Comparison of Verticality Alignment Ability Between Older Adults with Falls and Normal Elderlies Using A Virtual Reality System

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Highlights

- Older adults with falls would exhibit greater SVV deviations than controls.
- Older adults with falls would demonstrate poorer body alignment during VR reaching tasks.
- Vestibular–perceptual measures may help identify fall risk beyond clinical history.

Abstract

Background and Aim: Falls in older adults are a major clinical and public health issue, often linked to dizziness and vestibular dysfunction. Changes in verticality perception, visual dependence, and postural control can increase fall risk. This study compared vestibular–perceptual and and postural control characteristics using a virtual reality system between older adults with and without dizziness-related falls.

Methods: We enrolled 66 older adults in a fall group (n = 33) or a control group (n = 33) based on dizziness-related falls. All participants met the same criteria for cognitive status, sensory function, psychological health, medical stability, and vestibular integrity. We assessed static and dynamic subjective visual vertical (SVV) and used a virtual reality reaching task to measure postural control. Participants also completed self-reported dizziness-related disability and fear of falling measures. We compared groups and ran regression analyses, controlling for age.

Results: Compared to controls, older adults with falls showed greater deviations in static and dynamic SVV and higher visual dependence ($p < 0.05$). The fall group also had reduced center-of-pressure displacement and trunk excursion during the virtual reaching task. Dizziness-related disability and fear of falling correlated with vestibular–perceptual and postural measures.

Conclusion: Older adults who experience dizziness-related falls exhibit impaired verticality perception, greater reliance on visual cues, and altered postural control. These findings underscore the value of vestibular–perceptual assessments and virtual reality tasks for identifying fall risk and guiding targeted rehabilitation for older adults.

Keywords: vestibular dysfunction, ageing, falling, vertical perception, postural control, virtual reality

Introduction:

Global demographic shifts are leading to an unprecedented rise in the elderly population, with countries like Iran undergoing a rapid transition toward an aged society [1, 2]. This shift necessitates targeted healthcare strategies to address the escalating prevalence of falls, which represent a leading cause of injury, institutionalization, and reduced quality of life among older adults. While falls are often misconstrued as an unavoidable consequence of aging, they are actually multifactorial events that can be prevented by identifying and mitigating underlying physiological risk factors [3-5].

A critical factor contributing to fall risk is the age-related degradation of postural control and the sensory integration necessary for spatial orientation [6]. The vestibular system—particularly the otolith organs—plays a critical role in encoding head orientation relative to gravity and linear acceleration, providing an essential gravitational reference frame for postural control [7]. Age-related degeneration of vestibular structures, including a gradual loss of otolithic and semicircular canal function, has been well documented [8]. These changes reduce the fidelity of vestibular afferent signals, leading to impaired verticality estimation and increased postural instability [9]. Clinical and experimental studies have demonstrated that altered perception of verticality is associated with persistent dizziness, impaired balance, and recurrent falls in older adults [10]. Even small deviations from true vertical have been shown to substantially increase fall risk, with each degree of vertical misperception increasing the likelihood of falling by approximately 1.4-fold [11]. The Subjective Visual Vertical (SVV) test is a widely used, noninvasive, and reliable method for assessing perceived vertical orientation [12]. SVV primarily reflects visual–vestibular integration and is particularly sensitive to otolith dysfunction [13]. In older adults with a history of falls, SVV deviations are often increased, especially under dynamic visual conditions, suggesting heightened visual dependence and impaired sensory reweighting [6, 11]. Visual dependence, characterized by excessive reliance on visual cues when vestibular and somatosensory inputs are degraded, is common in aging and has been linked to postural instability and fall risk in visually complex or dynamic environments [11].

