Effects of Forward Leaning Characteristics on Protective Steps when Performing Voluntary-induced Stepping Response in Young and Older Adults: A Cross-Sectional Study

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From Lean to Step: Voluntary Stepping Response (VSR) in Aging and Balance Control

VSR testing procedure

• Lean the whole body forward to a rope target
• Use ankle as an axis of rotation

Rope target

Standing
Lean forward
Stepping

Effect of VSR leaning distance

Longer leaning distance

When leaning distance increases ($D_l > D_s$), protective step length extends.

Longer step length

Impact of aging

30 healthy young adults (Y)

10 healthy older adults (0)

Trunk leaning
Single step
Flexible body

Trunk bending
Multi-steps
Rigid body, but unstable

Conservative initiative strategy: Trunk bending
O 28% vs Y 5%

Risk of losing balance: Multiple steps & sway
O 27% vs Y 3%

Grasping
O 13 % vs Y 0%

Unstable ceasation strategy: Rigid body
O 71% vs Y 30%

Clinical application:

For VSR training in older adults, clinicians should pay attention to leaning distance and moveme atterns.

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ABSTRACT

Objective: To examine the effect of forward leaning distance and aging on protective step length, movement strategies, and postural stability during voluntary-induced stepping response (VSR).

Materials and Methods: Thirty healthy young adults (19.5 ± 0.7 years) and ten healthy older adults (68.9 ± 4.4 years) participated in a cross-sectional study. Young adults performed VSR under two conditions: short-distance (D_s) and long-distance (D_l), based on pelvis displacement ratios. Older adults performed VSR at their preferred leaning distance (D_p) and were instructed to recover balance with a single step. Protective step length, movement initiation and cessation strategies, and postural stability were assessed using 2D video analysis. Statistical comparisons were conducted using paired t-tests and chi-square tests ($\alpha = 0.05$).

Results: Step length was significantly greater in D_l than D_s ($p < 0.001$). Older adults in D_p showed no significant difference in step length compared to young adults in D_l. However, older adults more frequently used trunk bending (28% versus 5% of trials), rigid body strategies (71% versus 30%), grasping (13% versus 0%), body sway, and multi-step responses (27% versus 3%) ($p < 0.001$).

Conclusion: Forward-leaning distance influences step length during VSR. Aging is linked to altered movement strategies and reduced postural control. These findings suggest that VSR may serve as a targeted intervention to enhance dynamic stability in older adults, supporting broader goals of health promotion and overall well-being.

Keywords: Postural balance; accidental falls; gait; health; motor activity (Siriraj Med J 2026;78(3):207-217)

INTRODUCTION

Falls represent a global public health concern, accounting for an estimated 684,000 deaths annually worldwide, and ranking second only to road traffic injuries among causes of unintentional injury-related mortality.[1,2] Beyond their immediate physical consequences, falls often lead to psychological distress, reduced confidence, social withdrawal, and functional decline, particularly in later life.[2,3] The burden rises sharply with age: fall-related mortality among older adults has shown an increasing trend over recent decades, with rates exceeding 50 deaths per 100,000 population aged 60 years and older, whereas younger adults typically exhibit much lower rates, below 10 deaths per 100,000. This striking contrast highlights the disproportionate vulnerability of older populations.[2,4] These data underscore the need for preventive strategies tailored to aging populations.[5,6] Task-specific interventions targeting balance recovery, such as protective stepping response training, have shown promise in mitigating fall risk among older adults.[7]

Voluntary-induced stepping response (VSR) training has emerged as a low-cost, accessible method for enhancing protective stepping ability. A single 50-minute session has been shown to improve stepping performance without the need for specialized equipment. Participants with stroke demonstrated an average increase of approximately 10% in affected step length and greater affected-leg initiation (from 20.2% to 27% of trials). The participants also showed reductions in multiple steps (from 28.6% to 12.3%) and grasping (from 30.4% to 21.5%).[8] VSR involves two sequential actions: initiating an internal perturbation via forward leaning using the ankles as the axis of rotation, followed by executing a protective step. Although protective step length may appear similar across age groups, older adults demonstrate distinct movement patterns, including a greater reliance on trunk bending strategies (28% versus 10% of trials in young adults), potentially reflecting reduced postural control or lower tolerance for perturbation.[9]

The effectiveness of protective stepping depends not only on training methods such as VSR but also on how aging and perturbation magnitude shape the body's ability to recover balance. While higher perturbation intensities increase body momentum and the likelihood of stepping, older adults tend to initiate steps earlier under lower perturbation thresholds compared to younger individuals.[10] These findings suggest age-related declines in the capacity to counteract destabilizing forces. However, it remains unclear how voluntary forward leaning distance modulates perturbation magnitude during VSR and affects protective step execution and stability. Clarifying this relationship is important because VSR training relies on self-induced perturbations to strengthen balance recovery strategy. Understanding the dose–response effect of leaning distance is therefore crucial, as it positions VSR not merely as a training exercise but as a practical, scalable approach for integrating self-induced perturbations into fall prevention programs.

Therefore, this study aimed to determine whether increasing forward leaning distance during VSR leads to larger perturbations and longer protective steps, and to assess whether older adults demonstrate different movement strategies compared to young adults under identical conditions. We hypothesized that greater leaning distances would result in larger perturbation magnitudes and longer protective steps, and that aging would be associated with increased reliance on trunk bending strategies and greater instability during stepping.

