

Frequency-dependent effects of noisy galvanic vestibular stimulation on postural control

Aoi Kusano

aoi.kutan1028@gmail.com

Graduate School of Health and Welfare Sciences, International University of Health and Welfare

Hisato Nakazono

Fukuoka International University of Health and Welfare

Takanori Taniguchi

Fukuoka International University of Health and Welfare

Osuke Shibata

Fukuoka Sanno Hospital

Kensuke Matsuda

International University of Health and Welfare

Tsubasa Mitsutake

Saga University

Research Article

Keywords: center of pressure, noisy galvanic vestibular stimulation, vestibular dysfunction, postural stability

Posted Date: September 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11024657/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Background

Noisy galvanic vestibular stimulation (nGVS) is a noninvasive technique that modulates vestibular function via stochastic resonance. It can improve postural stability while standing on a compliant surface with eyes closed; however, the optimal stimulation frequency is unclear. We aimed to assess how varying nGVS stimulation frequencies affect postural sway while standing on a compliant surface with closed eyes.

Methods

Seventeen healthy young adults participated in this study. The participants maintained an eyes-closed standing posture on a compliant surface under the following randomized conditions: white noise-like stimulation within frequency ranges of 0–30 Hz, 0–100 Hz, and 100–640 Hz delivered at an intensity of 0.2 mA and sham. The center of pressure (COP) path length and sway area were measured. Changes relative to baseline were analyzed using the Friedman test. Spearman's rank correlation coefficient was used to examine the relationship between changes relative to sham stimulation and the Romberg ratio derived from the eyes-open and eyes-closed baseline conditions.

Results

No significant differences in the COP path length or sway area measurements were observed. However, under the 0–30 Hz condition, changes in the COP path length were significantly negatively correlated with the Romberg ratio. No significant associations with other conditions were observed.

Conclusions

nGVS with 0–30 Hz may enhance postural stability in individuals with greater visual dependence. Because individuals with vestibular dysfunction often adopt visually dominant postural control strategies, nGVS with 0–30 Hz may improve postural stability in populations with vestibular impairment.

1. Introduction

The postural control system maintains balance by regulating the relative contributions of visual, somatosensory, and vestibular inputs to prevent falls (Agrawal et al. 2020). These sensory modalities dynamically adjust their weighting based on environmental and situational conditions, thereby contributing to postural stability (Peterka et al. 2002). Falls frequently occur during multitasking activities, such as those that involve head movements while walking. Among the sensory systems, the vestibular system plays a crucial role in balance control by detecting head movement velocity (Yang et

al. 2015). Individuals with impaired vestibular function are at higher risk for falling during activities of daily living (Politi et al. 2022). Therefore, effective vestibular interventions may lead to fall prevention by improving postural control abilities.

Noisy galvanic vestibular stimulation (nGVS) is a noninvasive brain stimulation method that applies weak noise below the perceptual threshold to stimulate the vestibular terminal organs (Wardman et al. 2003; Nooristani et al. 2019a). By placing electrodes on both mastoid processes and applying a white noise-like waveform, neural activity in vestibular nerve pathways can be modulated (Iwasaki et al. 2014; Stefani et al. 2020). nGVS can induce a mechanism of stochastic resonance that enhances information processing and the detection of subthreshold signals (Nooristani et al. 2019a). Recently, nGVS has been shown to improve postural control abilities in young adults, older individuals, and patients with bilateral vestibular disorders (Fujimoto et al. 2016; Stefani et al. 2020). As a vestibular postural control mechanism, the lateral vestibulospinal tract can detect fall risk by regulating limb muscle tone via the vestibular nuclei (McLaren et al. 2023; Shiozaki et al. 2023). nGVS may contribute to improved postural stability under conditions in which vestibular input significantly affects postural control by affecting the excitability of the lateral vestibulospinal tract (Mitsutake et al. 2024). Several studies have reported the postural stabilizing effects of nGVS. These studies utilized various frequency bands. For example, studies that used the 0–30 Hz frequency band, which considers the vestibular-specific frequency range, reported improvements in postural stability measures such as the center of pressure (COP) sway velocity and gait performance (Eder et al. 2022). Furthermore, the 100–640 Hz frequency band similarly demonstrated improved postural control, with reduced COP sway and COP path length (Nooristani et al. 2019a). Based on these findings, nGVS using an optimal stimulation frequency may provide effective postural stabilization. However, despite evidence of effects across different frequency bands, the optimal stimulation frequency has not yet been defined.

Standing on a soft surface with eyes closed blocks visual information and prevents accurate somatosensory input from the floor, thereby increasing reliance on the vestibular system for postural control; therefore, it is used as an assessment of postural stability involving vestibular function (Horak 2006). By objectively evaluating body sway during nGVS adaptation at various stimulation frequencies under this standing condition, it may be possible to identify the optimal stimulation frequency. COP measurements are representative indicators of body sway, and nGVS reduces the COP sway velocity and COP sway area (Iwasaki et al. 2014). In this study, we aimed to investigate the importance of the stimulation frequency in postural control by examining the effects of nGVS with different frequency bands using a stabilometer to measure the COP sway.

