**Characteristics of Voluntary-induced Stepping Response in Persons with Stroke compared with those of healthy Young and Older Adults.**

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

[a]Faculty of Physical Therapy, Srinakharinwirot University, Nakhon Nayok, Thailand 26120

[b]School of Health Sciences, University of Salford, Salford, United Kingdom M6 6PU

[c]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, United Kingdom L3 3AF

*Corresponding author: Rumpa Boonsinsukh. Faculty of Physical Therapy, Srinakharinwirot University, 63 Moo. 7, Rangsit-Nakhon Nayok Rd., Ongkharak District, Nakhon Nayok Thailand 26120, Tel: +66 6495000 (ext 27314). Email: rumpa@g.swu.ac.th

**Abstract (300 words)**

**Background:** Impairment of protective steps to recover balance from external perturbation is evident after stroke. Voluntary-induced stepping response (VSR) can be used to practice protective steps by instructing an individual to voluntarily lean their whole body forward until they perceive a loss of balance and automatically induce a step. However, to improve protective stepping performance, detailed characteristics of VSR in healthy persons are required.

**Research question:** What is the difference in VSR between healthy and persons with stroke?

**Methods:** An observational study was conducted in 30 participants, (10 young, 10 older, and 10 persons with stroke). All participants performed VSR for 10 trials. Step length, step width, step duration, CoM position, CoM velocity, trunk-hip displacement, and strategies of response were recorded using a motion capture system and analysed using Matlab software. Statistical analysis was performed using One-way ANOVA and Chi-square.

**Results:** On average, participants with stroke had shorter step lengths and step durations than young and older adults. Step width of older adults and participants with stroke was wider than that of young adults ($p<0.05$). While multiple steps and losing balance were reported more frequently in participants with stroke than the others, the percentage of trials in which participants grasped the handrails was not significantly different between older adults and participants with stroke. CoM position, CoM velocity, and trunk-hip displacement at foot liftoff were significantly smaller in older adults and participants with stroke than young adults ($p<0.05$). Participants with stroke tended to use trunk bending rather than trunk leaning strategies to generate VSR in contrast to healthy participant. The prevalence of the trunk bending strategy was also greater in older adults than young adults.

**Significance:** Values obtained from healthy groups can be used as guidelines to set realistic goals during VSR training to improve protective steps in patients with stroke.

**Keyword:** postural control, balance, cerebrovascular accidents, age, fall risk

**Introduction** (4,538 words from introduction to conclusion)

Protective stepping is a type of automatic protective response characterized by the execution of at least one step to create new base of support for recapturing or decelerating the moving center of mass when the body stability is perturbed unpredictably in standing.[1] In comparison to a voluntary step that is pre-planned by the central nervous system, protective stepping uses online information from ascending sensory input regarding body orientation to form an appropriate movement to rapidly restore stability.[2, 3] Following stroke, protective stepping is often impaired.[4] Participants with stroke took a greater number of protective steps in response to external perturbation than healthy young adults and older adults.[5] Some persons with stroke could not execute protective steps, whereas some required external assistance to help maintain stability during perturbation.[4] Step kinematic, stability and segmental body control were also impaired in persons with stroke when compared with healthy persons.[5] An inability to make appropriate protective stepping responses and resist body movement prior to foot liftoff may result in multiple steps and falls in persons with stroke.

Protective stepping in persons with stroke can be effectively triggered and trained by using complicated instruments such as moveable platform or cable release system to generate unpredictable perturbation.[6, 7] As these training paradigms require expensive and complex equipment that cannot be readily used in most clinical settings, the application of these training methods in real clinical practice is limited. Therefore, it is necessary to search for an equivalent training for protective stepping in persons with stroke that requires none or simple equipment easily found in the clinical settings. Previous studies revealed that protective stepping can also be self-induced by performing voluntary-induced stepping response (VSR). Gray et al. (2012) first introduced the VSR [8] to examine the effect of fast functional movement on muscle activity during stepping. VSR consists of both voluntary and automatic components, triggering by instructing individuals to voluntarily lean their whole body forward (voluntary) until feeling loss of balance, which automatically induces a step (automatic). Combining VSR with fast squatting could increase anticipatory activity of postural muscles during voluntary task in persons with stroke.[9]