MATERIALS AND METHODS

Study design

This study was cross-sectional in design and was approved by The Institutional Review Board (PTPT2021-006).

Sample size

The sample size for young adults was determined using G*Power 3.1, with an alpha level of 0.05 and a power of 80%. The total sample size was calculated based on an estimated effect size of d = 0.47, derived from normalized step length data obtained from a pilot study of five young adults across different leaning conditions. Consequently, 30 young adults were conveniently sampled for the primary objective. These participants were recruited from university students and alumni, representing healthy young adults who were not athletes.

Additionally, data from 10 healthy older adults were obtained from a previously published study for the secondary objectives.[9] Older adults were eligible if they were at least 60 years of age, able to stand and walk independently without assistive devices for at least 6 meters, and had no cognitive deficits as assessed by the Mini-Mental State Examination (MMSE ≥ 24). Exclusion criteria included prior experience with perturbation testing or training within the past year, visual problems, or any neurological, cardiovascular, or musculoskeletal conditions that could interfere with task performance. Recruitment of older adults in the original study was conducted through local community centers and word-of-mouth invitations among acquaintances of faculty members and hospital staff, ensuring participants were community-dwelling.[9]

Participants

Healthy young adults aged 18 to 26 years were recruited for this study. Participants were excluded if they had visual, neurological, or musculoskeletal conditions that could impact protective stepping ability. All participants provided written informed consent prior to participation.

Procedures

Data on age, gender, weight, height, and body mass index (BMI) were collected from all participants prior to the VSR assessment. For older adults, falling history, fear of falling, and experience with perturbation training or testing were recorded using a simple binary question.

Additionally, older adults underwent functional and cognitive assessments to confirm that they were cognitively intact and physically independent. These included the Mini-Mental State Examination (MMSE),[11] the Activities-specific Balance Confidence (ABC) scale,[12] the Five-Times Sit-to-Stand Test (FTSST),[13,14] the Timed Up and Go (TUG) test, the Dynamic Gait Index (DGI),[15] and items 16-18 from The Balance Evaluation Systems Test (BESTest).[16] These clinical measures were employed to characterize health status, balance confidence, and functional mobility in older adults; accordingly, they were not administered to young adults.

Voluntary-induced stepping response assessment

To assess VSR, participants were instructed to lean their entire body forward using the ankles as the axis of rotation and to take a step upon sensing postural instability. For the primary objective, two controlled leaning conditions were examined: short-distance (D_s) and long-distance (D_l). The leaning distance was calculated in centimeters to facilitate setting a rope target for each leaning condition. The rope was positioned in front of the pelvis to define the leaning threshold. Young adult participants were instructed to lean forward until their pelvis contacted the rope and then took a step.

Leaning distances were pre-determined using the formula: D = Anterior Superior Iliac Spine (ASIS) displacement ratio × participant height. Ratios were derived from previous studies,[9] with D_l based on young adult data (0.13) and D_s designed to reflect the typical maximum leaning distance observed in older adults. The ASIS displacement ratios were calculated as follows: ASIS displacement ratio of D_l = Average ASIS displacement of young adults ÷ body height; and ASIS displacement ratio of D_s = Average ASIS displacement of older adults ÷ body height. Specifically, D_s was defined using a ratio of 0.10, corresponding to the average pelvic displacement (D_p) recorded in older adults during maximal voluntary leaning. This approach ensured that the short-distance condition represented a leaning distance similar to that naturally adopted by older adults, thereby facilitating meaningful comparisons across conditions.

To control for variability, leaning velocity was fixed at 0.39 m/s in both conditions. Participants synchronized

their movement with two consecutive beep sounds: the first signaling initiation and the second marking the endpoint, corresponding to the moment the pelvis contacted the rope. The interval between the first and second beep was calculated by dividing each participant's predetermined leaning distance (m) by the fixed velocity of 0.39 m/s. Rest intervals between test conditions were approximately 2–3 minutes, or longer if requested, to minimize fatigue. Each condition was assessed 10 times. The interval between observations was approximately 2–3 minutes, allowing participants to return to their original position and the researcher to recheck.

Participants completed at least 10 practice trials or practiced until they were familiar with the procedure. Practice and testing were conducted one condition at a time to reinforce the leaning technique. Rest periods were provided between conditions or as needed. To minimize the effects of fatigue and motor learning, the sequence of conditions was randomly assigned, and all trials were completed within a single day.

Participants stood barefoot in their preferred foot position, ensuring both feet were aligned at the same level in the anteroposterior direction. Foot placement was marked and consistently monitored throughout practice and testing. For safety, one end of the rope was secured to a floor-fixed pole, while the other was lightly taped to the wall beside the participant. This setup allowed the rope to detach easily upon contact with the pelvis, preventing tripping or other adverse incidents, as shown in Fig 1B.

Older adult participants performed the VSR by leaning forward as far as possible and attempting to take only a single step to regain stability, maintaining the final position for 5 seconds (D_p condition). To ensure consistency, participants performed approximately 10 practice trials before the actual assessment. During practice, the researcher guided the ASIS movement to help participants identify their maximum safe leaning distance that still permitted execution of a single protective step. If leaning was insufficient, participants were encouraged to lean further; if excessive leaning resulted in multiple steps, they were asked to reduce the distance slightly. Thus, the "preferred distance" reflected each participant's perceived maximum safe limit of stability. No rope was used in this group. Participants stood barefoot with a naturally comfortable foot width, maintaining the same stance across all trials. For safety, older participants wore safety harness, and a research assistant remained beside them throughout the session.