2. Methods

2.1. Participants

Seventeen healthy adults (10 male and 7 female adults; mean age, 22.2 ± 0.9 years) participated in this study. These participants were not using any medications, and none had a history of neurological or

orthopedic disorders that affected standing posture control. We explained the study details to the participants before the start of the experiment and obtained written informed consent. This study was conducted in accordance with the principles and guidelines of the Declaration of Helsinki and approved by the Ethics Review Committee of the Graduate School of International Health and Welfare (approval number: 24-KS-009). The sample size was determined based on previous research that examined postural stability using nGVS for healthy individuals (Mitsutake et al. 2022).

2.2. Experimental procedures

First, participants performed standing trials under eyes-open and eyes-closed conditions for 80 s on a soft mat as the baseline condition (Fig. 1). The COP sway was analyzed for 60 s beginning 20 s after measurement initiation. Subsequently, nGVS was administered under the following randomized stimulation conditions: 0–30 Hz frequency range; 0–100 Hz frequency range; 100–640 Hz frequency range; and sham condition. During stimulation, participants maintained an eyes-closed standing posture on a soft mat. Because the period immediately following the start of stimulation may include transient responses associated with fade-in and initial adaptation to the stimulation, the 60-s period after the initial 20 s of stimulation was analyzed to evaluate a stable postural control state. The stimulation duration was set to 110 s to ensure that measurements were obtained while stimulation was steadily applied. After completing the measurements, participants were asked to sit in a chair during a 2-min rest period.

2.3. nGVS

nGVS was performed using a transcranial electrical stimulation device (DC-Stimulator-Plus; NeuroCare, San Diego, CA, USA) and an external control unit (DC-Stim Editor; Medical Try System, Tokyo, Japan). The white noise stimulus waveform was applied, and the electrical signal consisted of Gaussian white noise with a zero mean within the target frequency ranges (0–30 Hz, 0–100 Hz, and 100–640 Hz). The nGVS waveform was generated for 110 s at a sampling frequency of 5 kHz, with fade-in and fade-out durations of 5 s. During nGVS, rubber electrodes (3 cm × 3 cm) were attached to both mastoid processes. Before applying the electrodes, the skin was pretreated with an abrasive and alcohol swabs, and the electrode impedance was adjusted to less than 10 k Ω . The nGVS stimulation intensity was set to 0.2 mA (peak-to-peak), which is below the threshold of perception (Inukai et al. 2020; Mitsutake and Sonobe 2024). The sham stimulation intensity was set to 0 mA.

2.4. COP measurements

COP displacement and the COP area of the participants were measured during the standing test using a posturograph (GW-5000; ANIMA, Tokyo, Japan). The COP path length allows the evaluation of activity levels during posture maintenance and subtle changes in stability. Therefore, it is a representative parameter for the sensitive detection of small changes and intervention effects (Nooristani et al. 2019b; Matsugi et al. 2020, 2022). The COP sway area indicates the area enclosed by the COP trajectory and allows for the assessment of the spatial extent of sway and stability limits; therefore, it exhibits high

sensitivity, particularly when balance is significantly disrupted (Prieto et al. 1996; Rocchi et al. 2004; Doyle et al. 2007). Additionally, this study calculated the Romberg ratio to assess the degree of reliance on visual information involved in postural control. The Romberg ratio is calculated by dividing the measurement obtained under the eyes-closed condition by the measurement obtained under the eyes-open condition. A greater Romberg ratio indicates deterioration in balance performance when visual information is removed, suggesting that postural control relies on visual information (Tjernström et al. 2015). During measurement, participants maintained a standing position on a surface mat (rubber mat; tensile strength, 2.1 kgf/cm²; thickness, 3.5 cm; ANIMA). During measurements under the eyes-open condition, participants were instructed to gaze at a mark positioned at eye level 300 cm ahead of them.

2.5. Statistical analysis

The statistical analysis was performed using IBM SPSS Statistics software version 26 (IBM Corporation, Armonk, NY, USA), with $p < 0.05$ considered significant. To evaluate changes in COP displacement and the COP area across different stimulation frequency conditions, we calculated the change from baseline under the eyes-closed condition for each nGVS stimulation condition (i.e., normalized COP values). Regarding these measurements, lower values indicated greater postural stability. The Shapiro-Wilk test indicated that the data did not follow a normal distribution. Therefore, they were evaluated using the Friedman test with “stimulus” as the factor. When a significant difference was observed, post hoc tests were conducted using the two-sided Wilcoxon signed-rank test for all combinations of the three conditions, and Bonferroni correction was applied to adjust for multiple comparisons. To examine the individual response to the different stimulation conditions, the mean values under the sham condition across all participants were used as reference values for COP trajectory length and area. According to this criterion, participants were classified as showing an improvement response when the COP path length was below 0.90 or the COP area was below 0.86; otherwise, they were classified as showing no response. Additionally, Spearman’s rank correlation coefficient was used to analyze the relationship between the change from the sham stimulation under each nGVS stimulation condition and the Romberg ratio under the eyes-open and eyes-closed conditions at baseline.

