

Subperceptual noisy galvanic vestibular stimulation in bilateral vestibulopathy: a double-blind, sham-controlled crossover pilot study

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Abstract

Bilateral vestibulopathy (BV) causes persistent balance impairment and gait instability, but treatment options are limited. Noisy galvanic vestibular stimulation (nGVS) has been proposed as a non-invasive treatment to restore gait and balance function in BV with residual vestibular function. We tested whether a single session of nGVS improved standing balance, gait and functional mobility in 10 BV patients using a randomised, sham-controlled, double-blind crossover pilot study design. BV was diagnosed according to Bárány Society criteria. Binaural, bipolar nGVS (zero-mean white noise, 0-100 Hz, ± 0.4 mA) or sham was delivered in counterbalanced order. Standing balance (postural sway on firm/foam surface with/without vision), gait (self-selected and slow speed walking), and functional mobility (timed up and go test) metrics were measured with optical motion capture. nGVS effects were tested for the group and for each participant using mixed-effects models and Mann-Whitney U tests, respectively. No participant reliably distinguished stimulation from sham, confirming that blinding was effective and that nGVS was subperceptual. nGVS had no effect on standing balance, functional mobility, or on the pace, rhythm, asymmetry or postural control domains of gait, at group- or participant-level. The sole positive finding was reduced step width variability during stimulation at group-level (3.5 versus 4.1 cm in sham; $p = 0.024$), but the effect did not survive separation by walking speed or correction for multiple comparisons, with little evidence at participant-level. nGVS did not improve balance, gait or mobility in BV. The protocol was feasible, adequately blinded and provides a template for definitive trials with larger cohorts.

Introduction

Bilateral vestibulopathy (BV) is a chronic disorder characterised by bilaterally reduced or absent vestibular function, resulting in impaired vestibulo-ocular and vestibulospinal reflexes (Strupp et al. 2017). Patients typically experience persistent balance impairment, oscillopsia during head movements, gait instability, and difficulty navigating complex or low-visibility environments (Lucieer et al. 2016; Kremmyda et al. 2016). These symptoms substantially impair mobility, independence, and quality of life, increasing the risk of falls, injury, social isolation, and psychological distress (Guinand et al. 2012). Beyond its impact on individuals, BV imposes a considerable societal burden through increased healthcare utilisation, reduced productivity, and long-term rehabilitation needs (Ward et al. 2013; Sun et al. 2014).

Current management is centred on vestibular rehabilitation, which aims to optimise central compensation and promote the use of visual and somatosensory cues to maintain balance (Porciuncula et al. 2012; Hall et al. 2022). Although rehabilitation improves function in many patients, recovery is often incomplete, particularly in those with profound bilateral vestibular loss (Gillespie and Minor 1999; Porciuncula et al. 2012). Pharmacological treatments have no established role, while vestibular implants remain in development and are currently available only in specialised centres (Chow et al. 2021; Mahmud and Kaski 2024). Consequently, there is a pressing need for accessible, non-invasive interventions that enhance balance and mobility in this population.

Noisy galvanic vestibular stimulation (nGVS) has emerged as a potential therapeutic approach for improving postural control and mobility (Iwasaki et al. 2014; Wuehr et al. 2016, 2017). Galvanic vestibular stimulation (GVS) involves the application of electrical current through electrodes placed over the mastoid processes to non-invasively modulate vestibular afferent activity (Fitzpatrick and Day 2004). nGVS is a form of GVS that delivers a stochastic current waveform characterised by random fluctuations in current amplitude and polarity (Fitzpatrick and Day 2004). At higher amplitudes (> 1 mA), nGVS can induce substantial gait and postural instability (Dakin et al. 2007; Forbes et al. 2017). In contrast, studies using lower-amplitude, typically subperceptual (< 0.6 mA) nGVS have reported reductions in postural sway in healthy younger and older adults, as well as in individuals with BV and Parkinson's disease (Mahmud et al. 2022; McLaren et al. 2022). However, these findings are based primarily on small cohorts and studies with unblinded designs and heterogeneous stimulation parameters. Although the underlying mechanisms remain elusive, it is suggested that subperceptual nGVS enhances the central processing of residual vestibular signals, thereby improving the reliability of vestibular information used for postural control. This may translate into improvements in postural stability, gait, and functional mobility in individuals with BV.

