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Effects of Stroboscopic Disruption on Static Postural Control in Elderly Individuals: Based on Rambling and Trembling Analysis

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Abstract

Purpose: This study investigated the effects of stroboscopic disruption (SD) on postural control strategies in elderly individuals by comparing center of pressure (CoP) variables between young and elderly individuals during bipedal standing tasks, with and without SD. **Methods:** Thirty-five participants, comprising 15 young and 20 elderly, completed 60-second bipedal quiet standing trials on a force plate. Excluding the initial and final 10-second preparation and recovery phases, the central 40 seconds of CoP trajectory were quantified using time-domain and frequency-domain parameters across the medial-lateral (ML), anterior-posterior (AP), and resultant spatial (RS) directions. Rambling (RM) and trembling (TR) components were also extracted. Statistical analysis was performed using a linear mixed-effect regression (LMER). **Results:** SD significantly affected CoP control, with the elderly exhibiting greater changes in most variables than the younger group. During the transition from transparent to SD conditions, time-domain parameters showed a significant increase in mean movement distance and root mean square in the RS direction for both traditional and RM components among the elderly. Additionally, the 95% confidence circle and ellipse areas were larger in the elderly group. In the frequency-domain parameters, such as 80% power frequency, frequency dispersion, and concentrated frequency decreased in the AP and RS directions for both traditional and RM components in the elderly group. **Conclusion:** The reduction in visual inputs caused by SD leads to decreased flexibility and automaticity in the postural control of elderly individuals, making it more difficult for them to control CoP sway and adapt to changes in visual input compared to younger individuals.

Keywords: Postural stability; Neuromechanical controls; Strobe; Center of pressure; Vision

1. Introduction

Maintaining an upright posture is essential for performing daily tasks. Due to the human body's disproportionate mass distribution concentrated in the upper region, remaining upright poses a challenge [5]. Failure to maintain balance can result in falls, which are particularly hazardous for elderly individuals. Age-related changes in the central and peripheral nervous systems lead to balance impairments, increasing the risk of falls over time. These falls can result in severe consequences, including permanent disability [46], significantly affecting an individual's quality of life. A population-based study in China reported a fall-related injury incidence of 19.5% [31], underscoring the severity of falls in diminishing independence and contributing to critical health problems [34]. Among individuals aged 50 and older, fall risk strongly correlates with age-related functional declines, making it imperative to address the issue of reduced postural control in elderly individuals [34].

Balance maintenance relies on an intricate interplay of multiple sensory systems, including somatosensory, visual, and vestibular inputs, to generate coordinated muscle responses [4], [28]. Vision plays a crucial role in spatial orientation and the integration of vestibular and proprioceptive information. It is sensitive to object motion perception, is highly responsive to dynamic environmental changes, and facilitates rapid processing essential for postural control [19], [21]. During ageing, spatial and postural processing accuracy decreases over time [9]. When one or more sensory systems are compromised, the central nervous system compensates by prioritizing reliable information to maintain postural stability [25], [28]. Elderly individuals exhibit an increased dependence on visual feedback [7], with the most extensive equilibrium changes observed when somatosensory feedback is inaccurate and visual input is removed [1]. However, aging also induces structural and functional deterioration in the visual system, such as reduced contrast sensitivity and slower processing speeds, which diminish the ability to detect and respond to environmental cues [9]. This reduction in visual input has been directly linked to an increased risk of falls [3]. The elderly could shift over-reliance on visual inputs for their posture control with more non-visual awareness, considering deactivation of the dorsal visual stream and visual error processing [44]. Thus, the heightened visual dependence could instead compromise spatial orientation and postural accuracy when visual inputs become unreliable [28], increasing the likelihood of falls and their adverse consequences, such as injury, diminished self-esteem, and loss of independence in daily life. Thus, understanding the change of visual inputs in postural control for elderly individuals has broad implications for fall prevention.

Stroboscopic disruption (SD), characterized by alternating flickering between transparent and opaque frames, creates intermittent visual input that challenges visuomotor adaptability. Unlike complete visual deprivation (via eye closure or darkness), SD intermittently presents visual information inputs. This form of visual perturbation forces individuals to adapt to fragmented visual cues while integrating the remaining inputs with other sensory inputs, fostering more sensory reweighting [48]. Although complete visual deprivation can highlight compensatory postural control strategies under extreme conditions, it often leads to unconventional adaptations because human movement is extremely limited with closed eyes [32], [41]. In contrast, SD provides an intermediary visual disturbance, allowing a more functional simulation of daily living challenges [26]. This approach has demonstrated its impact on sensory reweighting during the static balance task, revealing more challenges in posture control compared to eyes-open conditions [23], [25]. Nonetheless, most research has been conducted on younger individuals, with limited exploration of how SD affects postural control in elderly individuals. Furthermore, direct comparisons between age groups remain scarce, and the unique implications of SD for older individuals' postural control strategies are still underexplored.

The Center of Pressure (CoP) trajectory is utilized as a key indicator of balance stability and control strategies. To comprehensively assess postural control, a refined analysis method, Rambling-Trembling (RM-TR) decomposition, developed by Zatsiorsky and Duarte, offers valuable insights by dissecting CoP trajectory into these two components [49]. RM is the low-frequency component of CoP fluctuations, reflecting the overall trunk and body control trend. It is usually understood as a component related to target posture regulation, such as the expected adjustment action dominated by the central nervous system. RM describes the body's large-scale adjustment trajectory during center of gravity control, reflecting the posture control system's response to balance disturbances. TR is a high-frequency component in CoP fluctuations, reflecting subtle fluctuations caused by muscle tremors or posture adjustments. It is usually related to the mechanical properties and local regulation of the body, reflecting the rapid response characteristics of muscles and the nervous system [40], [43]. The combination of these components provides a comprehensive depiction of the dynamic interplay between central and peripheral systems during balance regulation. Hence, RM-TR analysis is uniquely positioned to highlight distinct sway dynamics caused by visual feedback or somatosensory deficits [13], [38], offering heightened sensitivity compared to traditional CoP parameters and aiding in monitoring fall risk in aging populations [18]. Additionally, interpreting time-domain parameters often requires considering evidence from other aspects of postural control. Performing spectral analysis and exploring the structural characteristics of CoP signals can further deepen our understanding of postural stability. To achieve a more comprehensive and nuanced understanding of postural control in individuals, it is necessary to examine both traditional CoP parameters and RM-TR components from the perspective of their frequency-domain characteristics [38].

Emerging research has demonstrated significant alterations in neural activity under SD conditions among elderly individuals, including expanded oscillatory activity in the α, β, and γ frequency bands and increased α activity, which are indicative of age-related sensory processing shifts [44]. Despite these findings, significant gaps remain in understanding not simply how elderly individuals regulate posture under SD, but also whether the postural control shifts more heavily to central mechanisms versus the peripheral system under SD, and these underlying mechanisms remain obscured when using traditional measures of CoP. Thus, this study leverages RM-TR analysis to identify postural control adaptations uniquely and capture these differences more effectively influenced by SD, with a particular focus on the elderly population. By doing so, it aims to clarify how postural control strategy is modulated to compensate for limited visual inputs created by SD, and to uncover previously unrecognized differences in reliance on central versus peripheral mechanisms between younger and elderly individuals. The findings will support the development of targeted interventions for elderly fall prevention and balance training.

In light of these considerations, we propose the following hypotheses:

H1. SD could exacerbate postural control challenges, inducing significant changes in CoP parameters.

H2. Younger and older individuals could exhibit differing adaptive capacities and postural control strategies under SD, with older individuals facing greater difficulty in maintaining stability due to sensory degradation and slower compensatory responses.

2. Materials and Methods

2.1 Sample Size Calculation

In this study, we determined the required sample size as specified in the experimental design using G*Power (Version 3.1.9, Heinrich Heine University Düsseldorf, Germany). Specifically, for the group-by-condition interaction, the effect size was estimated to be large ($\eta^2 = 0.21$) based on the findings from previous research examining similar effects of SD on static postural control [30]. Using a significance level of $\alpha = 0.05$ and a desired statistical power of $1 - \beta = 0.95$, the sample size calculation indicated a minimum of 16 participants in total. To account for a potential 20% rate of invalid samples, we increased the target sample size to 20 participants.

2.2 Participants

This study recruited eligible participants from schools and communities through posters and on-site visits from January to March 2025. Inclusion criteria in the young group are participants aged 18 to 35 years, and in the elderly group are participants aged ≥ 55 years [47]. Regardless of age, individuals were excluded from participation if they were unable to stand or walk without an assistive device or suffered from orthopedic disorders, spinal stenosis, inflammatory rheumatic diseases, musculoskeletal pain, or neuropathic pain, as well as cardiopulmonary, musculoskeletal, somatosensory, psychiatric, or neurological disorders associated with a high risk of falls, such as stroke, Parkinson's disease, muscular dystrophy, epilepsy, or Alzheimer's disease. Additional exclusion criteria included severe visual and vestibular loss (e.g., glaucoma or cataracts), ophthalmic disorders, obesity (body mass index ≥30), surgery within the last 12 months, endoprosthetic care, or a leg length discrepancy exceeding 1 cm. Participants were also excluded if they were taking medications associated with an increased risk of falls (e.g., hypnotics, antiepileptics, or antidepressants), had impaired cognition (Montreal Cognitive Assessment Basic score ≤26), or were unable to complete the experiment as required by the tester.

A total of 40 participants (20 young and 20 elderly) who met the inclusion criteria were initially recruited. However, due to scheduling conflicts and equipment failure, data from five young participants were not successfully collected and were excluded from the formal analysis. Finally, 35 participants (15 young and 20 elderly) participated in this study, and their data were used for analysis. The basic inputs of the participants are detailed in Table 1. All participants signed informed consent and were thoroughly familiarized with the study design. This study was approved by the Ethics Committee of Soochow University (SUDA20250108H03).

Table 1. Mean ± standard deviation for variables in the young and elderly groups.

Variables	Young (n=15)	Elderly (n=20)
Age (year)	23.0±6.2	60.0±3.4
Sex (M/F)	8/7	8/12
Height (m)	1.70±0.07	1.62±0.06
Weight (kg)	64.9±11.4	64.0±7.2
BMI (kg/m^2)	22.4±3.0	24.5±2.03
MoCA-B (score)	28.7±1.1	28.2±1.2

Abbreviation: M: male, F: female, BMI: body mass index; MoCA: Montreal Cognitive Assessment-Basic (MoCA-B)

2.3 Center-of-Pressure Recording and Data Extraction

One force plate (Type: 9281, Kistler Instruments Inc., Switzerland) was used to collect CoP trajectory at a sampling rate of 1000 Hz. This study used a frame with stroboscopic function that can attach to glasses to create SD (Type: GS06, Queling Sports, China), which can ensure the standard implementation of visual disturbances. SD was achieved using the Reflex Glasses mobile app set at 3 Hz, alternating between 0.10 s transparency and 0.23 s opacity. This configuration has been demonstrated to be effective in limiting visual information input [20], [30].

