ผลที่เกิดขึ้นในทันทีของการฝึกการก้าวขาเพื่อป้องกันการล้มด้วยการเหนี่ยวนำให้เกิดการล้มและการก้าวขาด้วยตนเองต่อการก้าวขาเพื่อป้องกันการล้มแบบอัตโนมัติในผู้ป่วยโรคหลอดเลือดสมอง

IMMEDIATE EFFECT OF VOLUNTARY-INDUCED STEPPING RESPONSE TRAINING ON THE COMPENSATORY PROTECTIVE STEP IN PERSONS WITH STROKE

PORNPROM CHAYASIT

Graduate School Srinakharinwirot University

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พรพรหม เชยะสิทธิ์

ปริญญานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตร
ปรัชญาดุษฎีบัณฑิต สาขาวิชากายภาพบำบัด
คณะสหเวชศาสตร์ มหาวิทยาลัยศรีนครินทรวิโรฒ
ปีการศึกษา 2562

IMMEDIATE EFFECT OF VOLUNTARY-INDUCED STEPPING RESPONSE TRAINING ON THE COMPENSATORY PROTECTIVE STEP IN PERSONS WITH STROKE

PORNPROM CHAYASIT

A Dissertation Submitted in partial Fulfillment of Requirements

for DOCTOR OF PHILOSOPHY (Physical Therapy)

Faculty of Health Science Srinakharinwirot University

2019

THE DISSERTATION TITLED

IMMEDIATE EFFECT OF VOLUNTARY-INDUCED STEPPING RESPONSE TRAINING

ON THE COMPENSATORY PROTECTIVE STEP IN PERSONS WITH STROKE

BY

PORNPROM CHAYASIT

HAS BEEN APPROVED BY THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DOCTOR OF PHILOSOPHY IN PHYSICAL THERAPY AT SRINAKHARINWIROT UNIVERSITY

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Title	IMMEDIATE EFFECT OF VOLUNTARY-INDUCED STEPPING RESPONSE TRAINING ON THE COMPENSATORY PROTECTIVE STEP IN PERSONS WITH STROKE
Author	PORNPROM CHAYASIT
Degree	DOCTOR OF PHILOSOPHY
Academic Year	2019
Thesis Advisor	Associate Professor Dr. Rumpa Boonsinsukh , Ph.D.

We aim to compare voluntary-induced stepping response (VSR) characteristics between young, elderly and persons with stroke (objective 1) and examine the immediate effect of VSR on protective steps, compared to DynSTABLE perturbation training (DST), in patients with stroke (objective 2). Ten young, 10 elderly, and 10 patients with stroke were assessed with VSR for 10 trials for objective 1. VSR was generated by voluntarily leaning forward until losing balance and take only a step. Then, a randomized controlled trial was conducted in 34 patients with chronic stroke (VSR=17 and DST=17) for objective 2. All participants received 1 session of VSR or DST training for 50 minutes. Protective steps were assessed prior to and immediately after training. We found that step kinematics, stability, and strategies of responses were more impaired in participants with stroke than young and elderly. Both training groups resulted in increased step width, but step length and stability increased more following DST. A Single step incidence increased significantly in both groups but the affected stepping increased only after VSR training. We concluded that VSR was impaired in persons with stroke. Normal characteristics of young can be used as guidelines for rehabilitation. As a single-day VSR training improved protective steps similar to DST, it may provide an alternative option to equipment-based training.

Keyword : postural control, balance, rehabilitation, age, cerebrovascular accident, falls

ACKNOWLEDGEMENTS

I would first like to express my sincere appreciation to my supervisor, Associate professor Dr. Rumpa Boonsinsukh, for her expertise and patience throughout the whole process of this thesis. She is the one who impressively guided and encouraged me to be a professional and do the right thing even when the road got tough. Without her persistent help, this project would not have been achieved. This work was supported by the Thailand Research Fund through the Royal Golden Jubilee Ph.D. Programme [grant numbers PHD/0076/2558]. Without their financial supports, this work would not have been realized. In addition, I would like to show my gratitude to Dr. Kristen Hollands and Dr. Mark Hollands who taking care of me during the data collection period in the United Kingdom. Their supports and suggestions help me lived comfortably and succeeded with the incredible data collection goal. The physical and technical contributions of the Brain And Spinal Injury Center in the United Kingdom and the Faculty of Physical Therapy of Srinakharinwirot University are truly appreciated. Their supports help me reached the thesis's goal conveniently. I wish to acknowledge my beloved mother, Pensiri Chayasit; and father, Kobkiat Chayasit for believing in me, standing beside me, and supporting me throughout the study period. Finally, I am indebted to my boyfriend, Boonlawat Triampitak who always supported, encouraged, and kept me going. This work would not have been possible without his input.

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INTRODUCTION

Background

Stroke is the major cause of balance disorders, gait deficits, and falls.(1-9) Falls can occur at every stage after stroke, even in high functional status survivors. (6) Persons with stroke are prone to have a higher risk of falls following discharge from the hospital than during hospitalization. (2, 4-6, 8-20) Patients with stroke who fell when hospitalized were more than twice as likely to fall at home after discharge.(8) Mackintosh and colleagues found functional balance performance as measured either by the Berg Balance Scale or Step Test combined with history of hospitalization falls predicted falls incidence after discharge.(2) Falls in patients with stroke can lead to serious injuries that require hospitalization such as contusion, abrasion, laceration and fracture.(4, 5, 8, 9) Studies suggest that individuals with stroke sustain more fractures than healthy elderly when they fall. (21) Falls also cause activity limitation and fear of falling, resulting in depression, social deprivation, poor quality of life, and deconditioning.(3, 5, 20)

Falls in person with stroke can be caused by loss of balance, misjudgment, lack of concentration, failure in recovery response, slip, trip, or foot dragging while performing different activities. (4, 5, 8, 11, 15) Transferring between beds and wheelchairs is the most common cause of falls in inpatient rehabilitation,(9, 10) whereas person with stroke who lives in the community often falls during walking.(4, 5, 8, 13, 15) Falls can occur in any direction (sideway, forward, backward). (4, 5, 10) Furthermore, previous study revealed information of near-falls in persons with stroke. A near-fall was defined as an occasion that an individual thought that they were about to fall but did not practically fall. It is interesting that almost all persons with stroke who reported near-falls showed saving reactions such as the use of limb movement strategies to prevent themselves from falling. (4) This study demonstrated the necessity of limb movement strategies to prevent falls in persons with stroke.

There are two distinct classes of movement strategies to recover balance and prevent falls: (1) fixed-support strategy (ankle or hip strategy) and (2) change-in-support strategy. Fixed support strategy is the ability to control the movement of the body's center of mass (COM) without changing the base of support (BOS). Change-in-support strategy is the ability to create new BOS to recapture or decelerate COM after receiving a perturbation. (22) A step taken to recover balance is also called a compensatory protective step (protective step). A protective step can be triggered by either small or large magnitude of perturbation even when the COM is well within the BOS. Selection of appropriate strategies is context-dependent. (23-27) However, in risky situation that COM are moving out of BOS after received a very large perturbation magnitude, effective protective steps to break COM displacement and velocity is needed. (28) Therefore, unsuccessful balance recovery, which is a failure to recapture the moving COM, is a leading cause of falls.

Studies of protective steps in young adults showed that, when faced with external perturbation, almost all participants successfully recovered their balance with a single protective step without falling. (29-31) After backward loss of balance resulting from movable platform translation to emulate a slip, young adults can move COM position and velocity anteriorly to a stable point with a single protective steps touchdown. (31) To generate faster step in response to perturbation, anticipatory postural adjustments (APA) in protective steps, as measured by mediolateral (ML) COP asymmetry, is frequently absent compared with APA during voluntary step. Interestingly, pre-perturbation load on the preferred limb may be an important parameter that may impose spatiotemporal characteristics for steps with preferred limb. When the preferred limb was loaded (>50% of body weight) before perturbation, the preferred limb exhibited non-significant trends toward faster swing time and more laterally ML step displacement when compared with symmetrical limb load condition. Furthermore, when participants were forced to step with the loaded limb (70% body weight loaded on preferred limb), young adults could adapt and respond with a shorter AP step length and greater ML step distance when compared with unconstraint equal loaded condition to encounter fall toward unsupported side.(29-31) Therefore, young adults showed flexibility of response in a variety of situations.

Protective steps are generated more often and easier in elderly than in young adults.(32, 33) Previous evidence investigated protective steps elicited from various range of perturbation magnitude. Researcher found that elderly was more likely to step in small perturbation magnitude than in young adults, even though COM are located well within the BOS.(32) Although foot liftoff time was faster in elderly than in young adults,(25, 30, 32-34) protective steps length and the length from COM to the point of foot landing was shorter in elderly.(31, 33, 34) Moreover, ability to slow the COM velocity was lesser in elderly than in young adults.(33) These suggested that, even though elderly compensated for faster protective steps onset, inadequate protective steps length to arrest the COM within the stability margin resulted in multiple steps in elderly.(30)

Protective steps are impaired post-stroke and this impairment is associated with increased fall rate during inpatient rehabilitation.(35) The clinical test for protective steps has been implicated in the Balance Evaluation System Test (BESTest), where the testing items instruct patients to lean in different directions beyond their limit of stability against the therapist's hand (lean on hand).(36) The therapist then releases the patients to evaluate their ability to perform protective steps.(37) Previous studies reported that some individuals with stroke were unable to perform a protective step with either limbs (i.e., no-step response, stepping with non-paretic limb, and/or need external assistance).(35) Other studies show that stroke patients prefer to step with non-paretic more than paretic limb.(31, 38-41) This strategy will impede a stroke patient's ability to prevent themselves from falling when faced an unpredictable perturbation from an external environment. For example, in the situation that non-paretic limb is limited to step in response to perturbation by environmental constraint, an inability to step with paretic limb will lead persons with stroke to have no or ineffective protective steps. Moreover, attempting to step with a non-paretic limb (which is frequently under greater load) may lead to more ML instability and failure to perform an effective protective steps resulting on a fall.

The possible underlying mechanisms for poor protective steps in persons with stroke may be asymmetrical preperturbation limb load and poor foot recovery as measured by Chedoke McMaster Stroke Assessment (CMSA).(38) Previous authors found that the improvement of foot recovery and decreased preperturbation limb load on paretic limb can decrease the probability of requiring assistance and increased proportion of preferred stepping with paretic limb, respectively.(38, 40) They reported that foot recovery as measured by Chedoke-McMaster Stroke Assessment impairment inventory of foot was a determinant of achievement of response from lean-and-release test. (38) This finding corresponded to the results of forward slip-like surface perturbation. Individuals with stroke showed inability to control their body upright in a single leg stance after perturbation onset when compared with young and age-matched control group. Their hips were dropped down until reaching peak value in the moment of time before non-paretic protective steps touchdown. This indicated inability to stabilize body with paretic stance leg. Furthermore, they also showed shorter step length compared with young adults and age-matched control group whether they used either paretic or non-paretic leg to step. (31) In combination, these studies suggest that a reduced ability to make appropriate compensatory stepping movements to recover from perturbations and altered COM control during protective steps may result in falls in persons with stroke.

Protective steps in persons with stroke can be improved with perturbation training using complicated instruments such as moveable platforms or cable release systems. A group of researchers perturbed balance while walking for a single trial and measured the adaptation at the next trial. They found that, after a single prior slip exposure, participants improved COM state stability (the combination of COM position and velocity) and reached a stable point where COM position and velocity shifted anteriorly toward zero. They also increased compensatory step length and improved protective steps choice within a single prior slip exposure. Abort step (a protective step that was initiated by lift-off of the heel followed by immediate touchdown without clearance of the foot off the floor) was reduced and replaced by the ability to perform effective protective steps.(42) The other group of researcher used external cue to guide paretic limb stepping during platform perturbation. With cue, frequency of protective steps with paretic limb in preferred response trial was increased. (43) In addition, individuals with stroke had COM position and velocity of paretic step touchdown (stability after paretic step touchdown) comparable to unaffected stepping that was not added any cue. Consistent results were also found for training with lean and release for 6 sessions on preperturbation limb load. Patient reduced preperturbation limb load on paretic limb, decreased unloading onset time, increased ability to face with increased perturbation magnitude, and did not need any of external assistance in all trials.(39) However, the application of these training methods in the real clinical practice is limited as these systems are cost limited and complicated to set up in clinic.

Improving the effectiveness of protective steps without expensive equipment may be possible using, voluntary-induced stepping response (VSR) training.(44, 45) In voluntary-induced stepping, participants were instructed to lean forward until they felt they were losing the balance and took a single step. After training for 50 repetitions, there were improvement of EMG in rectus femoris and second burst of biceps femoris for both paretic and non-paretic stepping leg, soleus and rectus femoris of paretic stance leg, and knee acceleration of unaffected limb stepping.(44) Another study that trained participant with a similar protocol reported the interesting result that people with stroke who trained with voluntary-induced stepping and fast squat, each for 50 repetitions, showed improved muscle activity during arm raise and load drop task and improved symmetrical weight bearing in asymmetrical weight bearing subject during both tasks.(45) Therefore, with the improvement in lower limb functions during postural control activity, voluntary induced-stepping may improve stability at the time of step touchdown both legs, during single leg support of paretic leg, and facilitate faster step for automatic postural response. However, the detailed characteristics of VSR and changes of VSR as a result of stroke as compared to healthy persons are lacking. In addition, whether or not the VSR training can directly improve the protective steps in persons with stroke has not been yet clarified.

Research question

C a n voluntary-induced stepping response (VSR) training improve Protective steps in persons with stroke?

Research objectives

1. To compare characteristics of VSR such as center of mass, mediolateral ground reaction force, and step kinematic in young, elderly and persons with stroke.

2. To examine the immediate effect of VSR training on the protective steps, compared to DynSTABLE perturbation training (DST), in persons with stroke.

Research hypotheses

1. VSR characteristics such as center of mass, mediolateral ground reaction force, and step kinematic will change with age and neurological deficit.

2. Similar to the DST, VSR training would improve protective stepping and stability when responding to surface perturbation in persons with stroke

Benefit of the study

This study will provide the information on the effectiveness of perturbation training for improving the protective steps without using the complicated high-cost instrument.

Definition of terms

Abort step: a protective step that is initiated by lifting the heel followed by immediate touch-down without clearing the foot off the floor.

Arm raise task: the task that instructs participants to raise the unaffected or dominant hand to horizontal as fast as possible.

Compensatory protective step or protective step: the steps taken to recover balance after receiving external perturbation. It is a subtype of change-in-support strategies. It creates new base of support to recapture the moving center of body mass.

Lean and release test: the test that instructs participants to lean forward and release the cable attached on the body unexpectedly to evoke the protective steps.

Load drop task: the task that instructs participants to hold a 2.2 kilograms load by unaffected or affected hand with arm extend horizontally in front and drop the load.

Preferred response or limb preference or preferred limb: the limb that participants step with most frequently out of five trials (≥ 3/5).

Preperturbation limb load: the ground reaction force under each limb measured at 1 second before perturbation onset.

Slip-like moveable platform or slip-like surface translation: a movable platform that is mounted invisibly with the floor to simulate slip-like perturbation by accelerating and decelerating body center of mass.

Unloading onset time: the time from the peak vertical force to foot lifting off. It indicates an occurrence of anticipatory postural adjustment.

Vertical limb support or peak hip descent or peak Z_{hip}: the vertical displacement (descending) of the hip after perturbation onset.

Voluntary-induced stepping response or VSR: the task that instructs participant to voluntarily lean until they loss of balance and take a step to recover balance.

CHAPTER 2
LITERATURE REVIEW

In this section, the review literatures include the following categories:

1. Overview of fall post stroke
2. Circumstance of falls in persons with stroke
3. Movement strategies, an important mechanism for balance recovery
4. Protective steps in healthy young adults
5. Protective steps in healthy elderly
6. Impairment of Protective steps post-stroke
7. Effect of perturbation training on Protective steps post-stroke
8. Voluntary-induced stepping response training and its effects on Protective steps

Overview of fall post stroke

Stroke is the major cause of balance disorders, gait deficits, and falls. A prospective cross-sectional hospital-based survey study showed that approximately 80 percent of persons with stroke had balance disability.(1) The extent of balance disability in persons with stroke depends on severity of stroke pathology, impairment after stroke, and functional balance ability.(1) Gait deficit is frequently found in person with stroke. Results from retrospective study showed that gait characteristic in 100 patients with stroke were characterized by some degree of temporospatial and kinematic asymmetry, which asymmetry ratio was calculated from [1 - (affected side/unaffected side)]. Subgroup analysis revealed that the extent of asymmetry between affected and unaffected leg depends on age, motor recovery, and walking velocity. Greater single support time asymmetry ratio; and lower ankle dorsiflexion during both stance and swing and plantarflexion during swing asymmetry ratio was reported in older (age $\geq$ 65 years) when compared with younger group (age < 65 years) of stroke. Patients with stroke who were in poor motor recovery group showed greater step length, hip extension, knee extension, and ankle dorsiflexion and plantarflexion during stance and swing asymmetry ratio than patients who were in good recovery group. Step length asymmetry ratio was also greater in slow walking speed than in fast walking speed group.(46) A narrative review concluded that there were reduction of preferred and maximum walking speed, reduction of cadence, increasing of stride time and double support time, and alteration of stance- and swing-phase of walking cycle.(7, 46) Balance dysfunction and gait deficit can also be the cause of falls post-stroke.(4, 8)

Falls can occur at every stage after stroke.(6) Fall is "an unexpected event in which the participants come to rest on the ground, floor, or lower level".(47) Fall also involves a failure in recovery response resulting from external force.(48, 49) Overall, the fall incidence rates in persons with stroke were much higher than those in the elderly population, which showed 1.8 falls per 1000 patient per day.(50) A prospective study of risk factor of falls in elderly indicated varieties of risk factor associated with fall. Accumulation of those risk factors (i.e. mobility impairment, poor mental state, orthostatic hypotension, and dizziness) would increase probability of falling to about 60% when compared with only 3% in person with no risk. Moreover, history of stroke was found to be a risk factor as it increased probability of falls to upto 83% when it was combined.(51) A previous review classified persons with stroke into three stages of care (acute hospital care, inpatient rehabilitation, and living in the community) and concluded the epidemiology of falls each stage.(6) Fall was the most common medical complication of stroke, with the incidence rate of 8.9 falls per 1000 patient per year,(19) as compared to other pathologies in acute hospital care period.(12) For inpatient rehabilitation, most patients are likely to falls at the first 3 weeks of rehabilitation and the fall incidence rate was 5.5 falls per 1000 patient per day.(10, 18) In community-dwelling stroke survivors, the fall incidence rate was also high (5-7.8 falls per 1000 patient per day). In addition, the proportion of fallers, persons with stroke who reported fall at least once, differed between each stage of care. Only 14%-30% and 11-37% of persons with stroke in acute hospital care and inpatient rehabilitation were reported as a faller.(9, 10, 12, 17-19) In contrast, 23% -73% of persons with stroke who lived in the community reported fall at least once. (2, 4, 5, 8, 11, 13-16, 20) Wide range of proportion of faller attributes to different methodology of falls data collection, recall period, definition of fall, eligible criteria for patients recruitment, and study design. The examples are, using questionnaire in asking person to recall falls history in the past 3-, 6-, or 12-months; using routinely medical or nursing record; or using falls diaries to prospectively collecting falls data effect on accuracy of reporting falls. Using a questionnaire in recalling fall retrospectively, the data may be contaminated from recall bias. On the other hand, collecting falls data using medical record or fall diaries the data may be limited by availability of reporting systems and under- or over-reporting falls of different participants, respectively. Furthermore, different definition of falls influence inclusion of falls data to analysis. Although there were wide ranges of proportion of faller, faller in community was visibly higher than in acute hospital care and inpatient rehabilitation stage. TABLE 1. shows the summary of falls incidence rate, proportion of faller, and methodology of falls data collection in 3 stages of stroke care (acute care, inpatient rehabilitation, and living in the community). Therefore, we can conclude that persons with stroke were prone to have higher risk of falls following discharge from the hospital than during hospitalization and these may associate with the activity that the majority of persons with stroke can do at that time or the environmental safety at each stage.