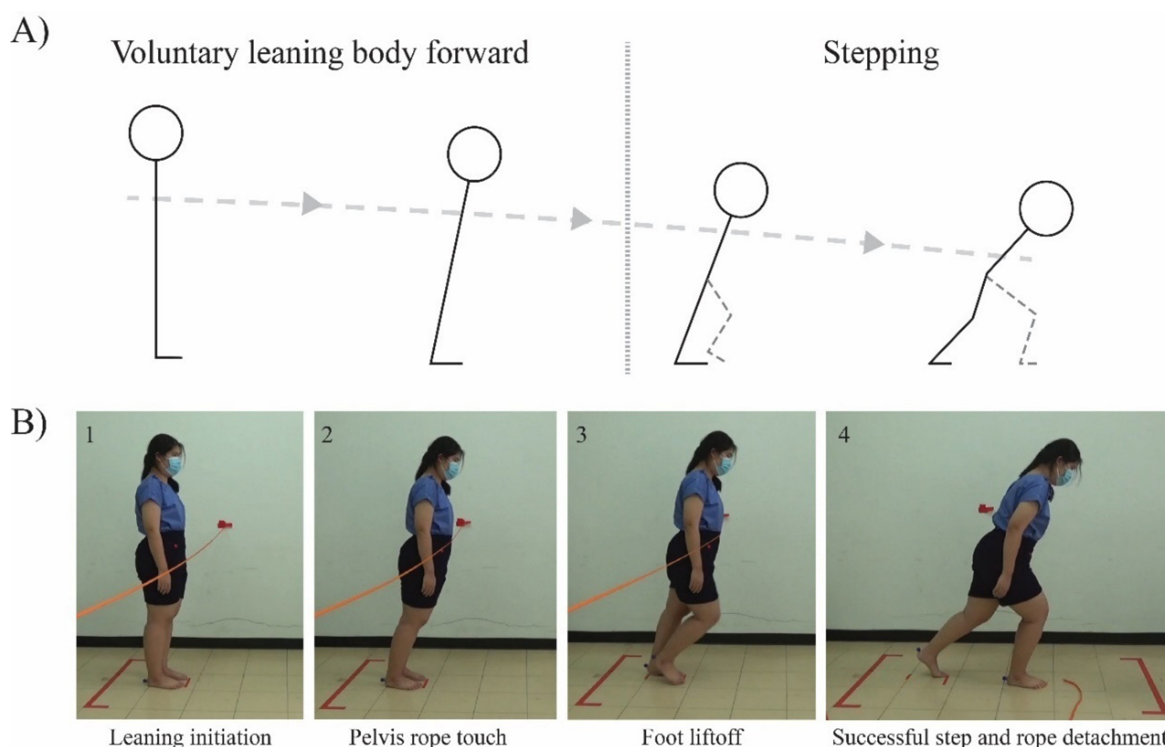

Fig 1. Presents the setup for evaluating a young adult participant. Panel (A) illustrates the VSR action using stick-figure drawings. Panel (B) showcases the assessment setting and an example of a VSR testing trial. Participants performed VSR in the following sequence: initiating the lean (B-1), continuing until the pelvis contacted the rope (B-2), followed by foot liftoff (B-3), and taking a step (B-4). The rope was designed for easy detachment, as shown in Fig B-4.

Measurement

Kinematic data were collected using a two-dimensional (1920×1080 pixels) video camera, capturing footage at 50 frames per second. The camera was positioned laterally to the participant, orthogonal to the movement plane, at a distance of 4 meters away from the recording area. The frame was calibrated using a perspective grid.

Four 3D foam markers were attached to participants' heels and ASIS before testing to define spatial positions. Heel positions were identified and exported using the KINOVEA software for protective step length calculation. The KINOVEA program has been validated as a reliable tool for measuring marker distances up to 5 meters.[17] During the pilot phase of this study, the researchers conducted interrater reliability for marker placement and identification in KINOVEA and found it to be excellent (ICC3,1 = 0.99, 95%CI 0.98-0.99).

Data analysis

A trial was deemed successful if the participant's pelvis contacted the rope precisely at the onset of the auditory cue, and foot liftoff occurred subsequently, following pelvic contact at the level of the ASIS marker.

Protective step length was defined as the anteroposterior distance between the heel markers of the stance and stepping limbs at foot touchdown. To account for inter-individual variability, step length was normalized to participant height.

Initiation strategies for voluntary stepping (trunk leaning vs. trunk bending), movement cessation strategies (flexible vs. rigid body), and compensatory responses (e.g., grasping, body sway, multiple steps, or foot adjustments) were evaluated via visual inspection of video recordings. All assessments were performed by a single researcher, and intra-observer reliability was examined prior to data collection. Repeated assessments were separated by a 1-day interval to minimize recall bias while maintaining participant stability. Prior to the main study, pilot testing was conducted with 10 participants, each performing 10 trials per condition (yielding 100 paired observations). These pilot data were analyzed using Kappa statistics and indicated substantial agreement (κ = 0.81). The pilot confirmed the feasibility of the protocol and the consistency of the measurement procedure; however, these data were not included in the main statistical analysis.

Forward leaning strategy was classified based on the temporal onset of hip and trunk motion. Simultaneous movement of both segments indicated a trunk leaning strategy, whereas earlier trunk motion relative to the hips indicated a trunk bending strategy.