For the bipedal standing task, participants stood with both legs and bare feet on the force plate. Their feet were shoulder-width apart and pointing forward. All participants were asked to maintain this stance as still as possible for 60 s with arms akimbo in a neutral position, facing straight ahead, and they were asked to gaze at a fixed target, at eye level, 5 m in front of them. When performing a bipedal standing test under strobe vision, it is necessary to wear strobe glasses and maintain other testing actions unchanged. They need to complete the bipedal standing task under two visual conditions (transparency and stroboscopic). Three successful trials in each condition were conducted for every participant. A rest period of at least one minute between consecutive conditions was used to prevent fatigue, and the order of visual conditions was randomized.

For the CoP trajectory collected from the bipedal standing task, the first and the last 10 s were excluded, and only the middle 40 s were evaluated and processed, which represent the stable posture. The data were then filtered with a low-pass 4th-order Butterworth filter by Vicon Nexus (Version: 2.16.0, Vicon, UK) with a cutoff frequency of 5 Hz. Downsampling to 100 Hz and extracting relevant indicators using the code written based on MATLAB (Version: 2023a, MathWorks, Inc., Natick, MA, USA). For each of the CoP trajectory and ground reaction force (GRF) in Medial-Lateral (ML) (Figure 1a), Anterior-Posterior (AP) (Figure 1b), and Resultant Spatial (RS) (Figure 1c) directions were extracted [29]. The CoP trajectory and GRF values in the RS direction are calculated based on the corresponding values in the ML and AP directions, and the specific formula is as follows:

$$CoP_{rs} = \sqrt{{CoP_{ML}}^2 + {CoP_{AP}}^2}$$

$$GRF_{rs} = \sqrt{{GRF_{ML}}^2 + {GRF_{AP}}^2}$$

In order to eliminate the potential influences of individual differences on the results, value extracted from every frame of CoP trajectories were baseline-adjusted using the first frame and normalized by individual height (meters) directly.

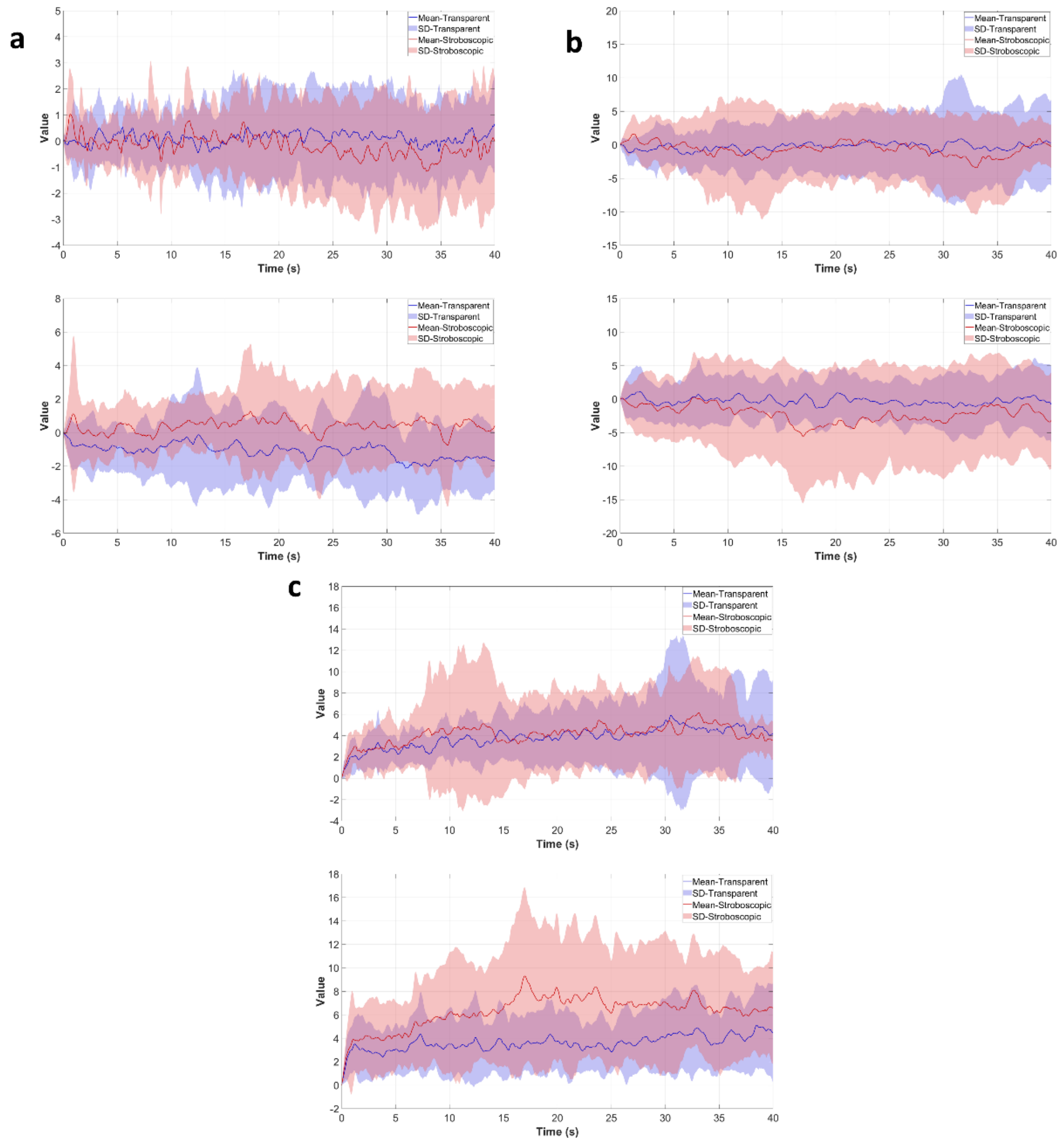

Figure 1. Temporal changes in CoP trajectories under transparent and stroboscopic vision conditions for young (upper) and elderly (lower) groups in (a) ML, (b) AP, and (c) RS directions.

2.4 Data analysis

Traditional time-domain and frequency-domain parameters were initially calculated. Subsequently, CoP trajectories in the three directions were decomposed into RM and TR components using the method proposed by Zatsiorsky and Duarte [49], enabling the calculation of their respective time-domain and frequency-domain parameters. This decomposition adheres to the following formula:

$$CoP_{total} = CoP_{rambling} + CoP_{trembling}$$

The RM component was derived by determining the instant equilibrium point trajectory, achieved by identifying zero-force points and interpolating these using a piecewise cubic Hermite polynomial. This trajectory reflects postural equilibrium adjustments. The TR component was calculated as the difference between the CoP and the RM components. Illustrations of the decomposed components for both groups under different vision conditions are presented in Figures 2 and 3.

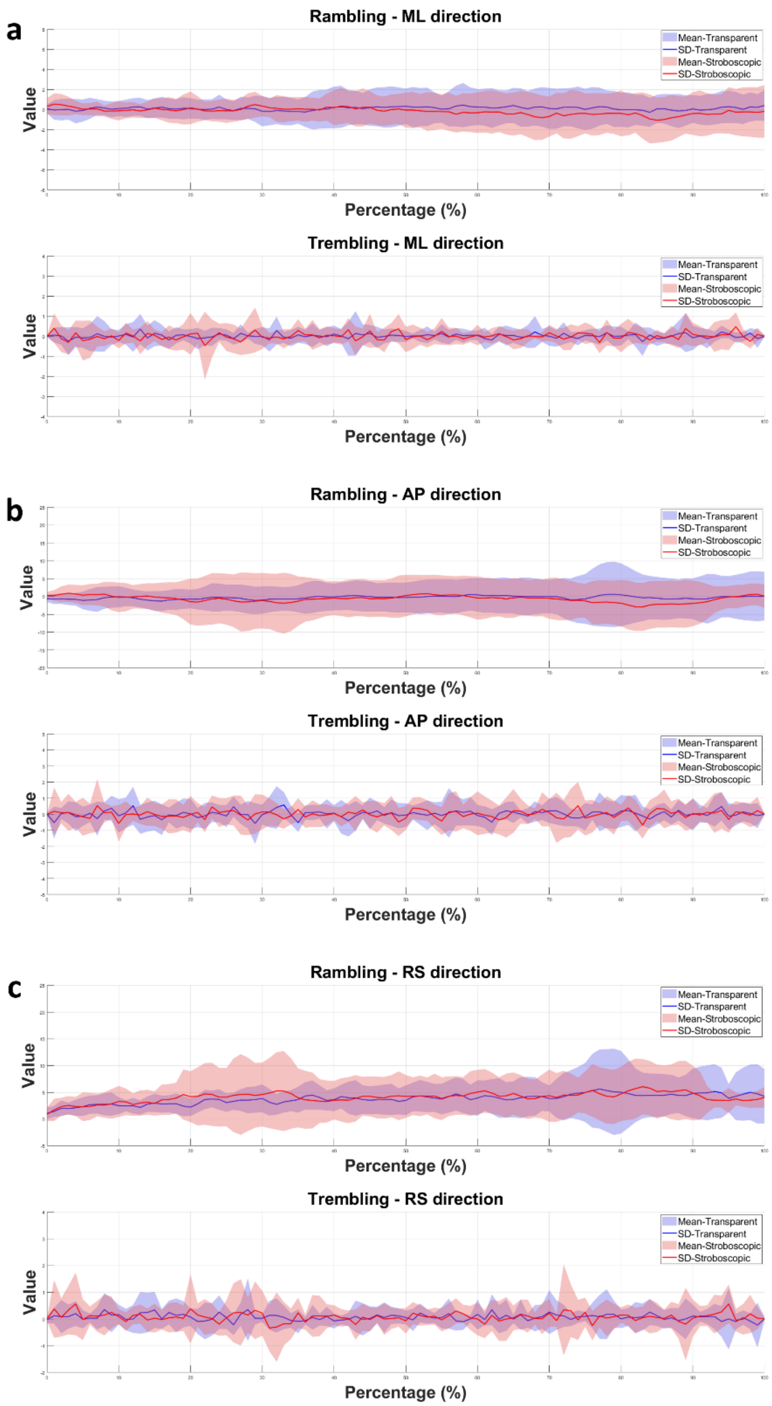

Figure 2. The decomposed components of CoP for the young group in (a) ML, (b) AP, and (c) RS directions.