Table 1 The summary of fall incidence and methodology of fall data collection in 3 stages of stroke care (acute care, inpatient rehabilitation, and the living in the community

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Acute care setting									
Davenport et al., 1996 (12)	Retrospective cohort study	n = 607	73	6 hours	Medical record	Not reported	A total of 299 falls were reported		134 (22% of stroke) fell at least once
Tutuarima et al., 1997 (19)	Retrospective cohort study	n = 720	Not reported	Not reported	Medical or nursing recorded	"Any event described as "a fall" in medical or nursing records."	A total of 173 falls were recorded	8.9 falls per 1000 patient-day	104 (14% of patients) fell at least once; 35 of 104 fell > 1
Inpatient rehabilitation									
Smith et al., 2006 (17)	Prospective cohort study	n = 225	78	Not reported	A STRATIFY fall risk was assessed within 2 weeks of admission, weekly, and within 48 hours before discharge by nurse or at the multidisciplinary team meeting	"An incident in which a patient suddenly and involuntarily comes to rest upon the ground or a surface lower than their original."			108 (30% of patients in inpatient study) fell at least once

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Sze et al., 2001 (18)	Retrospective cohort study	n = 677	Not reported	Not reported	Nurse and health care assistants reported fall incident. Patient or care-giver reported-falls were also investigated. After each fall, nurse specialist give advice to prevent further falls	"Any unplanned "touch to the floor" of any body part, excluding the feet, as reported by patient, their relative, or rehabilitation staff. Patient who were caught in the middle of a fall and were lowered to the floor by others were also reported as having fallen."	A total of 82 falls were reported	5.5 falls per 1000 patient-days	78 (11% of patients) fell at least once; 4 of 78 fell > 1
Teasel et al., 2002 (9)	Retrospective cohort study	n = 238	72.7±10.1	24.5±25.9 days	From incident report either by witness or faller during inpatient rehabilitation	"displacement of the body to the level of knee height or lower through an uncontrolled involuntary action"	A total of 180 falls were reported		88 (37% of patients) fell at least once; 23 of 88 fell > 1

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Aizen et al., 2007 (10)	Prospective cohort study	n = 263	Not reported	Not reported	A structure interview from patient or person who witnessed the fall	"An incident in which a patient suddenly and involuntarily came to rest upon the ground or surface lower than their original station"			41 (15.6% of patients) fell at least once
<u>In community</u>									
Forster and Young., 1995 (8)	A prospective cohort study	n = 108	70	Not reported	Face to face interview of patient and carers at discharge from hospital, 8 weeks, and 6 months post discharge.	NR	A total of 270 falls were reported.		79 (73% of patient) fell at least once. In addition, 50 (46%) patients reported fell at least once during hospitalization.

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Hyndman et al., 2002 (52)	Cross-sectional observational study	n = 41	69.7±11.6	50.4±58.2 months	A structure interview	"An event that results in a person coming to rest unintentionally on the ground or other lower level, not as a results of a major intrinsic event or overwhelming hazard. A near-fall is an occasion on which an individual felt that they were about to fall but did not actually fall."	A total of 51 falls events were reported		21 (50% of patients) fell at least once; 10 of 21 fell > 1; 32 (almost 80% of patients) experience near-fall

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Jørgensen et al., 2002 (15)	Prospective cohort study	n = 111 patients with stroke and n = 143 age- and gender matched controls	68±12 for patients with stroke and 67±13 for controls	10±8 years	Fall calendar and interview by physician	"An unintentional change in position to the floor or ground"	A total of 62 falls were reported by patients with stroke and 24 falls by controls	5 falls per 1000 patient-days for persons with stroke and 1.4 falls per 1000 patient-days for controlled were reported.	25 (23% of patient with stroke) and 16 (11% of controls) fell at least once. Persons with stroke was more than twice as likely to fall when compared with controlled (RR=2.3).
Lamb et al., 2003 (16)	Prospective cohort study	n = 94	76	48 months	Interview at 6 and 12 months after baseline assessment	"Falling on the ground or at some other level such as a chair"		7.8 falls per 1000 patient-days	45 (48% of patients) fell at least once; 29% of patients fell > 1

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Hyndman and Ashburn, 2004 (14)	Prospective cohort study	n = 63	68	20 months	Fall diary over 6 months period and telephone call every 2 weeks to remind patient to update their diary	"An event that results in a person coming to rest unintentionally on the ground or other lower level, not as a results of a major intrinsic event or overwhelming hazard. A near-fall is an occasion on which an individual felt that they were about to fall but did not actually fall."			30 (48% of patients) fell at least once; 15 (24% of patients) fell > 1; 11 (18% of patient) reported near-falls; 22 (35% of patient did not report any falls or near-falls)
Harris et al., 2005 (13)	Cross-sectional observational study	n = 99	69±9.5	4±4.3 years	Semi-structure interview for number of falls recall over 6 months	"Coming to rest on the floor or another lower level but was not due to seizure, stroke, or myocardial infarction, or an overwhelming displacing force (e.g., earth quake)."	A total of 117 falls were reported		49 (50% of patients) fell at least once

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Mackintosh et al., 2005 (5)	Prospective cohort study	n = 56	68.2±12.7	2.3±1.6 months	Fall diary over 6 months period and structure interview by telephone call or face-to-face interview after each fall.	“An event which results in a person coming to rest inadvertently on the ground floor or other lower level and other than a consequence of sustaining violent blow, loss of consciousness, sudden onset of paralysis such as stroke or an epileptic seizure.”	A total of 103 falls were reported		26 (46% of patient) fell at least once; 12 of 26 fell > 1
Watanabe, 2005 (20)	Survey	n = 49	65.8±13	Not reported	Postal questionnaire to patients or family members	Not reported	>99 falls after discharged; and 39 falls during in patient rehab were reported		33 (70% of patients) fell at least once after discharged; 27 of 33 fell > 1; and 19 (38% of patients) fell at least once during inpatient rehabilitation

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Belgen et al., 2006 (11)	Cross-sectional observational study	n = 50	59.9±11.9	62.2±62.1 months	A standard questionnaire to collect fall data	"An episode of unintentionally coming to rest on the ground or lower surface that was not the results of dizziness, fainting, sustaining a violent blow, loss of consciousness, or other overwhelming external factor."			20 (40% of patients) fell at least once; 11 (22% of patient) fell > 1
Mackintosh et al., 2006 (53)	Prospective cohort study	n = 55	68.1±12.8	2.3±1.6 months	Fall diary over 6 months period and telephone call every 2 weeks to remind patient to update their diary	"An event which results in a person coming to rest inadvertently on the ground floor or other lower level and other than a consequence of sustaining violent blow, loss of consciousness, sudden onset of paralysis such as stroke or an epileptic seizure."			25 (45% of patients) fell at least once

Table 1 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Documentation methods of falls	Definition of falls	No. of fall	Falls incidence rate	No. of faller
Smith et al., 2006 (17)	Prospective cohort study	n = 234	78	Not reported	A STRATIFY fall risk was assessed 3 months after discharged via telephone call	"An incident in which a patient suddenly and involuntarily comes to rest upon the ground or a surface lower than their original."			108 (30% of patients in inpatient study) fell at least once and 80 (34% of patients in post discharge study – after 3 months) fell □ 1

Patients with stroke whoever fell when hospitalized were more than twice as likely to fall at home after discharge.(5, 8) A systematic inquiry of falls in patients with stroke who live at home identified the history of fall during hospitalization as a predictor of repeated falling at home. This study classified patient who experience two or more falls as true faller, whereas nonfaller was the patient who fall only once or none. Despite faller had lower balance ability and more disability, only falls history during hospitalization was the only predictor with an odd ratio of 2 (95% confidential interval 1.2-3.5) for repeated falling at home.(8) Mackintosh and colleague, whose study aimed to identify the predictor with how accuracy they are in predicting recurrent falls (≥ 2 falls) in community dwelling stroke prospectively, showed additional results. Although falls history during hospitalization alone showed high sensitivity, specificity, and negative predictive value in predicting recurrent falls, the positive predictive value was only 48% . However, when combining falls history during hospitalization with Berg balance and step test (stepping on and off a 7.5 cm step in front with one foot), positive predictive value was increased to 71% and 63% , respectively. Functional balance performance as measured either by the Berg Balance Scale or Step Test combined with history of hospitalization falls predicted falls incidence after discharge with considerable accuracy.(2) Therefore, factors related to falls in community are balance ability and fall occurrence during hospitalization.

Falls in patients with stroke can lead to slight to serious injuries.(6) Injuries can occur at both upper and lower extremities, head, face, hip, and torso.(4, 9) Almost all of fall-related injuries post-stroke were about soft tissue injury such as contusion, abrasion, or laceration.(4, 5, 8, 9, 18) Serious injuries such as hematoma, open wound, head injury, intracranial hemorrhage, or joint dislocation were also reported in some.(4, 5, 8, 10, 15, 18-20) Even though fracture was uncommon (the proportion of fracture occurred after fall that was reported from varieties of studies range from 1% -9%) and its overall proportion in persons with stroke did not differ from general elderly population (~5%),(4-6, 8, 12, 18, 20, 50) patients with stroke are prone to have higher risk of sustaining fracture than in general population. A meta-analysis of six prospective and seven retrospective cohort studies of hip fracture showed, when pooled the data from all studies sample, that overall prevalence of hip fracture in patients with stroke (3.28% or 3,431 of 104,646) was higher than general elderly population (2.83% or 36,493 of 1,287,726). (21) These could be explained by bone mineral loss attributed to hospitalization or decreased physical activities after stroke.(54) The reduction of bone mineral content for paretic and lean body mass for both paretic and non-paretic leg over a 12-month follow-up was reported. Persons with stroke have higher chance to fracture at higher than person who was not suffered from stroke. Fracture can cause hospitalization, seeking varieties health profession services,(5, 12) or fatality. Mortality rate was reported to be double 3 month post-surgery relatively to patients without stroke. (6) These indeed emphasize the importance of fall prevention strategies to prevent patient's own from exposure to fall and hip fracture.

Falls also result in activity limitation and fear of falling which, in turn, caused depression, social deprivation, poor quality of life, and deconditioning. Mackintosh and colleague found that activities were restricted after 44% of falls in patients with stroke and varied from a little, somewhat, and a lot of limitation. (5) From self-complete questionnaire of 49 community dwelling with stroke revealed that 87.9% of faller developed fear of falling in different degree. Furthermore, beyond 70% of person with fear of falling were "afraid of falls almost all the time".(20) In qualitative study, authors interviewed and collected information of activity and psychosocial limitation form keyword that participant discuss or exclaim about. Impact of falls was explained by participants, as it limited their activity and participation according to physical changes and decrease activity after falls. Some participant chose to limit activity and participation themselves as a strategy to prevent falls. Some demonstrated the reduction of self-independence, as they needed walker, cane, banister, wheelchair, furniture, walls, or people to perform activity to feel safe. They also developed a fear of falling and constant worry about fall in every daily activity. Persons with stroke who concerned and discussed about fear of falling frequently talked to the experience of falling at the time of stroke onset because there was no one to help them up from the floor for hours.

Therefore, this may be the initial experience that cause them to have fear of falling that would mean having another stroke, having future injury or hurt.(3) Every participant in this study agreed that fall was a majority dramatic health threatening consequence. To develop fall prevention program, researcher needs to better understand the circumstances of falls regarding cause, place where fall occur, and activity separately each stage of care.

Circumstance of falls in persons with stroke

Fall circumstance in persons with stroke can be intrinsic (e.g., body impairment) or extrinsic (e.g., environmental constraint).(4, 5, 8) Foster and Young reported the information obtained from patients with chronic stroke, most falls occurred due to loss of balance. Performing transfers, foot got stuck, fell over obstacle, leg gave way, or dizziness were also the causes of fall in lesser extent.(8) This results correspond to the study by Hyndman and colleague.(4) They found that the majority of falls and near falls was caused by loss of balance. Other less common causes of fall in patients with stroke also include misjudgment, lack of concentration and foot dragging during walking.(4) Mackintosh and colleague found that external factor, such as slippery surface, step, obstacle, was also the cause of falls, as it involved in 39% of falls.(3, 5, 20) Falls also occurred most while patients wore inappropriate glasses. However, these external factors are associated with patient age and functional ability as measured by Berg Balance Scale (BBS) and Functional Independent Measure (FIM). Patients who are older were more likely to use multifocal or not wearing appropriate glasses but patients who have higher BBS and FIM score were more likely to use appropriate prescription glasses.(5) These suggest that age, balance, functional performance, and vision can be the risk factors associated with fall in community dwelling individuals with stroke.

Studies of individuals with stroke showed heterogeneous of activities which persons with stroke were performing while they fell during each stage of care (TABLE 2). For inpatient rehabilitation transferring between beds and wheelchairs was the most common activity.(9) In contrast, walking and transferring were the most basic activities for community-dwelling stroke. Only a few of persons with stroke fell while they were climbing stairs/ steps, turning, washing, bending, reaching, cooking, or carrying/ lifting.(4, 5, 8) Falls can occur in any directions (sideway, forward, or backward).(4, 5, 10) Patient fell more on weaker side than forward, backward, and stronger sides.(5) These may due to asymmetric weight distribution or asymmetric preventive ability of paretic side which, in turn, contributing to fall in different way.

Previous study revealed information of near-falls in persons with stroke. A near-fall was defined as an occasion on which an individual felt that they were about to fall but did not actually fall. This study observed 41 community stroke patients to compare characteristic of fallers and non-fallers. They found that 32 patients (almost 80%) experienced near falls. It is interesting that almost all persons with stroke who reported near-falls showed saving reactions. Saving reactions were performed by using their arm (50%), leg (12%), and recovery of balance (12%). They also reported that repeated fallers showed more arm impairment than a group of non-fallers with no near-fall.(4) It demonstrated the necessity of available limb movement to prevent falls in persons with stroke.

Therefore, focusing on the circumstances of falls revealed that falls occurred in persons with stroke could be generated both by intrinsic (e.g., balance impairment and misjudgment) and extrinsic factors. As falls can occur from multifactorial, the ultimate way to prevent falls from postural perturbation is to use patients' limb as postural strategies in balance recovery.

Table 2 Circumstances of falls.

Author	Study design	Sample size	Age (years)	Stroke duration	Circumstances				
					Activity	Time of day	Place	Cause of fall	Landing
Acute care setting									
Tutuarima et al., 1997 (19)	Retrospective cohort study	720 acute stroke	Not reported	Not reported	Most during sitting in wheelchair and staying in bed. Walking, bending, or standing were less frequent	Most during the day; falls in the evening, or at night were occurred in lesser extent	Most in patient's room; some fell in the toilet, bathroom, or corridor		
Inpatient rehabilitation									
Sze et al., 2001 (18)	Retrospective cohort study	677 inpatient stroke	Not reported	Not reported		Most at 7 am to 9 pm	Most at bed side; some fell in the toilet, cubicle, corridor, and other		
Teasel et al., 2002 (9)	Retrospective cohort study	238 inpatient stroke	72.7±10.1	24.5±25.9 days	Most during transferring from wheelchairs to beds.				

Table 2 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Circumstances				
					Activity	Time of day	Place	Cause of fall	Landing
Aizen et al., 2007 (10)	Prospective cohort study	263 inpatient stroke	Not reported	Not reported	Most fell from wheelchair.		Most beside the bed; some fell in the toilet or corridor	Most fell while being engaged in risk-taking activity	Patients showed falls in all directions (lateral, forward, backward, and oblique)
In community									
Forster and Young., 1995 (8)	Cross-sectional observational study	108 community stroke patients	60-89	Not reported	Most during walking and transferring. Stairs/steps, washing, bending, and cooking were less frequent	Most during the day; falls at night were less frequent	Most in the lounge or bedroom; some fell outside	Most because loss of balance. Transfers, foot got stuck, do not know, fell over obstacle, leg gave way, and dizziness were less frequent	
Hyndman et al., 2002 (52)	Cross-sectional observational study	41 community stroke patients	69.7±11.6	50.4±58.2 months	Most during walking. Turning and sitting were less frequent	Most in the morning or afternoon	Most in own home (in the garden, bedroom, and lounge)	Most because loss of balance. Misjudgment/ lack of concentration and foot dragging were less frequent	Patients showed falls in all directions (lateral, forward, and backward)

Table 2 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Circumstances				
					Activity	Time of day	Place	Cause of fall	Landing
Jørgensen et al., 2002 (15)	Prospective cohort study	111 community stroke patients and	68±12 for stroke patients	10±8 years	Most during walking. Transfer either from sitting to standing or laying down to sitting were less frequent	Most during the day; falls in the evening and at night were less frequent	Most indoor as well as outdoor	Most because intrinsic factor (impair balance and subject-specific factor); Extrinsic factor (slippery surface or obstacle) were less frequent	
Harris et al., 2005 (13)	Cross-sectional observational study	99 community stroke patients	69±9.5	4±4.3 years	Most during walking. Standing, transferring, and stair were less frequent		Most indoor		
Mackintosh et al., 2005 (5)	Prospective cohort study	56 community stroke patients	68.2±12.7	2.3±1.6 months	Most during walking. Transfer, reaching, turning, bending, carrying/lifting were less frequent	Most in the morning; falls in the afternoon, evening, or at night were less frequent	Most in bedroom and dinning room; some fell outdoor (in the home area, on the street, and with curb/step)	Hazard involved in 39% of falls. Falls occurred while: wear good fixation shoe > no shoe > poor fixation; and wear inappropriate > bifocal > don't wear > distance glasses	Patients showed falls in all directions (weaker side, forward, backward, stronger side)

Table 2 (Continued)

Author	Study design	Sample size	Age (years)	Stroke duration	Circumstances				
					Activity	Time of day	Place	Cause of fall	Landing
Belgen et al., 2006 (11)	Cross-sectional observational study	50 community stroke patients	59.9±11.9	62.2±62.1 months	Most during walking. Dressing were less frequent		Most indoor; some fell outdoor or at workplace	Most because misstepping, foot getting stuck, imbalance; falls due to trip, slipping on ice, or pain on knee while turning was less frequent	

Movement strategies, an important mechanism for balance recovery

Postural response is a coordination of movement strategies and external indirect assistive force that act to decelerate or arrest center of mass (COM) movement as a result of external perturbation.(26, 55) For example, individual grasps someone in front to prevent forward fall as a result of crashing from the others or individual step posteriorly to prevent backward fall as a results of slip on slippery surface. Tisserand and colleague suggested that fall prevention mechanism is inseparable from successful reactive recovery response. If perturbation turns the steady-state balance into unbalance state, successful recovery response will led individual to avoid fall and become to steady-state again (Figure 1).(26) That is, movement strategies, for the purpose of postural response, can be a last resort to prevent fall after failure of other internal resources or in an unpredictable perturbation from environment.(55)

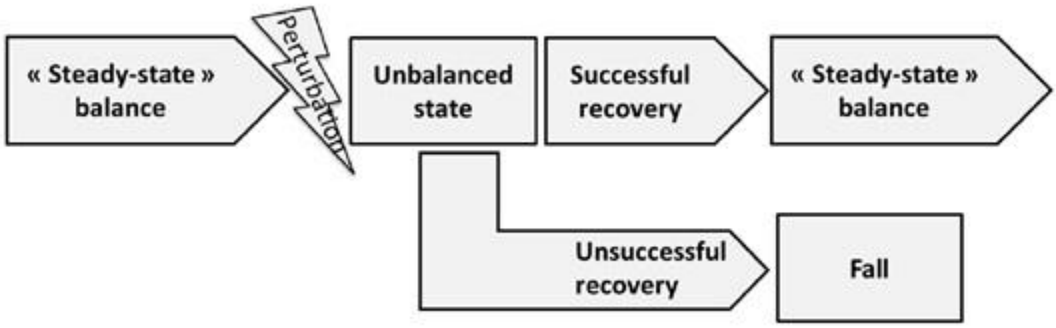

Figure 1 Balance recovery model.