Movement cessation strategy was determined from the first protective step touchdown until postural stability was regained. Trials exhibiting flexion of the neck, trunk, and hips during motion offset, followed by upright re-stabilization, were classified as employing a flexible body strategy. Conversely, trials in which the neck, trunk, hips, and legs remained rigid throughout the post-step phase were categorized as using a rigid body strategy.

Statistical analysis

Descriptive statistics were used to summarize participant characteristics. Data normality was assessed using the Shapiro–Wilk test. Given the limited sample size in the older adult group, visual inspection of QQ plots and histograms was additionally performed. Between-group comparisons (young vs. older adults) were performed using independent t-tests for normally distributed variables and Mann–Whitney U tests for non-normally distributed variables. Differences in sex distribution were analyzed using the chi-square test.

To address the primary objective, paired t-tests were conducted to compare protective step length between conditions D_s and D_l in young adults. For both conditions (D_s and D_l), data from 30 participants were analyzed. Each participant performed 10 test trials per condition, but the mean value of these trials was calculated for each participant before statistical analysis. Thus, 30 paired observations (D_s versus D_l) were included in the paired t-test. For the secondary objective, independent t-tests were used to compare protective step length between young adults in condition D_s and older adults in condition D_p. The mean value of 10 trials for each participant was also calculated prior to statistical analysis. Chi-square tests were applied to examine group differences in movement initiation and cessation strategies.

Statistical significance was set at $p < 0.05$. All analyses were performed using IBM SPSS Statistics (Version 26.0; IBM Corp., Armonk, NY, USA).

RESULTS

Data from 30 healthy young adults and 10 healthy older adults were presented. Participants' characteristics are shown in Table 1. One older adult reported a history of falling, but none expressed a fear of falling. There were no significant differences in sex, weight, height, or BMI between young and older adult participants.

The influence of leaning distance on step length

The results showed that protective step length was significantly longer in condition D_l than D_s as shown in Table 2.

Aging and protective step length

There was no significant difference in normalized protective step length between the D_p condition in older adults and the Ds condition in young adults, nor between D_p in older adults and D_l in young adults. In young adults, normalized step length was significantly larger for D_l than for D_s as shown in Table 2.

Aging and postural control during VSR

The results revealed that older adults were significantly more likely to employ a trunk-bending strategy during movement initiation, characterized by a forward sequence in which the trunk initiated motion prior to the hips, than young adults ($p < 0.001$), as illustrated in Fig 2A. Regardless of the initial strategy, older adults demonstrated a higher percentage to cease body motion with rigid body strategy than young adults ($p < 0.001$), as shown in Fig 2B.

In comparable leaning distances under both D_s and D_p conditions, no significant difference was observed in the percentage of balance loss between young and older adults ($p > 0.05$). Nevertheless, older adults exhibited more grasping, body sway after the first protective step touchdown, foot adjustments following initial foot touchdown, and multiple stepping, relative to young adults ($p < 0.001$), as illustrated in Fig 3A, B.

DISCUSSION

The primary finding of this study is that VSR effectively modulates the magnitude of internally generated perturbations, thereby influencing protective step length. Longer leaning distances corresponded to

TABLE 1. Participants' characteristics.

	Young adults (n = 30)	Older adults (n = 10)
Age (y)	19.5±0.7	68.9±4.4
Weight (kg)	59.5±12.2	68.6±16.5
Height (m)	1.7±0.1	1.7±0.1
BMI (kg/m^2)	19.9 (18.5 to 23.8)	24.1 (20.4 to 27.4)
Sex (M, %)	11 (35.5)	4 (40)
Fall history (Yes, %)	-	1 (10)
Fear of falling (Yes, %)	-	0 (0)
Perturbation experience (Y, %)	-	0 (0)
MMSE (/30)	-	29±1.6
ABC (/100)	-	98.0±2.4
FTSST (s)	-	9.5±2.3
TUG (s)	-	8.7±1.3
DGI (/24)	-	23.9±0.3
BESTest item 16-18 (/12)	-	11.6±1.0

Note: The data were presented in the mean ± SD. BMI data were not normal distributed, and it was reported in median (interquartile range). Gender, fear of falling, and perturbation experience are presented in frequency (percentage).

Abbreviations: BMI = Body Mass Index; MMSE = Mini-Mental State Examination; ABC = Activities-specific Balance Confidence scale; FTSST = Five-times-sit-to-stand Test; TUG = Timed Up and Go; DGI = Dynamic Gait Index; BESTest = Balance Evaluation System Test.

TABLE 2. Normalized protective step length of young adults underwent VSR in conditions D_s and D_l and older adults who performed VSR in conditions D_p.

	Young adults		Older adults	p - value
	D_s	D_l	D_p	
Leaning distance (cm)	16.9±0.8	22.4±1.0[a,b]	17.1±3.7	[a,b] p < 0.001 [a] MD 5.1 ± 0.4 (95% CI: 4.4 to 6.5) [b] MD 5.3 ± 0.6 (95% CI: 3.8 to 6.8)
Normalized step length	0.3 ± 0.1	0.4 ± 0.1[a]	0.4 ± 0.1	[a] p < 0.001 [a] MD 0.03 ± 0.04 (95% CI: 0.02 to 0.04)

[a] presents significant difference of outcomes between D_l and D_s.
[b] presents significant difference of outcomes between D_l and D_p.
Abbreviation and notes: MD is mean difference. Normalized protective step length = step length / participant height. Leaning distance is presented as mean ± SD in centimeters unit.