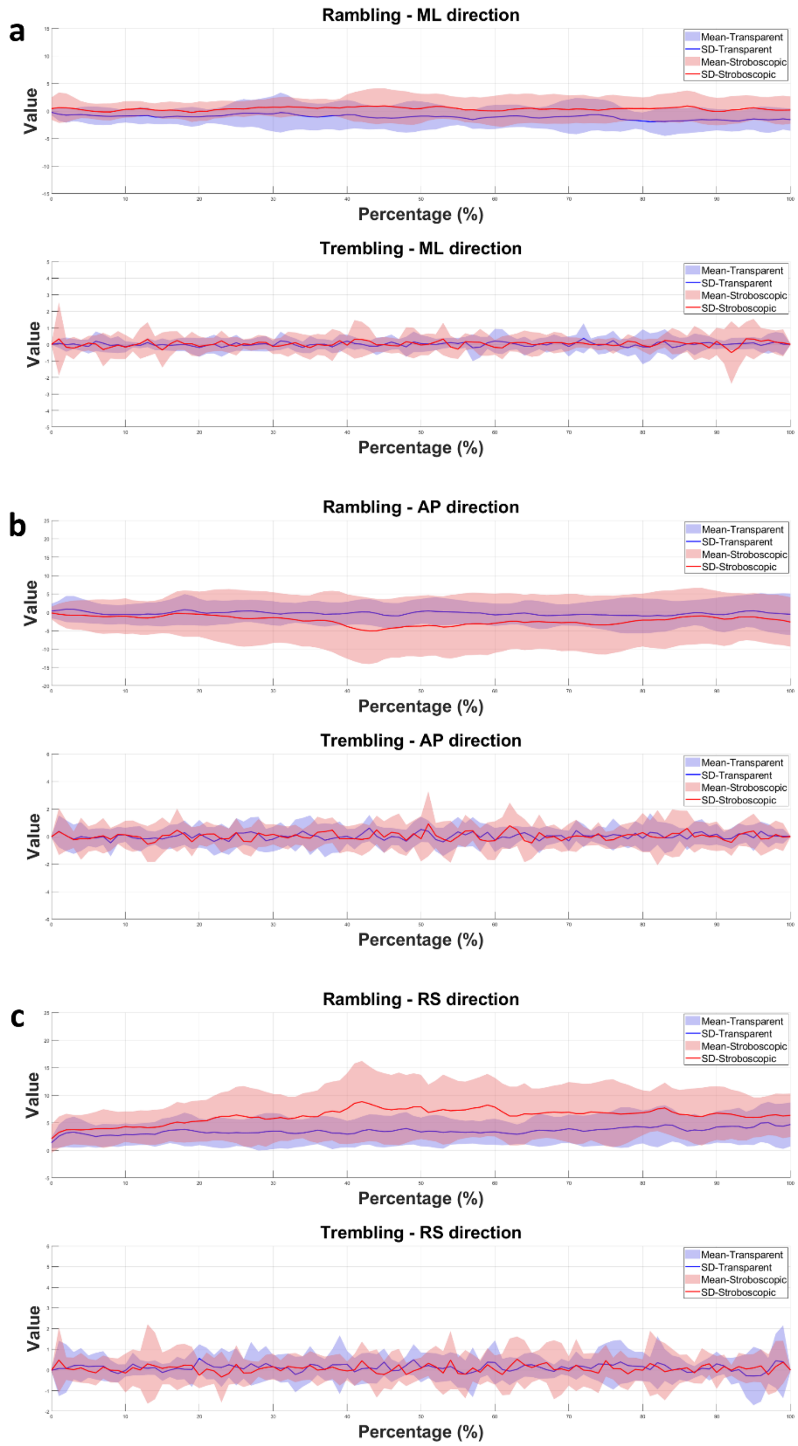

Figure 3. The decomposed components of CoP for the elderly group in (a) ML, (b) AP, and (c) RS directions.

2.5 Time-domain parameters

The parameters that can fully reflect the static posture control characteristics of the human body are selected for analysis [17], [38]. The time-domain parameters included: (I) mean sway distance: the average distance displaced by the CoP; (II) sway range: the maximum Euclidean distance between any two points on the CoP path; (III) pathlength: the cumulative distance covered by the CoP, calculated as the sum of distances between consecutive points on the CoP path; (IV) mean velocity: The average velocity of CoP displacement, computed as the total pathlength divided by the duration of the observation; (V) root mean square (RMS) of sway: the square root of the mean of the squared deviations of the CoP displacement from the first frame; (VI) The 95% confidence circle area: the area of a circle with a radius corresponding to the one-sided 95% confidence limit of the resultant CoP displacement time series; (VII) 95% confidence ellipse area: the area of the 95% bivariate confidence ellipse; (VIII) sway area: the total area enclosed by summing the areas of triangles formed by two consecutive points on the CoP path and the mean CoP position. Higher values of time domain parameters in this study suggested increased difficulty in CoP control. Calculation of the 95% confidence circle area, the 95% confidence ellipse area, and the sway area was not performed in the RM-TR analysis.

2.6 Frequency-domain parameters

The frequency-domain parameters, which were measured using a power spectral density (PSD) based on Welch's algorithm was used with a resolution of 0.024 Hz, included: (I) mean frequency (MF): the average frequency of the signal (Hz); (II) 80% power frequency (F80): the frequency below which 80% of the total power is concentrated (Hz), which was chosen as it is suggested best to characterize the modifications of the postural control system; (III) total power (TP): the integrated area under the power spectrum curve, providing a measure of the signal's overall energy (Hz); (IV) frequency dispersion (FD): a dimensionless measure that quantifies the variability in the frequency distribution of the PSD and (V) the frequency at which the spectral mass is concentrated (CF) is defined as the square root of the ratio of the second spectral moment to the zeroth spectral moment (Hz)

2.7 Statistical Analysis

The mean of the three trials per participant was used for further statistical analyses. A series of linear mixed-effect regression (LMER) models were used for statistical analysis, which are robust to violations of normality. Separate models compared time-domain and frequency-domain parameters with fixed-effects of group (young (reference condition), elderly) and vision (transparent (reference condition), stroboscopic), and random-effects to account for the within-participant manipulations. We conducted statistical analyses using RStudio and the lmerTest package [6]. The significance threshold for all statistical analyses was set at $\alpha = 0.05$. The unstandardized beta coefficient (β) for the fixed factors (i.e., Transparent vs. Stroboscopic) and the interaction term (group × vision) was reported, along with the corresponding significance level (p-value) and effect size (Hedge's g). Corrected effect sizes were interpreted as small at 0.20, medium at 0.50, and large at 0.80 [11].

3. Results

3.1 Traditional time-domain parameters

Table 2 summarizes the LMER analysis results for traditional time-domain parameters. A significant group effect was observed for the mean sway distance in the ML direction (β = -1.215, p = 0.027); however, post-hoc comparisons did not reveal statistically significant differences between groups (p = 0.390, g = 0.20).

Significant vision effects were identified for several parameters, including the range of sway in the AP direction (β = 3.18, p = 0.049), pathlength in the ML (β = 15.21, p = 0.009), AP (β = 27.87, p = 0.004), and RS (β = 20.88, p = 0.032) directions; sway velocity in the ML (β = 0.38, p = 0.009), AP (β = 0.70, p = 0.004), and RS (β = 0.52, p = 0.032) directions; and sway area (β = 58.67, p = 0.003). Post-hoc comparisons confirmed significant differences between the two vision conditions for all these parameters: sway range in the AP direction (p < 0.001, g = 0.63), pathlength in all three directions (all p < 0.001, g = 0.31 (ML), g =0.53 (AP), g = 0.55(RS), respectively), sway velocity in all three directions (all p < 0.001, g = 0.31(ML), g =0.53(AP), g = 0.55(RS), respectively), and sway area (p < 0.001, g = 0.42). Across these parameters, stroboscopic vision elicited significantly greater values compared to transparent vision.

Significant Group × Vision interaction effects were also observed for several parameters. These included mean sway distance in the ML (β = 1.77, p = 0.023) and RS (β = 2.33, p = 0.012) directions, the sway range in the RS direction (β = 3.39, p = 0.033), RMS of sway in the RS direction (β = 0.94, p = 0.017), 95% confidence circle area (β = 58.87, p = 0.029), and 95% confidence ellipse area (β = 33.59, p = 0.039). Post-hoc analyses revealed that these interactions were primarily driven by the elderly group's heightened sensitivity to vision condition changes. Specifically, when transitioning from transparent to stroboscopic vision, the elderly group exhibited significantly increased mean sway distance in the ML (p = 0.005, g = 0.95) and RS (p < 0.001, g = 1.48) directions (Figure 4a and 4b), significantly greater range (p < 0.001, g = 1.71) and RMS of sway (p < 0.001, g = 1.46) in the RS direction (Figure 4c and 4d), and significantly larger confidence circle and ellipse areas (p = 0.001, g = 1.11; p < 0.001, g = 1.49, respectively) (Figure 4e and 4f), with all effects exhibiting large effect sizes (g > 0.8).