Many positive nGVS reports in BV have individualised the stimulus amplitude to each participant by testing an array of amplitudes and selecting the 'optimal' amplitude based on changes to postural sway measures, or as a percentage of GVS cutaneous sensory or motion perception thresholds (Iwasaki et al. 2014; Wuehr et al. 2016; McLaren et al. 2023). However, individualising the stimulus complicates blinding, leaves open whether the benefit reflects the stimulus or the selection procedure, and shows little evidence of test-retest reliability (Fujimoto et al. 2018). Using fixed stimulation parameters across participants has shown similar benefits to postural sway (McLaren et al. 2023), with ± 0.4 mA a commonly chosen setting (Inukai et al. 2018b, a, 2020a, b; Nguyen et al. 2023). We have recently shown in healthy adults that a comparable fixed-stimulus modified balance and tonic vestibulospinal output during unpredictable surface perturbations (Mahmud et al. 2026).

This study aimed to determine whether a single session of subperceptual nGVS improves standing balance, gait and functional mobility in BV.

Methods

Study design

We conducted a randomised sham-controlled crossover pilot study to compare standing balance, gait, and functional mobility posture with and without nGVS in participants with BV (Fig. 1). The study was performed at the SENSE Research Unit at the UCL Queen Square Institute of Neurology.

Participants

Inclusion criteria:

1. Aged 18 years old and over
2. Confirmed BV according to the Barany Society diagnostic criteria (unsteadiness on walking, worsening in the dark, movement-induced oscillopsia, and confirmatory vestibular testing [horizontal angular VOR gain on both sides should be < 0.6 and/or the sum of the maximal peak velocities of the slow phase caloric-induced nystagmus for stimulation with warm and cold water on each side $< 6^{\circ}/s$]).

Exclusion criteria:

1. Unable to consent
2. Other balance issues, vestibular, neurological, or ophthalmological disorders
3. Unable to walk or stand unaided

We recruited 11 people with BV of various aetiology from local University College London Hospitals NHS clinical databases (Table 1). One participant was excluded from analysis due to technical problems. Participants underwent clinical vestibular assessment by senior Consultant Neuro-otologists to confirm BV and ensure no confounding vestibular disorders. All patients provided written informed consent. The study was approved by the London - Central Research Ethics Committee (REC reference 23/PR/1233) and conducted in accordance with the 1964 Declaration of Helsinki.

Table 1
Participant demographics.

ID	Age	Sex	Aetiology	Balance Vigilance (/30)	Functional Gait Assessment (/30)
1	73	Female	Gentamicin	25	-
2	80	Male	Small vessel disease; Cerebellar ataxia secondary to alcohol	28	22
3	63	Male	Gentamicin	21	16
4	60	Male	CANVAS	25	12
6	56	Female	Idiopathic	22	19
7	81	Male	Posterior fossa superficial siderosis	26	14
8	62	Female	Chemotherapy	23	11
9	77	Female	Idiopathic	24	18
10	80	Male	Idiopathic	24	23
11	71	Male	Idiopathic	15	22
Median [IQR]	72 [62.25,79.25]	-	-	24 [22.3,25]	18 [14,22]

Procedures

We assessed standing balance, gait, and functional mobility under baseline, then sham and nGVS stimulation conditions. The order of sham and stimulation conditions was randomised and counter-balanced between participants.

Standing balance

Participants stood with their feet separated by 10cm for 60s with or without vision on a firm or foam surface, resulting in four conditions (2 vision X 2 surface). Trials were performed in a set order: (1) firm, eyes open; (2) firm, eyes closed; (3) foam, eyes open; (4) foam, eyes closed; then repeated in reverse order (i.e. 4,3,2,1). Five participants were unable to stand without vision on foam.

