a task-oriented training program using perturbations to stance to evoke compensatory stepping reactions to help him to achieve his goal of safe, independent mobility. Our overall aim was to improve the capacity for executing successful compensatory stepping reactions, that is, stepping reactions that are

sufficient to regain stability without the need for external assistance. Because we observed reduced use of the more-affected limb for initiating stepping, an additional focus of training was to increase use of that limb.

Intervention

Six training sessions were administered over 2 weeks, each lasting 30 to 60 minutes, with 10 to 27 lean-and-release perturbations (as previously described) delivered per session. A variety of strategies were used to target specific features of reactive control (Tab. 2). These strategies included:

1. Evoking compensatory stepping with external perturbations. Each session (except training session 1) started with at least 4 trials of the patient's preferred response, with no specific instruction or constraint on responses.
2. Encouraging preperturbation stance symmetry to decrease loading of the affected lower limb by providing visual feedback of stance-loading symmetry. Feedback was provided on a 127-cm (50-in) plasma television screen placed approximately 2 m in front of the patient. A graphic representation of the percentage of body weight borne by the more-affected limb was displayed, and the participant was instructed to maintain 45% to 55% of body weight on the more-affected limb. Visual indicators changed color from green to red if the load was outside of this range.
3. Encouraging use of the more-affected limb. As sudden, unpredictable disturbances to stability can occur in any direction, a stepping strategy that relies on the nonparetic limb could be ineffective to reduce fall risk. We, therefore, encouraged stepping

responses of the right lower limb by:

- a. Manually blocking the left limb. The therapist placed her hand approximately 5 cm in front of the left shin to block stepping with that limb.
 - b. Encouraging use of the right limb by instruction. The patient was instructed to attempt to recover his balance by stepping with the right limb.
4. Encouraging step clearance by introducing an obstacle. A cane was placed on the floor approximately 5 cm in front of the patient's toes, and he was instructed to step over the cane.

Training strategies depended upon observation of persisting problems during the first preferred response trials (eg, if asymmetry persisted, we used biofeedback during that session). We aimed to progressively increase the task challenge (eg, increasing perturbation magnitude or adding a cognitive task) and progressively reduce feedback and external constraints on responses. The session duration and number of perturbations depended upon the patient's schedule and tolerance.

Although the same perturbation method was used in both training and examination, the training sessions differed from the examination in the following ways: (1) a set test protocol with a predetermined order and number of trials was used in the examination; no instructions or guidance were provided in the examination other than to "react naturally"; (2) the personnel who administered the examination sessions (Balance Mobility and Falls Clinic staff) were different from those who administered the training sessions (the patient's primary physical therapist and research staff); and

(3) the cognitive task included in one training session (words beginning with a letter) was different from that used in the examination (backward counting).

The patient also received 1 hour of physical therapy per day during inpatient rehabilitation as part of routine care. Physical therapy aimed to improve postural alignment, general muscle strength (force-generating capacity), awareness of the right side, functional mobility including control of directional changes, and aerobic fitness. Treatment generally involved functional retraining with increased challenge as balance control improved. Specific treatment approaches included: gait training without walking aids, stair climbing, quick stepping movements, negotiating an obstacle course in parallel bars, dancing, use of a vertical stepper, aerobic training on a recumbent stepper, and golf (putting).

Outcome

The patient had difficulty achieving and maintaining the targeted pre-perturbation lean position in the first examination, as evidenced by low percentage of body weight on the cable (approximately 2%–5%). Upon discharge, he more than doubled the percentage of body weight on the cable (>10%). Despite the increased perturbation magnitude, we observed significant reductions in the frequency of external assistance required to prevent a fall; the patient required assistance following every perturbation in the first examination but did not require any assistance at the time of discharge. Stance loading symmetry improved; the patient reduced the load borne on the more-affected limb from the initial examination to the discharge examination (from 75% to 61% of body weight). We observed dramatic reductions in time to complete the first step with repeated perturbations (Fig. 3), primarily due to

reduced time to unload the foot (ie, from 355–638 milliseconds during the initial examination to 109–223 milliseconds during the discharge examination). The above-mentioned adaptations were observed in the preferred response, encouraged-use, and cognitive task conditions that were completed in the first and discharge examinations (Tab. 3), indicating adaptations to the same task conditions used in training and transfer of adaptations to a different task condition that was not used in training (ie, the cognitive task condition). At discharge, increased use of the right limb to initiate compensatory stepping was observed in the encouraged-use condition, but not in the preferred response or cognitive task condition.