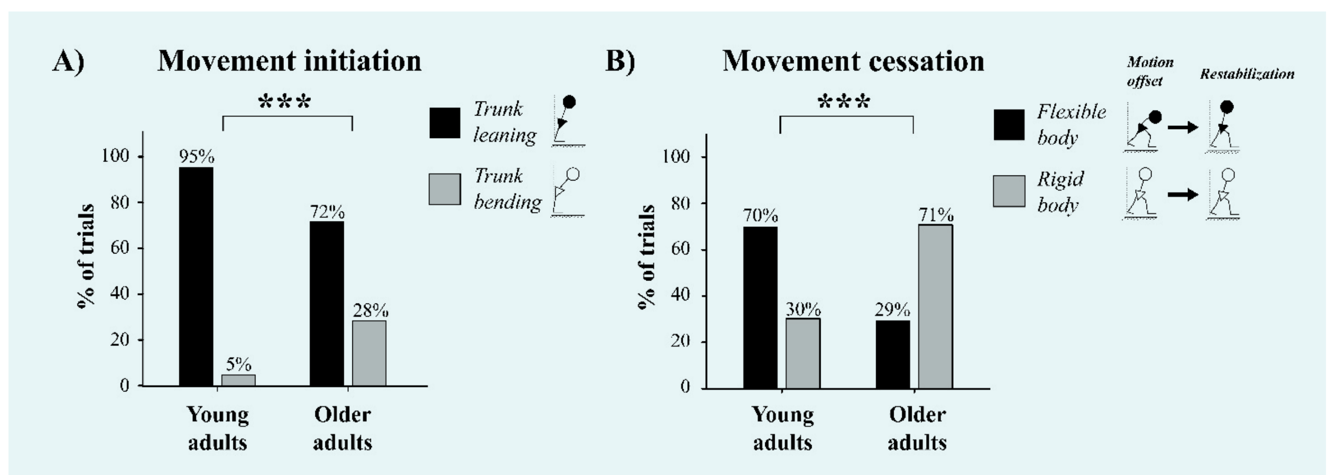

Fig 2. The bar charts present movement strategies during VSR in young (D_s) and older (D_p) adults, segmented into two phases: (A) movement initiation and (B) movement cessation. In phase A, two initiation strategies were identified. The trunk-leaning strategy involved simultaneous movement of the trunk and hips, whereas the trunk-bending strategy was characterized by sequential movement, with the trunk initiating motion ahead of the hips. In phase B, two cessation strategies were observed. The flexible-body strategy featured forward flexion of the neck, trunk, and lower segments at the point of motion offset, followed by gradual regaining of upright posture for restabilization. In contrast, the rigid-body strategy was characterized by persistent stiffness of the neck, trunk, and legs throughout the transition from motion offset to restabilization. *** p<0.001.

longer compensatory step lengths required to maintain balance. Furthermore, the results revealed age-related differences in perturbation response during VSR. Although older adults attempted to preserve postural stability by employing strategies (such as increased use of a trunk bending strategy during movement onset, using a rigid body strategy during movement cessation, and step lengthening), there was still a greater incidence of grasping, body sway, multiple foot adjustments, and multiple steps, indicative of postural instability compared to young adults.

The primary finding suggested that VSR replicates key mechanical characteristics of externally induced perturbations, such as those observed in waist-pull

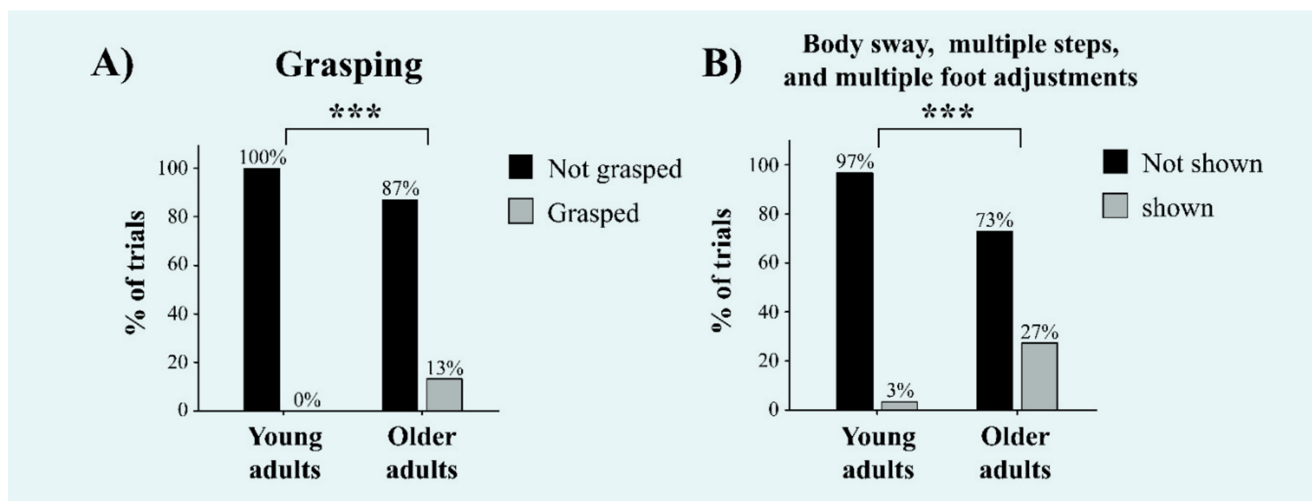

Fig 3. The bar charts present percentage of grasping (A) and percentage of body sway, multiple steps, or multiple foot adjustment (B) during VSR in young adults (D_s) and older adults (D_p).
*** p < 0.001.