Gait

Participants walked 6m at a self-selected comfortable speed and ~ 50% their self-selected comfortable speed, each repeated three times. In the baseline assessment, the time taken to walk 6 m was measured and used during sham/stimulation conditions to guide the ~ 50% speed. Slow walking was included as an additional challenge to balance because people with BV tend to walk faster to aid stability (Brandt et al. 1999; Schniepp et al. 2012, 2017; Wuehr et al. 2016). One participant did not walk at 50% speed because their self-selected speed was already very slow (0.6 m/s).

Functional mobility

Participants performed the Timed Up and Go (TUG) test which involved standing from an arm- and back-less chair, walking forward 3 meters, turning around, then walking back and sitting in the chair. TUG test was repeated three times with adequate rest provided between repeats.

Measurements

Standing balance, gait, and functional mobility performance was quantified using a gold-standard optical motion capture system sampled at 100Hz (16 camera Miquis M3; Qualisys, Gothenburg, Sweden). Markers were placed on the feet (1st and 5th metatarsal heads, calcaneus), ankles (lateral and medial malleoli), head (forehead, bilateral temporomandibular joints), and at the level of the sacrum (rigid cluster of 3 non-collinear markers). Feet, head, and ankle markers were affixed with double-sided tape; the sacral cluster was attached to a non-slip waistband. One participant wore orthopaedic shoes, otherwise participants were barefoot.

Participants also completed the Functional Gait Assessment (Wrisley et al. 2004) and Balance Vigilance Questionnaire (Ellmers and Kal 2024). Functional Gait Assessment consists of 10 tasks – walk at normal speed, at fast and slow speeds, with vertical and horizontal head turns, with eyes closed, over obstacles, in tandem, backward, and while ascending and descending stairs – each scored on a 4-level (0–3) ordinal scale and summed (maximum score = 30; lower score indicates greater functional impairment). Balance Vigilance Questionnaire (Ellmers and Kal 2024) is a 6-point questionnaire to assess how much time and attention participants devote to balance-related concerns (maximum score = 30; higher score indicates greater balance vigilance).

Noisy galvanic vestibular stimulus

Binaural, bipolar nGVS was delivered via 35 cm² (5 x 7 cm) carbon rubber electrodes placed over bilateral mastoid processes and secured using medical adhesive tape. The skin was cleaned prior to electrode placement with an alcohol swab. Conductive gel (SignaGel) was used to improve contact and ensure uniform current density. nGVS signals were generated using MATLAB R2025a (Mathworks, Natick, USA), digital-to-analog converted (National Instruments USB 6001), and delivered to the participant via an in-house voltage-controlled stimulator.

The signal was zero-mean gaussian white noise (0-100 Hz) with ± 0.4 mA current amplitude range. Stimulus parameters were fixed across participants instead of individualised because it is the simplest form to deploy clinically, it permits genuine blinding, and it avoids potential bias via a stimulation-parameter selection procedure. Our chosen amplitude has evidence of effectiveness in other studies (Inukai et al. 2018b, a, 2020a, b; Nguyen et al. 2023), is close to the ± 0.35 mA stimulus we have recently shown to modulate perturbation responses and tonic ankle EMG in healthy adults (Mahmud et al. 2026), and sits within the range at which individualised stimuli typically converge across studies in BV (McLaren et al. 2023).

To reduce stimulation onset/offset effects and aid stimulus blinding, a 5 second ramp up/down period was used at the beginning/end of each sham and stimulation condition. Sham stimulation was identical to nGVS except the stimulus turned off at the end of the ramp up period.

Data analysis and outcome measures

Motion capture marker trajectories were smoothed (bidirectional low-pass filter, 6 Hz cut-off, 4th order Butterworth) and gaps of less than 20 frames (200 ms) were filled using cubic spline interpolation in Matlab R2025a.

Standing balance

We computed postural sway as the sacral mean angular velocity over each standing balance trial.