3. Results

None of the participants reported adverse effects during or after the intervention. Additionally, none of the participants reported any skin sensations or dizziness caused by the stimuli. All participants reported that they were unable to distinguish between the different stimulus conditions.

The measured values at baseline and during stimulation are shown in Table 1. Figure 2 shows the changes in the COP path length and COP sway area under different stimulus frequency conditions. With regard to COP path length, the Friedman test revealed no significant difference for the “stimulus” factor ($\chi^2 [3] = 1.729$; $p = 0.63$). Similarly, no significant changes were observed in COP area of wobble ($\chi^2 [3] = 4.129$; $p = 0.278$). Next, to examine the inter-individual variability in the effects of nGVS, we calculated the proportion of participants who showed improvement with nGVS compared with sham stimulation. We found that the effects of nGVS varied among participants under all stimulation conditions (COP

trajectory length: 0–30 Hz condition, 47.1%; 0–100 Hz condition, 58.8%; 100–640 Hz condition, 29.4%; COP area: 0–30 Hz condition, 64.7%; 0–100 Hz condition, 52.9%; 100–640 Hz condition, 35.3%).

Figure 3 shows Spearman’s rank correlations between the change in each nGVS condition relative to sham stimulation and the Romberg ratio under eyes-open and eyes-closed conditions at baseline. The change observed with nGVS with the 0–30 Hz frequency band exhibited a significantly strong negative correlation ($r = -0.733$; $p = 0.003$) with the Romberg ratio. No significant correlations with the other stimulation conditions were identified ($p \geq 0.680$). Furthermore, no significant correlations with the COP area across all stimulation conditions were observed ($p \geq 0.133$).

	Baseline		nGVS			
	eye opne	eye close	nGVS	0-100 Hz	100–640 Hz	sham
COP path length	81.82 ± 23.06	120.99 ± 39.65	106.54 ± 27.98	106.35 ± 29.26	110.8 ± 31.57	107.85 ± 30.22
COP sway area	5.31 ± 2.5	7.89 ± 4.39	6.79 ± 3.85	6.72 ± 3.39	7.28 ± 3.88	6.01 ± 2.86

4. Discussion

We investigated the effects of nGVS across different frequency ranges on the COP sway while standing on a soft surface. The results indicated that no discernible effect of nGVS on postural control occurred under any frequency condition relative to sham stimulation. Studies have reported improvements in balance control with nGVS across various frequency bands (Inukai et al. 2020; Nooristani et al. 2021). For example, nGVS with a frequency range of 0–30 Hz improves postural stability by reducing body sway indicators, such as head and trunk acceleration and angular velocity (Goel et al. 2015). Furthermore, nGVS with a frequency range of 100–640 Hz also improved body sway, as evidenced by a reduction in head acceleration (Mitsutake and Sonobe 2023). On the contrary, studies reporting results similar to those of this study have shown no noticeable effects of nGVS. Specifically, no significant changes in the COP velocity or COP trajectory length were observed during stimulation with a frequency range of 0–640 Hz (Nooristani et al. 2019b). Furthermore, Mitsutake et al. (2022) suggested that the effects of nGVS may be affected by inter-individual differences in responsiveness to stimuli. In this study, to assess the distribution of responsiveness to stimuli, we defined cases in which the COP trajectory length or area was reduced compared with the sham stimulus as indicating an improvement in postural stability due to nGVS and calculated the proportion of participants meeting this criterion. The results showed that, although approximately half of the participants exhibited an improvement under the 0–30 Hz and 0–100 Hz conditions, this proportion was limited to approximately 30% under the 100–640 Hz condition. These results support the hypothesis that the response of nGVS to postural control is not uniform across subjects and varies from person to person. Standing postural stability is known to vary based on an individual’s reliance on visual, somatosensory, and vestibular inputs as well as the strategies used to

integrate these modalities (Inukai et al. 2018; Agrawal et al. 2020). Diversity in both vestibular function and integration may have affected the observed nGVS effects. However, as the primary objective of this study was not to evaluate inter-individual variability in nGVS, the sample size was insufficient, and there are limitations to the interpretation of these results. Future studies should use a larger sample size.