Beyond perceptual measures, functional balance tasks that challenge postural control during goal-directed movements provide valuable insight into mechanisms underlying falls. Reaching while standing is a common activity of daily living and a frequent context for falls [14]. Such tasks require anticipatory postural adjustments and effective multisensory integration to stabilize the body against movement-induced perturbations [15]. Age-related otolith dysfunction has been associated with increased trunk sway and reduced postural stability during reaching movements [16]. Virtual reality–based reaching paradigms offer a controlled yet ecologically valid approach to assess postural control under sensory manipulation, while minimizing physical risk to participants. Because up to 17.3% of falls occur during reaching or bending tasks that shift the body's center of mass, assessing verticality alignment during a functional, Virtual Reality-based task can yield unique insights into real-world fall mechanisms [17]. Beyond these physical deficits, the psychological impact of a fear of falling restricts daily activities, creating a debilitating cycle of self-imposed isolation and further physical decline [18].

Despite growing evidence linking altered verticality perception and postural instability to falls in older adults, few studies have simultaneously examined subjective vertical perception and functional postural alignment during dynamic, goal-directed, and virtual reality–based tasks. Moreover, the relationship between perceptual–vestibular deficits, fear of falling, and dizziness-related disability remains incompletely understood. Therefore, the primary aim of the present study was to compare subjective vertical perception and postural control during a virtual reality–based reaching task between older adults with and without a history of dizziness-related falls. A secondary aim was to evaluate visual dependence by assessing SVV under dynamic optokinetic stimulation at different velocities. Finally, this study aimed to explore the associations among perceptual–postural measures, fear of falling, and dizziness-related disability to provide a more comprehensive understanding of fall-related mechanisms in aging.

Methods

Study design and participants

This observational, cross-sectional comparative study examined vestibular–perceptual and postural control characteristics in older adults with and without a history of falls. The target population consisted of individuals aged 65 years and older, who were recruited from elderly patients referred to the Rofeideh Rehabilitation Hospital. The normal elderly was selected from the companions of the patients referring to the hospital. Using convenience sampling, 66 participants were enrolled in the study. The minimum sample size with a power of 80% based on the SVV variable information, was obtained in a similar study [11].

To minimize the influence of age-related comorbidities and potential confounding factors, all participants were initially screened using a uniform set of inclusion and exclusion criteria prior to group allocation. Eligible participants were required to have normal cognitive function, as indicated by a Montreal Cognitive Assessment (MOCA) score of 26 or higher [19], as well as normal or corrected-to-normal hearing and vision. Participants with clinically significant anxiety or stress, depressive symptoms (defined as a Geriatric Depression Scale (GDS) score greater than 8) [20], or any medical instability were excluded. Additional eligibility criteria included the ability to stand and ambulate independently without assistive devices, a stable medical condition with no uncontrolled cardiovascular, musculoskeletal, or metabolic disorders during the previous year, and no history of Meniere's disease, peripheral neuropathy, cerebellar disorders, central neurological disorders, or psychiatric conditions. Vestibular integrity beyond age-related deterioration was confirmed for all patients based on assessments in their previous files, including video nystagmography (VNG), video head-shake test (vHIT), and vestibular evoked muscle potentials (VEMP). In addition, the Dizziness Handicap Inventory (DHI) was administered to all participants.

After applying these general eligibility criteria, participants were assigned to one of two groups based on fall-related characteristics. Individuals were classified into the fall group if they reported at least one dizziness-related fall within the previous year [6]. Participants who reported no falls during the previous year and showed no clinically significant dizziness-related disability were allocated to the control group. Also, the normal group had to have a normal DHI score, otherwise they were excluded from the study. Each group consisted of 33 participants.

Participants were excluded from the study if they developed medical instability during the study, failed to continue meeting the inclusion criteria, or withdrew consent at any stage of participation.

Procedure

After obtaining ethical approval from the University of Social Welfare and Rehabilitation Sciences Research Ethics Committee (IR.USWR.REC.1403.239), written informed consent was obtained from all participants. Demographic information was collected through structured interviews, and participants were assigned to groups based on fall history and eligibility criteria. All assessments were conducted in a randomized order to minimize order effects, with sufficient rest periods between tests. Prior to each assessment, standardized instructions were provided.