Our recent study evaluated whether the training of persons with chronic stroke to perform VSR could transfer to the improvement of protective stepping. Using a single session training, participants with stroke were randomized into each of these two training paradigms; VSR or DynSTABLE training. For DynSTABLE training, the complex equipment; Dynamic Stability and Balance Learning ENvironment (DynSTABLE) instrument; was used to provide a surface translation generated by a two-degree of freedom translational platform with real-time visual and audio feedback. Participants were asked to stand in a comfortable position and act naturally for balance recovery when the platform translated randomly in the anterior, posterior, left, or right direction during the DynSTABLE training. The perturbation difficulty was programed so that individual's responses were shifted gradually from feet-in-place strategy to stepping response. After the training, protective stepping was assessed using the computer-assisted rehabilitation environment (CAREN) to simulate slip-like situations. Results showed that both types of training increased protective stepping in participants with chronic stroke but only participants in the VSR group generated protective stepping with the affected leg in a larger percentage of trials (27%) after training. This could be due to the fact that VSR is a task-specific training in which muscles were trained massively and repetitively in a particular action, i.e., taking a protective step with alternate leg. VSR training may facilitate the cortical component of protective stepping at the late phase of postural response which can be transferable to improve protective stepping performance under external perturbation. These results suggested that VSR can be used as an alternative to equipment-based protective stepping training in persons with chronic stroke.[10]

Although VSR training is feasible for improving protective stepping in persons with stroke, the implementation of VSR in clinic requires the normal values as reference goals to determine the success of ongoing training. Thus, the information of VSR characteristics in healthy persons is crucial, but such information from healthy young and older adults is hitherto lacking. Therefore, this study aimed to compare voluntary-induced stepping response (VSR) characteristics, in term of step kinematics, stability, and strategies of response in healthy young and older adults and persons with stroke. We hypothesized that VSR would be comparable between healthy young and older adults, but it would be significantly impaired in persons with stroke.

## Methods

### Participants

A cross-sectional study was conducted in three groups of participants (young adults, older adults and persons with stroke). Sample size was calculated by G*Power 3.1. Alpha was set at 0.05 and power at 80%. In this study the effect size was calculated using partial eta square based on the results of foot liftoff time of the previous study.[5] The partial eta square was calculated from the following formula:[11]

$$\eta_p^2 = \frac{F \times df_{effect}}{F \times df_{effect} + df_{error}}$$

When $F$ was 5.69, $df_{effect}$ was 2 and $df_{error}$ was 21.6. Therefore, the effect size was 0.73 and 10 individuals per groups was recruited to reach an actual power of more than 80%.

Young adults aged between 18 and 26 years were included in the study. Older adults were included if they were at least 60 years, could 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).[12] Persons with stroke were included if they were more than 6 months post-stroke, were medically stable, could stand independently without using assistive devices, could walk independently with or without a cane for at least 6 meters, and had no cognitive deficit.[12] The exclusion criteria were those who had experience of any perturbation testing or training within the past year, had visual problem, or had any other neurological, cardiovascular, or musculoskeletal conditions that could impede their ability to perform the task. This study was approved by our institutional review board and each participant signed an informed consent prior to participating in this study.

**Procedures**

Information regarding age, weight, height, gender, foot and leg length, type of stroke, stroke duration, hemiplegic side, assistive device usage, and falls history in the past 12 months were collected by self-report. The Fugl-Meyer Assesement (FMA) lower extremity and lower extremity sensation domains were used to test motor recovery and sensation of leg after stroke.[13] The Activities-specific Balance Confidence (ABC) scale was used to assess balance confidence in performing daily activity indoors and outdoors.[14] The five-time-sit-to-stand-test (FTSST) was used to assess functional leg muscle strength.[15] The timed Up and Go test (TUG) was administered to assess balance during walking and turning.[16] The Balance Evaluation Systems Test (BESTest) items 16-18 were used to assess protective stepping ability in the anterior, posterior, and lateral directions.[17]

**Voluntary-induced Stepping Response (VSR) assessment**

To perform VSR, participants were instructed to lean their whole body forward until they felt they were losing their balance and take a single step if possible, to prevent themselves from falling. The voluntary and automatic components of VSR were analyzed. The voluntary component was defined as the period from leaning the body forward until foot liftoff the platform. In contrast, the automatic component was defined as the period from foot liftoff until foot touchdown and the body stopped moving. Prior to testing, five practice trials were allowed to promote familiarity with the test and ensure response stability. VSR was assessed for 10 trials to represent average responses of each participant. Prior to each trial, participants were asked to stand bare feet with feet apart in their preferred foot position on a sheet of paper attached to the platform for 30 seconds until an audio cue signaled the start of VSR. The preferred foot positioning of each participant was marked and re-checked every trial. All participants wore a safety harness and a research assistant stood beside the participant to give support as needed. 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 the Vicon full body plug-in gait marker set.[18, 19] An additional four markers were attached on the long toe and fifth metatarsal of each foot to allow computation of the base of support (BOS). A ten cameras VICON motion capture system (VICON Motion Systems Ltd, Oxford, United Kingdom) was used to record full-body kinematics. Conventional video cameras were used to record all testing events of each participant.