We analyzed the correlation between the changes relative to sham stimulation under each nGVS condition and the baseline Romberg ratio derived from eyes-open and eyes-closed conditions to examine the effect of nGVS on individual differences in sensory strategies. Higher Romberg ratios indicate greater deterioration in balance ability when visual input is removed, suggesting increased reliance on visual information (Tjernström et al. 2015). Sensory integration in postural control is achieved through dynamic reweighting of visual, somatosensory, and vestibular inputs based on the reliability of each sensory input within a given environment (Peterka et al. 2002). Therefore, although standing on a soft mat in the eyes-closed condition, the reliability of somatosensory input decreases, and blocked vision leads to a relative increase in reliance on the vestibular system. Based on these findings, nGVS with a frequency range of 0–30 Hz may have a selective effect on postural stability among individuals with greater visual dependence. Under vestibular impairment conditions, reduced reliability of vestibular and somatosensory inputs disrupts effective sensory integration for postural control, leading to over-reliance on visual information and a shift toward visually dominant control strategies (Agrawal et al. 2020). Older adults also tend to exhibit greater visual dependence for postural regulation and instability under conditions in which visual or somatosensory information is restricted, such as standing on a soft surface with eyes closed (Lord et al. 1991). These findings suggest that stimulation with 0–30 Hz may have greater efficacy in populations with these postural control characteristics than in healthy populations.

The frequency-specific effects of nGVS observed in this study may be explained by several underlying mechanisms. nGVS is believed to enhance the detection accuracy of vestibular input through stochastic resonance, thereby reducing postural sway (Wuehr et al. 2018). In particular, stimulation in the low-frequency band of 0–30 Hz has been implicated in vestibular responses mediated by vestibular hair cells, and nGVS within this band may modulate vestibular nerve activity and facilitate the processing of vestibular information (Goel et al. 2015). Accordingly, nGVS with 0–30 Hz may have affected vestibular function and vestibular-dominant postural control. In contrast, no significant correlation was observed with 0–100 Hz stimulation, despite the inclusion of frequency components within the 0–30 Hz range. Therefore, the inclusion of high-frequency components may have attenuated the effect, thereby obscuring any relationship with visual dependence. Furthermore, although the 100–640 Hz frequency band showed no association with postural control, random noise stimulation within this frequency band may specifically act on the cerebral cortex. During transcranial random noise stimulation using white noise-like stimuli analogous to nGVS, application to the primary motor cortex has been shown to increase cortical excitability specifically within the 100–640 Hz range; however, no clear effects were observed at other frequencies (Terney et al. 2008). Notably, with regard to inter-individual variability in the effects, the 100–640 Hz condition had the lowest proportion of participants who showed improvements in either COP trajectory length or area compared with the other stimulus conditions.

Collectively, these findings suggest that the effects of random noise stimulation exhibit frequency specificity depending on the stimulation site, and that the 0–30 Hz frequency band may be particularly relevant for modulating vestibular function.

In this study, no significant correlation between the COP area and Romberg ratio was observed under any stimulus condition. The COP path length represents the overall activity level associated with postural control and is sensitive to subtle fluctuations, whereas the COP area is affected by large-amplitude fluctuations of the COP and more clearly reflects the spatial extent of sway (Prieto et al. 1996; Rocchi et al. 2004; Doyle et al. 2007). Compared with healthy older adults, young adults exhibit higher postural stability during postural control and a smaller COP area (Benjuya et al. 2004). The absence of significant correlations with the COP area across conditions in the present study may be attributable to the inclusion of young adults with inherently high postural stability, resulting in a ceiling effect.

This study has some limitations. First, the optimal stimulation intensity for nGVS has not yet been established. Previous research suggested that the optimal intensity may vary across individuals (Mitsutake and Sonobe 2024). Therefore, future studies should aim to determine individualized stimulation parameters. Second, because the present sample exclusively comprised healthy young adults, whether nGVS with 0–30 Hz is effective for older individuals at risk for falls or individuals with vestibular disorders is unclear. Our findings suggest that individuals with a high degree of visual dependence may be more likely to exhibit the beneficial effects of nGVS with 0–30 Hz; therefore, future studies should examine the differences in nGVS effects among young and older populations as well as among individuals with and without vestibular impairments.

In conclusion, nGVS with 0–30 Hz effectively affected individuals who used visually dominant postural control strategies. This finding suggests that individuals with impaired vestibular function who rely on visually dominant postural control may experience greater improvement in postural stability. Our findings provide novel insights into the mechanisms underlying nGVS and may contribute to the advancement of its therapeutic applications.

Declarations

Funding

No funding was received for conducting this study.

Competing Interests: The authors declare that they have no conflict of interest.

Compliance with Ethical Standards

Disclosure of potential conflicts of interest: The authors declare that they have no conflict of interest.

Research involving Human Participants and/or Animals: This study was conducted in accordance with the principles and guidelines of the Declaration of Helsinki and approved by the Ethics Review

Committee of the Graduate School of International Health and Welfare (approval number: 24-KS-009).