Gait

We computed the sixteen gait characteristics in the Lord et al. (Lord et al. 2013) model representing five domains of gait: pace (related to gait speed), rhythm (timing characteristics of gait), variability (step-to-step fluctuations), asymmetry (left-right differences), and postural control (related to maintenance of balance). Toe-off and heel-strike gait events were detected using an automated algorithm (Zeni et al. 2008; Ulrich et al. 2019), then visually inspected, and manually adjusted if needed, within an interactive program (Cowie et al. 2010). To restrict analysis to 'steady-state' gait, gait initiation and termination (first/last three steps of each walk) were excluded (Miller and Verstraete 1996; Lindemann et al. 2008; Macfarlane and Looney 2008; Muir et al. 2014). For each gait characteristic we computed mean and variability (standard deviation [SD]) per side within each trial before combining sides (Galna et al. 2013). Asymmetry was the absolute difference between left and right mean values. Note, variability of temporal gait characteristics (step, stance, and swing time variability) relate to gait pace (Lord et al. 2013), where increased variability is associated with slower pace.

Functional mobility

We computed TUG completion time and turning metrics (duration, peak and mean speed) for each TUG trial. Completion time was the duration from initiation of standing to termination of sitting from the chair. Stand initiation and sit termination times were detected from 5m/s^2 threshold crossings of low-pass filtered pelvis vertical acceleration (1.5 Hz cut-off, zero-lag 4th order Butterworth). Turn start and end

times were computed from pelvis yaw plane angular velocity using a validated algorithm (El-Gohary et al. 2014).

Perception

Immediately after the participants received the sham or nGVS stimulation, participants completed a symptom and side-effect questionnaire. Participants were asked to report any tingling, pressure, nausea, dizziness and overall comfort to discern if they could detect the nGVS. They were also asked whether they perceived any improvement in their balance, posture, and walking abilities (yes/no binary response).

Statistical analysis

We assessed the effect of nGVS on the group and each participant separately. Group-level effects were statistically analysed using mixed-effects linear regression models in Stata v18.5 (StataCorp LLC, College Station, TX). Models included task-specific fixed effects: standing balance (condition X vision X surface); gait (condition X speed); functional mobility (condition). All models included a random effect of participant to account for clustering of data within each individual. The extent to which models met assumptions were assessed by visual inspection of residuals. We report two-sided p values, tests of contrasts, estimated marginal means and 95% confidence intervals. Participant-level effects were statistically analysed for each task using Mann-Whitney U tests in Matlab R2025a. Trial-level measures across conditions were entered for each task Alpha was set at $p < 0.05$ for all analyses. Trial-level values were inputted to each statistical test. Perception was analysed informally without statistical procedures.

Results

Perception

No participant was able to confidently distinguish stimulation from sham, confirming the nGVS stimulation was subperceptual. One of ten participants subjectively reported improved gait with nGVS, specifically reduced blurring of vision when walking. No participant reported improved standing balance or functional mobility.

Standing balance

At group-level there was no evidence nGVS influenced postural sway overall or within any task (Fig. 2; condition: $\chi^2(1) = 3.02$, $p = 0.0831$; condition X vision: $\chi^2(1) = 1.07$, $p = 0.3019$; condition X surface: $\chi^2(1) = 2.27$, $p = 0.1320$; condition X vision X surface: $\chi^2(1) = 1.63$, $p = 0.2016$).

At participant-level there was no statistical evidence nGVS influenced postural sway for any participant (Fig. 2; all $p > 0.240$).

Gait

At group-level there was no evidence nGVS influenced any gait pace, rhythm, asymmetry, nor postural control characteristic (Fig. 3–4; all condition: $\chi^2(1) < 0.89$, $p > 0.3445$; all condition X speed: $\chi^2(1) < 1.95$,

$p > 0.1622$). Within the gait variability domain, there was evidence nGVS decreased step width variability overall (Fig. 3–4; stimulation: 3.5 cm [2.5,4.5]; sham: 4.1 cm [3.1,5.1]; condition: $\chi^2(1) = 5.07$, $p = 0.0243$) but not within either walking speed task (condition X speed: $\chi^2(1) = 0.15$, $p = 0.6986$). Other gait variability characteristics were not influenced by nGVS (step velocity variability, step length variability: condition: $\chi^2(1) < 1.07$, $p > 0.3001$; condition X speed: $\chi^2(1) < 1.55$, $p > 0.2136$).