**Data Analysis**

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

Reaction time (RT) was calculated from the time between audio cue onset to onset of CoM velocity shifting in anterior direction (the point at which CoM velocity shifted more than 2 SD of the baseline). Step onset time was the time from the onset of CoM velocity shifting to the time that foot lift off the platform. Both reaction time and step onset time were indicators for anticipatory and step initiation time, respectively, before taking a step. Step length and step width represented the magnitude of the stepping response and was calculated as the distance between the 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 according to participants's leg length. Step duration was defined as the period from foot lift off until it touched the ground. Foot liftoff time was defined as the time that the long toe marker moved up vertically beyond two 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) position and velocity were computed from the kinematic data relative to stance limb's heel position at foot liftoff. CoM position was normalized with respect to stance foot length in order to account for various foot length. Stance foot length defined as the length in AP direction between a long toe and a heel marker of a stance leg. A greater value of CoM position at foot liftoff indicates that the CoM was located in a more anterior position with respect to the stance limb's heel and would suggest greater ability of participant to move their body forward before taking a step. A value of CoM position greater than one also corresponded to the CoM being outside of the stance foot base of support at the time of foot liftoff. CoM velocity was calculated from the first order derivative of CoM position. A positive CoM velocity represents the speed of body movement in the anterior direction.

Position of markers located at C7, T10, and right (RASI) and left (LASI) anterior superior iliac spine at foot liftoff and touchdown subtracted with their initial positions were selected to represent trunk and hip displacement at foot liftoff and touchdown. Leaning strategies were also quantified by the onset of trunk and hip markers displacement as an individual was using the trunk leaning strategy or trunk bending strategy to initiate movement. Trunk leaning strategy was defined by similar onsets of C7, T10, RASI and LASI markers' initial displacement from the baseline, which indicated that the participants lean forward by initiating their trunk and hip movement simultaneously (Fig 1A). In contrast, different onsets of markers' initial displacement from the baseline were referred as trunk bending strategy which demonstrated that participants first moved their trunk forward followed by moving their hip (Fig 1B, 1C) The similarity or difference onset of each marker were identified qualitatively by visual inspection at the graphs showing displacement of 4 markers across time.

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 statistics were used to characterize participants' demographic data. One-way ANOVA 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 the three groups of participants. The Shapilo-Wilk test was used to test for normality of the variables. The Kruskal-Wallis test and Mann-Whitney U test were used to examine differences between groups for variable that were non-normally distributed. Number of steps, grasping, loss of balance, and other movement strategies were counted and expressed as a percentage of all trials. Comparisons between groups were made using the Chi-square test. In addition, since the ability to voluntarily move the CoM over the base of support was varied between participants, Pearson correlation coefficient was used to determine whether there was any correlation between step parameters and the state of the CoM at step initiation, where the correlation coefficient (r) of higher than 0.6 and higher than 0.8 indicates moderate and strong correlation, respectively. 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.

**Results**

Data from 30 participants (10 in each group) is presented. Subjects' characteristic for each group of participants was shown in Table 1. It can be seen that there was no age difference between participants with stroke and older adults. Weight and BMI were greater in participants with stroke than young adults. Mean height did not significantly differ between the three groups. All participants with stroke were male and were in the chronic stage (stroke duration range from 2.5 to 44 years). Six out of ten reported right-side weakness. Participant with stroke had mean FMA-LE of 23.7/34 (SD 7.8) and FMA-sensation of 10.9/12 (SD 1.6). Although percentage of faller did not significantly differ between groups, participants with stroke reported lower balance confidence, functional muscle strength, walking ability and reactive stepping performance (as indicated by BESTest score) than older adults.