Informed consent: We explained the study details to the participants before the start of the experiment and obtained written informed consent.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Agrawal Y, Merfeld DM, Horak FB, Redfern MS, Manor B, Westlake KP, Holstein GR, Smith PF, Bhatt T, Bohnen NI, Lipsitz LA (2020) Aging, vestibular function, and balance: proceedings of a National Institute on Aging/National Institute on Deafness and Other Communication Disorders workshop. *J Gerontol A Biol Sci Med Sci* 75:2471–2480. <https://doi.org/10.1093/gerona/glaa097>
2. Benjuya N, Melzer I, Kaplanski J (2004) Aging-induced shifts from a reliance on sensory input to muscle cocontraction during balanced standing. *J Gerontol Biol Sci Med Sci* 59:166–171. <https://doi.org/10.1093/gerona/59.2.m166>
3. Doyle RJ, Hsiao-Wecksler ET, Ragan BG, Rosengren KS (2007) Generalizability of center of pressure measures of quiet standing. *Gait Posture* 25:166–171. <https://doi.org/10.1016/j.gaitpost.2006.03.004>
4. Eder J, Kellerer S, Amberger T, Keywan A, Dlugaiczyk J, Wuehr M, Jahn K (2022) Combining vestibular rehabilitation with noisy galvanic vestibular stimulation for treatment of bilateral vestibulopathy. *J Neurol* 269:5731–5737. <https://doi.org/10.1007/s00415-022-11033-x>
5. Fujimoto C, Yamamoto Y, Kamogashira T, Kinoshita M, Egami N, Uemura Y, Togo F, Yamasoba T, Iwasaki S (2016) Noisy galvanic vestibular stimulation induces a sustained improvement in body balance in elderly adults. *Sci Rep* 6:37575. <https://doi.org/10.1038/srep37575>
6. Goel R, Kofman I, Jeevarajan J, De Dios Y, Cohen HS, Bloomberg JJ, Mulavara AP (2015) Using low levels of stochastic vestibular stimulation to improve balance function. *PLoS ONE* 10:e0136335. <https://doi.org/10.1371/journal.pone.0136335>
7. Horak FB (2006) Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age Ageing* 35:ii7–ii11. <https://doi.org/10.1093/ageing/afl077>
8. Inukai Y, Miyaguchi S, Kobayashi N, Otsuru N, Onishi H (2020) Noisy galvanic vestibular stimulation effect on center of pressure sway during one-legged standing. *J Clin Neurosci* 82:173–178. <https://doi.org/10.1016/j.jocn.2020.10.050>
9. Inukai Y, Otsuru N, Masaki M, Saito K, Miyaguchi S, Kojima S, Onishi H (2018) Effect of noisy galvanic vestibular stimulation on center of pressure sway of static standing posture. *Brain Stimul* 11:85–93. <https://doi.org/10.1016/j.brs.2017.10.007>

10. Iwasaki S, Yamamoto Y, Togo F, Kinoshita M, Yoshifuji Y, Fujimoto C, Yamasoba T (2014) Noisy vestibular stimulation improves body balance in bilateral vestibulopathy. *Neurology* 82:969–975. <https://doi.org/10.1212/WNL.0000000000000215>
11. Lord SR, Clark RD, Webster IW (1991) Physiological factors associated with falls in an elderly population. *J Am Geriatr Soc* 39:1194–1200. <https://doi.org/10.1111/j.1532-5415.1991.tb03574.x>
12. Matsugi A, Oku K, Mori N (2020) The effects of stochastic galvanic vestibular stimulation on body sway and muscle activity. *Front Hum Neurosci* 14:591671. <https://doi.org/10.3389/fnhum.2020.591671>
13. Matsugi A, Shiozaki T, Tanaka H (2022) Vestibulo-ocular reflex is modulated by noisy galvanic vestibular stimulation. *Front Neurol* 13:826739. <https://doi.org/10.3389/fneur.2022.826739>
14. McLaren R, Smith PF, Taylor RL, Niazi IK, Taylor D (2023) Scoping out noisy galvanic vestibular stimulation: a review of the parameters used to improve postural control. *Front Neurosci* 17:1156796. <https://doi.org/10.3389/fnins.2023.1156796>
15. Mitsutake T, Nakazono H, Shiozaki T, Taniguchi T, Yoshizuka H, Sakamoto M (2024) Neural interference effects on lateral vestibulospinal tract excitability by noisy galvanic vestibular stimulation. *Clin Neurophysiol* 168:153–160. <https://doi.org/10.1016/j.clinph.2024.11.002>
16. Mitsutake T, Sonobe M (2024) Noisy galvanic vestibular stimulation influences head stability in young healthy adults while standing on a moving platform. *Gait Posture* 107:177–181. <https://doi.org/10.1016/j.gaitpost.2023.09.014>
17. Mitsutake T, Taniguchi T, Nakazono H, Yoshizuka H, Sakamoto M (2022) Effects of noisy galvanic vestibular stimulation on the muscle activity and joint movements in different standing postures conditions. *Front Hum Neurosci* 16:891669. <https://doi.org/10.3389/fnhum.2022.891669>
18. Nooristani M, Bigras C, Lafontaine L, Bacon BA, Maheu M, Champoux F (2021) Vestibular function modulates the impact of nGVS on postural control in older adults. *J Neurophysiol* 125:489–495. <https://doi.org/10.1152/jn.00512.2020>
19. Nooristani M, Maheu M, Bacon BA, Champoux F (2019a) The importance of nGVS current density for postural control enhancement. *Brain Stimul* 12:1592–1594. <https://doi.org/10.1016/j.brs.2019.07.022>
20. Nooristani M, Maheu M, Houde MS, Bacon BA, Champoux F (2019b) Questioning the lasting effect of galvanic vestibular stimulation on postural control. *PLoS ONE* 14:e0224619. <https://doi.org/10.1371/journal.pone.0224619>
21. Peterka RJ (2002) Sensorimotor integration in human postural control. *J Neurophysiol* 88:1097–1118. <https://doi.org/10.1152/jn.2002.88.3.1097>
22. Poli L, Salerni L, Bubbico L, Ferretti F, Carucci M, Rubegni G, Mandalà M (2022) Risk of falls, vestibular multimodal processing, and multisensory integration decline in the elderly—predictive role of the functional head impulse test. *Front Neurol* 13:964017. <https://doi.org/10.3389/fneur.2022.964017>

23. Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM (1996) Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng* 43:956–966. <https://doi.org/10.1109/10.532130>
24. Rocchi L, Chiari L, Cappello A (2004) Feature selection of stabilometric parameters based on principal component analysis. *Med Biol Eng Comput* 42:71–79. <https://doi.org/10.1007/BF02351013>
25. Shiozaki T, Okada Y, Nakamura J, Ueta K, Tanaka H, Moritani M, Kitahara T (2023) Relationships between changes in lateral vestibulospinal tract excitability and postural control by dynamic balance intervention in healthy individuals: a preliminary study. *Front Hum Neurosci* 17:1109690. <https://doi.org/10.3389/fnhum.2023.1109690>
26. Stefani SP, Serrador JM, Breen PP, Camp AJ (2020) Impact of galvanic vestibular stimulation-induced stochastic resonance on the output of the vestibular system: a systematic review. *Brain Stimul* 13:533–535. <https://doi.org/10.1016/j.brs.2020.01.006>
27. Terney D, Chaieb L, Moliadze V, Antal A, Paulus W (2008) Increasing human brain excitability by transcranial high-frequency random noise stimulation. *J Neurosci* 28:14147–14155. <https://doi.org/10.1523/JNEUROSCI.4248-08.2008>
28. Tjernström F, Björklund M, Malmström EM (2015) Romberg ratio in quiet stance posturography–test to retest reliability. *Gait Posture* 42:27–31. <https://doi.org/10.1016/j.gaitpost.2014.12.007>
29. Wardman DL, Taylor JL, Fitzpatrick RC (2003) Effects of galvanic vestibular stimulation on human posture and perception while standing. *J Physiol* 551:1033–1042. <https://doi.org/10.1113/jphysiol.2003.045971>
30. Wuehr M, Boerner JC, Pradhan C, Decker J, Jahn K, Brandt T, Schniepp R (2018) Stochastic resonance in the human vestibular system–noise-induced facilitation of vestibulospinal reflexes. *Brain Stimul* 11:261–263. <https://doi.org/10.1016/j.brs.2017.10.016>
31. Yang Y, Pu F, Lv X, Li S, Li J, Li D, Li M, Fan Y (2015) Comparison of postural responses to galvanic vestibular stimulation between pilots and the general populace. *Biomed Res Int* 2015:567690. <https://doi.org/10.1155/2015/567690>