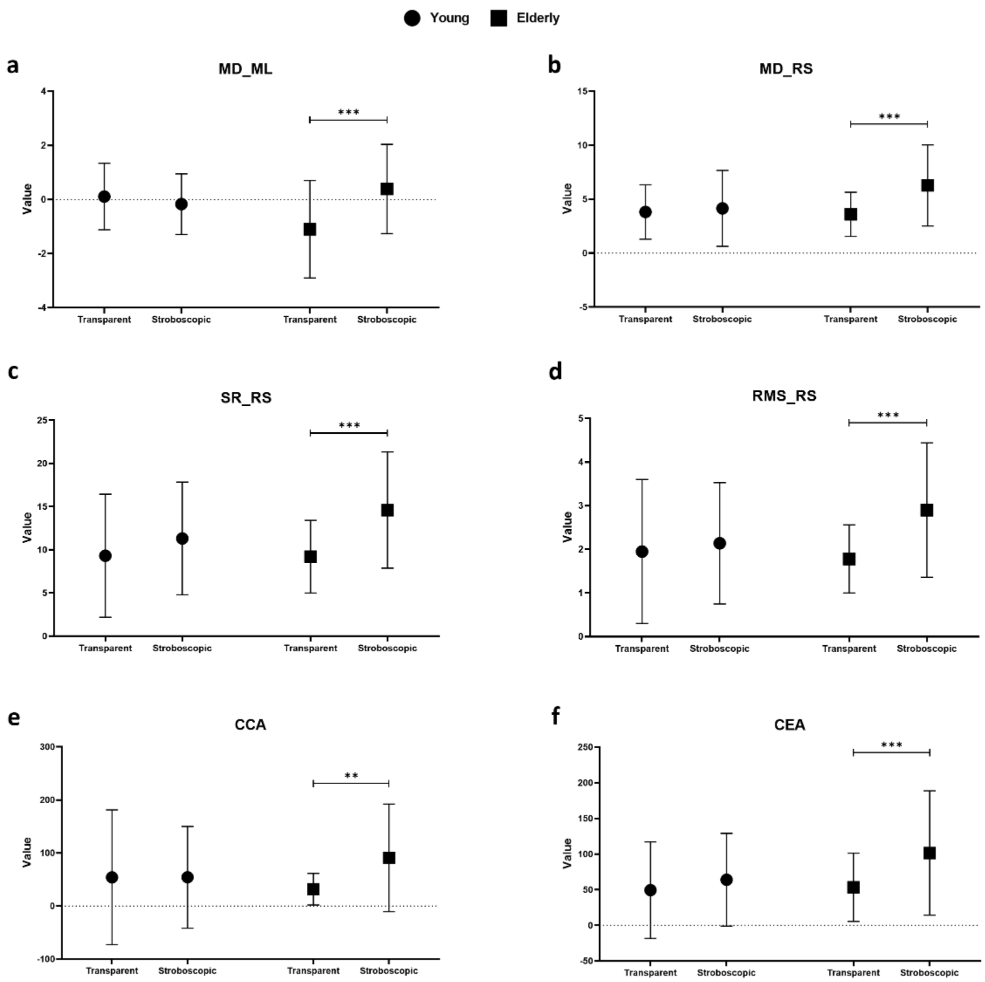

Figure 4. Post hoc comparisons of the interaction effects between group and vision on the traditional time-domain parameters: (a) MD_ML, (b) MD_RS, (c) SR_RS, (d) RMS_RS, (e) CCA, and (f) CEA.

Table 2. Comparison of time domain parameters for the center of pressure (CoP) between young and elderly groups during bipedal standing under transparent and stroboscopic visions. Shown are the mean ± standard deviation for each variable.

Variables	Young (n=15)		Elderly (n=20)	
	Transparent	Stroboscopic	Transparent	Stroboscopic
MD_ML [ac]	0.11±1.23	-0.17±1.12	-1.10±1.80	0.39±1.65
MD_AP	-0.29±3.93	-0.65±4.66	-0.27±2.84	-2.21±6.40
MD_RS [c]	3.81±2.52	4.14±3.52	3.60±2.04	6.27±3.76
SR_ML	5.26±3.16	6.66±3.49	6.43±4.18	8.44±6.04
SR_AP [b]	12.55±7.98	15.73±7.81	12.59±4.30	17.72±6.93
SR_RS [c]	9.31±7.13	11.31±6.53	9.20±4.21	14.59±6.73
Pathlength_ML [b]	100.59±51.16	115.80±59.78	100.76±26.93	113.17±40.89
Pathlength_AP [b]	151.40±52.23	179.27±60.36	159.28±42.99	189.14±60.71
Pathlength_RS [b]	141.14±48.49	162.02±61.00	141.42±34.58	175.35±59.62
MV_ML [b]	2.52±1.28	2.90±1.49	2.52±0.67	2.83±1.02
MV_AP [b]	3.79±1.31	4.48±1.51	3.98±1.08	4.73±1.52
MV_RS [b]	3.53±1.21	4.05±1.53	3.54±0.86	4.38±1.49
RMS_ML	0.90±0.60	1.12±0.49	1.15±0.85	1.53±0.97
RMS_AP	2.53±1.90	2.93±1.62	2.44±0.85	3.39±1.50
RMS_RS [c]	1.95±1.65	2.14±1.39	1.78±0.78	2.90±1.54
CCA [c]	54.16±126.96	54.28±95.85	31.79±29.85	90.77±101.47
CEA [c]	49.42±67.75	63.93±65.00	53.51±47.87	101.62±87.20
SA [b]	163.33±229.92	222.00±265.69	149.33±102.96	251.04±193.93

Abbreviation: MD: mean sway distance, ML: medial-lateral, AP: anterior-posterior, RS: resultant spatial, SR: sway range, MV: mean velocity, RMS: root mean square of sway, CCA: 95% confidence circle area, CEA: 95% confidence ellipse area, SA: sway area.

Note: In the ML direction, positive values represent medial movement, while negative values represent lateral movement; In the AP direction, positive values represent the anterior movement, while negative values represent the posterior movement. Results from LMER showed a) an effect of group, b) an effect of vision, and c) an interaction effect of group × vision.

3.2 Traditional frequency-domain parameters

Table 3 displays the LMER analysis results for traditional frequency-domain parameters. No significant main effects for either group or vision were observed.

Significant Group × Vision interaction effects were identified for several parameters: MF in the AP (β = -0.06, p = 0.003) and RS (β = -0.02, p = 0.044) directions; F80 in the AP direction (β = -0.09, p = 0.002); FD in the AP (β = -0.05, p = 0.015) and RS (β = -0.03, p = 0.029) directions; and CF in the AP (β = -0.07, p = 0.007) and RS (β = -0.04, p = 0.031) directions. Post-hoc analyses revealed that these interaction effects were predominantly attributed to the elderly group's response to visual condition changes. Under stroboscopic vision, the elderly group reported significantly reduced MF in the AP (p = 0.003, g = 1.02) and RS (p = 0.027, g = 0.73) directions (Figure 5a and 5b), F80 in the AP direction (p = 0.003, g = 1.03) (Figure 5c), FD in the AP (p = 0.005, g = 0.95) and RS (p = 0.010, g = 0.87) directions (Figure 5d and 5e), and CF in the AP (p = 0.004, g = 0.99) and RS (p = 0.012, g = 0.84) directions (Figure 5f and 5g). All these results were associated with medium to large effect sizes. Conversely, the young group exhibited statistically insignificant increases across these parameters.

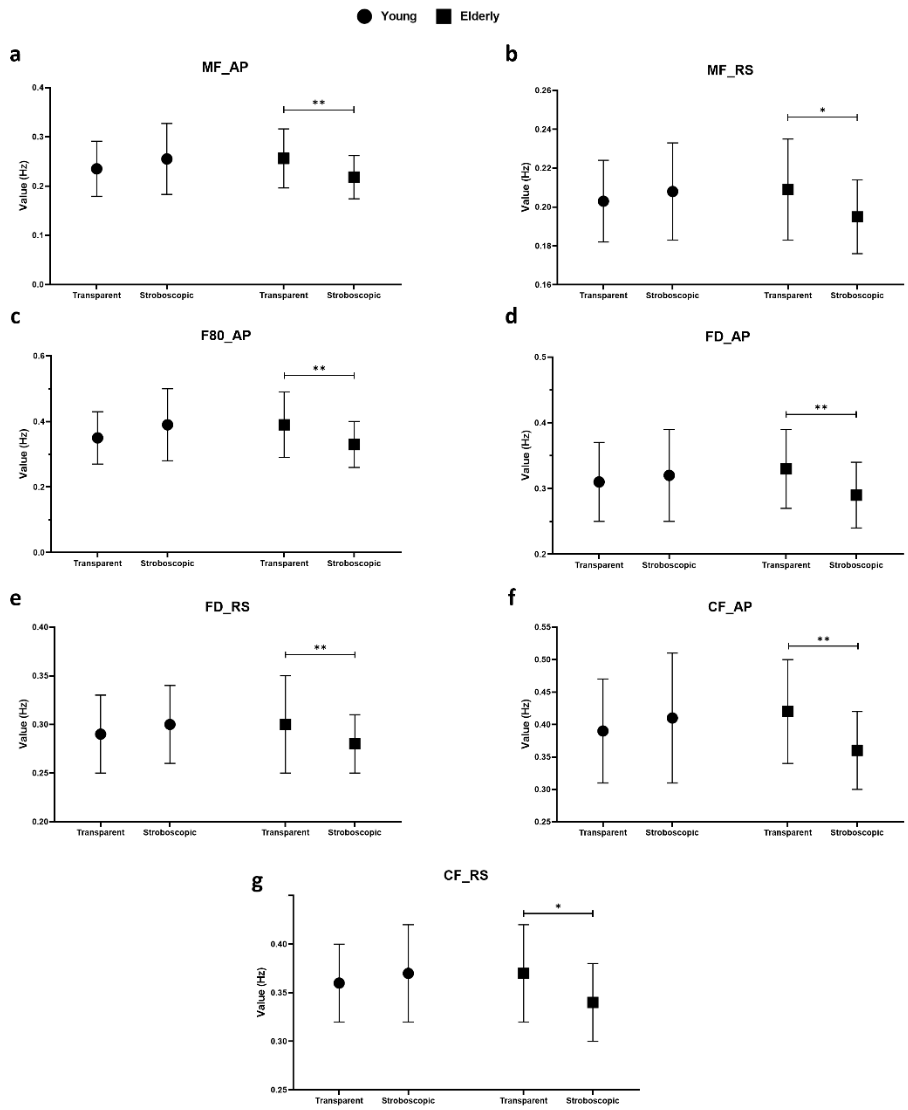

Figure 5. Post hoc comparisons of the interaction effects between group and vision on the traditional frequency-domain parameters: (a) MF_AP, (b) MF_RS, (c) F80_AP, (d) FD_AP, (e) FD_RS, (f) CF_AP, and (g) CF_RS.

Table 3. Comparison of frequency domain parameters for the center of pressure (CoP) between young and elderly groups during bipedal standing under transparent and stroboscopic visions. Shown are the mean ± standard deviation for each variable.