### Step kinematics

Reaction time (RT) were 0.83±0.19 s in young, 0.94±0.39 s in older adults, and 1.03±0.45 s in participants with stroke. Step onset time were 2.86±1.12 s in young, 2.6±1.27 s in elderly, 3.28±1.71 s in participant with stroke. Both RT and step onset time did not significantly differ between groups. Comparison of step length, step width and step duration were shown in Figure 2. Results indicated that step length (Fig 2A) was shorter in stroke than in young and older adults ($F_{2,27}$ = 16.67, p < 0.001). Step width (Fig 2B) was significantly wider in stroke and older adults than young adults ($F_{2,27}$ = 6.69, p = 0.004). Step duration (Fig 2C) was significantly longer in older adults when comparing with participants with stroke ($F_{2,27}$ = 6.39, p = 0.005).

### Stability and trunk control

Significant differences in our measures of stability and trunk control during foot liftoff were found between young adults, older adults, and participants with stroke. CoM position at foot liftoff was significantly greater in young adults when compared with older adults and stroke ($F_{2,26}$ = 11.23, p < 0.001) (Fig 3A). Likewise, CoM velocity at foot liftoff was greater in young adults compared to that of older adults and stroke groups ($F_{2,26}$ = 16.44, p < 0.001)(Fig 3B). Our further analysis revealed significant correlation between step parameters (step length and step width) and the state of CoM (both position and velocity) at foot liftoff when data from all participants were included in the analysis. The CoM position at foot liftoff was moderately correlated with step length (r = 0.658, p < 0.001) and step width (r = -0.768, p < 0.001), but not with step duration. Similarly, moderate correlations were found between the CoM velocity at foot liftoff and step length (r = 0.744, p < 0.001) as well as step width (r = -0.642, p < 0.001). Such correlations indicated that the farther or faster a person moved the body forward, the longer step length or shorter step width would be observed.

There were significant differences between groups in both trunk and hip displacement at both foot liftoff and touchdown (Table 2). While participants with stroke showed significantly smaller displacement in all trunk and hip markers at foot liftoff as compared to young adults, older adults showed significantly smaller displacement of only T10, RASI and LASI when compared with young adults. No difference in trunk and hip displacements was found between older adults and participants with stroke at foot liftoff. At foot touchdown, participants with stroke also showed significantly smaller displacement of the trunk and hip compared with young adults and older adults. In addition, older adults showed lesser T10 displacement when compared with young adults.

### VSR outcomes

Figure 4 showed that young adults, older adults, and participants with stroke used difference strategies to recover their balance and some of them failed to perform VSR successfully. While young adults executed a single step every trial, older adults and participants with stroke executed single step 97% and 73.2% of trials, respectively (Fig 4A). Only one participant with stroke could step with the affected foot whereas the remaining used the unaffected foot to step. Frequency of grasping was significantly greater in older adults (13%) and participants with stroke (20.6%) than in young adults who showed no grasping (Fig 4B). In addition, 28.9% of trials in participants with stroke were reported as losing of balance during a trial (Fig 4C). Young adults used trunk leaning strategy for 89.9% of trials but participants with stroke mainly used trunk bending strategy (Fig 4D).

## Discussion

This is the first study that examined the characteristics of the voluntary-induced stepping response (VSR) among young adults, older adults, and persons with stroke. VSR characteristic in this study was shaped by both perturbation intensity (as indicated by CoM position and CoM velocity) and motor ability. Results confirmed that VSR characteristics were vastly deteriorated in participants with stroke but VSR was also impaired in older adults, especially in the voluntary component of VSR.

### Age-related change in VSR

In contrast to young adult who executed trunk leaning strategy, i.e., leaning their body forward using the ankle joint as an axis of rotation, the use of trunk bending strategy with delayed hip movement together with lesser trunk and hip movements in the older adults indicated a reduction in limit of stability which was associated with increasing age.[20] 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 older adults.[21] Therefore, the use of trunk bending strategy in our older adults group may be due to a reduction in ankle plantarflexor strength. For automatic component, the significant increase in step width and grasping reaction may reflect some problems of lateral stability in older adults 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.[22] Nevertheless, our findings of inverse correlation between the state of CoM during foot liftoff and the step width suggested that age-related change in stepping response found in the older adults may also be influenced partly by the ability to voluntarily shift the CoM over the base of support.