Source: Tisserand et al. Comparison between investigations of induced stepping postural responses and voluntary steps to better detect community-dwelling elderly fallers. Neurophysiologie clinique = Clinical neurophysiology. 2015 Nov; 45(4-5): 269-84

Movement strategies for balance recovery during standing can be classified into two distinct classes based on the base of support (BOS); fixed-support and change-in-support strategy. (22) Fixed-support strategies are the strategies that decelerate COM without changing BOS. It consist of ankle strategy, a controlling of small amount of COM movement by moving body like invert pendulum around ankle axis, and hip strategy, which hip muscle generate hip torque to quickly move COM horizontally opposite to destabilizing side. Fixed-support strategies will often be selected during small and/or slow perturbation in particular context, as a results of limitation of foot size (BOS) and muscular activation torque.(26) Change-in-support strategies, that was believed to respond only for large magnitude of perturbation in the past, on the other hand, is currently found to occur even when perturbation is small and COM was well within limited of stability.(22, 32) Change-in-support strategies execute limb movement to create new BOS to enhance contact surface which will, in turn, generate reactive force to break moving COM with higher efficacy than fixed-support strategies. Two main strategies are grasping and stepping which is also known as a protective steps.(22) A compensatory protective step (protective step) is a response that change BOS by taking a step in specific direction with perturbation.(22) All movement strategies mentioned above are initiated by ascending sensory inputs (visual, vestibular, somatosensory information) compared with internal representation of desire state of body in the central set.(23, 55) Selection of appropriate strategies is context-dependent, depending on expectation or predictability, experience, instruction, direction and magnitude of perturbation, initial position, environmental constraint on movement trajectory, the nature of ongoing motor task, and configuration of base of support (BOS) (TABLE 3).(23-27)

Table 3 Example of effect of each context-dependent on selection of appropriate strategies and protective steps response characteristic

Context-dependent	Example
Expectation or predictability	• Pre-cueing about direction of perturbation prior to perturbation onset reduced frequency of response with protective steps from 42% to 22% of trials (it was replaced by fixed supported strategies).(24)

Table 3 (Continued).

Context-dependent	Example
	• Contextual uncertainty from instruction to step in response to light cue followed by unexpected platform movement delayed foot liftoff time (~ 260 ms) compared with the condition without contextual uncertainty.(25)
Experience	• A Protective step was used frequently and occurred earlier in the elderly than young adult, even though perturbations are small and/or of slow magnitude due to the elderly learned from their experience that the fixed-support strategies are inadequate.(25)
Instruction	• Different instruction (i.e. the first condition instructed participants to maintain standing equilibrium, whereas the second condition instructed to step as soon as participants felt the perturbation) resulted in present or absent of protective steps.(23)
Direction and magnitude of perturbation,	• A Protective step was exhibited 91% in response to large; 32% to medium and 2% to small perturbation magnitude. • A Protective step pattern in response to anterior platform translation was differed from pattern in response to other directions.(24)
Environmental constraint on movement trajectory,	• Protective steps elicited in lateral constraint condition had foot placement in more medial direction compared with no obstacle and obstacle in front condition.(27)

Table 3 (Continued).

Context-dependent	Example
Nature of ongoing motor task,	• Counting backward task before perturbation onset was used to reduce preplanning aspect of protective steps.(27)
Configuration of BOS	• Reduction of dynamic BOS due to physical limitation reduce available area of COM movement.(28)

When COM are well within the BOS, persons have the opportunity to choose whether or not to step and selection of appropriate strategies depend on other context. However, in no option condition where perturbation magnitude was very large and people are losing balance as a results of COM out of feasible region, protective steps was triggered with no choice as a last resort to avoid fall.(32) Figure 2 showed an example of normal feasible region (the dynamic limit of balance in horizontal plane) from mathematic model. Therefore, failure of protective steps post-stroke, resulting in ineffective deceleration of COM, is a leading cause of falls.(26, 35)

In summary, a movement strategy, specifically a protective step, is necessary for postural recovery. Protective steps can be triggered from either large or small perturbations. Protective steps are necessary when COM moves out of dynamic limit of balance, therefore, failure of protective steps after stroke led to higher risk of fall.

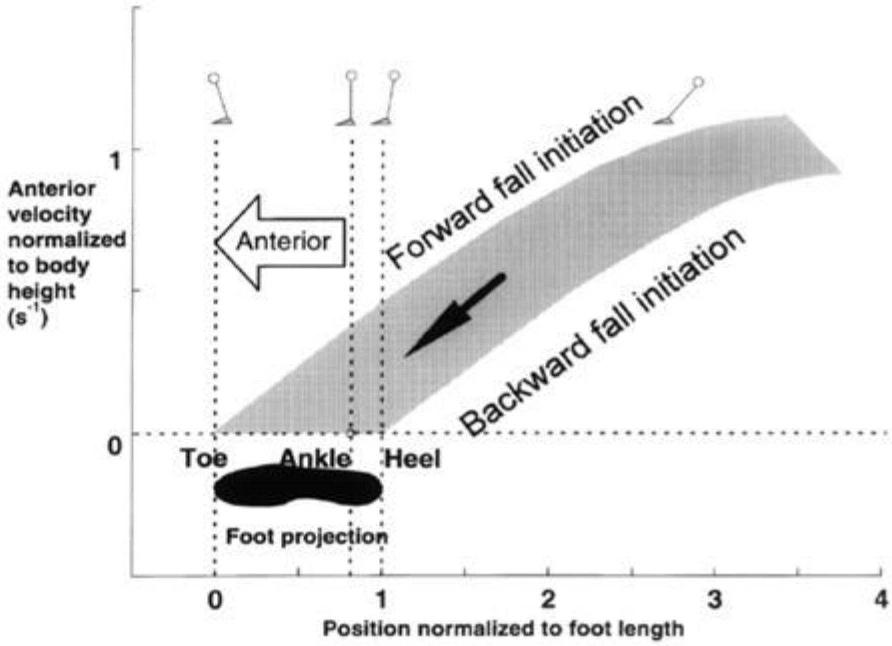

Figure 2 Normal feasible region (gray shading) according to foot projection. The x-axis showed COM velocity normalized to body height and the y-axis showed COM position normalized to foot length.

Source: Pai Y-C, Patton J. Center of mass velocity-position predictions for balance control. Journal of Biomechanics. 1997 Apr; 30*(4):* 347-54

Protective steps in healthy young adults

Postural control deteriorates with age and neurological disorders. Aging results in general progressive alterations in sensorimotor and central processing system. Decline sensory integration and perception, cognition, muscular activation, and reaction with age will reduce accuracy of CNS decision for postural control against external environment.(56) Neurological disorder such as that occurred in persons with stroke will further impair balance in a particular aspect. (36) Therefore, protective steps, a subcomponent of postural control that is the rapid response to stabilize the body when there is an external perturbation to the body, may differ in population with different age and pathology.

Only a single protective step was adequate to recover balance in almost all perturbation trials in young adults.(30, 31, 57) Previous studies reported that 57-80% of young participants took a step backward in response to forward platform translation that triggered backward loss of balance.(30, 31) After backward loss of balance, protective steps of young adults were rapidly initiated and executed with long backward step length. Therefore, at protective steps touchdown, their COM position and velocity shifted anteriorly toward a stable point within a single step.(31) This result corresponded with a study by Lakhani reporting that young participants did not fall when they were perturbed to trigger forward fall. 97% of trials were achieved with a single forward step, whereas during the remaining 3% of trials, participants chose not to step.(57) These studies emphasized the importance of protective steps, which requires the ability of the swing limb to perform effective protective steps.

As protective steps was so rapid, (23, 34, 58) a mediolateral (ML) anticipatory postural adjustments (APA) occurred shortly or was frequently absent during protective steps in response to perturbation.(22, 23, 25, 30, 58, 59) ML APA was defined as a ML COP asymmetry, which will occur invariably in voluntary step to propel COM toward stance leg. This characteristic will provide stability in a single leg support period. However, previous evidence showed that APA had small functional benefit on lateral stability (accelerate body toward swing limb) during response with protective steps.(58) Absent of APA often showed in a novel perturbation experience, an unfamiliar event where a protective step was not preplanned.(59) When there was no time to respond with APA in large perturbation magnitude, step initiation (the time from perturbation onset to foot liftoff) occurred faster than in moderate perturbation magnitude.(24) However, step initiation was delayed with predictability such as in the condition of pre-cueing of perturbation direction.(24) For this reason, absence of ML APAs, especially during unfamiliar perturbation, may initiate faster response and quicker COM stabilization.(22, 26)

Pre-perturbation load, the load measured form ground reaction force under each limb averaged over a 1 second before perturbation onset, influences the selection of swing leg after perturbation. Previous study using multi-axial surface perturbation showed that unloaded legs were selected as limbs preference to step for 96% of stepping responses. In contrast, when pre-perturbation load was symmetrical, proportions of left and right leg selection were reported equally (50.5% and 49.5% of stepping response).(24) These corresponded with the study that test only forward loss of balance with cable release system test.(29) This study found that preferred limb to step was confined to be one limb (may be dominant or non-dominant limb each individual) for 44/49 or 90% of trials during symmetric limb loading condition than another one. Furthermore, dominant limb was not always the limb that was often chosen to step. Same result was also reported for the effect of asymmetrical pre-perturbation limb load on limb preference that the greater the loading on preferred limb (≥ 55% of body weight), the greater the proportion (>80% of trials) of utilizing unloaded non-preferred limb.(29) Therefore, only pre-perturbation limb load is associated with stepping strategies in protective steps.

Interestingly, some of temporospatial characteristic of preferred limb in young participants were also influenced by pre-perturbation limb load. When the preferred limb was loaded (60% of body weight) before perturbation, the preferred limb exhibited non-significant trends toward faster swing time and more laterally ML step displacement when compared with symmetrical limb load condition. Furthermore, with more difficult task, when non-preferred limb was constrained and participants were forced to step with the loaded limb, young adults could adapt their step accurately with a shorter AP step length but greater ML step distance and trend toward faster foot liftoff and swing duration to prevent fall toward unsupported side.(29) Therefore, young adults, in asymmetrical weight distribution condition, can adapt their response accurately to take only a step. This response may be caused by flexibility of CNS in response in variety of situations.

Protective steps in healthy elderly

Protective steps are generated easier in elderly than in young adults.(32, 33) Across different range of perturbation magnitude (0.15 m, 0.4 m/s, 9.4 m/s^2 for small; 0.15 m, 0.6 m/s, 12.5 m/s^2 for medium; and 0.15 m, 0.8 m/s, 15.2 m/s^2 for large magnitude) of platform translation in backward direction, elderly were more likely to use protective steps (95% of trials) to recover balance than in young adults (62% of trials). Age difference affected ability to respond to difference perturbation magnitude. Although all participants stepped to regain stability in large perturbation trials, elderly used protective steps strategy much more than young adults in response to small perturbation magnitude, i.e. 84% of elderly vs. less than 15% of young adults elicited protective steps. Furthermore, the majority of protective steps was selected while the CoM located well within the BoS and before trunk angular momentum reached maximal value.(32) These results showed that the elderly rely to use protective steps strategy to regain balance and stepped easily in the less demand condition when compared to young adults.

Although foot liftoff time was much longer in the elderly than in young adults during voluntary step, elderly contributed to shorter or similar time to liftoff the foot as compared to young during protective steps task.(25, 30, 32-34) Previous studies of waist-pull perturbation showed that elderly elicited comparable protective steps onset latency and unloading phase duration with young adults so that foot lift off time was no significantly different than young adults.(25, 33) This was similar to studies using anteroposterior platform translation that showed no differences of reaction time to step between young and elderly group.(32, 34) However, elderly elicited shorter protective steps length (especially in backward direction) than young adults after forward platform translation.(31, 33, 34) These suggested that, even though elderly compensated for faster generating step onset latency, they showed insufficient protective steps length to arrest the COM within the stability margin. As a result, multiple steps were frequently exhibited in the elderly. Previous study found that the length from COM to the point of foot landing was smaller in elderly than in young adults for backward protective steps and, even though there was no statistical difference, elderly showed lesser ability to slow the COM velocity themselves (from -22 to -6 m/s) than young adults (from -29 to -6.2 m/s). It has been shown that elderly exhibited a second step nearly 50% and a third step in 10% of trials, compared with young adults who required a second step only <10% of trials and never need more than 2 steps.(33) McIlroy and Maki also found that elderly used multiple step (63% of trials) more frequent than young adults (35% of trials). Multiple step frequently occurred in the first 3 trials in young adults but consistently occurred in later trials in elderly.(30)

Impairment of Protective steps post-stroke

Protective steps are impaired post-stroke. A retrospective study of 136 patients with stroke reported the relationship between protective steps characteristic and fall during inpatient rehabilitation within 2 years. When classifying patients with stroke as faller (fall ≥ 1) and non-faller from falls history during inpatient rehabilitation, persons with stroke who have unsuccessful or inefficient protective steps such as those with no step response, step with no foot clearance, delayed unloading onset time, delayed foot liftoff time, or need external assistance, were more likely to fall during inpatient rehabilitation. Therefore, the characteristic of protective steps is strongly related to increased fall rate during inpatient rehabilitation.(35)

The clinical assessment of protective steps has been developed as a part of Balance Evaluation System Test (BESTest) that is the clinical test for assessing underlying postural control system impairment. With no sophisticated equipment in protective steps assessment (item 16-18), patients were instructed to lean in different directions (forward, backward, lateral) beyond their limit of stability against the therapist's hand (lean on hand) and the therapists released patients unpredictably. The BESTest has been recommended for clinical balance assessment as it showed excellent interrater reliability ($ICC_{2,1}$ = 0.91 and 0.92 for total and postural subsection score respectively) and moderate convergent validity of the BESTest with Activities-specific Balance Confidence (ABC) scale (r = 0.689). Three items of protective steps assessment were ranking among the moderate level of difficulty when compare with other items of the BESTest. Participants' score distributed from 0 (inability to perform) to 3 (perfectly perform protective steps) so that these test may be used to assess participant across a wide range of protective steps deficits.(37) To investigate protective steps impairment in subacute stroke clinically, the BESTest has been validated in this group of population. The BESTest demonstrated excellent intrarater and interrater reliability in persons with subacute stroke (ICC > 0.85 for both total and each of subsection score); no floor or ceiling effect; and higher accuracy (suggested cut off score for low function was 49% of BESTest) to classify participants with low and high functional ability than BBS and Mini-BESTest. For convergent validity, the BESTest showed excellent convergent validity when correlating with BBS (r = 0.96), Postural Assessment Scale for Stroke Patients (r = 0.96), Community Balance and Mobility Scale (r = 0.91), and Mini-BESTest (r = 0.96).(36)

Previous studies reported the preference of stepping limb during protective steps in persons with stroke. In a case report of patient with stroke, non-paretic limb was used to generate step in all trials of natural responses.(39) In retrospective observational study whose data was collected from protective steps of inpatient stroke participants, 59.1% of trials were the step with non-paretic leg whereas 37% were trials with paretic limb, and 3.8% were trials with no-step responses. More than half of participants reported the preference of using non-paretic limb to step than the use of paretic limb.(38) Even in the patients who were ready to discharge from the hospital, the majority selected the non-paretic limb for stepping.(41) These results are in agreement with a study by Salot and colleagues, who found that 10 of 14 participants with stroke initiated first protective steps with non-paretic limb and 2 of 14 participants exhibited no step strategy.(31) Furthermore, in constraint condition where non-paretic limb was blocked to encourage step with paretic limb, persons with stroke showed difficulty to step with paretic limb. A case report of patient with stroke demonstrated that paretic limb was used only 1/3 of trials in the constraint condition.(39) Mansfield and colleagues reported that 21% of trials were performed with inappropriate strategy such as stepping with blocked (non-paretic) limb and no-step response. In addition, external assistance was needed for patient who had inappropriate response than those who had appropriate response.(38) The use of non-paretic limb, that is frequently under greater load, to step can trigger more instability in the ML direction, leading to fall in persons with stroke. Therefore, preference of non-paretic limb can impede an ability to recover from unpredictable external perturbation.

Determinants of ineffective protective steps in persons with stroke are asymmetrical preperturbation limb load and poor foot recovery. Previous study found that only preperturbation limb load and Chedoke McMaster Stroke Assessment inventory of foot score were related to limb preference to step such that decreased preperturbation limb load and increased foot recovery can improve the probability to step with the paretic limb.(38) The authors reported that paretic leg was more likely to step in the condition that paretic limb load less than non-paretic limb. (38-41) Furthermore, reducing foot recovery was associated with frequency of external assistance with odd ratio of 0.47. With this odd ratio, patients with low CMSA foot score (e.g., CMSA foot score = 2) had 73% and 60% probability of requiring external assistance when step with paretic and non-paretic limb, respectively. In contrast, patient with high CMSA foot score (e.g, CMSA foot score = 7) had 6% and 3% probability of requiring external assistance when step with paretic and non-paretic limb, respectively.(38)

Persons with stroke who could initiate successive step clearance showed impaired step characteristic when compared with young and age-matched control group.(31) The shortest step length compared with young and age-matched control group; and shorter swing duration and slower foot liftoff time when compared with young adults was reported in community-dwelling stroke. As a result, COM velocity at the first protective steps touchdown did not shift anteriorly to a stable point. Although persons with stroke performed the second step, they still showed no improvement of COM velocity toward a stable point at its step touchdown. Moreover, persons with stroke exhibited greatest hip descending after perturbation when compared with young and age-matched control group. Importantly, hip descending of persons with stroke reached peak value at the moment of time before the first protective step touchdown. This suggested inability to control their body upright in a single leg stance period in individual with stroke. The combination between reduced ability to swing the leg appropriately and altered COM control on stance leg during protective steps resulted in multiple stepping and falls in 71.4% of persons with stroke after backward loss of balance, compared with no fall on young and age-matched control group. (31) In addition, no difference of the falls frequency and number of step was reported in neither paretic nor non-paretic stepping response.(43)

Compensatory characteristic of each population (young adults, elderly, and stroke) are summarized in TABLE 4. We can summarize that persons with stroke preferred to step with non-paretic than paretic limb as a result of increasing of preperturbation limb load and reducing foot recovery of paretic limb. This strategy led to uncontrolled balance both during swing and stance phases. Therefore, training to generate step with both legs may increase probability to effectively prevent fall in persons with stroke.