Figures

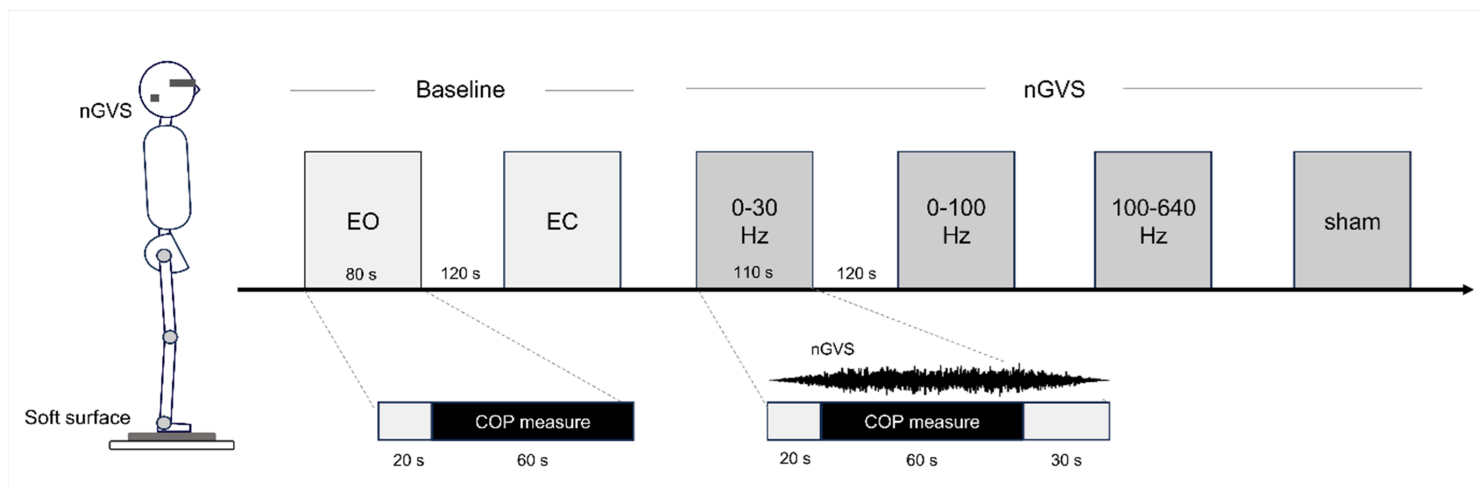


Figure 1

Experimental procedure. Baseline postural measurements were performed for 60 s under eyes-open (EO) and eyes-closed (EC) conditions following an initial 20-s period. Subsequently, four stimulation conditions (0–30 Hz, 0–100 Hz, 100–640 Hz, and sham) were applied in randomized order. During each stimulation condition, the center of pressure (COP) sway was analyzed for 60 s following a 20-s adaptation period. Stimulation continued for 110 s. A 2-min seated rest period was allowed between trials. nGVS, noisy galvanic vestibular stimulation

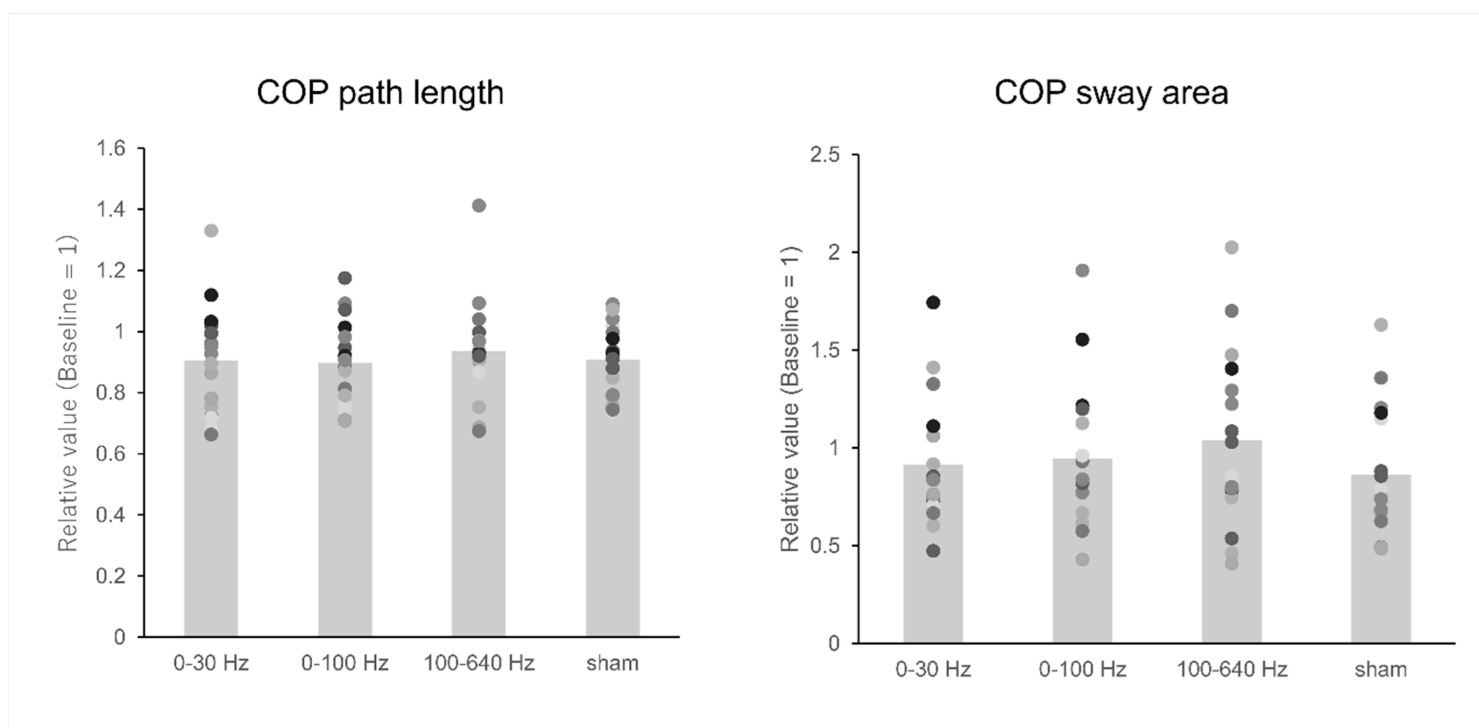


Figure 2

Changes in the center of pressure (COP) path length and COP sway area under each stimulation condition relative to baseline during standing on a soft surface in the eyes-closed condition. Lower

values indicate better postural stability. No significant differences among stimulation conditions were observed for either parameter