### Effect of cerebrovascular accident on VSR

Stroke is associated with deficits in several characteristics of VSR and these deficits are greater than the age-related change. Focusing on voluntary component of VSR, we demonstrated that stroke led to further reduction in ability to control trunk and hip movement properly during trunk leaning when compared with older adults. Even though the magnitude of CoM position and trunk-hip displacement did not significantly differ between these two groups, the majority (65.5%) of participants with stroke used a trunk bending strategy to generate a step. A similar compensatory pattern of trunk movement in persons with stroke was also reported during leaning forward in sitting when their trunk movement amplitude and velocity were not different from those of older adults.[23] In that study, people with stroke demonstrated compensatory movement during lean forward in sitting by moving their upper trunk rather than lower trunk while they kept weight on buttock rather than feet.

Several factors may contribute to compensatory trunk movement pattern in persons with stroke. Apart from reduced ankle plantarflexor muscle strength as a result of age-related changes, altered postural alignment after stroke could be another contributing factor. People with stroke demonstrated problems with controlling pelvic and spinal alignments during upright standing and standing with trunk flexion, i.e., they stood with more forward spinal inclination and had lesser anterior pelvic tilt during trunk flexion when compared with healthy older adults.[24] Ankle plantarflexor inflexibility could also lead to the reduction in pelvic movement and gait speed of hemiplegic patients.[25] Moreover, our participants with stroke reported low balance confidence when compared with older adults. As balance confidence was correlated with static standing balance and cautious gait, low balance confidence in persons with stroke may affect the ability to perform fall-like position during VSR.[26] Taken together, these changes following neurological deficits could lead to larger impairments of voluntary component of VSR in persons with stroke as compared to healthy elderly.

Regarding the automatic component of the VSR, even though both reaction time and step onset time did not significantly change following stroke, the variability of these two variables were higher than those in young participants. The higher variation of reaction time in persons with stroke and healthy elderly, as compared to young participants, could indicate that the variation of anticipatory time may be resulted from age-related change. In contrast, the variation of step initiation time may be due to the effect of neurological deficits, as persons with stroke seemed to have larger variation of step onset time than those healthy young and older participants. In addition, we found that stepping responses to recapture balance were impaired in the participants with stroke. Similar to previous studies, almost all of our participants with stroke took the first step with the unaffected leg.[5, 27] With weakness and poor motor control on the affected leg, individuals with stroke had difficulty in shifting the body weight onto it, which results in more difficulty in controlling lateral stability during stepping. Therefore, it is not surprising to find that their step length was shorter whereas step width was wider and step duration was faster in order to regain body stability quickly. Although these adaptability could increase margin of stability in the frontal plane, it deteriorated gait stability in anteroposterior direction in persons with stroke when compared to older adults.[28] 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 when compared with healthy persons.

**Clinical implication**

Our findings demonstrated specific impairments of VSR characteristics in persons with stroke and older adults as well as normal values of VSR characteristics from young adults. Therefore, clinicians can apply this information in their training programs to improve VSR in both older adults and persons with stroke. For example, information obtained from healthy older adults can be used as a reference for the clinician to set training goal for their patients with stroke. We showed that the average amount of trunk leaning in the young adults, as shown by trunk-hip displacement at foot liftoff, were 291 mm with T10 reference and 225 mm with ASIS reference (Table 2), thus, these numbers can be used as the maximum goal when training voluntary component of VSR in patients with stroke. Clinicians may set the rope or yardstick at the trunk or hip levels to be the target point and encourage the use of trunk leaning strategy during VSR training, as this strategy was frequently used in young adults.

Although results of this study indicated that all participants were able to move the CoM out of the BoS before taking a step (Fig 3A), our instruction "to lean their whole body forward until they felt they were losing their balance and take a single step if possible, to prevent themselves from falling" was considered subjective, as each participant's perception of loss of balance may not be the same. The risk-taking capacity may influence the magnitude of leaning forward and may potentially be a cause of unnecessary step. Therefore, to ensure that every participant correctly understand the sense of loss of balance during VSR training and to avoid unnecessary step, demonstration together with physical guidance of moving the trunk and pelvic forward must be provided a few times to emphasize the proper magnitude of forward leaning.

VSR is the alternative training where participants can voluntarily perturb themselves and practice stepping responses at their own pace. With sufficient safety protocols, VSR can be given to participants as a home exercise which would probably encourage long-term training and behavior adaptation for fall prevention. Nevertheless, therapists may encounter some patients who have fears of falling and refuse to perform VSR. In those cases, we suggested the use of similar method that assessed protective stepping ability in item 16-18 of the BESTest where a therapist is present to control the amount of participant's trunk leaning and stepping response. Until the participants regained their balance confidence, the VSR can be implemented as the next step of training.