Table 4 Compensatory characteristics of young adults, elderly, and individuals with stroke

Author	Participant	Condition of assessment	Results: Temperospatial parameter	Results: COM	Results: Force	Results: Strategies
Burleigh et al., 1994 (23)	young adults (n=10; age 26.5±3.2)	3 conditions: I) voluntary step; II) constraint protective steps; III) inplace strategy.	Time spend on ML APA in II < I condition (72.6±4.7 vs 82±5.4%). Step onset latency II < I (150±27 vs 204±40 ms). Foot liftoff time in II < I (516±51 vs 674±70 ms).	COM displaced A direction 12% of foot length in I vs 31% in II at heel off. It displaced 23% in I vs 51% in II at foot off. COM velocity was increased from heel off to foot off in I (18±4.5 to 28.4±5.9 m/s). It was not increased in II (31.4±3.4 to 35.2±6.8).	ML APA was initiated by all participants in II.	
McIlroy and Maki., 1995 (59)	young adults (n=7; age 21-35)	Unconstraint protective steps	Step onset latency of ranging between 160-300 ms. Unloading onset, foot liftoff, and contact time was delayed when APA was presented. Step length was longest in a person who used a single protective steps.		There was no any of APA in a novel slip trial for all subject. It was also absent after the trial of no step strategy.	- All participants stepped after a novel perturbation.Most of them had multiple step in the 1st few trial excepted only one participants, whose step length was longest, used only a single step all trial. After exposed to the number of perturbation, participants who have multiple step used only a single step.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Maki et al., 1996 (24)	young adults (n=10; age 22-31)	Constraint protective steps in 8 directions each at 3 magnitudes (small, medium, and large) either with or without cue	Faster unloading onset and foot liftoff time, longer swing duration and step length, and slower step velocity in L or O than in pure AP direction. Foot liftoff time when using unloaded < loaded leg (370 vs 570 ms). Precueing delayed foot liftoff and contact time by 30-40 ms. Increase perturbation magnitude resulted in faster foot liftoff time, faster step velocity, and longer step length.			Protective steps is controlled by online state of stability. Thus, step occurred 91% of trials in large, 32% in medium and 2 % in small perturbation magnitude. Precueing reduced protective steps frequency from 42% to 22% of trials. Unloaded leg was used 96% of trials in response to L and O directions. Rt. and Lt. leg were used equally in pure AP direction.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
McIlroy and Maki., 1999 (58)	young adults (n=5; age 22-28 for original study and n=5: age 21-28 for additional data)	3 conditions: **I**) voluntary step; **II**) unconstraint protective steps; **III**) constraint protective steps. Supplementary data were collected from unconstraint condition.		ML COM was displaced toward stance limb at the time of foot contact in 90% of **I** trials, but it was displaced toward swing limb > 95% of **II** and **III** trials regardless present or absent of ML APA. Only trials that present, ML APA had no benefit on lateral stability during protective steps but adding supplementary data, displacement of ML COM toward swing limb in trials without ML APA was seen.	ML APA occurrence was strongly affected by condition. It was seen 100% of trial in **I**; 78% of trials in **III**; and 56% of trials in **II**. There was main effect of condition on functional effect of ML APA (ML COP toward stance leg). Large ML APA was associated with ML COP toward stance leg in I.	

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Lakhani et al., 2011 (60)	young adults (n=10; age 24±3)	3 conditions of preperturbation load: I) symmetric unconstraint protective steps; II) asymmetric unconstraint protective steps; III) asymmetric constraint protective steps.	Results of preferred limb, step onset latency, foot liftoff time, swing duration, step length, and lateral step displacement was not differed between I and II. Step length in III < I (378±137 vs 551±70). Lateral step displacement in III > I (113.9±43.1 vs 15.3±11.3).		When compared only the results of preferred limb, ML APA occurrences were not differed between I and II.	In I, the dominant limb was used as a preferred limb by 7/10 participants. 64% of protective steps trials was dominant limb stepping. It did not differ from random chance. 90% of participants rely to use 1 limb (dominant/nondominant) as preferred limb. In II, preferred limb stepping decreased from > 80% of trials, when it was loaded up to 50% of BW, to < 20% of trials as loading was increased.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
McIlroy and Maki., 1996 (30)	young adults (n=5; age 22-28) and elderly (n=9; 65-81)	Unconstraint protective steps	ML APA created 30-100 ms discrepancy between step onset latency and unloading onset time.	COM displacement and velocity at the time of foot contact did not differ between groups for both A and P direction and both ML and AP dimension.	ML APA were occurred in young adults > elderly (72% vs 45% of trials).	98% of participant stepped at least 1 (51% of them use a single step; 49% used at least 2 steps).
			Step onset latency in young < elderly (198 vs 241 ms). It was not differed when analyzed only trials without ML APA.	AP COM velocity at foot contact of 1st step was higher in multiple step than a single step.		Multiple step was used in elderly > young adults (63% vs 35% of trials). It mostly occurred in early trials in young but until later trials in elderly.
			Unloading onset time and duration, foot liftoff and contact time, swing duration, and step length and velocity was not differed between groups.			The most common multiple stepping pattern: same leg directed laterally for forward and alternate leg same direction for backward loss of balance.
			1st step length of alternate same leg pattern was 40-50% shorter than others patterns.			Lateral directed stepped occurred ~ 33% in elderly vs 8% of trials in young adults.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Jensen et al., 2001 (32)	young adults (n=16; age 25.93±4.62) and elderly (n=19; age 72.1±3.78)	Constraint protective steps 3 magnitudes (small, medium, and large)		Protective steps was used in 83% of trials in elderly while COM are well within the BOS, whereas 76% of trials was used in young adults across the range perturbation magnitude. These because of higher horizontal linear acceleration of head at instance of foot liftoff.		Across all magnitudes protective steps was used to recover balance in elderly > young adults (95% vs 62% of trials). Age affected on ability to response to different level of magnitude. 84% of elderly, but < 15% of young adults stepped in low magnitude. All elderly, but 75% of young adults stepped in medium magnitude

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Rogers et al., 2003 (25)	young adults (n=14; age 31) and elderly (n=32; age 73)	All participants were tested with 4 task condition: I) certain voluntary step; II) certain unconstraint protective steps; III) uncertain voluntary; IV) uncertain unconstraint protective steps.	Step onset latency was delayed when in III and IV. APA duration was not differ between I and II; and III and IV. Elderly < young adults in II and IV. APA duration in IV > II but not differed between I and III. Unloading duration in IV > III. It was not differed between II and I. Elderly > young adults during I and III. Foot liftoff time in IV > III and IV > II.			

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Schulz et al., 2005 (33)	young adults (n=13; age 23±3.6), healthy elderly (n=12; age 71±5.6), and impaired balance women (n=15; age 76±6.3)	Unconstraint protective steps	Step onset latency did not differ between groups in P direction. Elderly < young (0.5±0.28 vs 0.78±0.31) in A direction. No group differences in any temporal or amplitude properties of protective steps in trials with ML APA. Foot liftoff time did not differ between young and elderly in response to P (0.8±0.35 vs 0.82±0.34) and A pull direction (0.94±0.37 vs 1.08±0.56).	Safety margin after protective steps in young adults > elderly in P direction. Ability to reduce COM velocity did not differ between groups in P direction. No difference of COM displacement and velocity between groups in A direction.	60% of all protective steps were proceeded by an ML APA. It did not differ between groups or perturbation magnitudes in P direction. 63% of all step were preceded with APA and not differed between groups in A direction.	Protective steps was used only 4% of trials in 1% of BW magnitude, whereas it was used in 88% of trials in 5% of BW magnitude (rose sharply between 3% and 4% of BW magnitude) in P direction. Abort step in elderly > young adults. Although probability of protective steps initiation did not differ between groups, number of steps differed (in 4% and 5% of BW magnitude, elderly required 0.5 more step than young in P direction).

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
			Swing duration did not differ between groups both A and P direction. The initial step length of young adults were slightly longer than elderly (0.14±0.07 vs 0.09±0.05) in P direction. It was not differed between groups in A direction. Step velocity was not differed between groups in both A and P directions.			Young adults used 2nd step <10% of trial and never need more steps, whereas nearly 50% of trials of 2nd step and 10% of trials of 3rd step was showed in elderly. No difference in number of steps between groups in A direction.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Lee et al., 2014 (34)	Young adults and elderly (n=26)	Participant were divided into 2 task condition: I) voluntary (n=13) and II) unconstraint protective steps (n=13).	Step reaction time in P < A direction both age groups. Step was elicited earlier in II than I both directions and age groups. Step length in P < A direction in elderly. It did not differ between directions in young. Step length and knee angular velocity in II > I both directions and group was observed. Knee angular velocity in P < A direction both groups. Elderly < young adults both directions and conditions.			

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Mansfield et al., 2011 (39)	Stroke patient (n=1; age 68; stroke duration 52 days)	Release-from-lean in 3 conditions: I) unconstraint protective steps; II) cognitive task with unconstraint protective steps; III) constraint protective steps	Patient showed delay unloading onset, foot liftoff, and foot contact time.		Patient had weight-bearing asymmetry with 69-80% of body borne on paretic side	Patient took multiple shorter steps that ineffective to regain balance in all perturbation trials. Patient need assistant to prevent falls in all trials. Non-paretic limb was used in all trials in I, 2/3 of trials in II and 2/3 of trials in III.
Mansfield et al., 2012	Stroke patients (n=49; age 59.8±14.7; stroke duration 27.5± 18.9 days)	Release-from-lean in 2 conditions: I) unconstraint protective steps and II) constraint protective steps			Patients who were in no limb preference and strong non-paretic limb preference group loaded on paretic limb at preperturbation more than during quiet stance.	Preperturbation limb load and CMSA foot score were related with limb preference to step. Of all participant in I, 40.4% strong preferred on non-paretic and 14.9% on paretic leg.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
					This was not found in patients who were in strong paretic preference group.	Increased frequency of assistance need was related with decreased CMSA foot score, but not related with frequency of protective steps with paretic limb. In II, 79% of trials were protective steps with the appropriate (unblocked limb) and 21% with inappropriate responses (stepping with unblock limb and no-step). External assistance is need in patient who had inappropriate > appropriate response (50% vs 9.6% of trials).

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Martinez et al., 2013 (40)	Stroke patients (n=10; age 59.6±13.1; stroke duration 2.9±1.1 years)	All participants were tested with 2 conditions: I) voluntary step and II) unconstraint protective steps in 3 A directions	Step duration in II < I. Step duration during paretic > non-paretic. Unloading onset time of non-paretic in II < I. Foot liftoff time in II < I. Foot liftoff time during paretic > non-paretic step. Step height of non-paretic > paretic both I and II. Step length was tended toward longer during non-paretic than in paretic step.		Paretic leg had greater ability to step in the condition that it borne weight >47% of BW than during symmetrical weight bearing and weight bearing >53% of BW.	4/10 stroke took a step in at least 1 trials. Multiple steps were used 88.8% of trials. No patient need external assistant. 8/10 subject initiate protective steps with both leg and 2/10 always step with non-paretic leg. 65% of trials in II were non-paretic and 35% were paretic protective steps. Pulling toward paretic limb resulted in non-paretic protective steps in 76.7% of trials. Pulling toward non-paretic limb resulted in paretic protective steps in 51.7% of trials.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Mansfield et al., 2013 (35)	Stroke patients (n=136; age 65.3±14.2 for fallers and 66.6±13.7 for non-fallers)	Release-from-lean in 2 conditions: I) unconstraint protective steps and II) constraint protective steps	Increased unloading onset and foot liftoff time was correlated with increased fall rate. No relationship between foot-contact time and fall rate.			Increased fall rate was correlated with increased frequency of no-step response and slide step, but was not correlated with frequency multiple steps (at least 3) in I. Protective steps with blocked limb and no-step response in II was not related to fall rate.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Inness et al., 2014 (41)	Stroke patients (n=139; age 66±14.2; stroke duration 46.1± 18.8 days)	Release-from-lean in 2 conditions: I) unconstraint protective steps and II) constraint protective steps			Preperturbation limb load was not differed between failed, multiple, and successful protective steps responses. Protective steps with paretic leg had preperturbation limb load on paretic lesser than preperturbation limb load on non-paretic leg during protective steps with non-paretic leg.	71% of participants exhibited impaired protective steps (failed step and multiple steps responses). CMSA leg score of paretic did not differ between paretic and non-paretic protective steps. However, it tended toward higher in paretic protective steps. In I, 51% of trials was non-paretic and 49% was paretic protective steps. Frequency of falls and multiple steps did not differ between legs. In II, 78% of trials was protective steps with appropriate (unblocked) and 22% was protective steps with inappropriate (blocked) limb.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Mansfield et al., 2015 (61)	Stroke patients (n=95; age 48.1-77.3 years; stroke duration 20.5-77.1 days)	Release-from-lean in 2 conditions: I) unconstraint protective steps and II) constraint protective steps				No relationship of No. of step, slide step, inability to step with unblocked limb, or external assistance requirement with fall status or fall rate. Increased inability to step with unblocked limb, decreased paretic limb contribution, decreased between-limb synchronization while quiet stance, and increased step length variability while walking were related to fall rate.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Salot et al., 2016 (31)	Young control (n=14; age 23.9±3.7); age-matched control (n=14; age 58.5±6.2); and stroke patients (n=14; age 58.4±6.1; stroke duration 7.5±5.6 years)	Unconstraint protective steps	Peak hip descent in stroke > young and age-matched control. Time to peak descent of stroke group was observed before 1st step touchdown, whereas young and age-matched control occurred after 1st step touchdown. Stroke and AC had shorter step duration, slower foot liftoff time, and shorter step length than YC group during 1st protective steps response.	COM position shifted anteriorly in stroke but less than young and age-matched control groups at 1^{st} step liftoff to touchdown. From 1^{st} to 2^{nd} step touchdown, age-matched control shift COM position anteriorly at 2^{nd} protective steps touchdown but stroke did not improve and tended to shift it posteriorly. Stroke unable to break COM velocity from 1st step liftoff to touchdown when compared with improving toward 0 in young and age-matched control. At 2nd step touchdown, stroke still unable to improve COM velocity toward 0.		Protective steps backward in stroke < young control (64% vs 100%). Aborted step found in 1 age-matched control and 3 stroke participants. No-step found in 2 stroke participants. No. of step in stroke > age-matched control > young control group. 2^{nd} step was exhibited by all age-matched control and 11/12 stroke participants. Only stroke group (71.4%) experienced a fall with protective steps backward, abort step, or no-step. 83.3% of individuals with stroke initiated the 1st step with the non-paretic leg.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
Inness et al., 2015 (62)	Stroke patients (n=105; age 63.5±12.8; stroke duration 43.2±18.6)	Release-from-lean in 2 conditions: I) unconstraint protective steps and II) constraint protective steps	No difference of foot liftoff time between paretic and non-paretic protective steps (351±89 vs 365±97 ms). Increased ability to maximally loaded on paretic and non-paretic leg and increased cable load was associated with decreased foot liftoff time of paretic protective steps (R^2=23.8%). Increased ability to maximally loaded on non-paretic leg and increased cable load was associated with decreased foot liftoff time of non-paretic protective steps (R^2=22.7%).		Paretic limb load during quiet stance > preperturbation in paretic protective steps (43.7±7.5% vs 44.8±10% of BW), but < preperturbation in non-paretic protective steps (43.7±7.5% vs 50.1±9.2% of BW). Preperturbation limb load of paretic leg during paretic < non-paretic protective steps.	16/105 (15%) fell in the trials that they stepped with paretic limb; 7/105 (7%) fell in the trials that they stepped with non-paretic limb.

Table 4 (Continued)

Author	Participant	Condition of assessment	Results			
			Temperospatial parameter	COM	Force	Strategies
			associated with the likelihood of falls (OR = 1.009); foot liftoff time of paretic protective steps was not associated with the likelihood of falls (OR=1).			

Effect of perturbation training on Protective steps post-stroke

Protective steps in persons with stroke can be improved with perturbation training using sophisticated equipment such as moveable platform or cable release system. Due to limited research in the field of protective steps in persons with stroke, only evidences of protective steps adaptation after a single training session and a case report of 6 weeks protective steps training were provided. (39, 42) Protective steps adaptation was recorded, when researcher perturbed participants' balance with a forward slip-like moveable platform while walking. To generate forward slip with non-paretic leg, the moveable platform was triggered unpredictably in the forward direction 50 ms after non-paretic step touchdown. Adaptation occurred as early as the second trial where protective steps length was longer than the 1st trial with no change in foot liftoff time and swing duration. Moreover, COM position was significantly increased to beyond the threshold and COM velocity increased after perturbation onset, compared with lower than the threshold at the first slip trial. The improvement of COM position and velocity reflected the changes in protective steps choice and slip outcome such that backward loss of balance was reduced from 100% of participants during the first trial to 65% of participants in the second trial. The frequency of abort step was also decreased (from 65% to 30%) and replaced by an increase of ability to perform protective steps (from 30% to 60%).(42) Figure 3 showed the example of COM state stability relative to the threshold. In this case, COM state of stability, a length between the combination point of COM position and velocity and COM state stability threshold, which was backward to COM state stability threshold indicated likelihood toward backward loss of balance.

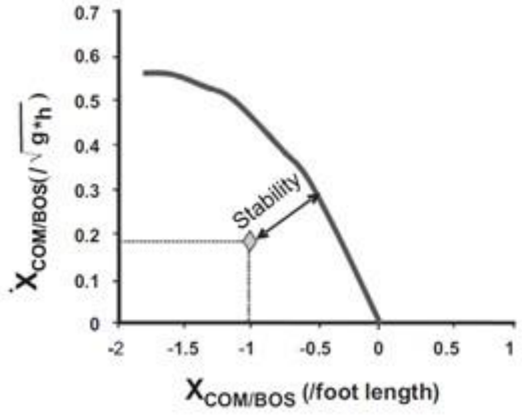

Figure 3 The example of COM state stability. The thick back line indicated computational threshold for backward loss of balance. The diamond indicated instantaneous COM state which had shortest perpendicular distance (double head arrow) to the threshold. This length showed stability at that time of participants. More positive stability (stability > 0) indicated the greater the likelihood toward more stable of the body in anterior direction, in contrast, more negative (stability < 0) indicated the greater likelihood toward less stable or falls backward direction.