Data from preferred response trials in training sessions are presented in Table 3 and Figure 3. These data show the time course of the observed adaptations. There is some evidence of use of the right limb to initiate compensatory stepping in the preferred response condition within the training sessions (stepping was initiated with the right limb in 17%–50% of these trials in some sessions). Three trials in training session 1 were initiated with slide steps (ie, limited foot clearance); no slide steps were observed beyond session 1.

Discussion

This case report demonstrates the potential to modify compensatory stepping reactions after stroke, at least in the short term, using targeted perturbation training. Adaptations to compensatory stepping reactions following perturbation training have been observed in older adults who were healthy¹² and individuals with Parkinson disease,¹³ but not those with stroke. We observed reduced reliance on external assistance to prevent a fall following the perturbation with training, indicating

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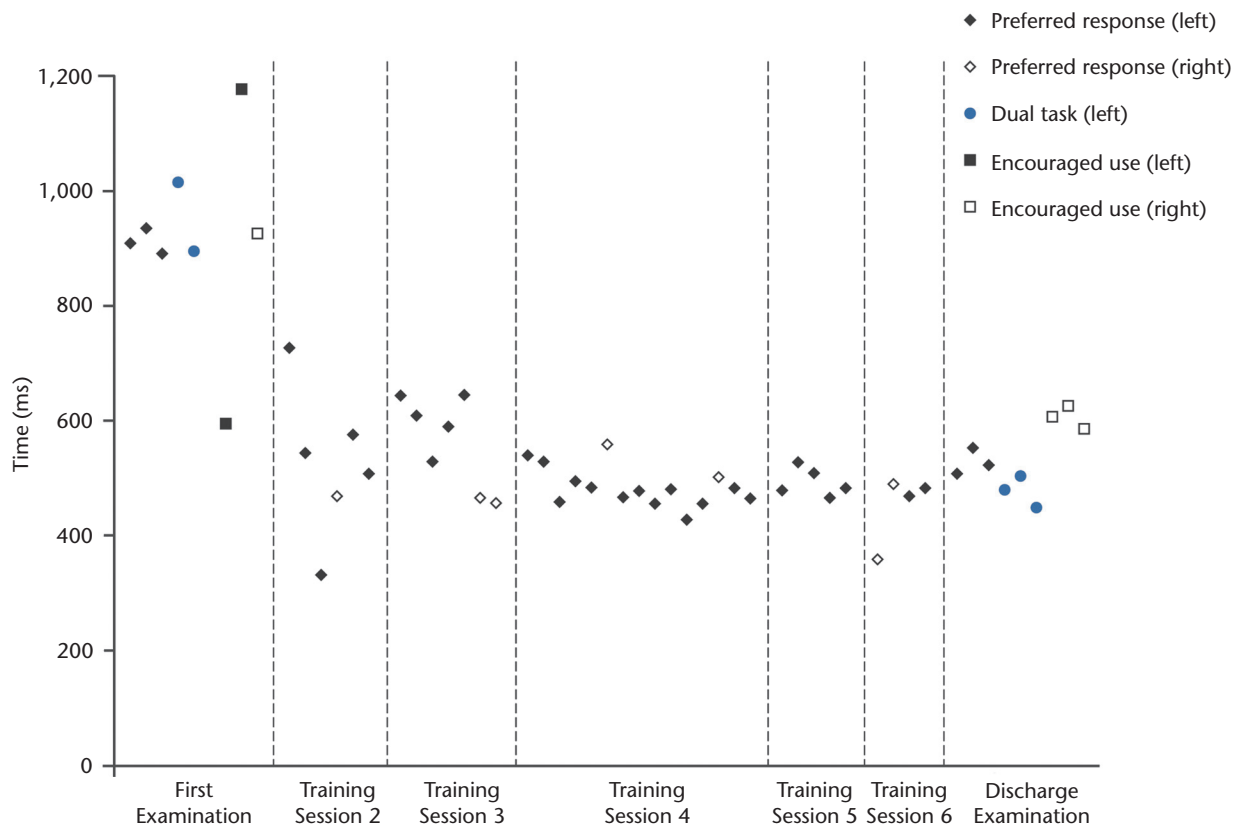


Figure 3.