protocols.[18] By emphasizing anterior displacement of the ASIS in the horizontal plane while maintaining rigid body alignment around the ankle axis, VSR facilitates displacement of the center of mass (CoM) beyond the base of support (BoS). This displacement triggers a protective step to reestablish stability. Such mechanical demands closely resemble real-world destabilizing scenarios (e.g., tripping or slipping), thereby making VSR a functionally relevant task. Among healthy young adults, greater forward lean distances were significantly associated with longer compensatory steps. This association also aligns with biomechanical principles: as the CoM shifts further from the BoS, the resulting increase in destabilizing moments requires a correspondingly faster muscle activation and a longer step to regain balance.[19,20]

While the present study is observational, it offers mechanistic insight into the utility of VSR for perturbation-based training. Prior interventional research has shown that VSR can enhance protective stepping capacity, particularly by promoting change-in-support strategies.[8] Unlike in-place responses, which rely on joint torques and are often insufficient under large perturbations, protective steps offer a dynamic means of restoring stability.[21] VSR generates self-induced instability of sufficient magnitude to trigger protective stepping. The findings also suggest that voluntary leaning distance during VSR influences the intensity of such internal perturbations. This task-specific stimulus supports scalable, progressive protocols to strengthen change-in-support strategies, especially for individuals at high risk of falling.

Secondary findings highlighted age-related differences in protective stepping strategies during VSR. Older adults predominantly employed trunk bending rather than trunk leaning to initiate movement. This pattern reflected reduced tolerance to perturbation magnitude and an attempt to pre-compensate for instability. By keeping the center of mass (CoM) within the base of support (BoS) and minimizing forward momentum, they sought to maintain stability.[10] In contrast, young adults adopted a flexible body strategy, characterized by continued neck–trunk–hip motion at step touchdown. This strategy facilitated dynamic stabilization by displacing the center of mass (CoM) toward the stepped foot. The cessation strategy promoted a more favorable alignment of the ground reaction force (GRF) vector relative to the center of pressure (CoP), thereby counteracting forward momentum during VSR.[22,23] This favorable GRF–CoP alignment, referring to the spatial relationship between the GRF vector and the CoP, may reduce mechanical demand on the hip extensors.[24] Collectively, these findings underscore that aging is associated with a shift from flexible, momentum-absorbing strategies toward more rigid, cautious responses. This shift increases reliance on hip extensor moments, which are well documented to decline with age, and, together with age-related reduction in quadriceps strength,[10,24] may further limit stabilizing capacity and ultimately compromise postural stability under perturbation.

Protective stepping during VSR may be influenced not only by mechanical demand but also by age-related neural factors. In the present study, older adults in the D_p condition exhibited protective step lengths comparable to those of young adults in the D_l condition, despite leaning a shorter distance. This pattern suggests that step lengthening in older adults reflects a compensatory response to reduced postural control. Neurophysiological

evidence supports this interpretation, showing that cortical responses to perturbation, particularly from the supplementary motor area (SMA), can affect postural control during step execution.[25] For example, larger perturbation-evoked N1 potentials have been observed in individuals with poorer balance, indicating heightened cortical engagement during recovery.[25] Moreover, experimental inhibition of SMA and posterior cerebellar activity has been shown to shorten anticipatory postural adjustment (APA) duration and maladapt step execution.[26] These findings align with evidence that aging-related structural changes in the cerebellum and basal ganglia, together with altered motor control in the SMA, may affect the scaling of protective stepping responses.[27,28] Thus, even under equivalent perturbation magnitudes, older adults may exhibit longer step lengths as a compensatory strategy to offset diminished postural control and sensorimotor integration.[29]

Clinical implications

The findings of this study provide new evidence that VSR can elicit quantifiable age-related differences in protective stepping strategies under controlled conditions. Specifically, older adults were more likely to employ trunk bending and rigid body strategies and showed greater instability indicators (grasping, sway, multiple steps) despite comparable step lengths to young adults. These results highlight that protective step length alone is not a sufficient marker of successful recovery in older adults. Clinically, the use of VSR offers a safe and repeatable method to provoke protective stepping without relying on accidental falls, allowing clinicians to systematically adjust task difficulty by modifying forward leaning distance. Monitoring movement strategies and instability signs during VSR may therefore provide practical markers for tailoring interventions aimed at improving balance recovery in populations at risk of falling. Importantly, the frequent use of multi-step responses observed in older adults carries clinical relevance. Geriatric literature indicates that the inability to recover balance in a single step is a strong predictor of future fall risk.[30] Thus, documenting multi-step responses during VSR may serve as an early indicator of impaired balance recovery capacity and help identify individuals who require targeted fall-prevention interventions.

Limitations and future directions

It should also be noted that the findings for older adults were based on only 10 participants, which further limits the generalizability of the results. A post-hoc power analysis indicated 38% power at $\alpha = 0.05$, underscoring the limited statistical strength of this subsample. Accordingly, these results are considered pilot findings that provide preliminary insight into age-related differences and should be interpreted with caution. Future research should therefore involve larger and more representative samples of older adults to strengthen statistical power and provide more definitive conclusions.