Source: Kajrolkar et al. Dynamic stability and compensatory stepping responses during anterior gait-slip perturbations in people with chronic hemiparetic stroke. Journal of biomechanics. 2014 Aug; 47*(*11*):* 2751-8

Improvement of COM state stability at the instance of foot liftoff and probability of stepping with paretic limb were also revealed in the study of slip-like perturbation training with external cue to guide paretic limb stepping during balance recovery.(43) Cueing resulted in greater proportion of protective steps with paretic limb than no-cueing condition (42% versus 6% of trials, respectively). The increase in paretic step frequency across trial was found, specifically, in cueing condition. Furthermore, paretic protective steps during cued condition led to more body stability at the instance of foot liftoff than stepping with non-paretic limb during no cue condition. It also provided more effective proactive stepping reaction, as shown by more trunk flexion angle at foot liftoff, than no-cued non-paretic protective steps.(43)

Long-term perturbation training with lean and cable release system 6 sessions for 2 weeks revealed consistent results of protective steps improvement in a person with stroke. Training was administered with a variety of strategies including evoked protective steps with no constraint; encouraged preperturbation load symmetry with visual biofeedback; encouraged paretic protective steps by blocking non-paretic leg with hand and instructed patient to step with paretic leg; and encouraged step clearance with obstacle while stepping. Utilization of each strategy depended upon the performance on pre-test each session. Over the course of training, protective steps initiation with paretic limb in natural response was reported in 17%-50% of trials in some sessions. At discharge, patient was able to tolerate more percentage of body weight on the cable pull (from 2% -5% to 10% of body weight); not require external assistance; reduce load on affected leg (from 75% to 61% of body weight); and reduced unloading onset and foot contact time dramatically (from 355-638 ms to 109-223 ms). The frequency of protective steps with paretic leg in encourage use condition (obstructing left leg to step) was also increased from 2/3 trials to 3/3 trials at discharge.(39)

It can be seen from the above information that person with stroke can improve their protective steps when exposing to balance threatening for a few trials or for a period of time through the training with a movable platform or cable release system. However, the application of these training methods is limited by the cost and complicated set up in real clinic, thus, another simple and affordable training method is needed.

Voluntary-induced stepping response training and its effects on protective steps

Protective steps had been trained without any instrument. Previous evidence of agility exercise program, the speed-emphasized training, reported faster postural reflex after training 3 time per week for 10 weeks. The program consisted of agility, multisensory approach, and standing perturbation task (i.e. destabilized participant with pushing from instructor or participant pushing instructor to destabilize themselves). This exercise program was compared with stretching/weight shifting exercise program that encouraged increased force onto paretic limb. With agility program, community participants with stroke who were able to walk independently and had moderate to severe balance deficit (BBS ≤ 52/56) showed reduction in number of falls that occurred during anteroposterior platform translation. This reduction was not observed in another stretching/weight shifting exercise group. Although there was improvement of paretic tibialis anterior, medial gastrocnemius, biceps femoris; and non-paretic leg rectus femoris onset latency either immediately after intervention or at 1-month follow-up, only the changes of paretic rectus femoris onset latency differed between groups.(63) Therefore, agility exercise, which includes manual perturbation training, can possibly reduce fall (as measured from frequency of requiring external assistance) and promote faster postural reaction of rectus femoris that was used to counterbalance with posterior instability after intervention.

Improving the effectiveness of protective steps without expensive equipment may be possible using voluntary-induced stepping response (VSR) training as the easiest way to induce perturbation by self-activation.(44, 45) In this training, participants were instructed to lean forward until they felt they were losing balance and took a single step. After training participant to performed VSR with paretic and non-paretic alternatively every 5 trial until reach 50 trials each leg, improvement was evidenced in both stepping and stance legs. After training, there was an increase in knee acceleration amplitude when stepping with non-paretic leg, but not with paretic leg. EMG area of 2nd burst biceps femoris and rectus femoris in both paretic and non-paretic leg was increased after training when compared with pre-test. In stance leg, EMG area of paretic soleus and rectus femoris was increased after training.(44)

Further results of VSR training were available from a study that trained participant with a similar protocol.(45) Researchers reported that people with stroke who were trained with voluntary-induced stepping and fast squat, each for 50 repetitions, showed improved muscle activity and improved symmetrical weight bearing during both arm raise and load drop tasks. In arm raise task, participants with stroke showed delayed time to burst peak of paretic biceps femoris and smaller EMG peak area for paretic and unaffected biceps femoris when compared with control. With training, reduction in time to burst peak of paretic biceps femoris and improvement of EMG peak area for paretic biceps femoris were reported. In load drop task, anticipatory EMG deactivation area was less in paretic leg than non-paretic leg. With training, anticipatory EMG deactivation area increased by 2 different ways: increasing EMG modulation and shifting of the anticipatory EMG deactivation. Asymmetrical weight bearing subgroup of stroke showed more weight shifted to paretic leg after training than symmetrical subgroup, especially, in arm raise task, some of participant in asymmetrical subgroups was able to shift to symmetrical subgroup.(45) These results shed some light to the ability to transfer the skill of one task (voluntary-induce automatic postural response) to another task (anticipatory postural adjustment) in patients with stroke.

Although evidences showed that there were 2 possible trainings with inexpensive instrument using velocity to improve effectiveness of protective steps, one such training (perturbation from pushing force) was only a part multi-task training exercise program that aimed to enrich varieties of outcome. Therefore, the improvement of protective steps responses and fall reduction after long-term training could not be attributable to perturbation training from pushing force alone. Another possible way to achieve the protective steps is the training with VSR through the improvement of lower limb functions during postural control activity, resulting in improved stability during step touchdown of both legs, during single leg support of paretic leg, and faster step for automatic postural response. With this training, people with stroke also showed the ability to transfer skill from one task to another different task. However, the detailed characteristics of VSR and changes of VSR as a result of stroke as compared to healthy persons are lacking. In addition, whether or not the VSR training can directly improve the protective steps in persons with stroke has not been yet clarified.

CHAPTER 3
METHODOLOGY

This study was divided into two sub-studies, according to the objectives of the study.

Methodology of study 1

Research objectives

To compare characteristics of VSR such as center of mass, mediolateral ground reaction force, and step kinematic in young, elderly and persons with stroke.

Study design

A cross-sectional study was conducted in 3 groups of participants (young adults, elderly and persons with stroke) from September 2017 to July 2018 at the Brain And Spinal Injury Center, Salford, United Kingdom.

Sample size

Sample size was calculated by G*Power 3.1. Alpha was set at 0.05 and power at 80%. Effect size was calculated from F value of different foot lift off time between groups of young adults, elderly and persons with stroke in backward platform translation assessment.(31) Therefore, a minimum of 10 individuals per group was recruited.

Participants

Young adults who aged between 18 to 26 years were included in the study. Elderly were included if they were at least 60 years, can stand and walk independently without using assistive device for at least 6 meters, and had no cognitive deficit (assessed by Mini-Mental State Examination using cutoff score of 24).(64) Persons with stroke were included if they had stroke more than 6 months, were medical stable, can stand independently without using assistive device, can walk independently with or without cane for at least 6 meters, and had no cognitive deficit.(65) The exclusion criteria were those who had experience with any of perturbation testing or training within the past year, have visual problem that cannot be corrected with glasses, or have other neurological, cardiovascular, or musculoskeletal conditions that could impede ability to perform testing. This study was approved by institutional review board of the faculty of physical therapy of Srinakharinwirot University; Research, Innovation and Academic Engagement Ethical Approval panel of University of Salford; and Health Research Authority of England. Each participant signed an informed consent form prior to participating in this study.

Procedures

Information regarding age, sex, weight, height, foot and leg length, type of stroke, stroke duration, hemiplegic side, assistive device, falls history in the past 12 months, fear of falling and preferred stepping foot were collected by self-report. Falls was defined as an unexpected event in which the participants come to rest unintentionally on the ground, floor, or lower surface. Fall also involves a failure in recovery response resulting from external force.(47-49) Information of preferred foot was simply collected by a question that ask about which of the foot that a participant preferred to kick the ball in front of their legs. Fugl-Meyer Assessment was used to test motor recovery and sensation of leg after stroke. The total score for leg motor recovery is 34 and sensation is 12. The Balance Evaluation System Test (BESTtest) item 16-18 were used to assess protective steps ability in anterior, posterior, and lateral direction. Score range from 0 (inability to step) to 3 (perform one large step). During the test, participant was instructed to lean the body against therapist’s hand which was then released unpredictably.(36) ABC scale was used to assess balance confident level in performing daily activity indoor and outdoor. A participant was asked to rate each item from 0% (not confident) to 100% (completely confident). Five-time-sit-to-stand-test (FTSST) was used to assess functional leg muscle strength. Time Up and Go (TUG) was administered to assess balance during walking and turning. Fear of falling was asked with a yes/no question (i.e., Are you afraid of fall?)(see APPENDIX A-F for assessment tools and data collection form).

Voluntary-induced Stepping Response (VSR) assessment

To perform VSR, participants was instructed to lean their whole body forward until they feel they are losing balance and take only 1 single step, if possible, to prevent themselves from falling. The voluntary and automatic components of VSR were analyzed. The voluntary component was defined from leaning the body forward until foot liftoff the platform. In contrast, the automatic component was defined from foot liftoff until foot touchdown and the body stop moving. VSR was assessed for 10 trials in each participant. During the trial, participants were asked to stand bare feet with foot apart in preferred foot position on a paper that attached on the platform for 30 seconds until audio cue signaled the start of VSR. Preferred foot position of each participant was marked and re-checked every trial. All participants wore safety harness and a research assistant stood beside the participant to give support as needed. Prior to testing, three to five times of practice trial were allowed to promote familiarity with the test and ensure response stability. Resting was permitted as needed to prevent fatigue.

Thirty-nine markers were adhered to the head, trunk, bilateral bony landmark at upper extremities and lower extremities to compute COM position and all body kinematics according to full body plug-in gait marker set.(66, 67) Additional four markers were attached on long toe and fifth metatarsal of both feet to compute the base of support (BOS). Ten cameras VICON motion capture system (VICON Motion Systems Ltd, Oxford, United Kingdom) was used to record full-body kinematics. Video cameras were used to record all testing events of each participant.

Data Analysis

All of the following variables: 1) step onset latency, 2) step length and step width, 3) step duration, 4) COM position and velocity and 4) changes in trunk and hip displacement, were computed by Matlab software (MathWorks, Inc., Natick, Massachusetts).

Step onset latency was calculated as initial time that the foot lift off the force plates after hearing auditory cue. Step onset latency was the indicator for anticipation and preparation time of each participant before taking a step. Step length and step width represented how far and large the stepping response was by calculating the distance between stance limb's heel at initial position and stepping limb's heel at foot touchdown in the anteroposterior (AP) and mediolateral (ML) direction, respectively. Step length and step width were normalized by participants's stepping leg length to minimize the leg length confounding. Leg length was measured from anterior superior iliac spine to medial malleolus of the same leg. Leg length might differ between stepping leg and stance leg in some participants, therefore, this study calculated leg length of the stepping limb in that trial for normalizing each trial's step length and step width. Step duration was a duration of stepping response starting from foot lift off until it touched the ground. Foot liftoff time was defined from the first point of the long toe marker moved up vertically beyond 2 standard deviation of initial position. Foot touchdown was the time that stepping heel's or toe's marker was at the lowest position after foot liftoff.

Center of mass (CoM) displacement and velocity were computed from the kinematic data in relative to stance limb's heel at foot liftoff. CoM displacement was normalized with stance foot length in order to account for various foot length. Stance foot length was a length in AP direction between a long toe and a heel marker of a stance leg. A larger CoM displacement at foot liftoff indicates that the CoM was located more forward from the stance limb's heel and would suggest greater ability of participant to move their body forward before taking a step. CoM velocity was calculated from the first order derivative of CoM position. A more positive CoM velocity means that the body move faster in the anterior direction.

Trunk and hip displacement at foot liftoff and touchdown was computed from position of markers at C7, T10, and right (RASI) and left (LASI) anterior superior iliac spine at foot liftoff and touchdown subtracted with their initial positions. Leaning strategies were also analyzed in term of using trunk leaning strategy or trunk bending strategy to initiate movement. Trunk leaning strategy reflected that the participants lean forward by initiating their trunk and hip movement simultaneously (Figure 4A). Trunk bending strategy demonstrated that participants lean forward by first moving their trunk forward followed by moving their hip (Figure 4B, 4C)

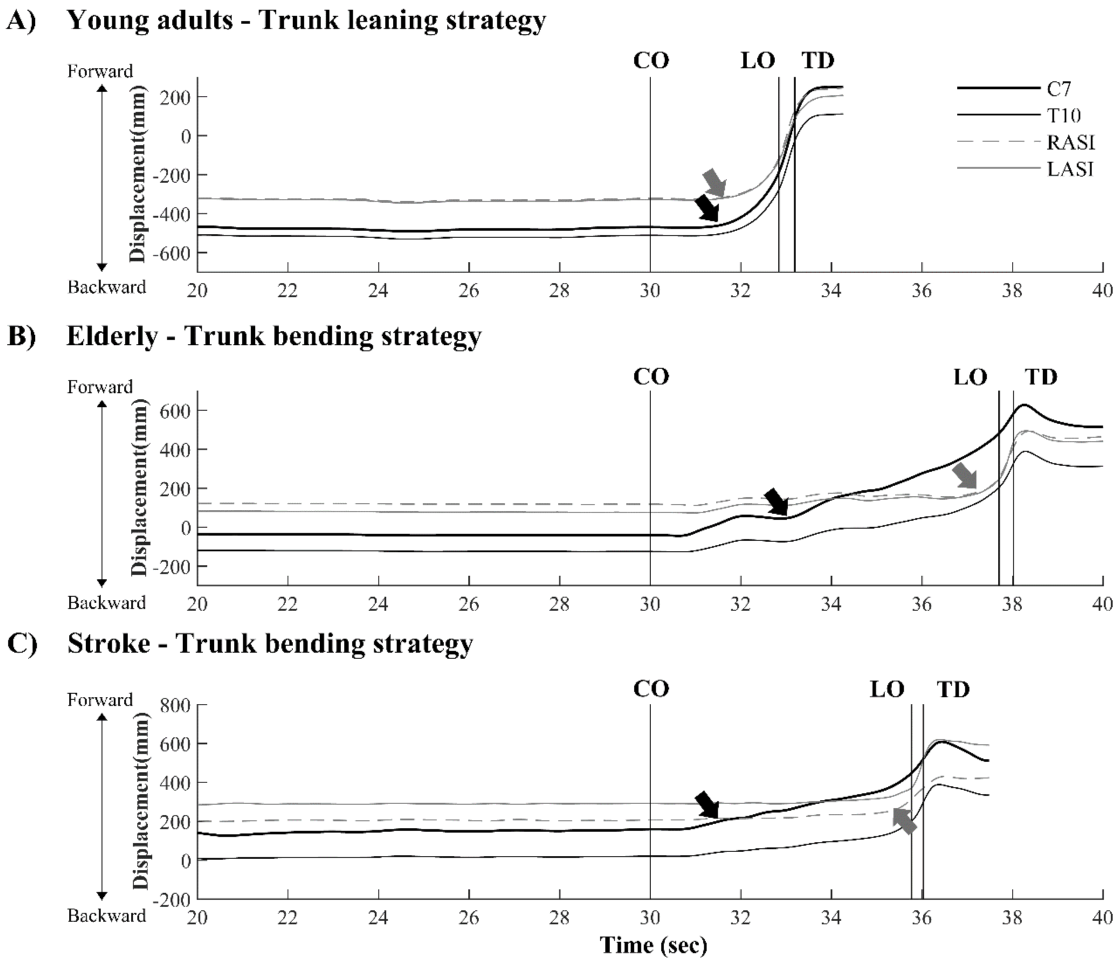

Figure 4 Leaning strategies of representative young adults (A), elderly (B), and stroke (C). Trunk leaning strategy means that a participant lean forward by moving both trunk and hip forward closely in time. Trunk bending strategy means that a participant moved trunk forward closely after cue onset then moved hip just before foot liftoff. Trunk movement was represented by trajectories of cervical 7^{th} (C7, thick black line) and thoracic 10^{th} (T10, thin black line). Hip movement was represented by trajectories of right anterior

superior iliac spine (RASI, dash gray line) and left anterior superior iliac spine (LASI, thin gray line). Thick black arrows indicate a point at which trunk begin to move. Thick gray arrows indicate a point at which hip begin to move. Abbreviation: CO = Auditory cue onset; LO = foot liftoff; TD = foot touchdown.

Number of steps, grasping, losing of balance (as defined from using harness to prevent body from falling), and other movement strategies were recorded real-time and re-checked from video record files.

Statistical analysis

Descriptive statistic was used to characterize participants' demographic data. One-way ANOVA (3x1) followed by Tukey post hoc analysis was used to determine differences in step onset latency, step length and step width, step duration, COM position and velocity, changes of trunk and hip displacement between 3 groups of participants. Kruskal-Wallis test and Man-Whitney U test were used to examine differences between groups for variable that had non-normally distributed. Number of steps, grasping, losing of balance, and other movement strategies was calculated as frequency and percentage of all trials and, then, analyzed with Chi-square. IBM SPSS statistics version 24 (IBM Corporation, Armonk, New York) was used for all statistical analysis with p-value of 0.05. Bonferroni correction for p-value in multiple comparison was also used when appropriate.

Methodology of study 2

Research objectives

To examine the immediate effect of VSR training on the protective steps, compared to DynSTABLE perturbation training (DST), in persons with stroke.

Study design

A two parallel-arm randomized, controlled trial was conducted in participants with chronic stroke at the Brain And Spinal Injury Center, Salford, United Kingdom from September 2017 to July 2018. This study was a part of a larger study that assessed both immediate and retention effects of VSR training that was registered with Thai Clinical Trials Registry [URL http://www.clinicaltrials.in.th/; registration number TCTR20170827001].

Sample size

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

Participants

Participants were recruited to the study if they experienced a stroke more than 6 months previously, were medically stable, able to stand independently without an orthotic device and able to walk independently with or without cane for at least 6 meters. The exclusion criteria were those who had 1) perturbation testing and/or training within the past year; 2) a neurological condition other than stroke, 3) cardiovascular disorders (e.g., uncontrolled hypertension, or acute deep vein thrombosis), or 4) 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 participating.

Procedures

Demographic information regarding age, sex, weight, height, stroke duration, hemiplegic side, fall history, and fear of falling were collected via self-report. Cognitive function was assessed by Mini-Mental State Examination (MMSE),(65) balance confidence by Activities-specific Balance Confidence scale (ABC),(68) recovery after stroke by Fugl-Meyer Assessment of lower extremity motor (FMA-LE)(69) and sensation subscale, functional muscle strength by Five-Time-Sit-to-Stand-Test (FTSST).(68) Clinical test for protective steps was assessed by item 16 to 18 of the Balance Evaluation System Test (BESTest).(36, 70) A participant could be rated as 0 (inability to step) to 3 (perform one large step) on each item. Time Up and Go (TUG) and Dynamic Gait Index (DGI) were also administered to assess balance during walking and turning.(71) Falls history was collected and a "faller" was defined as a person who reported falling at least once in the past 12 months.(48)

Protective steps assessment

To examine the immediate effect of training on protective steps, participants were assessed with unpredicted platform movements in two consecutive events (baseline and immediate assessment after training). The Computer Assisted Rehabilitation ENvironment (CAREN, Motekforce Link, Amsterdam, The Netherlands) system that consists of a movable computer-driven 2m-diameter platform was used to simulate slip-like situations.(72) Perturbations were delivered by rapidly moving the platform backward (acceleration of 4 m/s2 with acceleration and deceleration period each for 300ms) to elicit a forward fall of participants while standing on the platform. Participants wore a safety harness and stood with bare feet foot width apart on an A3 paper taped on the top of the moveable platform to standardize preferred foot position. The safety harness was set with sufficient room for participants to take steps while preventing their hands and knees from touching the platform. Platform perturbations were delivered for 10 trials both before and immediately after training. Participants were instructed to act naturally to recover balance and had a chance to see how the platform would move prior to testing. No instruction was given of which leg should step.