Changes in foot-contact time over the course of the intervention. Foot-contact time was the time after foot-off when the vertical force recorded either by the forceplate under the stepping foot or the front forceplate was greater than 1% of body weight (see Fig. 2). Preferred response, dual task, and encouraged-use trials are shown for the first and discharge examinations, whereas only preferred response trials are shown for the training sessions. Steps with the right foot are illustrated with white symbols, and steps with the left foot are illustrated with black (preferred response) or blue (cognitive task) symbols. This figure shows reduced time to foot contact over the course of the intervention, reduced variability in foot-contact time over the course of the intervention, occasional spontaneous use of the right limb for initiating stepping during the intervention, and reduced time to complete stepping response in the cognitive task condition at discharge compared with the first examination.

more-effective compensatory stepping. More-effective compensatory steps may reflect improved stability control of the stance limb or improved control of the swing limb. The following adaptations were observed in the discharge examination compared with the initial examination and likely contributed to the increased effectiveness of stepping responses: improved preperturbation stance symmetry, increased use of the more-affected limb (when the less-affected limb was blocked), and faster step reactions.

The patient showed a high degree of stance loading asymmetry, with

more weight on his more-affected side. Such asymmetry is uncommon after stroke and may indicate subclinical signs of “pushing”^{24,25} or may be related to right-side inattention and misperception of vertical orientation.^{26,27} Increased load on one limb reduces the likelihood that steps will be initiated with that limb.²⁰ We believed that asymmetry was a contributing factor to reduced use of the right limb for stepping in our patient. Within-session improvements in symmetry with stance-loading feedback seemed to increase the likelihood of initiating a stepping response with the right limb.

The patient was reluctant to initiate compensatory steps with the more-affected limb. A previous study that attempted to evoke steps with the more-affected limb by blocking the less-affected limb with obstacles was unsuccessful, and participants collided with the obstacles.⁸ Blocking the less-affected limb with the therapist’s hand successfully evoked stepping with the more-affected limb in the current report. It is possible that the potential to hurt the therapist by colliding with her hand increased our success in evoking affected-limb steps. The patient increased use of the more-affected limb during these encouraged-use

Table 3.
Changes in Perturbation and Step Characteristics With Training^a

Session	Condition	Time Poststroke (d)	Cable Load (% Body Weight)	Preperturbation Stance Loading (% Body Weight on Right Foot)	Right Foot Steps (Proportion of Trials)	Assists (Proportion of Trials)
First examination	Preferred response	52	5.07 (0.35)	74.5 (1.6)	0/3	3/3
	Dual task		2.3 (0.83)	70.0 (1.8)	0/2 ^b	3/3
	Encouraged use		3.4 (0.55)	75.9 (3.7)	1/3	3/3
Training session 1	Preferred response ^c	62				
Training session 2	Preferred response	68	10.52 (2.20)	68.9 (6.3)	1/6	2/6
Training session 3	Preferred response	69	10.63 (2.41)	69.3 (4.1)	2/7	0/5
Training session 4	Preferred response	74	13.32 (1.56)	67.6 (2.7)	2/15	1/5
Training session 5	Preferred response	75	11.38 (1.46)	62.3 (4.5)	0/5	0/5
Training session 6	Preferred response	76	13.93 (1.56)	50.5 (5.7)	2/4	0/5
Discharge	Preferred response	79	12.60 (0.87)	61.3 (3.7)	0/3	0/3
	Dual task		11.4 (0.55)	58.4 (3.4)	0/3	0/3
	Encouraged use		12.3 (0.76)	61.8 (3.2)	3/3	0/3

^a Values shown are means or proportions, with standard deviations in parentheses. Data are presented for the preferred response trials in each session. *Cable load* is the percentage of body weight loaded on the cable attached to the wall prior to the perturbation and is an indication of the magnitude of forward lean. *Stance symmetry* was defined as the percentage of body weight loaded on the right forceplate prior to the perturbation (preperturbation stance loading). *Right foot steps* is the proportion of trials in which stepping was initiated with the right (more-affected) leg. *Assists* is the proportion of trials in which assistance was external required, either from the physical therapist or from the harness, to prevent a fall to the floor.