Variables	Young (n=15)		Elderly (n=20)	
	Transparent	Stroboscopic	Transparent	Stroboscopic
MF_ML (Hz)	0.35±0.12	0.32±0.10	0.29±0.12	0.27±0.08
MF_AP (Hz) [c]	0.24±0.06	0.26±0.07	0.26±0.06	0.22±0.04
MF_RS (Hz) [c]	0.20±0.02	0.21±0.03	0.21±0.03	0.20±0.02
F80_ML (Hz)	0.54±0.21	0.48±0.18	0.44±0.20	0.40±0.13
F80_AP (Hz) [c]	0.35±0.08	0.39±0.11	0.39±0.10	0.33±0.07
F80_RS (Hz)	0.30±0.02	0.31±0.03	0.31±0.02	0.30±0.02
TP_ML ($\times 10^2$)	1.07±2.09	1.37±1.60	2.62±4.19	2.45±3.00
TP_AP ($\times 10^2$)	9.91±19.76	13.38±32.95	5.82±6.18	23.92±30.48
TP_RS ($\times 10^2$)	10.98±19.84	14.75±33.46	8.44±9.37	26.38±30.63
FD_ML (Hz)	0.46±0.13	0.44±0.11	0.40±0.12	0.37±0.11
FD_AP (Hz) [c]	0.31±0.06	0.32±0.07	0.33±0.06	0.29±0.05
FD_RS (Hz) [c]	0.29±0.04	0.30±0.04	0.30±0.05	0.28±0.03
CF_ML (Hz)	0.57±0.18	0.54±0.14	0.50±0.17	0.46±0.14
CF_AP (Hz) [c]	0.39±0.08	0.41±0.10	0.42±0.08	0.36±0.06
CF_RS (Hz) [c]	0.36±0.04	0.37±0.05	0.37±0.05	0.34±0.04

Abbreviation: MF: mean frequency, ML: medial-lateral, AP: anterior-posterior, RS: resultant spatial, F80: 80% power frequency, TP: total power, FD: frequency dispersion, CF: concentrated frequency.

Note: In the ML direction, positive values represent medial movement, while negative values represent lateral movement; In the AP direction, positive values represent the anterior movement, while negative values represent the posterior movement. Results from LMER showed c) an interaction effect of group × vision.

3.3 RM time-domain parameters

Table 4 reports the LMER analysis results for RM time-domain parameters. No significant group effects were observed. However, vision significantly influenced several parameters, including pathlength in the ML ($\beta = 4.75$, $p = 0.045$) and AP ($\beta = 10.68$, $p = 0.014$) directions, and sway velocity in the AP direction ($\beta = 0.26$, $p = 0.017$). Post-hoc analyses revealed statistically significant differences across vision conditions for each of these parameters: pathlength in the ML direction ($p = 0.005$, $g = 0.28$), pathlength in the AP direction ($p < 0.001$, $g = 0.66$), and sway velocity in the AP direction ($p < 0.001$, $g = 0.66$). In all cases, stroboscopic vision induced significantly higher values compared to transparent vision.

Additionally, significant Group × Vision interaction effects were observed for the mean sway distance in the RS direction ($\beta = 2.42$, $p = 0.011$) and RMS of sway in the RS direction ($\beta = 0.80$, $p = 0.045$). Post-hoc analyses indicated that these interactions were primarily attributable to the elderly group's greater response to vision condition changes. Specifically, under stroboscopic vision, the elderly group exhibited significantly greater mean sway distance ($p < 0.001$, $g = 0.53$; medium to large effect size) and RMS of sway ($p < 0.001$, $g = 0.14$; small effect size) (Figure 6a and 6b).

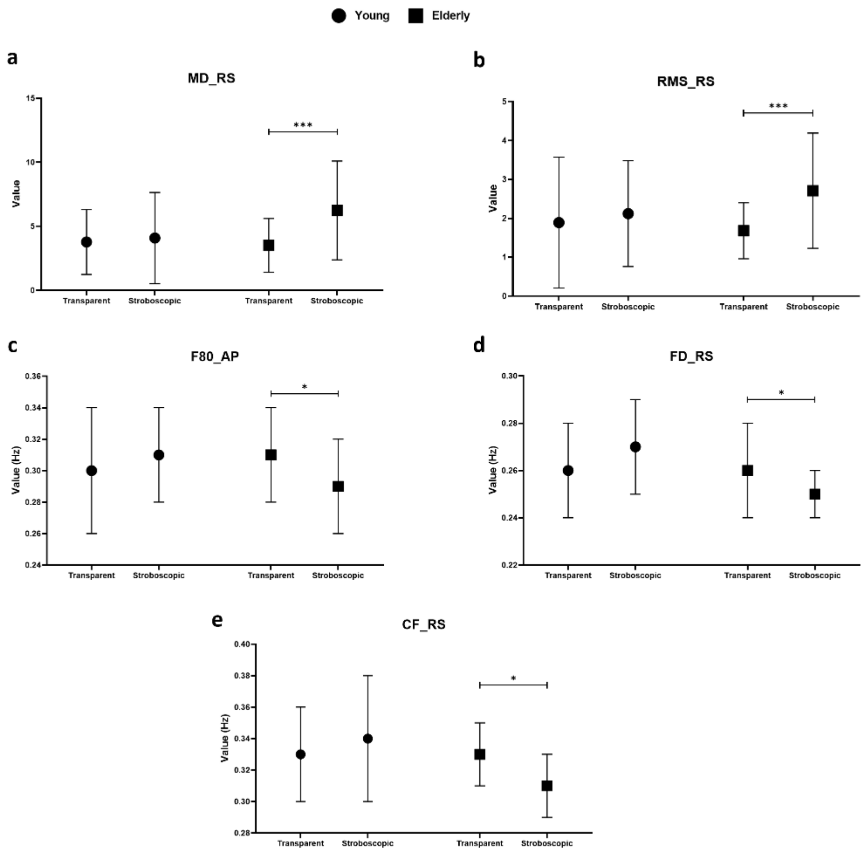

Figure 6. Post hoc comparisons of the interaction effects between group and vision on rambling time- and frequency-domain parameters: (a) MD_RS, (b) RMS_RS, (c) F80_AP, (d) FD_RS, and (e) CF_RS.

Table 4. Comparison of time domain parameters for the Rambling (RM) component between young and elderly groups during bipedal standing under transparent and stroboscopic visions. Shown are the mean ± standard deviation for each variable.

Variables	Young (n=15)		Elderly (n=20)	
	Transparent	Stroboscopic	Transparent	Stroboscopic
MD_ML	0.11±1.24	-0.17±1.41	-1.10±1.81	0.37±1.64
MD_AP	-0.32±3.92	-0.68±4.71	-0.30±2.83	-2.23±6.46
MD_RS [c]	3.77±2.53	4.08±3.56	3.51±2.10	6.24±3.86
SR_ML	3.61±2.39	4.54±1.82	4.84±3.27	6.06±3.62
SR_AP	10.06±7.47	11.69±7.28	9.83±4.01	13.78±5.62
SR_RS	8.62±7.29	11.07±5.95	8.39±3.74	12.50±5.66
Pathlength_ML [b]	40.35±15.59	45.10±14.28	45.35±16.56	49.73±17.94
Pathlength_AP [b]	68.07±21.29	78.76±28.51	70.61±14.45	87.65±21.26
Pathlength_RS	98.14±37.55	107.50±41.10	84.50±19.20	105.15±35.32
MV_ML	1.02±0.40	1.14±0.36	1.15±0.42	1.27±0.46
MV_AP [b]	1.73±0.53	2.00±0.72	1.79±0.36	2.22±0.54
MV_RS	2.49±0.96	2.73±1.03	2.15±0.49	2.67±0.91
RMS_ML	0.75±0.58	0.93±0.42	0.98±0.77	1.30±0.82
RMS_AP	2.23±1.91	2.55±1.61	2.11±0.84	2.97±1.45
RMS_RS [c]	1.89±1.68	2.12±1.36	1.68±0.72	2.71±1.48

Abbreviation: MD: mean sway distance, ML: medial-lateral, AP: anterior-posterior, RS: resultant spatial, SR: sway range, MV: mean velocity, RMS: root mean square of sway.

Note: In the ML direction, positive values represent medial movement, while negative values represent lateral movement; In the AP direction, positive values represent the anterior movement, while negative values represent the posterior movement. Results from LMER showed b) an effect of vision, and c) an interaction effect of group × vision.

3.4 RM frequency-domain parameters

Table 5 outlines the LMER analysis results for RM frequency-domain parameters. While no significant group and vision effects were observed.

Group × Vision interaction effects were significant for several parameters, including MF in the RS direction (β = -0.01, p = 0.047); F80 in the AP (β = -0.03, p = 0.046) and RS (β = -0.02, p = 0.044) directions; FD in the RS direction (β = -0.02, p = 0.041); and CF in the RS direction (β = -0.02, p = 0.041). Post-hoc analyses highlighted that these interactions were mostly driven by the elderly group's responses to vision changes, except in the case of MF and F80, in the RS direction, which showed no significant change (p = 0.055, p = 0.150). Specifically, under stroboscopic vision, the elderly group exhibited significantly reduced F80 in the AP direction (p = 0.035, g = 0.69) (Figure 6c), FD in the RS direction (p = 0.037, g = 0.69) (Figure 6d), and CF in the RS direction (p = 0.042, g = 0.67) (Figure 6e). All these results were associated with medium to large effect sizes. Conversely, the younger group showed marginal and statistically nonsignificant increases in these measures.

Table 5. Comparison of frequency domain parameters for the Rambling (RM) between young and elderly groups during bipedal standing under transparent and stroboscopic visions. Shown are the mean ± standard deviation for each variable.

Variables	**Young (n=15)**		**Elderly (n=20)**	
	Transparent	**Stroboscopic**	**Transparent**	**Stroboscopic**
MF_ML (Hz)	0.23±0.06	0.22±0.03	0.22±0.05	0.21±0.05
MF_AP (Hz)	0.19±0.03	0.20±0.02	0.20±0.02	0.19±0.02
MF_RS (Hz) [c]	0.19±0.02	0.20±0.02	0.19±0.02	0.18±0.02
F80_ML (Hz)	0.35±0.09	0.33±0.05	0.33±0.06	0.33±0.08
F80_AP (Hz) [c]	0.30±0.04	0.31±0.03	0.31±0.03	0.29±0.03
F80_RS (Hz) [c]	0.30±0.02	0.31±0.04	0.30±0.02	0.29±0.02
TP_ML (×10^2)	0.96±2.09	1.16±1.44	2.42±3.95	2.02±2.68
TP_AP (×10^2)	9.11±18.40	12.90±33.89	5.11±5.78	23.18±30.66
TP_RS (×10^2)	10.61±19.26	14.82±34.40	7.91±9.22	26.01±31.22
FD_ML (Hz)	0.31±0.06	0.30±0.04	0.29±0.05	0.28±0.06
FD_AP (Hz)	0.26±0.02	0.26±0.02	0.26±0.01	0.25±0.01
FD_RS (Hz) [c]	0.26±0.02	0.27±0.03	0.26±0.02	0.25±0.01
CF_ML (Hz)	0.38±0.08	0.37±0.05	0.36±0.07	0.35±0.08
CF_AP (Hz)	0.32±0.03	0.32±0.02	0.33±0.02	0.31±0.02
CF_RS (Hz) [c]	0.33±0.03	0.34±0.04	0.33±0.02	0.31±0.02

Abbreviation: MF: mean frequency, ML: medial-lateral, AP: anterior-posterior, RS: resultant spatial, F80: 80% power frequency, TP: total power, FD: frequency dispersion, CF: concentrated frequency.