Thirty-nine markers were adhered, according to full body plug-in gait marker set including four markers adhered on the long toe and fifth metatarsal to compute COM position.(66, 67) Additional three markers were placed on the platform to calculate onset movement during perturbation trials. Full-body markers 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 of each participant.

Participants were randomly allocated to either Voluntary-induced Stepping Response (VSR) or DynSTABLE Perturbation Training (DST) group using stratified randomization with a 1:1 allocation ratio. Stratified randomization was performed based on cutoff score recommended by previous study (<14.5 of FMA-LE score was classified low functional participants)(73) to obtain balanced groups on stroke severity. The randomization sequence was computer generated and operate by an internet randomization service (www.rando.la). This web-based randomization provided unpredictable sequences by simply generate randomized result of each individual after filled in participant's code and FMA-LE score, therefore, selection bias was alleviated. As randomization, allocation, and intervention were operated by one researcher (an experienced physical therapist), intervention allocation could not be completely concealed, and assessment and treatment could not be blinded. However, outcome measures were objective assessment so that risk of assessor bias is limited.

Training protocol

Voluntary-induced Stepping response (VSR) was produced by instructing participants to lean their whole body forward without bending at the hip and knee until they felt a loss of balance and then take a step. Participants were asked to perform VSR for up to 10 minutes at a time alternately stepping with unaffected and affected legs, with rest (approximately 10 minutes) interspersed as needed. A maximum of 3 sessions of 10 minutes were performed for all participants. DynSTABLE perturbation training (DST) is a mode of training in Dynamic STability and Balance Learning Environment (DynSTABLE) instrument (Motekforce Link, Amsterdam, The Netherlands). DynSTABLE includes a set of training application providing real-time feedback in challenging physical, visual and cognitive environments created by three screens with projectors, an audio system, and a 2 degrees of freedom moveable platform. Perturbations were introduced randomly by translating a movable platform in 4 directions (anterior, posterior, right, left).(74, 75) During training, participants were asked to stand with feet apart in a comfortable position, watch the virtual screen in front and act naturally to recover balance. The training was conducted in the same way for the same period of time as for VSR training (Figure 5). Perturbation challenge was gradually increased from level 1 to 10 (acceleration = 9.8 m/s^2) within a session.

Prior to training with VSR or DST, all participants received a warm up for 7 minutes including lower extremities muscle stretching, weight shifting practices, and voluntary forward stepping for 10 times with each leg. They also received leg stretching after training for 3 minutes as a cool down. During both training, the researcher stood beside participants to give them an instruction individually and for safety.

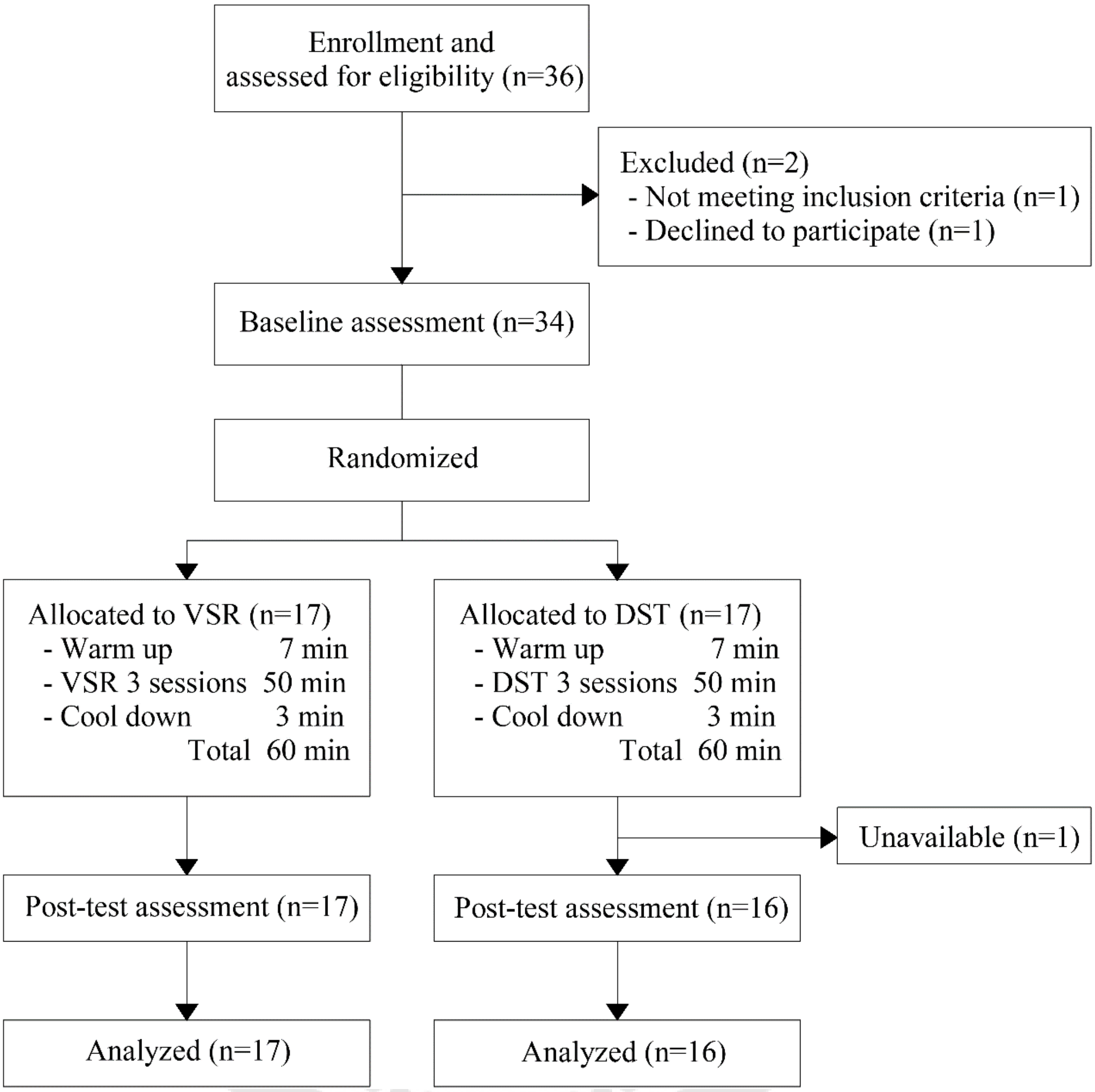

Figure 5 Flow diagram of participant enrolment. VSR is Voluntary-induced Stepping Response training and DST is DynSTABLE Perturbation Training.

Data analysis

The primary outcomes including step length, step width and COM position at 1st stepping foot touchdown measured at pre- and post-test were calculated and analyzed using MATLAB software (MathWorks, Inc., Natick, Massachusetts). Step length and step width were defined as the distance between the stance and stepping limb's heel at the point of stepping foot touchdown in the anteroposterior and mediolateral direction, respectively. Step length and width were normalized by stepping leg length and multiply by 100 to find percentages of stepping leg length. Foot touchdown was the first point at which difference between vertical position of stepping limb's heel or toe (depended on which one touched first) and floor marker were within 2 SD of resting baseline value.

CoM position at foot touchdown was computed from the kinematic data relative to stepping limb's heel marker in anterior direction. A more negative CoM position indicates that the CoM locates far away forward from stepping limb's heel at foot touchdown and would suggest greater instability in forward direction. In contrast, a more positive CoM position indicates better ability to resist forward instability at stepping foot's touchdown (Figure 6)

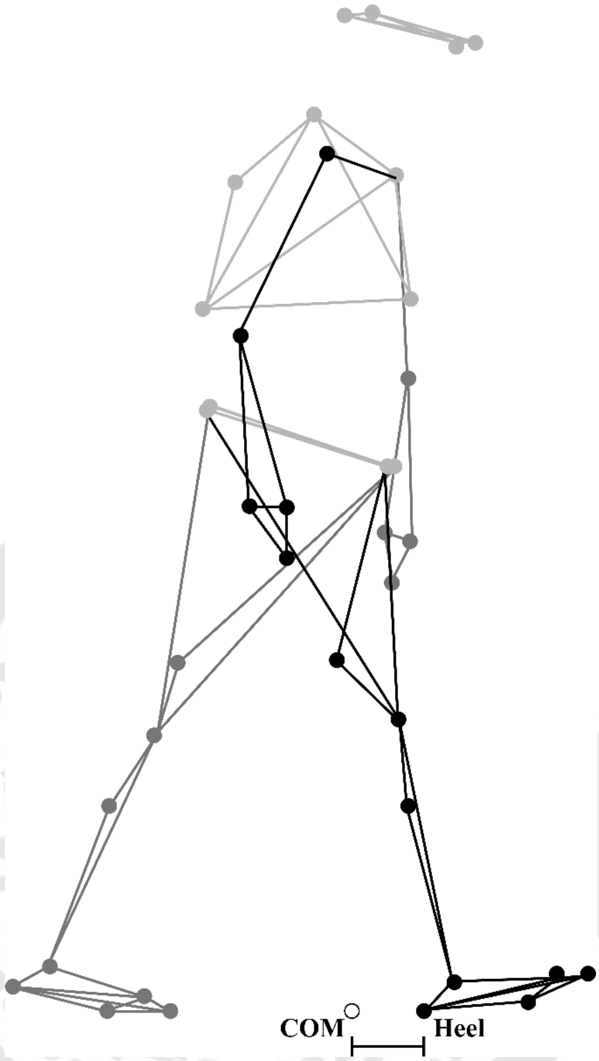

Figure 6 Center of Mass (CoM) position relative to stepping's leg at foot touchdown. Stepping side was in black, stance side in dark gray and head and trunk in light gray. Filled circles represented markers. An empty circle showed a location of the body's CoM position projected on the floor.

Secondary outcomes were number of protective steps per trial, choice of first stepping leg and grasping handrails. They were recorded real-time during baseline assessment and post-test, then, re-checked with video recorded files. Affected and unaffected step length and width were analyzed separately to determine whether improvement differed between legs.

Statistical analysis

Descriptive statistics were used to describe subject characteristics. Independent t-test and Mann-Whitney U test (for nonparametric data) were used to compare subject characteristics between groups. Mixed analysis of variance (2x2) was used to determine the effect of VSR and DST on protective steps at baseline and post-test, and Bonferroni comparison was then used to resolve significant interaction. Number of stepping response, choice of first stepping leg and grasping handrails per trials were calculated as frequency and percentage of all trials in either group. Chi-square and McNemar were used to compare percentage differences between group and between pre- and post-test, respectively. All statistical analyses were performed using the IBM SPSS statistics version 24 (IBM Corporation, Armonk, New York) with a significant level of 0.05. Effect size was calculated using Cohen's d based on these criteria; 0.2 = small; 0.5 = medium and 0.8 = large.(76)

CHAPTER 4
RESULTS

Results of study 1

The data from 30 participants (10 for young adults (Y), 10 for elderly (E), and 10 for persons with stroke (S)) were analyzed in this study. In a group of persons with stroke, CoM position and velocity, change of trunk and hip displacement were analyzed from 9 participants according to T10 occlusion by harness during the test. Subject's characteristic for each group of participants was shown in Table 5. Even though age, weight, and gender differed between young adults, elderly, and participants with stroke, height did not differ among 3 groups. All participants with stroke were in chronic stage (stroke duration range from 2.5 to 44 years). Five out of 10 participants had hemorrhagic stroke, 2 had ischemic stroke, the other 3 from other causes. Six out of ten reported right-side weakness. Only one participant in stroke group reported fear of falling and three participants with stroke reported at least 1 fall in the past year. Participants with stroke had mean MMSE of 29.1 out of 30 (SD 1.3), ABC of 66.9 out of 100 (SD 20.9), FMA-LE of 23.7 out of 34 (SD 7.8), FMA-sensation of 10.9 out of 12 (SD 1.6), FTSST of 20.3 sec(12.6), TUG of 18.5 sec(SD 6.5) and BESTest items 16-18 of 5.1 out of 12 (SD 3.1).

Table 5 Subject characteristics

	Young	Elderly	Stroke
Age (y)	21.45±2.38	68.9±4.43†	63±12.39*
Weight (kg)	59.82±11.38	68.61±16.51	80.71±10.77*
Height (m)	1.69±8.52	1.69±0.1	1.74±0.05
Gender - Male (%)	5 (50)	4 (40)†	10 (100)*

Note: Age, weight, and height are reported in mean±SD; Gender is reported in n(%); Abbreviation: y = year; Kg = kilogram; m = meter;

*Significant difference between Young and Stroke at $p < 0.05$;

[†]Significant difference between Young and Elderly at $p < 0.05$;

Step kinematic

Step onset latency, the indicator of anticipation and preparation time of participant to perform the task, were 6.94±12.12 seconds in young, 5.44±15.83 seconds in elderly, and 10.51±18.85 seconds in participants with stroke. Step onset latency did not significantly differ between groups ($F_{2,27}$ = 0.27, p > 0.05), although the persons with stroke demonstrated a trend of longer onset latency. Step length, step width and step duration were compared between 3 groups in Figure 7. Results indicated that step kinematic of VSR significantly differed between groups. Step length was shorter in stroke than in young and elderly ($F_{2,27}$ = 16.67, p < 0.001, 95% CI of S vs Y [-0.44 to -0.17]; S vs E [-0.35 to -0.08], Figure 7A). Step width was significantly wider in stroke and elderly than young adults ($F_{2,27}$ = 6.69, p = 0.004, 95% CI of S vs Y [0.03 to 0.17]; E vs Y [0.002 to 0.14], Figure 7B). Step duration was significantly longer in elderly when comparing with stroke ($F_{2,27}$ = 6.39, p = 0.005, 95% CI of E vs S [17.86 to 98.65], Figure 7C).

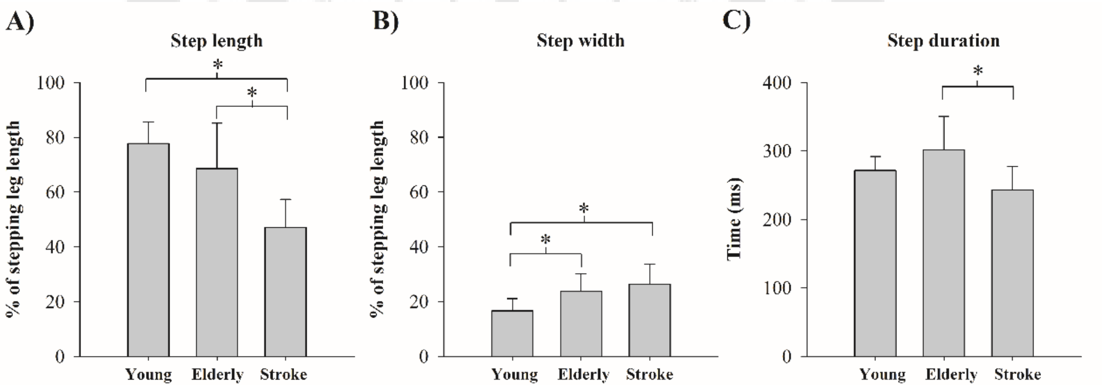

Figure 7 showed step length (A), step width (B), and step duration (C) in 3 groups of participants. Step length and step width were normalized by stepping leg length and was reported as percentage of stepping leg length. Value are shown in mean+SD. * represented p<0.05

Stability and trunk control

Significant differences of body stability during foot liftoff were found among young adults, elderly, and stroke (Figure 8). CoM displacement at foot liftoff was significantly larger in young adults when compared with elderly and stroke ($F_{2,26}$ = 11.96, p < 0.001, 95% CI of Y vs E [0.07 to 0.42]; Y vs S [0.16 to 0.51], Figure 8A). Furthermore, CoM velocity at foot liftoff was faster in young adults than elderly and stroke ($F_{2,26}$ = 15.31, p < 0.001, 95% CI of Y vs E [0.1 to 0.39]; Y vs S [0.16 to 0.45], Figure 8B). These results indicated that young adults can displace their CoM more forward and faster than elderly and persons with stroke.

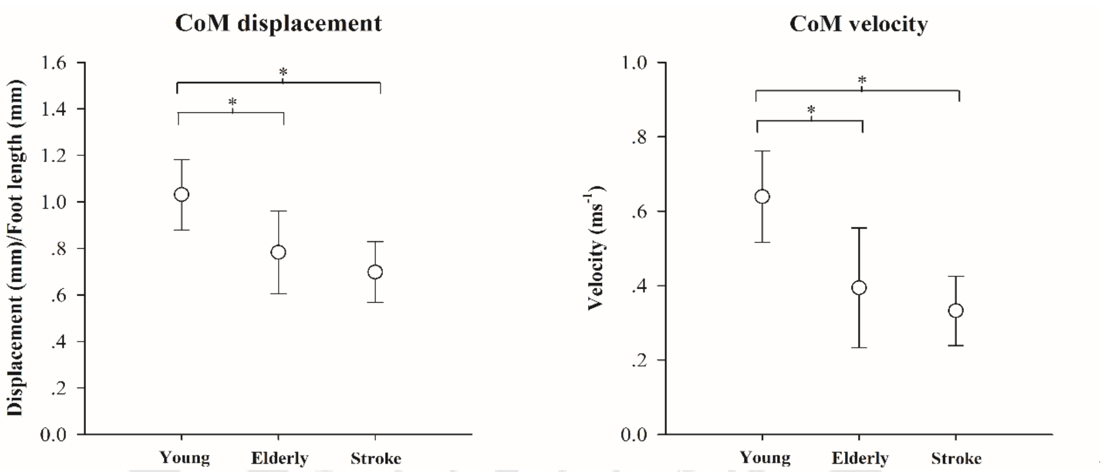

Figure 8 Center of Mass (CoM) displacement (A) and CoM velocity at foot liftoff (B) in young adults, elderly, and participants with stroke. Center of Mass (CoM) displacement at foot liftoff was normalized by a participant's stance foot length. Value are shown in mean±SD. * represented p<0.05

Regarding trunk and hip movement (Table 6), trunk and hip displacement measured from C7, T10, RASI, and LASI markers showed significant differences between groups at both foot liftoff and touchdown. While participants with stroke showed significantly lesser displacement in all trunk and hip markers at foot liftoff as compared to young adults, elderly showed significantly lesser only T10, RASI and LASI displacement when compared with young adults. No difference in trunk and hip displacements was found between elderly and stroke at foot liftoff. These results indicated that persons with stroke and elderly voluntarily made a small movement of their body in order to induced steps, whereas young adults made a larger movement of both trunk and hip.

Table 6 Changes in trunk-hip displacement at foot liftoff and touchdown of participants in 3 groups; young adults, elderly and persons with stroke.

	Young	Elderly	Stroke
Trunk-hip displacement (mm)			
At foot liftoff			
- C7 displacement	371.02±77.43	317.93±76.86	280.81±68.03*
- T10 displacement	291.39±49.11	231.23±52.98†	200.65±57.44*
- RASI displacement	225.63±28.48	167.34±39.07†	138.96±49.92*
- LASI displacement	228.41±34.12	175.00±40.10†	141.13±47.67*
At foot touchdown			
- C7 displacement	598.72±114.63	437.16±217.24	382.72±92.32*
- T10 displacement	483.25±75.84	385.36±100.25†	286.86±75.80*‡
- RASI displacement	409.35±59.64	321.83±102.46	215.82±68.46*‡
- LASI displacement	389.86±54.49	324.72±100.83	226.70±62.17*‡

Note: Values were shown in mean±SD; C7 = cervical 7th marker; T10 = thoracic 10th marker displacement; RASI = right anterior superior iliac spine marker; LASI = left anterior superior iliac spine marker;

*Significant difference between Young and Stroke at $p < 0.05$;

†Significant difference between Young and Elderly at $p < 0.05$;

‡Significant difference between Elderly and Stroke at $p < 0.05$

At foot touchdown, participants with stroke showed significantly lesser displacement of trunk and hip when compared with young adults and showed significantly lesser T10, RASI, and LASI displacements when compared with elderly. In addition, elderly showed lesser T10 displacement when compared with young adults.