^b There was no attempt to step in one trial in this condition.

^c The “preferred response” condition was not completed during this training session.

trials. There was some evidence of increased use of the more-affected limb when reactions were unconstrained, although this effect did not persist in the discharge session in either the preferred response or cognitive task condition.

As is the nature of a case report, it is impossible to discern how much of the observed adaptations were due to the normal recovery process, regular physical therapy, or the novel intervention, although the within-session changes would suggest that perturbation training was beneficial. Regular physical therapy also focused on improved symmetry, increased use of and attention to the right limb, and rapid movements. Symmetry training and encouraged use of the right limb in regular physical therapy might have influenced the adaptations observed in our patient. However, it is unlikely that the voluntarily initiated movements included in regular physical therapy were fast enough to influence the

timing of compensatory stepping²⁸ because compensatory steps are initiated and executed much faster than even the fastest voluntary steps.^{29,30}

It is important to note that we completed the prescribed training program despite the patient’s cognitive and communication difficulties. Although this patient had difficulty following some instructions, which somewhat limited activities that could be included in other physical therapy plans, it was possible to evoke and train automatic postural reactions with minimal instructions and external constraints to target specific control problems. Implementing symmetry feedback was the most challenging component of the program. By using a simple visual display and providing additional cues (ie, green indicator when symmetry is achieved), the patient was able to benefit from feedback.

This case report demonstrates the utility of incorporating technology

into the routine clinical examination of postural control. Without some means to quantify stance loading, we would not have been able to identify the severity of the asymmetry and provide accurate feedback to improve symmetry. In our clinic, we use forceplates to quantify stance loading asymmetry, although other less-expensive weight-measuring technology could be modified and used instead (eg, 2 weighing scales or load-measuring video-game controllers). Forceplates also afford the ability to precisely measure timing of each phase of the stepping response and to identify when delays occur (ie, that stepping responses were slow due to a delayed time to begin to initiate any response rather than delayed time to lift the foot or increased swing duration).

Although this case report provides important information regarding the potential to train compensatory stepping after stroke, there are several limitations to be considered.

We trained stepping responses only to forward fall postural perturbations. Although it is likely that individuals with stroke will show difficulty executing compensatory grasping reactions or compensatory steps in response to lateral perturbations, the specific characteristics of these reactions after stroke have not been investigated.⁸ Although we showed transfer of some adaptations to different test conditions (ie, the cognitive task condition), we do not know whether the observed adaptations are specific to the perturbation method used in this study. It is important to show that adaptations transfer to a different type of perturbation.¹² Additionally, this patient had another stroke approximately 2 months after discharge from rehabilitation, so we were unable to complete a follow-up examination to determine whether the observed training effects were retained in the long term. It is not known whether the observed adaptations ultimately will result in improved ability to prevent falling in daily life, particularly considering other deficits (eg, inattention) that increase falls risk. Future research should characterize and train compensatory grasping reactions and laterally directed compensatory steps in individuals after stroke, examine transfer of adaptations to different types of perturbation, evaluate the long-term retention of training effects, and examine the potential effect on fall rates.

This case report describes our initial attempts to train compensatory stepping reactions in an individual with stroke. The targeted training program focused on features of reactions that were found to be impaired upon initial examination. Control of compensatory stepping appeared to improve with training, as evidenced by reduced reliance on external assistance to recover from postural perturbations, reduced stance loading asymmetry, increased use of the

more-affected limb, and reduced time to initiate and execute compensatory steps. The implications of these findings for improved recovery from real-world losses of balance and fall risk warrant further investigation.

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