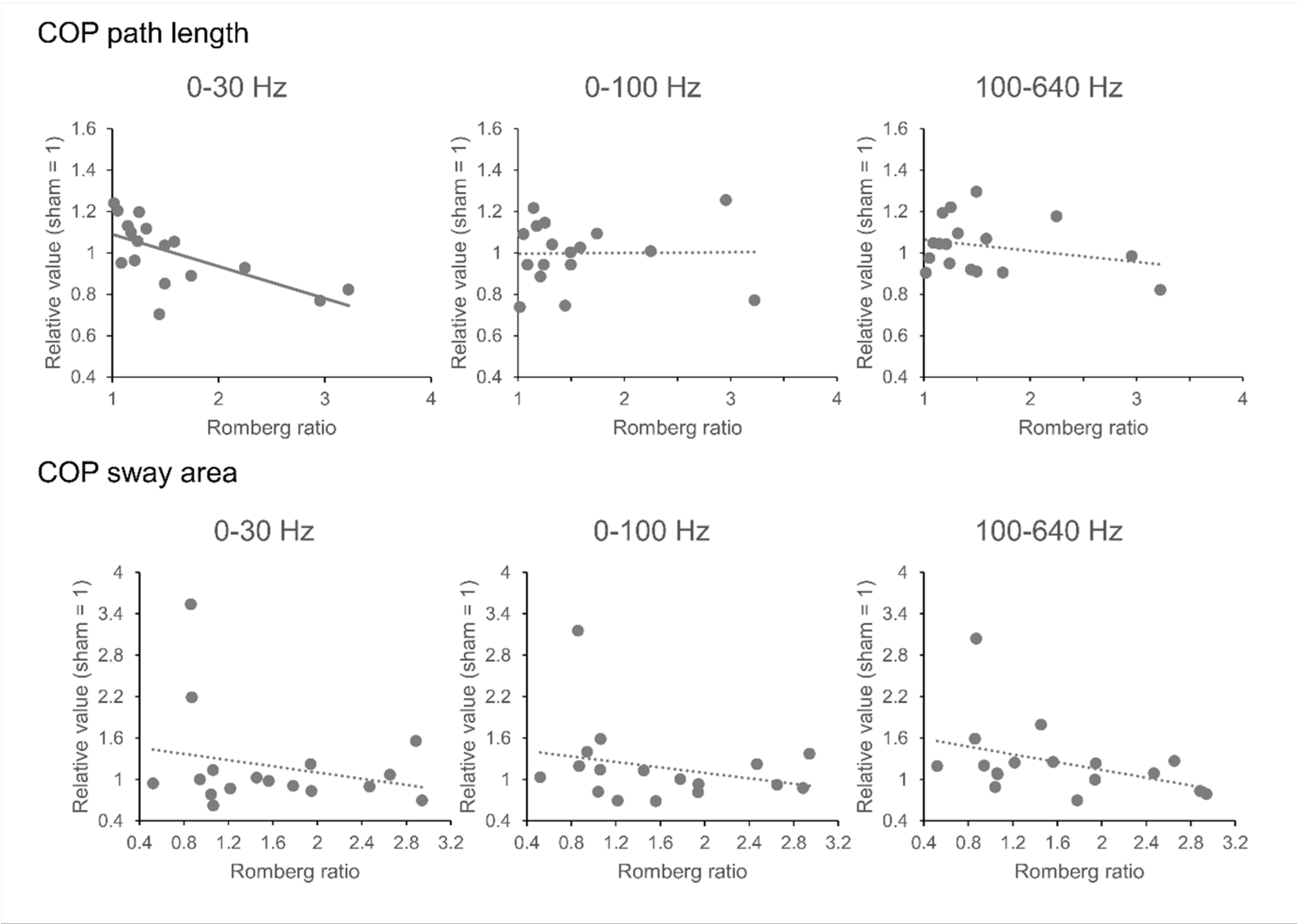


Figure 3

Spearman’s rank correlations between changes in the center of pressure (COP) path length and COP sway area relative to sham stimulation and the Romberg ratio at baseline under each stimulation frequency condition. A significant negative correlation was observed only for the COP path length under the 0–30 Hz stimulation condition. No significant correlations were observed for the COP sway area