These findings demonstrated that in the automatic component of stepping responses, persons with stroke and elderly still moved their body less than young adults.

VSR outcomes

Our results showed that, during a trial, young adults, elderly, and stroke used difference strategies to recover their balance and some of them failed to perform VSR successfully. Results reported that number of steps significantly differed between groups. While young adults used a single step for 100% of all trials for all participants, elderly and stroke used only 97% of all trials (3 out of 10 participants) and 73.2% of all trials (7 out of 10 participants), respectively. Furthermore, 6.2% of all trials (2 out of 10 participants) in stroke was reported as multiple steps (Figure 9A). In addition, we found that only 1 participants with stroke could step with affected foot in all trials and the remaining 9 participants with stroke used unaffected foot to step. Frequency of grasping was significantly greater in elderly (13%) and stroke (20.6%) than in young adults who showed no grasping. Frequency of grasping did not significantly differ between elderly and stroke (Figure 9B). Even though young adults and elderly performed VSR successfully in all trials for all participants, 28.9% of trials in stroke were reported as losing of balance during a trial (Figure 9C). Young adults leaned forward by using trunk leaning strategy (leaning forward with whole body by using ankle joint as an axis of rotation) for 89.9% of trials but elderly and persons with stroke demonstrated more trunk bending strategy (leaning forward with delay hip movement) (Figure 9D).

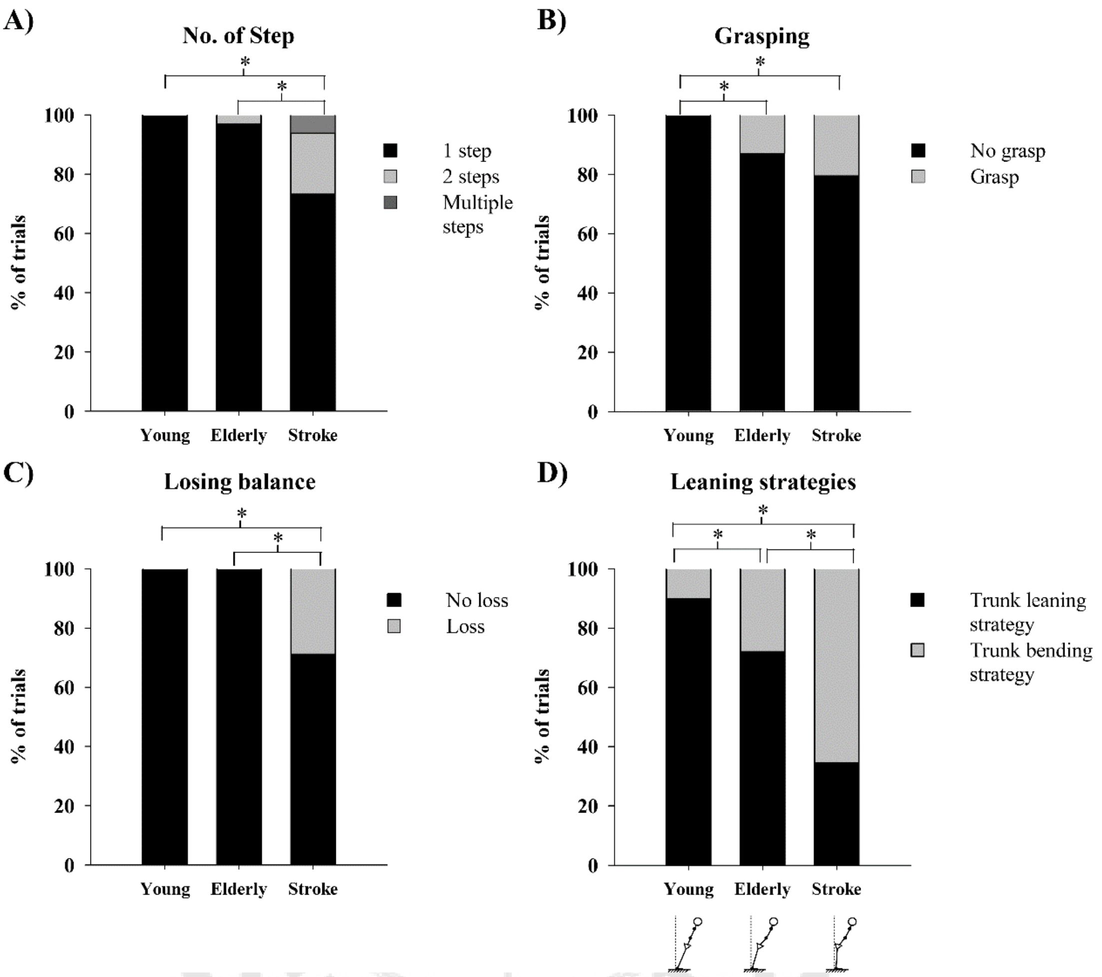

Figure 9 Percentage of number of step (A), grasping (B), losing of balance (C), and leaning strategies (D) in 3 groups of participants. “Multiple steps” means performing VSR with more than 2 steps. Trunk leaning strategy means that a participant lean forward by moving both trunk and hip forward closely in time. Trunk bending strategy means that a participant moved trunk forward closely after cue onset then moved hip just before foot liftoff. * represented $p<0.05$

Results of study 2

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

Table 7 Subject characteristics at 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,	5.1(10.2)	6.4(4.9)*
range)	(0.6 - 44)	(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)
Preferred foot†		
- Affected	6(35.3)	4(23.5)
- Unaffected	11(64.7)	12(70.6)
- Other	0(0)	1(5.9)
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)

	VSR (n=17)	DST (n=17)
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 mean(SD); *significant difference between groups with $p < 0.05$.
†categorical data are in n(%); Abbreviation: 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-Time-Sit-to-Stand-Test, TUG = Time Up and Go, BESTest = Balance Evaluation System Test, VSR = Voluntary-induced Stepping Response, DST = DynSTABLE Perturbation Training

Step kinematic

Step length and step width at baseline were not statistically different between groups (Figure 10A and 10D). The overall step width (Figure 10D) was larger in both groups after training (p<0.05, 95%CI 1.46 to 4.56, Cohen's d = 0.31). However, interaction effect (p<0.01) suggested that overall 1st step length (figure 10A) was longer after training only in the DST group (p<0.001, 95%CI 3.12 to 7.87, Cohen'd = 0.54). No significant change was found in unaffected step length after either training method but if the participants used the affected leg to step, significant longer step length post training was found in both groups (p=0.01, 95%CI 1.52 to 9.67, Cohen's d = 0.50) (Figure 10C).

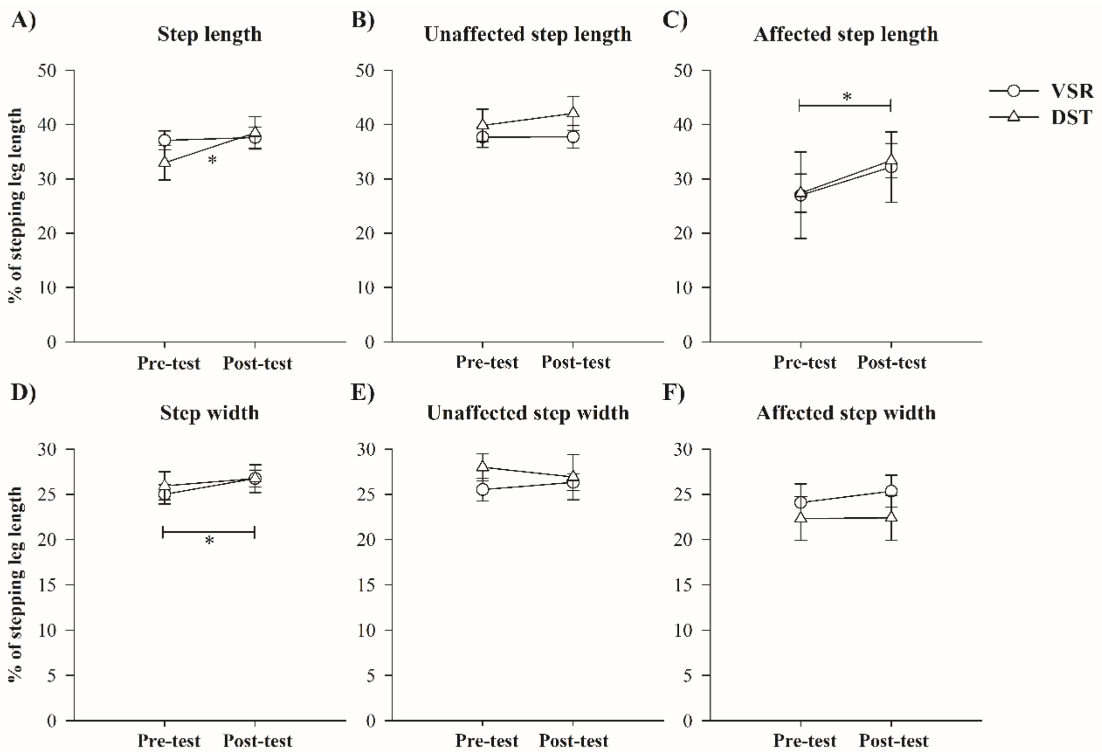

Figure 10 Step length and step width of 1st protective steps when combined both legs (A and D), only unaffected leg (B and E) and only affected leg (C and F) with standard error. VSR is Voluntary-induced Stepping Response training and DST is DynSTABLE Perturbation Training. *p<0.05.

Center of mass

There was no difference of CoM position at baseline between DST and VSR (Figure 11) but significant interaction between time and training group (p=0.02) indicated that only the CoM position improved after training in DST (p<0.01, 95% CI, 13.94 to 48.79, Cohen'd = 0.48), by shifting from negative toward positive value at post training. In VSR, the CoM positions were positive during both pre and post training, suggesting that VSR was able to maintain CoM in the appropriate position before training, hence, no improvement was found.

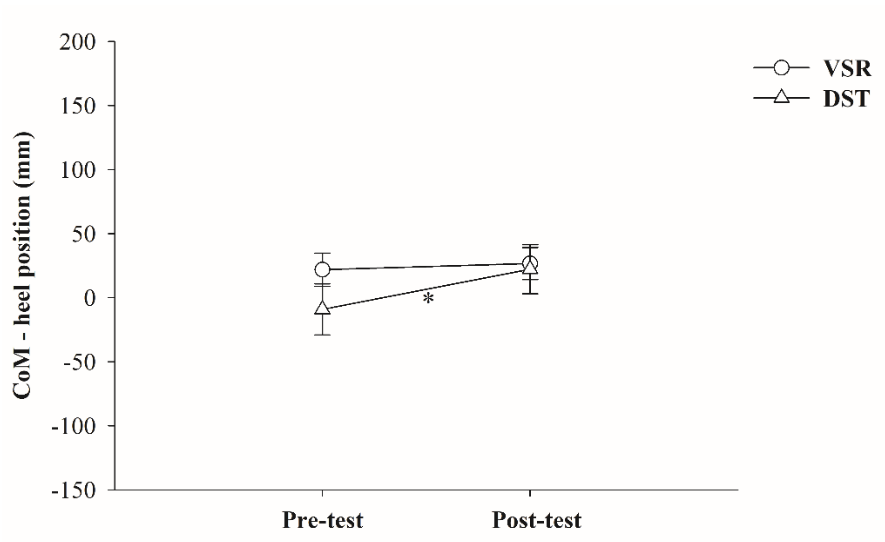

Figure 11 Center of Mass (CoM) position relative to stepping limb's heel at 1st foot touchdown during pre- and post-test in VSR and DST with standard error. VSR is Voluntary-induced Stepping Response training and DST is DynSTABLE Perturbation Training. *p<0.05.

Secondary outcomes

There were significant differences in number of protective steps, choice of first protective steps leg, and grasping between groups at pre- and post-test. After training, frequency of trials with single step increased, whereas frequency of trials with multiple steps decreased in both VSR and DST. Only VSR training group showed significant changes in choice of first protective steps leg where there was a significant increase in the use of affected leg and a significant decrease in the use of unaffected leg after training. Although both groups showed decrease in grasping, a significant reduction was found only in the VSR (table 2).

Table 8 frequency of number of stepping response, choice of first protective step leg, and grasping.

		VSR		DST	
		Pre-test N(%)	Post-test N(%)	Pre-test N(%)	Post-test 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 first protective steps 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	No	117 (69.6)	128 (78.5)**	84 (50)	97 (63)
	Grasp	51 (30.4)	35 (21.5)**	84 (50)	57(37)

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

CHAPTER 5
DISCUSSION

Discussion of study 1

This is the first study that aimed to examine the characteristics of the voluntary-induced stepping response (VSR) among young adults, elderly, and persons with stroke. The results support our hypothesis that VSR characteristics were deteriorated in participants with stroke more than elderly. Although elderly showed similar impairment of voluntary components of VSR as participants with stroke in almost all parameters, automatic component of VSR was slightly impaired in elderly but greatly impaired in participants with stroke when compared with young adults.

This study used results of healthy young adults to outline normal characteristics of the VSR. For voluntary component, we found that young adult used trunk leaning strategy such that they leaned their body forward similar to the use of ankle strategy where the ankle joint was an axis of rotation. For automatic component of VSR, young participants used only a single large step without grasping nor requiring external support for maintaining balance in all trials. In comparison to young adults, elderly demonstrated more variation in VSR, especially in the voluntary than automatic components. Higher percentages of trials with the delayed hip movement (trunk bending strategy) together with lesser trunk and hip movements were demonstrated in elderly as compared to young adults. The trunk bending strategy used by some of elderly participants indicated a reduction in limit of stability which was associated with increasing age.(77) A previous study showed that anterior center of pressure (CoP) displacement, an indicator of limit of stability, was highly correlated with strength of ankle plantarflexor muscle which was decreased in elderly.(78) Therefore, the use of trunk bending strategy in our elderly group may be due to a reduction of ankle plantarflexor strength. For automatic component, the significant increase in step width and grasping reaction may reflect some problems of lateral stability in elderly during both static and dynamic stability. For example, mediolateral CoM peak displacement and velocity during walking especially on narrow path was larger when age increased, indicating instability in the lateral plane.(79, 80)

Stroke is associated with deficits in several characteristics of VSR and these deficits are greater than the deterioration with age. Focusing on voluntary component, we demonstrated that stroke led to reduced ability to control trunk and hip movement properly during trunk leaning. The majority (65.5%) of all participants with stroke used trunk bending strategy to generate a step. Similar pattern of trunk movement was also reported during sitting such that when moving body forward, people with stroke moved upper trunk rather than lower trunk while kept weight on buttock rather than feet.(81) In addition, trunk, hip, and CoM motion prior to step initiation was smaller in participants with stroke than young participants. Limit of stability of persons with stroke was associated with combined core and affected leg muscle strength, as well as step length and step duration which were reduced after stroke.(82, 83) Regarding the automatic component of VSR, even though step onset latency did not significantly change, we showed that stepping response to recapture balance was impaired in the patients with stroke. Similar to previous studies, almost all of our participants with stroke took the first step with preferred unaffected leg.(31, 40) With weakness and poor motor control on the affected leg, individuals with stroke had difficulty in shifting the body weight onto the stance affected leg which results in more difficulty in controlling lateral stability during stepping. Therefore, it is not surprising to find in persons with stroke that their step length was shorter whereas step width was wider and step duration was faster in order to regain body stability quickly. Reduction in lateral stability and impairment of stepping execution may be a reason of reduced amplitude of body movement before foot liftoff, multiple steps, grasping and losing balance in persons with stroke.

The results of this study can be used as a guideline for rehabilitation. Our results indicated that VSR could be used to differentiate protective steps performance between groups of populations. VSR can simulate fall-like situation that patient loss of balance and have a postural response without any instruments required. Therefore, it can be used as screening tool to assess the impairment of protective steps performance in patients or as training exercise to regain protective steps ability in clinical setting that have no standard equipment. In addition, impairments in either voluntary or automatic components impact on the whole performance of VSR as shown in elderly and patients with stroke. A specific training to fix an impaired characteristics may improve VSR. For example, static and dynamic balance training to increase limit of stability; muscle strengthening to increase leg muscle strength and stability or reactive or voluntary step training to improve stepping performance in patients may improve VSR. These training techniques have been used in previous pilot study to successfully improve protective steps performance in patients with stroke after support surface translation. (84) Moreover, the rehabilitation goal can be set using the normal characteristics that found in young adults, such as encouraging the use of trunk leaning rather than trunk bending strategy for achieving longer step length.

This study has some limitations. A previous study suggested that performing voluntary stepping in reaction time task that had contextual certainty, older reported similar anticipatory duration with young adults. (25) In our study, all participants performed the same task for 10 trials, the predictability of the task may affect step onset latency and result in similarity between groups. Every participant also had the opportunity to choose their maximum leaning magnitude in order to trigger a step. Therefore, not only physical performance affected VSR ability, but also did balance confidence and fear of falling. Our participants with stroke had low ABC score, even if all of them were in chronic stage and had high functional performance. The low balance confidence may affect ability to perform fall-like position during VSR as an evidence showed that balance confidence was correlated with static standing balance and cautious gait. (85) In addition, 9 out of 10 participants with stroke stepped with unaffected leg. Characteristics of affected leg stepping needs further exploration. Moreover, average age of our participants with stroke is above 60 years old. Impairments of VSR found in our stroke groups may be attributable to a combination of age and neurological deficit. Testing VSR in persons with stroke with younger age in further study is required to unravel the effect of cerebrovascular accident on VSR.

Discussion of study 2

This study is the first to examine the immediate effect of Voluntary-induced Stepping Response (VSR) training on automatic protective steps responses in persons with chronic stroke. We hypothesized that VSR would be a potential training method to improve protective steps in the same way as the use of the complicated platform translation instrument. The findings supported our hypothesis that both VSR and DST can improve protective steps, i.e. they can improve step width, step length on affected limb, ability to maintain CoM position in anterior direction, and ability to maintain stability using only single step. Although there are significant differences in the effects of using VSR or DST training methods, but they are small when compared with overall results.

DST was selected in this study to be a reference training because it is an instrument that can simulate slip-like situation during training for participants and there was evidence that slip-like perturbation training could improve protective steps in elderly. (74, 75) DST also includes virtual reality where sensory feedback and tasks training can be systematically manipulated. A study reported that the use of virtual reality for locomotion training could promote motor recovery and cortical changes in persons with chronic stroke. (86) Improvement of protective steps following DST, according to our protocol, was in line with results from a recent study of instrument perturbation training in persons with chronic stroke for 5 weeks where the percentage of a single step during forward perturbation significantly increased. (87) Even though the period of training was shorter in our study, this demonstrated that DST was an effective method that could improve protective steps post-stroke.