Assessment tools:

Participants completed two validated Persian-language questionnaires assessing dizziness and fear of falling as follows:

Dizziness handicap inventory: The DHI is a self-reported questionnaire designed to evaluate perceived disability due to dizziness and balance disorders. It comprises 25 items across three subscales: physical, functional, and emotional. Responses are scored on a 3-point scale (0 = no, 2 = sometimes, 4 = yes), yielding a total score ranging from 0 to 100, with higher scores indicating greater perceived disability. Scores of 0–14 indicate no disability, 16–26 mild, 28–44 moderate, and ≥ 46 severe disabilities. The validated Persian version of the DHI was administered [21].

Geriatric fear of falling measure : The GFFM assesses fear of falling and fall-related perceptions in older adults. It consists of 15 items across three domains: psychosomatic symptoms, risk-prevention attitudes, and behavioral changes. Items are rated on a 5-point Likert scale (1 = not at all concerned to 5 = very concerned), with total scores ranging from 15 to 75; higher scores reflect greater fear of falling. The Persian version of the GFFM has demonstrated acceptable psychometric properties, with a content validity index of 0.86 [22].

Vestibular assessment

SVV was assessed in a completely dark environment with participants seated upright to minimize proprioceptive cues. Static SVV was measured using a black background, while dynamic SVV was assessed using optokinetic visual stimulation rotating clockwise and counterclockwise at angular velocities of 20° and 40°per second. Each participant completed 21 trials. Visual dependence was calculated as the mean absolute deviation of dynamic SVV values minus static SVV values. The use of absolute values was intended to quantify the magnitude of visual dependence irrespective of directional bias [11].

Virtual reality reaching task

Postural control during reaching was assessed using a virtual reality system equipped with a Kinect motion capture sensor and a 32-inch display [23]. Participants stood barefoot on a platform (30 × 50 cm) at a distance of 2 m from the sensor, with feet positioned approximately 20 cm apart. In the first phase, participants were asked to reach a target while standing in a fixed position. The subject performed a lateral (right and left) movement and reached the target. This phase was considered the baseline. The subject was then asked again to perform the movement by moving the trunk without moving the legs and head to either side, but this time without providing a visual cue, and then returned to the initial position. The center of pressure (COP) coordinates and the amount of their displacement were measured using a smart balance board system equipped with a pressure sensor, as well as the amount of deviation from the vertical alignment of the body relative to the baseline phase using a system for obtaining kinematic points defined in the system for recording their moments with an infrared camera. The trunk deviation values represent the cumulative angular deviation obtained from leftward and rightward reaching trials rather than a single-body tilt angle to the left or right. The distance for each participant was adjusted before data collection to ensure that they had a range of motion in each direction (mean 0.5 m) while standing. The received changes in the center of pressure and the three-dimensional kinematic components of the individual's trunk were recorded and stored in files as (x-y-z) in units of time. The above raw data were then extracted and, after applying spatiotemporal filtering with a cutoff frequency of 3 Hz, the data were converted into process able data COP displacement in centimeters and body deviation from the perpendicular in degrees) for statistical analysis.

Statistical analysis

Basic statistics, such as averages, standard deviations, and frequencies, were calculated to summarize demographics and outcome variables. Continuous variables were checked for normality using the Shapiro–Wilk test. Differences in group variances were measured with Levene's test. Differences in sex distribution between groups were checked with the chi-square test. Relationships between vestibular–perceptual and postural control variables and questionnaire scores (DHI and GFFM) within the fall group were examined with Pearson's correlation. Because age differed between the fall and control groups, age was treated as a possible confounding variable. Linear regression was performed within each group to examine how age affected vestibular–perceptual and postural outcomes, including static and dynamic SVV, visual dependence, COP displacement, and trunk deviation angle. Regression coefficients and P-values were reported. All analyses were done in SPSS software version 17, with significance set at 0.05.