Note: In the ML direction, positive values represent medial movement, while negative values represent lateral movement; In the AP direction, positive values represent the anterior movement, while negative values represent the posterior movement. Results from LMER showed b) an effect of vision, and c) an interaction effect of group × vision.

3.5 TR time-domain parameters

Table 6 presents the LMER analysis results for TR time-domain parameters. No significant group effect and group × vision interaction effect were observed. However, vision significantly influenced several parameters, including the sway range in the AP ($\beta = 1.41$, $p = 0.035$) and RS ($\beta = 1.18$, $p = 0.040$) directions, pathlength in the ML ($\beta = 13.44$, $p = 0.012$), AP ($\beta = 10.68$, $p = 0.014$), and RS ($\beta = 20.57$, $p = 0.002$) directions, sway velocity in the ML ($\beta = 0.33$, $p = 0.017$), AP ($\beta = 0.58$, $p = 0.011$), and RS ($\beta = 0.52$, $p = 0.002$) directions, and RMS of sway in the RS direction ($\beta = 0.14$, $p = 0.016$).

Post-hoc comparisons confirmed significantly higher parameter values under stroboscopic vision than transparent vision. Notably, significant differences were observed for sway range in the AP ($p < 0.001$, $g = 0.69$) and RS ($p = 0.003$, $g = 0.48$) directions; pathlength in the ML, AP, and RS directions (all $p < 0.01$, $g = 0.28$ (ML), $g = 0.45$ (AP), $g = 0.47$ (RS), respectively); sway velocity in the ML, AP, and RS directions (all $p < 0.001$, $g = 0.29$ (ML), $g = 0.44$ (AP), $g = 0.47$ (RS), respectively); and RMS of sway in the RS direction ($p < 0.001$, $g = 0.41$).

Table 6. Comparison of time domain parameters for the Trembling (TR) component between young and elderly groups during bipedal standing under transparent and stroboscopic visions. Shown are the mean ± standard deviation for each variable.

Variables	Young (n=15)		Elderly (n=20)	
	Transparent	Stroboscopic	Transparent	Stroboscopic
MD_ML	0.01±0.03	0.01±0.03	0.00±0.04	0.02±0.05
MD_AP	0.01±0.03	0.01±0.05	0.02±0.05	0.01±0.05
MD_RS	0.06±0.06	0.08±0.11	0.11±0.11	0.07±0.11
SR_ML	3.44±2.54	4.16±2.47	3.34±1.62	4.70±3.84
SR_AP [b]	5.14±1.67	6.55±1.91	5.45±1.51	7.17±3.34
SR_RS [b]	4.09±1.39	5.27±2.11	4.99±2.48	6.15±3.07
Pathlength_ML [b]	85.75±47.24	99.19±55.43	83.61±20.23	92.86±32.56
Pathlength_AP [b]	115.89±46.36	139.50±52.12	123.77±42.60	144.78±55.84
Pathlength_RS [b]	92.91±37.63	113.47±48.97	104.06±32.11	122.95±46.33
MV_ML [b]	2.17±1.20	2.50±1.39	2.12±0.51	2.37±0.85
MV_AP [b]	2.95±1.17	3.53±1.31	3.14±1.07	3.67±1.41

MV_RS [b]	2.36±0.96	2.88±1.23	2.65±0.82	3.12±1.18
RMS_ML	0.41±0.25	0.50±0.28	0.44±0.21	0.59±0.40
RMS_AP	0.73±0.26	0.88±0.27	0.81±0.29	1.00±0.50
RMS_RS [b]	0.47±0.14	0.61±0.23	0.65±0.35	0.78±0.39

Abbreviation: MD: mean sway distance, ML: medial-lateral, AP: anterior-posterior, RS: resultant spatial, SR: sway range, MV: mean velocity, RMS: root mean square of sway.

Note: In the ML direction, positive values represent medial movement, while negative values represent lateral movement; In the AP direction, positive values represent the anterior movement, while negative values represent the posterior movement. Results from LMER showed b) an effect of vision.

3.6 TR frequency-domain parameters

Table 7 summarizes the LMER analysis results for TR frequency-domain parameters. No significant Group × Vision interaction effects were observed for these parameters. Significant group effects were observed for FD ($\beta = -0.11$, $p = 0.033$) and CF ($\beta = -0.15$, $p = 0.049$) in the RS direction, with post-hoc comparisons indicating that the young group had significantly higher values for these parameters compared with the elderly group ($p = 0.016$, $g = 0.74$; $p = 0.032$, $g = 0.66$, respectively).

Vision significantly influenced TP in the RS direction ($\beta = 7.82$, $p = 0.011$). Post-hoc comparisons confirmed that TP values were significantly greater under stroboscopic vision compared to transparent vision ($p < 0.001$, $g = 0.35$).

Table 7. Comparison of frequency domain parameters for the Trembling (TR) component between young and elderly groups during bipedal standing under transparent and stroboscopic visions. Shown are the mean ± standard deviation for each variable.

Variables	Young (n=15)		Elderly (n=20)	
	Transparent	Stroboscopic	Transparent	Stroboscopic
MF_ML (Hz)	0.90±0.20	0.91±0.20	0.83±0.18	0.78±0.23
MF_AP (Hz)	0.70±0.12	0.72±0.16	0.69±0.13	0.67±0.10
MF_RS (Hz)	0.83±0.21	0.81±0.16	0.73±0.19	0.72±0.14
F80_ML (Hz)	1.18±0.24	1.22±0.31	1.06±0.20	1.04±0.30
F80_AP (Hz)	0.98±0.18	1.02±0.24	0.98±0.20	0.95±0.15
F80_RS (Hz)	1.22±0.30	1.21±0.26	1.07±0.30	1.04±0.20
TP_ML	9.76±12.93	13.28±17.06	9.74±11.87	19.04±29.00
TP_AP	24.92±16.42	34.86±18.15	30.35±22.78	50.01±60.97

TP_RS [b]	9.67±5.53	17.49±11.29	21.87±27.44	31.16±33.15
FD_ML (Hz)	0.82±0.20	0.80±0.23	0.80±0.21	0.76±0.27
FD_AP (Hz)	0.62±0.14	0.58±0.13	0.56±0.10	0.55±0.07
FD_RS (Hz) [a]	0.81±0.18	0.77±0.14	0.70±0.17	0.65±0.12
CF_ML (Hz)	1.22±0.27	1.22±0.30	1.16±0.25	1.09±0.34
CF_AP (Hz)	0.93±0.18	0.93±0.20	0.89±0.15	0.86±0.11
CF_RS (Hz) [a]	1.17±0.26	1.12±0.21	1.01±0.25	0.97±0.18

Abbreviation: MF: mean frequency, ML: medial-lateral, AP: anterior-posterior, RS: resultant spatial, F80: 80% power frequency, TP: total power, FD: frequency dispersion, CF: concentrated frequency.

Note: In the ML direction, positive values represent medial movement, while negative values represent lateral movement; In the AP direction, positive values represent the anterior movement, while negative values represent the posterior movement. Results from LMER showed a) an effect of group, and b) an effect of vision.

4. Discussion

This study explored the influence of SD on CoP trajectory and its RM and TR components in individuals of different ages. We used transparent and stroboscopic vision conditions to input different volumes of visual information and analyze the role of visual dependence in the posture control of the elderly.

4.1 Effects of SD in the elderly during bipedal standing

Based on the above results, the emergence of SD led to significant changes in CoP control in both the AP and RS directions. Time-domain parameters primarily indicated an increase in CoP pathlength, sway velocity, and sway area, accompanied by greater sway range and variability in the TR component. These findings support ***H1***, confirming that SD substantially impacts human postural control strategies. Furthermore, the quantification of these indicators suggests that SD specifically increases instability and challenges in balance. This outcome aligns with prior research showing that partial visual occlusion impairs postural control during bipedal stance [45].

When SD was introduced, the discrepancies in CoP parameters between age groups became more pronounced. These results, consistent with ***H2***, preliminarily suggest that younger and older individuals employ differing postural control strategies under SD. A reduction in the circle or ellipse area of CoP sway is often interpreted as more efficient integration of multisensory inputs [24]. Our results corroborate this perspective. Elderly individuals, when faced with reduced visual input, exhibited a significant increase in 95% confidence circle and ellipse area, respectively; the RMS of CoP sway in the RS direction also increased, whereas younger displayed no such change. These findings are consistent with previous studies, where under the interference of SD, young individuals do not experience an increase in ellipse area [29]. In contrast, elderly individuals experience an increase in CoP fluctuation characteristics (such as RMS) [44]. This discovery highlights the poor adaptability of elderly individuals to visual changes due to age-related decline in sensory processing ability and slower compensatory responses, making it difficult for them to rely on remaining visual information to maintain posture stability. However, this result is inconsistent with those of Schmidt et al. They conducted visual manipulation using four approaches (including blackout glasses) for different age groups but did not find any visual influence on balance control in either the young or the elderly groups [37]. Proske et al. argue that vision plays a major role in standing stability for individuals up to age 65; however, as visual acuity declines with age, the influence of other sensory factors on postural control may gradually become more prominent [33]. Considering that the average age of the elderly in this study was 60, while the average age in Schmidt et al. was 69, we believe that the difference in results is due to age differences. This further means that SD may have a greater impact on the postural control of elderly individuals in specific age groups.