At participant-level there was no statistical evidence nGVS influenced any gait characteristic in self-selected speed (Fig. 3; all $p > 0.100$) nor slow walking (Fig. 4; all $p > 0.0570$) for any participant.

Functional mobility

At group-level there was no evidence nGVS influenced TUG completion time (Fig. 5; condition: $\chi^2(1) = 0.10$, $p = 0.7548$), turn peak speed (condition: $\chi^2(1) = 0.05$, $p = 0.8296$), nor turn mean speed (condition: $\chi^2(1) = 0.01$, $p = 0.9255$).

At participant-level there was no statistical evidence nGVS influenced TUG completion time, turn peak speed, nor turn mean speed for any participant (Fig. 5; all $p > 0.100$).

Discussion

A single session of subperceptual nGVS did not improve standing balance, gait or functional mobility in this cohort of patients with bilateral vestibulopathy. Group estimates for almost every outcome sat close to sham, and no participant showed a convincing individual response. The one exception was a modest reduction in step width variability during walking, which did not survive separation by walking speed. We discuss our findings in the context of study design, the proposed mechanism of nGVS action, statistical power, and stimulus intensity and selection.

The case for blinded, sham-controlled designs

Much of the evidence for nGVS rests on small, open-label or single-blind crossover studies in which stimulation was compared with no stimulation. A meta-analysis in BV concluded that nGVS reduced postural sway but also identified a consistent risk of bias across trials and substantial heterogeneity in stimulation parameters (McLaren et al. 2022). We observed a similar pattern in our own meta-analysis of GVS in Parkinson's disease, in which a favourable pooled effect on postural balance was accompanied by small sample sizes, substantial between-study heterogeneity and limited statistical power (Mahmud et al. 2022). These limitations do not necessarily invalidate the reported findings, but they constrain the conclusions that can be drawn from unblinded crossover studies. This is particularly relevant for an intervention with potentially small effects, whose outcomes may be influenced by effort and attention, and with a stimulation device that may be difficult to conceal. To date, the only large, double-blind, placebo-controlled trial of nGVS was negative (Fujimoto et al. 2025), which highlights the importance of adequately blinded, placebo-controlled designs.

Against that background, the present study demonstrates that a properly blinded protocol is feasible in this population. Ramped on- and offset of the sham stimulus, in addition to low intensity stimulation, achieved blinding, confirmed by participants' inability to distinguish active from sham stimulation, while only one reported any subjective change. Standing balance across four sensory conditions, sixteen gait characteristics measured at two walking speeds, and functional mobility were all captured within a single session using optical motion capture, in patients recruited from routine clinical practice. We argue the design represents a workable template for a definitive trial.

Stochastic resonance, vestibular drive, and nGVS

The therapeutic rationale for nGVS has largely been framed in terms of stochastic resonance, whereby an optimal level of added noise enhances the detection of otherwise subthreshold sensory signals. However, recent evidence suggests that this mechanism alone may not fully account for the effects of nGVS and may have important implications for interpreting our findings. Rice and colleagues (Rice et al. 2026) demonstrated that subperceptual nGVS, at amplitudes routinely used in stochastic resonance paradigms, does not simply act as featureless noise but can also produce deterministic, stimulus-locked effects on postural control. Coherent postural responses were observed in most healthy participants at 0.5–0.7 mA and were detectable in some participants at amplitudes as low as 0.1 mA. These responses were more pronounced when participants stood on foam, consistent with increased reliance on vestibular input when somatosensory information is degraded. Thus, changes in balance during subperceptual nGVS may reflect a combination of stochastic facilitation and direct vestibular drive. Consistent with this interpretation, postural responses to ± 0.6 mA nGVS have also been reported in older adults (Osler and Reynolds 2026). In our own work in healthy adults, a comparable fixed stimulus (± 0.35 mA, 0–30 Hz) reduced trunk responses to postural perturbations and increased tonic ankle EMG without altering perturbation-evoked muscle responses (Mahmud et al. 2026). These findings further suggest that subperceptual currents can modulate vestibulospinal output.