A key limitation of this study is its exclusive focus on anteroposterior (AP) dynamics during VSR, without direct assessment of mediolateral (ML) stability. Although forward leaning primarily challenges AP balance, ML control also plays an important role in compensatory stepping and whole-body coordination.[18,31] Our use of 2D video analysis limited the ability to capture ML instability or transverse plane rotations as effectively as 3D motion capture, which may be particularly relevant for older adults. Future studies should incorporate ML measures (e.g., frontal-plane kinematics, step width variability, CoM–CoP relationships) to provide a more comprehensive characterization of balance recovery.

Another limitation is that anticipatory postural adjustments (APA) prior to leaning or stepping were not quantified. APA reflect central preparatory mechanisms that optimize dynamic stability and may differ between young and older adults.[32] Without evaluating APA-related parameters (e.g., CoP shifts, EMG activity), it remains unclear whether age-related impairments in VSR arise from deficits in feedforward control or purely reactive mechanisms. Future work should examine APA responses to clarify their contribution to protective stepping.

Finally, anthropometric scaling must be considered when interpreting step length outcomes. We normalized step length to participant height, which is widely adopted, practical, and yields outcomes comparable to leg length normalization.[33-36] Prior studies also highlight the influence of height on postural balance and gait performance.[37,38] Thus, height normalization was deemed appropriate for the present study.

CONCLUSIONS

This study demonstrates that voluntary leaning modulates perturbation intensity and stepping responses during VSR. However, aging alters postural strategies in ways that may compromise dynamic stability, particularly under challenging conditions.

Data Availability Statement

The data supporting the findings of this study are not publicly available due to ethical restrictions and participant confidentiality.

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DECLARATIONS

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Conflict of Interest

There is no conflict of interest to be declared.

Registration Number of Clinical Trial

As this study was observational and did not involve any intervention, clinical trial registration was not required.

Author Contributions

Conceptualization and methodology, P.C. and R.B. ; Investigation, P.C. ; Formal analysis, P.C. and R.B. ; Visualization and writing – original draft, P.C. ; Writing – review and editing, P.C. and R.B. ; Funding acquisition, P.C. ; Supervision, R.B. . All authors have read and agreed to the final version of the manuscript.

Use of Artificial Intelligence

We would like to declare that generative AI (Copilot) was used solely for assistance in checking and refining the English language in this manuscript. The authors entirely generated the content, ideas, and findings presented in the manuscript without AI assistance. After language editing, the authors reviewed and validated the final version to ensure its accuracy and integrity.

REFERENCES

1. World Health Organization. Falls [Internet]. 2021. Available from: https://www.who.int/news-room/fact-sheets/detail/falls/.
2. James SL, Lucchesi LR, Bisignano C, Castle CD, Dingels ZV, Fox JT, et al. The global burden of falls: global, regional and national estimates of morbidity and mortality from the Global Burden of Disease Study 2017. Inj Prev. 2020;26(Suppl 1): i3-i11.
3. Gambaro E, Gramaglia C, Azzolina D, Campani D, Molin AD, Zeppegno P. The complex associations between late life depression, fear of falling and risk of falls. A systematic review and meta-analysis. Ageing Research Reviews. 2022;73:101532.
4. Monteiro YCM, Vieira MAdS, Vitorino PVdO, Queiroz SJd, Policena GM, Souza ACSE. Trend of fall-related mortality among the elderly. Rev Esc Enferm USP. 2021;55:e20200069.
5. Montero-Odasso M, van der Velde N, Martin FC, Petrovic M, Tan MP, Ryg J, et al. World guidelines for falls prevention and management for older adults: a global initiative. Age and Ageing. 2022;51(9):afac205.
6. Dajpratham P, Thitisakulchai P, Pongratanakul R, Prapavanond R, Haridravedh S, Muangpaisan W. Effectiveness of Personalized Multifactorial Fall Risk Assessment and Intervention in Reducing Fall Rates Among Older Adults: A Retrospective Study. Siriraj Medical Journal. 2025;77(1):64-72.
7. Bhatt T, Wang Y, Wang S, Kannan L. Perturbation Training for Fall-Risk Reduction in Healthy Older Adults: Interference and Generalization to Opposing Novel Perturbations Post Intervention. Front Sports Act Living. 2021;3:697169.
8. Chayasit P, Hollands K, Hollands M, Boonsinsukh R. Immediate effect of voluntary-induced stepping response training on protective stepping in persons with chronic stroke: a randomized controlled trial. Disabil Rehabil. 2022;44(3):420-7.
9. Chayasit P, Hollands K, Hollands M, Boonsinsukh R. Characteristics of Voluntary-induced Stepping Response in Persons with Stroke compared with those of healthy Young and Older Adults. Gait Posture. 2020;82:75-82.
10. Jensen JL, Brown LA, and Woollacott MH. Compensatory Stepping: The Biomechanics of a Preferred Response Among Older Adults. Experimental Aging Research. 2001;27(4):361-76.
11. Folstein MF, Folstein SE, McHugh PR. “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res. 1975;12(3):189-98.
12. Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. J Gerontol A Biol Sci Med Sci. 1995;50A(1):M28-M34.
13. Bohannon R, Shove M, Barreca S, Masters L, Sigouin C. Five-repetition sit-to-stand test performance by community-dwelling adults: A preliminary investigation of times, determinants, and relationship with self-reported physical performance. Isokinet Exerc Sci. 2007;15:77-81.
14. Lord SR, Murray SM, Chapman K, Munro B, Tiedemann A. Sit-to-stand performance depends on sensation, speed, balance, and psychological status in addition to strength in older people. J Gerontol A Biol Sci Med Sci. 2002;57(8):M539-43.
15. Shumway-Cook A, Baldwin M, Polissar NL, Gruber W. Predicting the probability for falls in community-dwelling older adults. Phys Ther. 1997;77(8):812-9.
16. Horak FB, Wrisley DM, Frank J. The Balance Evaluation Systems Test (BESTest) to differentiate balance deficits. Phys Ther. 2009;89(5):484-98.
17. Puig-Diví A, Escalona-Marfil C, Padullés-Riu JM, Busquets A, Padullés-Chando X, Marcos-Ruiz D. Validity and reliability of the Kinovea program in obtaining angles and distances using coordinates in 4 perspectives. PLoS One. 2019;14(6):e0216448.
18. Zhu RT, Lyu PZ, Li S, Tong CY, Ling YT, Ma CZ. How Does Lower Limb Respond to Unexpected Balance Perturbations? New Insights from Synchronized Human Kinetics, Kinematics, Muscle Electromyography (EMG) and Mechanomyography (MMG) Data. Biosensors (Basel). 2022;12(6).
19. Bair WN, Prettyman MG, Beamer BA, Rogers MW. Kinematic and behavioral analyses of protective stepping strategies and risk for falls among community living older adults. Clin Biomech