Results

A total of 66 older adults (35 females and 31 male) participated in this study. Participants were included in two groups based on inclusion criteria: older adults with a history of dizziness-related falls (fall group, $n = 33$) and older adults without a history of falls (control group, $n = 33$). The mean age of participants in the control group was 68.52 ± 5.05 years, and in the fall group was 71.97 ± 5.75 years. Chi-square analysis demonstrated no statistically significant difference in sex distribution between the fall and control groups ($p = 0.81$), indicating appropriate gender matching. Independent samples t-test revealed a statistically significant difference in age between the two groups ($p = 0.012$). Therefore, age was controlled as a confounding variable in subsequent regression analyses. Table 1 shows descriptive statistics and between-group comparisons for static and dynamic SVV, visual dependence, COP displacement, and trunk deviation angle.

The results of the independent t-test showed that there was a significant difference between the two groups in static and dynamic SVV values in all optokinetic conditions ($p < 0.05$). Also, in the study of visual dependence, a significant difference was observed between the two groups in the counterclockwise conditions ($p < 0.05$). In contrast, no significant difference was observed in the clockwise conditions ($p > 0.05$). In addition, as shown in Table 1, during the virtual reality reaching test, the mean displacement of the COP and the angle of deviation from the vertical line in the falling group were significantly lower than in the normal group ($p < 0.001$). Because multiple outcome variables were analyzed, the Holm–Bonferroni sequential procedure was applied to control the family-wise error. Statistical significance was determined based on the Holm-adjusted p-values.

Due to a significant age difference between the two groups (normal and fallen elderly), the regression analysis method was used to control for age in the comparison of means. After removing the effect of age in the linear regression model, the difference between the two groups of normal and fallen elderly in the variables of static SVV, dynamic SVV in the conditions of -20, +40, and -40 degrees/sec, visual dependence in the counterclockwise position, center of pressure displacement, and body angle deviation remained significant.

The average DHI score was 21.52 ± 7.30, indicating a moderate level of perceived disability due to dizziness. The mean score of the GFFM was 21.03 ± 10.08. Significant positive correlations were observed between dynamic SVV deviation at 20°/s (counterclockwise) and GFFM scores ($r = 0.355$, $p = 0.043$). A significant negative correlation was also found between COP displacement and GFFM scores ($r = -0.352$, $p = 0.045$), indicating reduced reaching displacement in individuals with greater fear of falling. DHI scores showed significant positive correlations with static SVV deviation ($r = 0.426$, $p = 0.013$) and dynamic SVV deviation at 20°/s ($r = 0.406$, $p = 0.010$). COP displacement was negatively correlated with DHI scores ($r = -0.342$, $p = 0.050$). In addition, DHI and GFFM scores were moderately correlated ($r = 0.50$, $p = 0.004$). No significant effects of gender were observed for any vestibular–perceptual or postural variables ($p > 0.05$).

Examining the correlation between the scores of the GFFM and DHI questionnaires showed that as the severity of dizziness-related disability increases, the level of fear of falling also increases ($r = 0.5, p = 0.004$).

Discussion

The present study investigated how perception and posture relate to falls in older adults. We compared subjective visual vertical, visual dependence, and postural control during a virtual reality–based reaching task. The participants were older adults, split into groups with and without a history of dizziness-related falls. The results showed clear differences between groups in perceptual and motor abilities. Impaired verticality perception and changed postural strategies were key factors in fall risk for older adults.

SVV is a well-established measure of verticality perception and otolith-mediated vestibular function [13]. In the present study, older adults with a history of falls exhibited significantly greater deviations in static SVV compared with age-matched controls. This indicates that impaired verticality perception, as reflected by altered SVV, may be associated with poor postural stability and increase the risk of falls in older adults.