VSR is a type of internal perturbation training as participants need to lean forward with their whole body to induced forward instability and voluntarily generate a step. Our result demonstrated that VSR training can improve protective steps following an external perturbation. This was in accordance with previous RCT study comparing the effect of combined internal and manual external perturbation training with conventional therapy (balance and mobility exercises) which showed that automatic response to maintain body stability improved after 6-week training and retained for 12 months in the perturbation training group. (88) A possible explanation for the improvement of protective steps in response to perturbation after short-term VSR training may be due to task-specific training. Task-specific training is a type of neuromotor intervention that train muscles to function specifically for a particular action. (89) This type of training emphasizes goal-directed task, mass practice and repetitions of skills for regaining functional abilities by using either undamaged area or recruiting supplementary area of the brain.(90) A systematic review and meta-analysis of task-specific training of upper limb function in persons with sub-acute and chronic stroke revealed changes in sensorimotor cortex when measured with TMS, fMRI, PET, and SPECT at pre- and post-test with standardized effect size of 0.84.(91) VSR can be considered as task-specific training for protective steps, as participants would experience with body lean forward angle as similar to that occur while standing on backward translational platform. In addition, there is an evidence of cortical involvement during late phase of automatic postural response(92) and protective steps may be controlled by voluntary control at that phase.(93) These findings coupled with our own raise the possibility that VSR training may facilitate the cortical components of protective steps, resulting in improvement of protective responses under external perturbation.

Several important issues must be considered prior to applying the VSR training in clinics. Firstly, only participants with chronic stroke who could stand and walk independently with low scores of BESTest item 16-18 were recruited. Thus, improvement after training can be expected from persons who have these characteristics so that these should be set as criteria for selecting persons with stroke for VSR training. Secondly, therapists should train voluntary step repetitively using both affected and unaffected legs. This process will facilitate successful protective steps under different constraint. For some persons with stroke who could not lean forward with their whole body at the beginning, clinicians should provide manual guidance by moving the persons' body forward until they lose balance and take a step. All persons with stroke should wear a waist safety belt and therapist should stand beside them throughout VSR training period for safety.

Even with careful randomization, the stroke duration was longer in DST than VSR which is a common problem for a small RCT. However, this should not confound our results, as all participants were in the chronic stage where no spontaneous recovery is thought to occur(94) and they had similar functional ability (as measured by FM-LE, FTSST, TUG, DGI). Nevertheless, future studies may explore the effects of time since stroke on response to VSR training. Furthermore, this study included only participants with chronic stroke who could stand and walk independently so that the VSR training protocol may not be applicable to other stages of stroke recovery. Lastly, our study investigated only immediate effects of VSR; whether improvement of protective steps will retain for a longer period is uncertain. Therefore, further study is required to examine the effectiveness of long-term VSR training program on motor learning, retention and/or transferability in persons with stroke.

CHAPTER 6
CONCLUSION

Step kinematic, stability, and strategies of response which were the representative of voluntary and automatic components of voluntary induced stepping response (VSR) were impaired in elderly and persons with stroke. However, impairments found in persons with stroke were more prominent than that found in older persons. The VSR characteristics in young adults can be used to develop a goal in regaining VSR. A 50-minute VSR training can improve automatic protective steps such as increased use of a single protective steps and use of affected leg stepping in persons with stroke. As a result, VSR provides a simple and cost-effective option for training in clinics where instrumented platform perturbation is unavailable.

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APPENDICES

APPENDIX A

APPENDIX A

ACTIVITIES-SPECIFIC BALANCE CONFIDENCE SCALE

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following rating scale:

0% 10 20 30 40 50 60 70 80 90 100%

no confidence completely confident

"How confidence are you that you will not lose your balance or become unsteady when you…

1. … walk around the house?____%
2. … walk up or down stairs?____ %
3. … bend over and pick up a slipper from .the front of a closet floor____%
4. … reach for a small can off a shelf at eye level?____%
5. …stand on your tiptoes and reach for something above your-head?____%
6. …stand on a chair and reach for something?____%
7. ....sweep the floor?____%
8. …walk outside the house to a car parked in the driveway?____%
9. …get into or out of a car?____%
10. …walk across a parking lot to the mall?____%
11. …walk up or down a ramp?____%

13. …walk in a crowded mall where people rapidly walk past you?____%

13. …are bumped into by people as you walk through the mall?____%

14. …step onto or off an escalator while you are holding onto a railing?____%

15. …step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing?____%

16. …walk outside on icy sidewalks?____%

APPENDIX B

APPENDIX B

BALANCE EVALUATION SYSTEM TEST

BESTest			
Section	Item	Observe score	Note
I	**Biomechanicals constraints**		
	1. Base of support		
	2. COM alignment		
	3. Ankle strength/ROM		
	4. Hip/trunk strength		
	5. Sit on floor/stand up		
	Total I	/15	
II	**Stability limit**		
	6A. Sitting verticality		
	Right		
	Left		
	6B. Lateral lean		
	Right		
	Left		
	7. Funtional reach forward		
	8. Functional reach lateral		
	Right		
	Left		
	Total II	/21	
III	**Transition-Anticipatory postural adjustment**		
	9. Sit to stand		
	10. Rise to toe		
	11. Stand on one leg		
	Right		
	Left		

BESTest			
Section	Item	Observe score	Note
	12. Alternate stair touch		
	13. Standing arm raise		
	Total III	/18	
IV	**Reactive postural response**		
	14. Inplace response-forward		
	15. Inplace response-backrward		
	16. Compensatory stepping correction-forward		
	17. Compensatory stepping correction-backward		
	18. Compensatory stepping correction-lateral		
	Right		
	Left		
	Total IV	/18	
V	**Sensory orientation**		
	19A. Eyes open, firm surface		
	19B. Eyes close, firm surface		
	19B. Eyes open, foam surface		
	19B. Eyes close, foam surface		
	20. Incline-eyes close		
	Total V	/15	
VI	**Stability in gait**		
	21. Gait-level surface		
	22. Change in gait speed		
	23. Walk with head turn horizontal		
	24. Walk with pivot turn		
	25. Step over obstacle		
	26. Time "get up and go"		
	27. Time "get up and go" with dual task		
	Total VI	/21	
	Total	/108	

APPENDIX C

APPENDIX C

DYNAMIC GAIT INDEX (DGI)

		Observations				
1	Gait level surface		0	1	2	3
2	Change in gait speed		0	1	2	3
3	Gait with horizontal head turns		0	1	2	3
4	Gait with vertical head turns *(Do not perform when patient has vertigo/severe balance problems)*		0	1	2	3
5	Gait and pivot turn		0	1	2	3
6	Step over obstacle		0	1	2	3
7	Step around obstacles		0	1	2	3
8	Steps		0	1	2	3
TOTAL SCORE			………/24			

APPENDIX D

APPENDIX D

FUGL MEYER ASSESSMENT (FMA)

FUGL Meyer (Lower limb score)

- Movement with non-affected extremity first.
- Repeat each movement 3x on the affected side and score best performance. Only test Coordination/speed one time.

	I. Reflex activity			**Score**		
1a	Supine	Achilles reflex	*0=no reflex, 2=reflex exists*	**0**		**2**
1b		patellar reflex		**0**		**2**
	IIA. Flexor synergy					
2a	Supine	Hip flexion	*0=can't do, 1=part range, 2=full range*	**0**	**1**	**2**
2b		Knee flexion		**0**	**1**	**2**
2c		Ankle dorsiflexion		**0**	**1**	**2**
	IIB. Extensor synergy					
2d	Sidelying/Supine	Hip extension	*0=can't do, 1=part resistance, 2=full resistance*	**0**	**1**	**2**
2e		Hip adduction		**0**	**1**	**2**
2f		Knee extension		**0**	**1**	**2**
2g		Ankle plantar flexion		**0**	**1**	**2**
	III. Movement combining synergies					
3a	Sitting	Knee flexion (90°)	*0=can't do, 1=part range, 2=full range*	**0**	**1**	**2**
3b		Ankle dorsiflexion		**0**	**1**	**2**
	IV. Movement out of synergy					
4a	Standing	Knee flexion (90°)	*0=can't do, 1=part range, 2=full range*	**0**	**1**	**2**
4b		Ankle dorsiflexion		**0**	**1**	**2**
	V. Normal Reflexes					
5	Sitting	Patellar and	*0=both hyper,*	**0**	**1**	**2**

	ONLY DONE IF THE SUBJECT ATTAINS A SCORE OF 4 ON SECTION IV, OTHERWISE SCORE 0.	Achilles phasic reflexes (reflex hammer) and knee flexors (quick stretch of the affected leg)	*1=one hyper,* *2=normal*			
	VI. Coordination/speed					
6a	Sitting	Tremor	0=pronounced, 1=slight, 2=absent	**0**	**1**	**2**
6b	Heel to opposite knee repetitions in rapid succession (5 times)	Dysmetria		**0**	**1**	**2**
6c		Speed (compared to normal leg)	0= >6 s 1=2-5.9 s 2=<2 s	**0**	**1**	**2**
Total lower limb score				**... /34**		

FUGL Meyer (Lower limb score) - sensory information

- Test first with eyes open, then repeat with eyes closed

			Score		
	a. Light touch				
1c	Test with eyes open (unaffected muscle belly) Eyes closed Unaffected followed by affected side If sensation ok, repeat and ask for differences	thigh	**0**	**1**	**2**
1d		Sole of foot	**0**	**1**	**2**
	b. Proprioception				
	Move the joint through a small range of motion (approximately 10 degrees for the limb joints and 5 degrees for the digit joints of the hand and foot) Move the limb at least 4 times in random directions. If the subject is wrong on any direction, then add several more to determine if the accuracy is great than 75% (score 2) or 75% or less (score 1). Examine differences in side	Hip (supine)	**0**	**1**	**2**
		Knee (supine)	**0**	**1**	**2**
		Ankle (supine or sitting)	**0**	**1**	**2**
		Toe (sitting or sitting)	**0**	**1**	**2**
Total lower limb score			**... /12**		

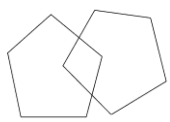
APPENDIX E

APPENDIX E

MINI-MENTAL STATE EXAMINATION

Patient’s Name:____ Date:____________

Instructions: Score one point for each correct response within each question or activity.

Maximum score	Patient’s Score	Question
5		“What is the year? Season? Date? Day? Month?”
5		“Where are we now? State? County? Town/city? Hospital? Floor?”
3		The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them. The patient’s response is used for scoring. The examiner repeats them until patient learns all of them, if possible
5		“I would like you to count backward from 100 by sevens.” (93, 86, 79, 72, 65, …) Alternative: “Spell WORLD backward.” (D-L-R-O-W)
3		“Earlier I told you the names of three things. Can you tell me what those were?”
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		“Repeat the phrase: ‘No ifs, ands, or buts.’”
3		“Take the paper in your right hand, fold it in half, and put it on the floor.” (The examiner gives the patient a piece of blank paper.)
1		“Please read this and do what it says” (Written instruction is “Close your eyes”)
1		“Make up and write a sentence about anything.” (This sentence must contain a noun and a verb)
1		“Please copy this picture.” (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.) 
30		TOTAL

APPENDIX F

APPENDIX F

DATA COLLECTION FORM

Part 1 :Personal information

Gender ....……….……..….……..………Birth date (dd/mm/yyyy)………………Age….......…..…..……

Weight......… ....Height...…......….……Tel No......................…...……………..… .

Self-report Other medical problems

- ☐ Diabetes Mellitus
- ☐ Uncontrolled hypertension
- ☐ Cardiovascular disease
- ☐ Parkinson's Disease
- ☐ Alzheimer's Disease
- ☐ Arthritis
- ☐ Osteoporosis
- ☐ Fever
- ☐ Lower extremities amputation
- ☐ Hip/knee arthroplasty
- ☐ Fracture and surgery within the past 12 months
- ☐ Visual problem that cannot correct with glasses
- ☐ Other ....

Part 2 :For participants with stroke only

1. Type of stroke (Ischemic/Hemorrhagic/Other) 2. Hemiplegic side (Lt./Rt./B)

3. Date of stroke/time since stroke………… ....…4. Hemispheric lesion………………………

5. Assistive device...……….……..…………

Fall history and Fear of falling

Frequency of fall in the past 12

months………………………………………………………………………………

Circumstance of fall

- Cause………………………………………………………………………………………………….
- Activity…………………………………………………………………………………………………
- Location……………………………………………………………………………………………….
- Time of day……………………………………………………………………………………………
- Landing………………………………………………………………………………………………..
- Protective reaction……………………………………………………………………………….…

Fear of falling (Yes/No)

Preferred foot

(Which is the foot that you preferred to kick the ball?)

Experience with perturbation training (for example; CAREN or DynStable training that give feeling like a bus stop or slip)

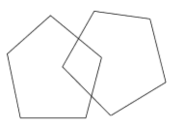
- Yes/No
- How many day per week?………………………………………………………………………
- …………………
- Duration per day…………………………………………………………………………………
- How many week you receive? …………………………………………………………………
- What is the characteristic of training………………………………………………………

Experience of other physical treatment

………

Part 3: Clinical measurement

Mini-Mental State Examination

Maximum score	Patient's Score	Question
5		"What is the year? Season? Date? Day? Month?"
5		"Where are we now? State? County? Town/city? Hospital? Floor?"
3		The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them .The patient's response is used for scoring .The examiner repeats them until patient learns all of them, if possible
5		"I would like you to count backward from 100 by sevens". (93, 86, 79, 72, 65,...) Alternative" :Spell WORLD backward ".(D-L-R-O-W)
3		"Earlier I told you the names of three things .Can you tell me what those were?"
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		"Repeat the phrase' :No ifs, ands, or buts"'.
3		"Take the paper in your right hand, fold it in half, and put it on the floor". (The examiner gives the patient a piece of blank paper).
1		"Please read this and do what it says" (Written instruction is "Close your eyes")
1		"Make up and write a sentence about anything". (This sentence must contain a noun and a verb)
1		"Please copy this picture". (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below .All 10 angles must be present and two must intersect). 
30		TOTAL

Activities-specific Balance Confidence Scale

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following rating scale:

0%	10	20	30	40	50	60	70	80	90	100%

no confidence completely confident

“How confidence are you that you will not lose your balance or become unsteady when you…

1 … .walk around the house?_____%

2 … .walk up or down stairs?_____ %

3 … .bend over and pick up a slipper from .the front of a closet floor_____%

4 … .reach for a small can off a shelf at eye level?_____%

5… .stand on your tiptoes and reach for something above your-head?_____ %

6… .stand on a chair and reach for something?_____ %

7.... .sweep the floor?_____%

8… .walk outside the house to a car parked in the driveway?_____ %

9… .get into or out of a car?_____ %

10… .walk across a parking lot to the mall?_____ %

11… .walk up or down a ramp?_____ %

13… .walk in a crowded mall where people rapidly walk past you?_____ %

13… .are bumped into by people as you walk through the mall?_____%

14… .step onto or off an escalator while you are holding onto a railing?_____ %

15… .step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing?_____ %

16… .walk outside on icy sidewalks?_____%

FUGL Meyer (Lower limb score)

- Movement with non-affected extremity first.
- Repeat each movement 3x on the affected side and score best performance. Only test Coordination/speed one time.

	I. Reflex activity			Score		
1a	Supine	Achilles reflex	*0=no reflex, 2=reflex exists*	0		2
1b		patellar reflex		0		2
	IIA. Flexor synergy					
2a	Supine	Hip flexion	*0=can't do, 1=part range, 2= full range*	0	1	2
2b		Knee flexion		0	1	2
2c		Ankle dorsiflexion		0	1	2
	IIB. Extensor synergy					
2d	Sidelying/Supine	Hip extension	*0=can't do, 1=part resistance, 2= full resistance*	0	1	2
2e		Hip adduction		0	1	2
2f		Knee extension		0	1	2
2g		Ankle plantar flexion		0	1	2
	III. Movement combining synergies					
3a	Sitting	Knee flexion (90°)	*0=can't do, 1=part range, 2= full range*	0	1	2
3b		Ankle dorsiflexion		0	1	2
	IV. Movement out of synergy					
4a	Standing	Knee flexion (90°)	*0=can't do, 1=part range, 2= full range*	0	1	2
4b		Ankle dorsiflexion		0	1	2
	V. Normal Reflexes					
5	Sitting ONLY DONE IF THE SUBJECT ATTAINS A SCORE OF 4 ON SECTION IV, OTHERWISE SCORE 0.	Patellar and Achilles phasic reflexes (reflex hammer) and knee flexors (quick stretch of the affected leg)	*0=both hyper, 1=one hyper, 2=normal*	0	1	2

	VI. Coordination/speed					
6a	Sitting	Tremor	0=pronounced, 1=slight, 2=absent	0	1	2
6b		Dysmetria		0	1	2
6c	Heel to opposite knee repetitions in rapid succession (5 times)	Speed (compared to normal leg)	0= >6 s 1=2-5.9 s 2=<2 s	0	1	2
Total lower limb score				……. /34		

FUGL Meyer (Lower limb score) - sensory information

- Test first with eyes open, then repeat with eyes closed

	a. Light touch		Score		
1c	Test with eyes open (unaffected muscle belly) Eyes closed Unaffected followed by affected side If sensation ok, repeat and ask for differences	thigh	0	1	2
1d		Sole of foot	0	1	2
	b. Proprioception				
	Move the joint through a small range of motion (approximately 10 degrees for the limb joints and 5 degrees for the digit joints of the hand and foot) Move the limb at least 4 times in random directions. If the subject is wrong on any direction, then add several more to determine if the accuracy is great than 75% (score 2) or 75% or less (score 1). Examine differences in side	Hip (supine)	0	1	2
		Knee (supine)	0	1	2
		Ankle (supine or sitting)	0	1	2
		Toe (sitting or sitting)	0	1	2
Total lower limb score			… /12		

Five time sit to stand test

I want you to stand up and sit down 5 times as quickly as you can when I say 'Go'."

Time

Timed up and go

When I say go, I want you to walk to that tape on the floor, turn, walk back and sit down again. Walk at your normal pace.

Time

Balance Evaluation System Test

BEST			
Section	Item	Observe score	Note
IV	**Reactive postural response**		
	16 .Compensatory stepping correction-forward		
	17 .Compensatory stepping correction-backward		
	18 .Compensatory stepping correction-lateral		
	Right		
	Left		
	Total IV	/12	

Dynamic Gait Index

		Observations				
1	Gait level surface		0	1	2	3
2	Change in gait speed		0	1	2	3
3	Gait with horizontal head turns		0	1	2	3

4	Gait with vertical head turns *(Do not perform when patient has vertigo/severe balance problems)*		0	1	2	3
5	Gait and pivot turn		0	1	2	3
6	Step over obstacle		0	1	2	3
7	Step around obstacles		0	1	2	3
8	Steps		0	1	2	3
TOTAL SCORE			…/24			

Part 5 :Information for motion capture analysis

1 .Shoulder offset (Rt./Lt.) …...........…mm

2 .Elbow width (Rt./Lt.)……………….. mm

3 .Wrist width (Rt./Lt.) ……………..…mm

4 .Palmar width (Rt./Lt.)……………..... mm

5. Leg length (Rt./Lt.) …......... ....…mm

6 .Knee width (Rt./Lt.)………........ …. mm

7 .Ankle width (Rt./Lt.)……………… mm

8 .Inter ASIS distance ..……........…… mm

VITA

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