**Study limitations and further studies**

In our study, only male participants with stroke were recruited. Gender has been reported to be involved in balance confidence related to static and dynamic balance.[29] Therefore, distinctive impairment of VSR may be found in persons with stroke if women were also recruited to the study. In addition, our participants with stroke had higher BMI than young adults. Although it has been reported that obesity was related to the fall risk, our participants with stroke were still categorized as “overweight”. A previous study demonstrated that the overweight has no relationship with fall history in older adults so higher BMI in stroke group should not confound our results.[30]

There were three persons with stroke in this study who reported fall in the past 12 months (faller). Further studies with a larger sample size of faller with stroke are required to determine whether there is a relationship between faller and VSR characteristics that clinician should concern during VSR training. VSR requires voluntary movement to place one's body off-balance, thus, the amount of balance loss is not consistent between participants. Relationship between the position and velocity of CoM at foot liftoff and the step parameters suggested that future study where the amount of balance loss during VSR is controlled, should be carried out to further unravel the effect of age and neurological deficits on VSR characteristics. Finally, VSR was performed during standing where the perturbation magnitude was smaller as compared to that during walking. Studies also reported that the majority of falls in persons with chronic stroke occurred during walking. Therefore, it is unclear whether the improvement of protective stepping from VSR training could reduce falls during real life perturbation and, thus, requires further studies.

## Conclusion

Stroke leads to impairment of both voluntary and automatic components of the voluntary-induced stepping response (VSR). VSR was also impaired in older adults, especially in the voluntary component.

## Declaration of interest

None

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**Figure legend**

**Figure 1** Leaning strategies of representative young adults (A), older adults (B), and participants with stroke (C). Trunk leaning strategy means that a participant leans forward by moving both trunk and hip forward closely in time. Trunk bending strategy means that a participant moved trunk forward 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.

**Figure 2** step length (A), step width (B), and step duration (C) in 3 groups of participants. Step length and step width were normalized by leg length and was reported as percentage of stepping leg length. Value are shown in mean+SD. * represented $p<0.05$

**Figure 3** Center of Mass (CoM) position (A) and CoM velocity at foot liftoff (B) in young adults, older adults, and participants with stroke. Center of Mass (CoM) position at foot liftoff was normalized by a participant's stance foot length. The horizontal dashed-line indicates anterior margin of stance foot base of support (BoS). Value are shown in mean±SD. * represented $p<0.05$

**Figure 4** 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 leans forward by moving both trunk and hip forward closely in time. Trunk bending strategy means that a participant moved trunk forward after cue onset then moved hip just before foot liftoff. * represented $p<0.05$

**Table 1** Subject characteristics

| | Young adults | Older adults | 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* |
| **BMI** | 21.6±2.63 | 23.88±3.89 | 26.62±3.55* |
| **Height (m)** | 1.69±8.52 | 1.69±0.1 | 1.74±0.05 |
| **Gender - Male (%)** | 5 (50) | 4 (40) | 10 (100) ‡ |
| **Faller (%)** | | 1(10) | 3(30) |
| **ABC (/100)** | | 97.96±2.4 | 66.88±20.85‡ |
| **FTSST (s)** | | 9.45±2.31 | 20.3±12.61‡ |
| **TUG (s)** | | 8.53±1.24 | 18.51±6.52‡ |
| **BESTest (/12)** | | 11.6±0.97 | 5.1±3.07‡ |

Note: age, weight, BMI, height, stroke duration, ABC score, FTSST, TUG, and BESTest are reported in mean±SD. Gender is reported in n(%). Abbreviation: y = year; Kg = kilogram; m = meter; BMI = Body Mass Index; ABC = Activities-specific Balance Confidence Scale; FTSST = Five-Time-Sit-to-Stand-Test; TUG = Time Up and Go; BESTest = Balance Evaluation System Test.

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

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

‡Significant difference between Older adults and Stroke at $p < 0.05$;

**Table 2** Changes in trunk-hip displacement at foot liftoff and touchdown of participants in 3 groups; young adults, older adults and persons with stroke.

| | **Young** | **Older adults** | **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 7$^{th}$ marker; T10 = thoracic 10$^{th}$ 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 Older adults at $p < 0.05$;

‡Significant difference between Older adults and Stroke at $p < 0.05$