Analysis of the CoP spectrum revealed that, under SD, elderly individuals experienced significant reductions in frequency-domain parameters (MF, F80, and CF) compared to the transparent vision condition, whereas younger individuals did not show such changes. Similar to McCreary et al. [29], who found minimal effects of SD on the postural stability of young individuals, our results support their notion that the challenge brought by SD in static posture control for the young population is relatively small. In contrast, previous studies conducted by Degani et al. and Prieto et al. [14], [32] reported that elderly individuals generally exhibit higher MF and greater high-frequency signal power during quiet standing, regardless of visual conditions. Moreover, Prieto et al. also observed increased indicators of instability, such as ellipse area and sway speed, in elderly individuals following visual deprivation [14]. Notably, however, our results differ from these findings: SD in our study led to a decrease in frequency-domain parameters among the elderly, not an increase. This discrepancy may be due to the heightened challenge presented by SD, which may have exceeded the adaptive capacity of the elderly, resulting in a shift towards relying more on low-frequency control strategies. Delmas et al. [15] similarly reported increased CoP variability and a predominance of low-frequency components in elderly individuals during challenging balance tasks, which supports our observations. Richer et al. suggested that higher contributions from high-frequency bands during complex postural tasks are related to increased postural automaticity [35]. Postural control improvements observed in healthy young individuals under complex task conditions are believed to result from directing attention away from postural control, facilitating greater automaticity, effectively enhancing stability, and reducing the risk of falls [35], [42]. Our findings suggest that the increase in low-frequency signals under SD reflects a decline in automaticity among elderly individuals, indicating less efficient postural adjustment when visual input is limited. Notably, the inability to select appropriate balance strategies remains among the most common risk factors for falls among elderly individuals [12]. This inefficiency in postural control may lead to delayed or inappropriate motor responses when sensory information is compromised, such as in low-light environments or when other sensory cues are diminished [10]. Therefore, based on our findings, impaired automaticity in selecting or switching balance strategies under limited visual information input conditions is an important factor contributing to a higher fall risk in elderly individuals.

In addition, if the intricate workings of the postural control system are able to generate precise and timely responses to maintain stability, external factors could not disrupt postural control [22]. Postural control inherently involves continuous modulation of sensory inputs, neural integration, and motor outputs. This system used in controlling body sway in the elderly is more irregular and random than young individuals [14]. In theory, the elderly should have a higher value of FD when vision condition transitions to SD to adapt to their standing challenge. However, our results revealed a significant decrease in FD for elderly individuals transitioning from transparent to stroboscopic vision. This decline suggests that under SD, postural strategies in the elderly become more rigid and lack the adaptability necessary for efficient balance regulation. Tsai et al. reached similar conclusions, noting that SD challenges postural regulation by increasing the regularity of postural movements while reducing the frequency of corrective attempts [44]. This rigidity in postural control strategy likely hinders the elderly from adapting swiftly and maintaining balance under visual interference.

In terms of specific CoP trajectory components, the previous studies suggest that RM trajectories are centrally-controlled, driven by intentional shifts in position, while TR trajectories are primarily peripherally-controlled, influenced by reflexes and changes in mechanical properties [39]. Chen et al. found that a larger sway of RM component during stance balance suggests that the supraspinal central nervous system was responsible for maintaining stability on a larger scale [8]. Similarly, we observed elderly individuals have higher RMS values in the RS direction of the RM component, suggesting that SD has a greater influence on CoP control in this direction, and this population requires greater supraspinal contribution to compensate for sensory deficits in this visual condition [18]. Spectrum analysis of RM trajectories further revealed that, under SD, elderly individuals had decreased FD and CF in the RS direction. This finding indicates that SD leads to a more regular control process at the supraspinal level, corresponding to the "rigidity" commonly reflected in traditional frequency-domain parameters. Donker et al.similarly suggested that increasing postural task difficulty through visual deprivation could result in an increase of CoP variability and a decrease in local stability in individuals, accompanied by a more regular CoP trajectories control strategy for CoP trajectories [16]. The latter change can be attributed to the individuals actively monitoring their posture in order to cope with the increased postural task difficulty [16]. However, they also suggested that this monitoring instead makes it difficult for elderly individuals to cope with posture control challenges more "automatically" under visual interference. In summary, elderly individuals appear to have greater difficulty adapting to changes in visual conditions caused by SD, and supraspinal control strategies become more intentional but less adaptable.

Moreover, no obvious change in elderly TR parameters was detected under SD conditions. Considering Rubega et al. found that elderly showed more muscular activity compared to the younger during difficult balance task [36], and due to the fact that TR components usually imply the regulation of balance contributions from spinal reflex components, our finding further suggests that when faced with posture challenges brought by SD, the peripheral tissue (including reflex control as well as joint, ligament, and muscle) did not receive more activation to regulate elderly individuals' posture. This behavior may make it take longer for them to deal with postural challenges induced by SD and also make it more difficult for them to face potential fall risks. Besides, Gerber et al. also revealed that characteristics of TR sway were significantly affected by the sensory challenges introduced by the test, whereas the RM component remained largely unchanged, and such changes are typical of healthy individuals who are capable of effectively reweighting sensory inputs [19]. In contrast, younger individuals maintained stable RM and TR control strategies under SD, indicating more effective sensory reweighting and adaptability. Overall, our findings reveal that, compared with young individuals, the elderly exhibit reduced automaticity and adaptability in both central and peripheral postural control mechanisms under visual challenges, resulting in increased rigidity, slower responses, and a higher risk of instability and falls.

4.2 Clinical implications

The findings of this study highlight how SD, which limits visual information input, exposes the reduced and unstable adaptive capacity of postural control in elderly individuals. Unlike young individuals, who demonstrate enhanced adaptation to challenging postural states under SD, the elderly face greater difficulty, as evident in their increased sway parameters (e.g., higher values of the 95% confidence ellipse area and elevated value of RM components) in this study. These results suggest that the residual sensory information available to elderly individuals (e.g., vestibular, somatosensory inputs) may be insufficient to compensate for the restricted visual feedback during postural tasks fully. From a clinical perspective, considering the feasibility and safety of training, stroboscopic glasses can provide a controllable yet challenging environment that reduces over-reliance on visual feedback, strengthens other sensory pathways, and helps reconstruct central nervous system control mechanisms in the elderly, thereby supporting better overall balance and motor function and ultimately contributing to fall prevention and improved quality of life. Besides, although visual biofeedback interventions have been proven to have the potential to improve posture balance in the elderly [2], when conducting such intervention training, the cost of equipment cannot be ignored, which may limit the widespread adoption of training. Stroboscopic glasses are relatively easy to access and have a low cost, and have already been successfully employed in training high-performance populations, such as athletes, to enhance adaptability under dynamic conditions [27]. Similarly, clinical practitioners could leverage these devices to design postural control training protocols for elderly individuals who often experience a decline in sensory reweighting and central nervous system processing efficiency. Future studies should investigate the longitudinal efficacy of SD-based rehabilitation or training in elderly populations, particularly in individuals with impaired somatosensory input due to injuries or aging-related conditions.

4.3 Limitations

This study still has several limitations: First, only one frequency of SD was investigated in this study. It remains unclear whether comparable effects would be observed in elderly individuals under other frequency settings. Second, this study was limited to assessments during bipedal standing, which restricts the generalizability of the findings. Future studies should investigate a wider array of postures, such as gait or unipedal stance, which are essential for evaluating fall risk in daily life, to provide a more holistic understanding of SD's effects. Lastly, as an exploratory investigation, while the results indicate that SD can affect postural control and may have potential in mitigating visual dependence in the elderly, further clinical studies are essential to validate the therapeutic efficacy of strobe glasses in improving postural stability within this population.

5. Conclusion

In this study, we preliminarily found that SD, by reducing visual input, impairs postural automaticity and diminishes the flexibility of postural control in elderly individuals, particularly when compared to their younger counterparts. Under SD conditions, elderly individuals tend to rely less on rapid, automatic corrective responses and instead employ slower, less efficient strategies for postural adjustment. This reduced ability to regulate CoP sway under stroboscopic visual conditions underscores an age-related vulnerability in balance maintenance and reflects increased dependence on visual input for postural control in elderly individuals. Using stroboscopic glasses to challenge and potentially recalibrate this reliance may offer a promising approach to enhance automatic balance regulation in elderly individuals, helping lower their risk of falling injuries.

6. References

1. Alcock, L., O'Brien, T.D., Vanicek, N. Association between somatosensory, visual and vestibular contributions to postural control, reactive balance capacity and healthy ageing in older women. Health Care Women Int. 2018, 39, 1366–1380. DOI: 10.1080/07399332.2018.1499106.

2. Alhasan, H., Hood, V., Mainwaring, F. The Effect of Visual Biofeedback on Balance in Elderly Population: A Systematic Review. Clin. Interv. Aging 2017, 12, 487–497. DOI: 10.2147/CIA.S127023.

3. Althomali, M.M., Leat, S.J. Binocular Vision Disorders and Visual Attention: Associations With Balance and Mobility in Older Adults. J. Aging Phys. Act. 2018, 26, 235–247. DOI: 10.1123/japa.2016-0349.

4. Babayi M, Mortazavi Najafabadi SM, Ashtiani MN, Grzelczyk D. General muscle fatigue changed joint regulations in static and dynamic balance. Acta Bioeng Biomech. 2023,25(2):125-132. DOI: 10.37190/ABB-02293-2023-02.

5. Balasubramaniam, R., Wing, A.M. The dynamics of standing balance. Trends Cogn. Sci. 2002, 6, 531–536. DOI: 10.1016/s1364-6613(02)02021-1.

6. Bates, D., Mächler, M., Bolker, B., Walker, S. Fitting Linear Mixed-Effects Models Using Lme4. J. Stat. Softw. 2015, 67, 1–48. DOI: 10.18637/jss.v067.i01.

7. Bohlke, K., Perera, S., Baillargeon, E.M., Redfern, M.S., Sparto, P.J., Sejdic, E., Rosso, A.L. Exercise interventions, postural control, and prefrontal cortex activation in older adults. Brain Cogn. 2023, 171, 106063. DOI: 10.1016/j.bandc.2023.106063.

8. Chen, X.P., Wang, L.J., Chang, X.Q., Wang, K., Wang, H.F., Ni, M., Niu, W.X., Zhang, M. Tai Chi and Yoga for Improving Balance on One Leg: A Neuroimaging and Biomechanics Study. Front. Neurol. 2021, 12, 746599. DOI: 10.3389/fneur.2021.746599.

9. Chepisheva, M.K. Spatial orientation, postural control and the vestibular system in healthy elderly and Alzheimer's dementia. PeerJ 2023, 11, e15040. DOI: 10.7717/peerj.15040.

10. Choi, J.S., Kang, D.W., Shin, Y.H., Tack, G.R. Differences in gait pattern between the elderly and the young during level walking under low illumination. Acta Bioeng Biomech. 2014, 16, 3–9. DOI: 10.5277/ABB-00088-2013-02.

11. Cohen, J. Statistical power analysis for the behavioral sciences, 2nd edn. Lawrence Erlbaum Associates, New York, 1988.