(Bristol). 2016;36:74-82.
20. Lugade V, Lin V, Chou L-S. Center of mass and base of support interaction during gait. Gait & Posture. 2011;33(3):406-11.
21. Mille ML, Rogers MW, Martinez K, Hedman LD, Johnson ME, Lord SR, et al. Thresholds for Inducing Protective Stepping Responses to External Perturbations of Human Standing. Journal of Neurophysiology. 2003;90(2):666-74.
22. Zadravec M, Olenšek A, Rudolf M, Bizovičar N, Goljar N, Matjačić Z. Assessment of dynamic balancing responses following perturbations during slow walking in relation to clinical outcome measures for high-functioning post-stroke subjects. Journal of NeuroEngineering and Rehabilitation. 2020;17(1):85.
23. Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol. 1986;55(6):1369-81.
24. Ren X, Lutter C, Kebbach M, Bruhn S, Bader R, Tischer T. Lower extremity joint compensatory effects during the first recovery step following slipping and stumbling perturbations in young and older subjects. BMC Geriatrics. 2022;22(1):656.
25. Payne AM, Ting LH. Worse balance is associated with larger perturbation-evoked cortical responses in healthy young adults. Gait & Posture. 2020;80:324-30.
26. Richard A, Van Hamme A, Drevelle X, Golmard J-L, Meunier S, Welter M-L. Contribution of the supplementary motor area and the cerebellum to the anticipatory postural adjustments and execution phases of human gait initiation. Neuroscience. 2017;358:181-9.
27. Radhakrishnan V, Gallea C, Valabregue R, Krishnan S, Kesavadas C, Thomas B, et al. Cerebellar and basal ganglia structural connections in humans: Effect of aging and relation with memory and learning. Frontiers in Aging Neuroscience. 2023;Volume 15 - 2023.
28. Zapparoli L, Mariano M, Paulesu E. How the motor system copes with aging: a quantitative meta-analysis of the effect of aging on motor function control. Communications Biology. 2022;5(1):79.
29. King GW, Akula CK, Luchies CW. Age-related differences in kinetic measures of landing phase lateral stability during a balance-restoring forward step. Gait & Posture. 2012;35(3):440-5.
30. Carty CP, Cronin NJ, Nicholson D, Lichtwark GA, Mills PM, Kerr G, et al. Reactive stepping behaviour in response to forward loss of balance predicts future falls in community-dwelling older adults. Age Ageing. 2015;44(1):109-15.
31. Singer JC, Prentice SD, McIlroy WE. Age-related challenges in reactive control of mediolateral stability during compensatory stepping: A focus on the dynamics of restabilisation. Journal of Biomechanics. 2016;49(5):749-55.
32. Tisserand R, Robert T, Chabaud P, Livet P, Bonnefoy M, Cheze L. Comparison between investigations of induced stepping postural responses and voluntary steps to better detect community-dwelling elderly fallers. Neurophysiol Clin. 2015;45(4-5):269-84.
33. Hof AL. Scaling gait data to body size. Gait Posture [Internet]. 1996;4:222-3 [cited 2026 Feb 4].
34. Pierrynowski MR, Galea V. Enhancing the ability of gait analyses to differentiate between groups: scaling gait data to body size. Gait Posture. 2001;13(3):193-201.
35. Rygelová M, Uchytil J, Torres IE, Janura M. Comparison of spatiotemporal gait parameters and their variability in typically developing children aged 2, 3, and 6 years. PLoS One. 2023;18(5):e0285558.
36. Mobbs L, Fernando V, Fonseka RD, Natarajan P, Maharaj M, Mobbs RJ. Normative Database of Spatiotemporal Gait Metrics Across Age Groups: An Observational Case–Control Study. Sensors [Internet]. 2025;25(2):581.
37. Eom GM, Kwon YR, Kim DY, Ko J, Kim JW. The influence of height on test-retest reliability of postural balance measures in healthy young adults. J Mech Med Biol. 2022;22(9).
38. Unluer N, Taş S. Effects of anthropometric factors, age, gender, and foot posture on single leg balance performance in asymptomatic subjects. Fizyoterapi Rehabilitasyon. 2019;30:154-60.