The magnitude of static SVV deviation observed in the fall group aligns closely with findings reported by Totilienė et al., who demonstrated that older adults with falls show greater vertical misperception, likely reflecting age-related otolith dysfunction [11]. Dynamic SVV revealed more pronounced group differences, particularly during optokinetic stimulation at angular velocities of 20° and 40°/s. These findings suggest that perceptual errors become more evident under visual–vestibular conflict, reflecting increased reliance on visual information when vestibular cues are less reliable. Accordingly, visual dependence, defined as greater reliance on visual cues for spatial orientation and balance control, was significantly higher in the fall group, particularly during counterclockwise optokinetic stimulation [24]. This increased visual dependence is consistent with age-related decline in vestibular function and corroborates findings from Hayashi et al., who demonstrated that greater visual dependence and larger SVV errors are associated with poorer balance performance and increased fall risk in older adults [25].

The virtual reality reaching task provided a functional assessment of postural control under conditions requiring anticipatory postural adjustments and trunk displacement without stepping. Contrary to intuitive expectations, COP displacement was significantly smaller in the fall group compared with controls (10.42 cm vs. 23.16 cm, $p < 0.001$), indicating impaired postural stability during goal-directed reaching in older adults with a history of falls. This finding is consistent with prior studies indicating that reduced COP excursion may reflect a rigid or cautious postural strategy rather than superior stability [11, 24]. Similarly, trunk deviation angle from the vertical axis was significantly smaller in the fall group, suggesting restricted movement amplitude during reaching. This reduced trunk excursion may reflect fear-related movement avoidance, muscular weakness, or impaired estimation of body orientation relative to gravity [26]. Age-related degradation of vestibular, visual, and proprioceptive inputs further compromises accurate body orientation, leading to conservative movement strategies and diminished postural flexibility [27].

The fall group exhibited moderate levels of dizziness-related disability and fear of falling, as indicated by DHI and GFFM scores, respectively. These findings are clinically meaningful, as dizziness and fear of falling are well-established predictors of future falls and activity restriction in older adults [28]. Significant correlations were observed between dynamic SVV deviation and GFFM scores, indicating that greater perceptual distortion of verticality is associated with increased fear of falling. Additionally, a higher fear of falling was associated with reduced COP displacement, suggesting that psychological factors directly influence postural behavior. These findings support the concept that fears of falling is not merely a psychological consequence of falls, but an integral component of balance dysfunction that shapes motor strategies [18]. The positive correlation between DHI and GFFM scores further highlights the interdependence of dizziness-related disability and fear of falling. This interaction may create a maladaptive cycle in which dizziness exacerbates fear, leading to reduced activity, deconditioning, and increased fall risk [28]. These results underscore the importance of a comprehensive assessment that integrates perceptual, motor, and psychological dimensions of balance.

Age affected static SVV and selected dynamic SVV conditions in both groups. This is consistent with evidence that vestibular hair cell loss, reduced otolith sensitivity, and central vestibular pathway degeneration occur with aging [11]. Previous studies report mixed results on age-related changes in SVV [29, 30], but these findings support that aging selectively impairs verticality perception, especially under challenging sensory conditions.

This study suggests that impaired vertical perception under dynamic visual may be associated with impaired postural stability in older adults. SVV testing, especially dynamic SVV, may be a sensitive tool for identifying older individuals at higher risk of falls. VR-based reaching tasks reveal compensatory postural strategies and movement limitations not seen in static balance tests. Adding perceptual assessments to functional balance and psychological evaluations may help target fall-prevention and vestibular-rehabilitation strategies. Interventions to reduce visual dependence, improve vestibular integration, and address fear of falling may be especially helpful for older fallers.

This study has several limitations. The cross-sectional design precludes causal inference. Fall history was based on retrospective self-report and may have been affected by recall bias. Although vestibular screening was performed, detailed vestibular findings were not analyzed separately. Visual and auditory sensitivity in the elderly was assessed using self-reports and clinical observations. In the study, assessor blinding between the two groups was not performed. There are many confounding variables in old age, not all of which can be precisely controlled. Finally, the results of this study are valid within the stated conditions and its generalization requires more scientific research.