12. Coulter, J.S., Randazzo, J., Kary, E.E., Samar, H. Falls in Older Adults: Approach and Prevention. Am. Fam. Physician 2024, 109, 447–456.

13. Danna-Dos-Santos, A., Degani, A.M., Zatsiorsky, V.M., Latash, M.L. Is Voluntary Control of Natural Postural Sway Possible? J. Mot. Behav. 2008, 40, 179–185. DOI: 10.3200/JMBR.40.3.179-185.

14.Degani, A.M., Leonard, C.T., Danna-Dos-Santos, A. The Effects of Early Stages of Aging on Postural Sway: A Multiple Domain Balance Assessment Using a Force Platform. J. Biomech. 2017, 64, 8–15. DOI: 10.1016/j.jbiomech.2017.08.029.

15.Delmas, S., Watanabe, T., Yacoubi, B., Christou, E.A. Age-Associated Increase in Postural Variability Relates to Greater Low-Frequency Center of Pressure Oscillations. Gait Posture 2021, 85, 103–109. DOI: 10.1016/j.gaitpost.2020.12.019.

16.Donker, S.F., Roerdink, M., Greven, A.J., Beek, P.J. Regularity of Center-of-Pressure Trajectories Depends on the Amount of Attention Invested in Postural Control. Exp. Brain Res. 2007, 181, 1–11. DOI: 10.1007/s00221-007-0905-4.

17.Gerber, E.D., Huang, C.K., Moon, S., Devos, H., Luchies, C.W. Sensory reweighting of postural control requires distinct rambling and trembling sway adaptations. Gait Posture 2024, 112, 16–21. DOI: 10.1016/j.gaitpost.2024.04.028.

18.Gerber, E.D., Nichols, P., Giraldo, C., Sidener, L., Huang, C.K., Luchies, C.W. Rambling-Trembling Center-of-Pressure Decomposition Reveals Distinct Sway Responses to Simulated Somatosensory Deficit. Gait Posture 2022, 91, 276–283. DOI: 10.1016/j.gaitpost.2021.10.017.

19.Guerraz, M., Bronstein, A.M. Ocular versus extraocular control of posture and equilibrium. Neurophysiol. Clin. 2008, 38, 391–398. DOI: 10.1016/j.neucli.2008.09.007.

20.Han, S., Lee, H., Son, S.J., Hopkins, J.T. The Effects of Visual Feedback Disruption on Postural Control with Chronic Ankle Instability. J. Sci. Med. Sport 2022, 25, 53–57. DOI: 10.1016/j.jsams.2021.07.014.

21.Hülsdünker, T., Fontaine, G., Mierau, A. Stroboscopic vision prolongs visual motion perception in the central nervous system. Scand. J. Med. Sci. Sports 2023, 33, 47–54. DOI: 10.1111/sms.14239.

22.Kędziorek J, Błażkiewicz M. The impact of external perturbations on postural control. Acta Bioeng Biomech. 2025 Jan 28,26(2):3-11. DOI: 10.37190/abb-02422-2024-02.

23.Kim, K.M., Kim, J.S., Grooms, D.R. Stroboscopic Vision to Induce Sensory Reweighting During Postural Control. J. Sport Rehabil. 2017, 26, 5. DOI: 10.1123/jsr.2017-0035.

24.Lacour, M., Bernard-Demanze, L., Dumitrescu, M. Posture Control, Aging, and Attention Resources: Models and Posture-Analysis Methods. Neurophysiol. Clin. 2008, 38, 411–421. DOI: 10.1016/j.neucli.2008.09.005.

25.Lee, H., Han, S., Hopkins, J.T. Altered Visual Reliance Induced by Stroboscopic Glasses during Postural Control. Int. J. Environ. Res. Public Health 2022, 19, 2076. DOI: 10.3390/ijerph19042076.

26. Lee, H., Han, S., Hopkins, J.T. Visual Disruption and Neuromechanics During Landing-Cutting in Individuals With Chronic Ankle Instability. J. Athl. Train. 2024, 59, 822–829. DOI: 10.4085/1062-6050-0379.23.

27. Li, T., Zhang, C., Wang, X., Zhang, X., Wu, Z., Liang, Y. The Impact of Stroboscopic Visual Conditions on the Performance of Elite Curling Athletes. Life 2024, 14, 1184. DOI: 10.3390/life14091184.

28. Ma, L., Marshall, P.J., Wright, W.G. The impact of external and internal focus of attention on visual dependence and EEG alpha oscillations during postural control. J. Neuroeng. Rehabil. 2022, 19, 81. DOI: 10.1186/s12984-022-01059-7.

29. McCreary, M.E., Lapish, C.M., Lewis, N.M., Swearinger, R.D., Ferris, D.P., Pliner, E.M. Effects of Stroboscopic Goggles on Standing Balance in the Spatiotemporal and Frequency Domains: An Exploratory Study. J. Appl. Biomech. 2024, 40, 462–469. DOI: 10.1123/jab.2023-0285.

30. Miao, Y., Ge, Y., Wang, D., Mao, D., Song, Q., Wu, R. Effects of Visual Disruption on Static and Dynamic Postural Control in People with and without Chronic Ankle Instability. Front. Bioeng. Biotechnol. 2024, 12, 1499684. DOI: 10.3389/fbioe.2024.1499684.

31. Peng, K., Tian, M., Andersen, M., Zhang, J., Liu, Y., Wang, Q., Lindley, R., Ivers, R. Incidence, risk factors and economic burden of fall-related injuries in older Chinese people: A systematic review. Inj. Prev. 2019, 25, 4–12. DOI: 10.1136/injuryprev-2018-042982.

32. Prieto, T.E., Myklebust, J.B., Hoffmann, R.G., Lovett, E.G., Myklebust, B.M. Measures of postural steadiness: Differences between healthy young and elderly adults. IEEE Trans. Biomed. Eng. 1996, 43, 956–966. DOI: 10.1109/10.532130.

33. Proske, U., Gandevia, S.C. The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. Physiol. Rev. 2012, 92, 1651–1697. DOI: 10.1152/physrev.00048.2011.

34. Ravindran, R.M., Kutty, V.R. Risk Factors for Fall-Related Injuries Leading to Hospitalization Among Community-Dwelling Older Persons: A Hospital-Based Case-Control Study in Thiruvananthapuram, Kerala, India. Asia Pac. J. Public Health 2016, 28, 70S–76S. DOI: 10.1177/1010539515611229.

35. Richer, N., Lajoie, Y. Automaticity of Postural Control while Dual-Tasking Revealed in Young and Older Adults. Exp. Aging Res. 2020, 46, 1–21. DOI: 10.1080/0361073X.2019.1693044.

36. Rubega, M., Formaggio, E., Di Marco, R., Bertuccelli, M., Tortora, S., Menegatti, E., Cattelan, M., Bonato, P., Masiero, S., Del Felice, A. Cortical Correlates in Upright Dynamic and Static Balance in the Elderly. Sci. Rep. 2021, 11, 14132. DOI: 10.1038/s41598-021-93556-3.

37. Schmidt, D., Carpes, F.P., Milani, T.L., Germano, A.M.C. Different Visual Manipulations Have Similar Effects on Quasi-Static and Dynamic Balance Responses of Young and Older People. PeerJ 2021, 9, e11221. DOI: 10.7717/peerj.11221.

38. Shin, S., Milosevic, M., Chung, C.M., Lee, Y. Contractile Properties of Superficial Skeletal Muscle Affect Postural Control in Healthy Young Adults: A Test of the Rambling and Trembling Hypothesis. PLoS One 2019, 14, e0223850. DOI: 10.1371/journal.pone.0223850.

39. Shin, S., Motl, R.W., Sosnoff, J.J. A Test of the Rambling and Trembling Hypothesis: Multiple Sclerosis and Postural Control. Motor Control 2011, 15, 568–579. DOI: 10.1123/mcj.15.4.568.

40. Shumway-Cook A., Woollacott M.H., Rachwani J., Santamaria V., Motor Control: Translating Research into Clinical Practice, Lippincott Williams & Wilkins, 2014.

41. Song, K., Rhodes, E., Wikstrom, E.A. Balance Training Does Not Alter Reliance on Visual Information During Static Stance in Those with Chronic Ankle Instability: A Systematic Review with Meta-Analysis. Sports Med. 2018, 48, 893–905. DOI: 10.1007/s40279-017-0850-8.

42. St-Amant, G., Rahman, T., Polskaia, N., Fraser, S., Lajoie, Y. Unveiling the cerebral and sensory contributions to automatic postural control during dual-task standing. Hum. Mov. Sci. 2020, 70, 102587. DOI: 10.1016/j.humov.2020.102587.

43. Tahayor, B., Riley, Z.A., Mahmoudian, A., Koceja, D.M., Hong, S.L. Rambling and trembling in response to body loading. Motor Control 2012, 16, 144–157. DOI: 10.1123/mcj.16.2.144.

44. Tsai, Y.Y., Chen, Y.C., Zhao, C.G., Hwang, I.S. Adaptations of postural sway dynamics and cortical response to unstable stance with stroboscopic vision in older adults. Front. Physiol. 2022, 13, 919184. DOI: 10.3389/fphys.2022.919184.

45. VanDeMark, L.H., Vander Vegt, C.B., Ford, C.B., Mihalik, J.P., Wikstrom, E.A. Progressive Visual Occlusion and Postural Control Responses in Individuals with and without Chronic Ankle Instability. J. Sport Rehabil. 2021, 30, 1115–1120. DOI: 10.1123/jsr.2020-0466.

46. Viswanathan, A., Sudarsky, L. Balance and gait problems in the elderly. Handb. Clin. Neurol. 2012, 103, 623–634. DOI: 10.1016/B978-0-444-51892-7.00045-0.

47. Wang, Y.F., Tang, Z., Guo, J., Tao, L.X., Liu, L., Li, H.B., Li, D.T., Guo, X.H., Yang, X.H. BMI and BMI Changes to All-Cause Mortality among the Elderly in Beijing: A 20-Year Cohort Study. Biomed Environ Sci 2017, 30, 79–87. DOI: 10.3967/bes2017.011.

48. Wilkins, L., Appelbaum, L.G. An early review of stroboscopic visual training: Insights, challenges and accomplishments to guide future studies. Int. Rev. Sport Exerc. Psychol. 2020, 13, 65–80. DOI: 10.1080/1750984X.2019.1582081.

49. Zatsiorsky, V.M., Duarte, M. Rambling and trembling in quiet standing. Motor Control 2000, 4, 185–200. DOI: 10.1123/mcj.4.2.185.