Conclusion

This study shows that older adults with a history of dizziness-related falls have significant impairments in verticality perception and postural control compared with age-matched healthy controls. Greater deviations in static and dynamic subjective visual vertical and increased visual dependence indicate compromised vestibular sensory integration in older fallers. These perceptual deficits could be due altered postural strategies during a virtual-reality reaching task, characterized by reduced center-of-pressure displacement and limited trunk excursion, reflecting a cautious but maladaptive balance-control pattern.

Strong associations between perceptual, postural, and self-reported measures show that dizziness-related disability and fear of falling are closely linked to both sensory misperception and motor behavior. Age influences verticality perception, especially under dynamic visual conditions, highlighting age-related vestibular decline and its role in fall risk. These findings suggest impaired vertical perception as a relevant and potentially modifiable factor in falls among the elderly. Dynamic SVV assessment and VR-based functional tasks may become sensitive clinical tools for identifying individuals at increased risk of falls and guiding targeted vestibular and balance rehabilitation.

Ethical considerations

In this study, the research team has considered and applied ethical guidelines. The Ethics Committee of the University of Social Welfare and Rehabilitation Sciences approved this study method (Ethical Code: IR.USWR.REC.1403.239).

Funding

This study received no external funding.

Authors' contributions

FK: Study design, acquisition of data, statistical analysis, interpretation of results, and drafting the manuscript. PJA: Providing editorial feedback and copy-editing. SM: Study design, supervision, statistical analysis, interpretation of results, and critical revision of the manuscript. MHA: Study design, supervision, interpretation of results, and critical revision of the manuscript. EB: Statistical analysis and critical revision of the manuscript.

Conflict of interest

The authors declared no conflict of interest

Acknowledgment

The authors thank all participants in this study, as well as the University of Social Welfare and Rehabilitation Sciences and the Clinical Research Development Center of Rofeideh Rehabilitation Hospital, Tehran, Iran, for their support and cooperation throughout the study period. We also thank Mostafa Alavian, Mofavqian Research Center for Neurorehabilitation Technologies, Tehran, Iran, for his cooperation.

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Table 1. Comparison of Subjective visual vertical visual dependence, and postural control variables between two groups

Variable		groups		Raw P-value*	Holm-adjusted P-value**
		Control (Mean ± SD)	Fall (Mean ± SD)		
Static SVV		*1.30 ± 0.70*	*2.50 ± 1.10*	*0.001*	*0.011*
Dynamic SVV	20° CW	*2.50 ± 1.80*	*4.06 ± 2.40*	*0.006*	*0.018*
	20° CCW	*2.30 ± 2.20*	*6.30 ± 4.10*	*0.001*	*0.011*
	40° CW	*2.70 ± 1.90*	*4.40 ± 2.50*	*0.003*	*0.015*
	40° CCW	*3.80 ± 2.10*	*7.10 ± 4.01*	*0.001*	*0.011*
Visual Dependency	20° CW	*1.20 ± 1.70*	*1.50 ± 2.50*	*0.577*	*0.577*
	20° CCW	*1.06 ± 1.70*	*3.80 ± 3.90*	*0.001*	*0.011*
	40° CW	*1.40 ± 1.90*	*1.90 ± 2.90*	*0.407*	*0.577*
	40° CCW	*2.50 ± 1.90*	*4.60 ± 3.40*	*0.004*	*0.016*
COP displacement (cm)		*23.16 ± 6.02*	*10.42 ± 4.12*	*0.001*	*0.011*
Trunk deviation angle		*74.43 ± 8.46*	*24.5 ± 5.12*	*0.001*	*0.011*

*SVV: Subjective Visual Vertical; CW: Clockwise; CCW: Counterclockwise; COP: Center of Pressure. * P-values were calculated using independent samples* t-tests. ***Holm–Bonferroni sequential procedure was applied to control the family-wise error.*