This interpretation has two important implications. First, the stimulus amplitudes at which coherent postural responses were observed in healthy participants were generally higher than the fixed ± 0.4 mA used in our study. Thus, our stimulation intensity may have been insufficient to produce substantial activation of vestibular afferents. Second, and more fundamentally, both the stochastic and deterministic effects of nGVS are likely to depend on the presence of residual vestibular afferent function. In individuals with profound bilateral vestibular loss, the physiological substrate that nGVS is intended to augment may be substantially reduced or absent. Our cohort was aetiologically heterogeneous and included patients with severe loss, which could attenuate an average treatment effect. This interpretation is also consistent with previous observations that greatest benefit may occur in individuals with impaired balance who retain some residual vestibular function (Fujimoto et al. 2019). If direct vestibular drive contributes meaningfully to the therapeutic effects of nGVS, measures of residual vestibular function should predict individual treatment response.

Stimulus optimisation

The clearest methodological difference between this study and much of the literature reporting beneficial effects of nGVS is that we did not individualise the stimulation intensity. Several studies reporting positive effects have first identified an individualised optimal intensity, either by testing a range of amplitudes during quiet stance and selecting the intensity associated with the greatest reduction in postural sway (Iwasaki et al. 2014) or by setting the current as a fixed proportion of each participant's nGVS cutaneous or motion perception threshold (Wuehr et al. 2016). Optimal amplitudes in BV are higher than in healthy adults and widely dispersed, averaging around 0.45 to 0.50 mA (McLaren et al. 2023, 2025), and vary within the same individual across days (Fujimoto et al. 2023). Our fixed ± 0.4 mA stimulus therefore falls at or below the lower end of the reported range, raising the possibility that a higher or individually optimised intensity might have produced a greater effect.

However, substantial interindividual variability in optimal stimulation intensity provides an important counterpoint. If ± 0.4 mA were an effective intensity for a meaningful proportion of patients, some participants might be expected to show measurable benefit by chance, yet no participant demonstrated a response on any outcome. Furthermore, the largest adequately blinded trial to date used an optimal stimulation intensity for each participant but nevertheless found no significant benefit, including within the BV subgroup (Fujimoto et al. 2025). These findings suggest that individualisation may be important for maximising the magnitude of any treatment response, but that individualised stimulation may not account for the absence of an effect in our study.

The one positive signal, limitations and next steps

We found reduced step width variability in stimulation compared to sham, which is corroborated by similar findings in other studies (Wuehr et al. 2016; Chen et al. 2021). However, it was the only statistically significant change of the 16 gait characteristics tested, and would not survive correction for multiple comparisons so should be interpreted with caution.

The study has clear limitations. Ten analysable participants of mixed aetiology gave power to detect only large effects. While we tested an array of abilities (standing balance, gait and mobility), a larger volume of data per participant may have improved statistical power. Five participants could not stand on foam with eyes closed, producing a floor effect in the condition where vestibular reliance, and therefore any nGVS effect, should be greatest. However, nGVS also did not restore the ability to stand on foam with eyes closed in any participant, corroborating the absence of a nGVS effect. We tested a single session of concurrent stimulation, whereas the more encouraging clinical data come from cumulative paradigms, or from measurements taken after stimulation has ceased (Fujimoto et al. 2018), or when nGVS has been delivered alongside vestibular rehabilitation (Eder et al. 2022).

Our data suggests no clear benefit of ± 0.4 mA nGVS on balance, gait or functional mobility in bilateral vestibulopathy. Future work should develop biomarkers of nGVS responders and conduct sufficiently large, well-powered double-blinded sham-controlled studies to definitively establish the efficacy of nGVS.

Declarations

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the London - Central Research Ethics Committee (REC reference 23/PR/1233).

Consent

Informed consent was obtained from all subjects involved in this study, including consent to publish data collected during the study.

Data availability statement

Data is available from the corresponding author upon reasonable request.

Conflict of interest

The study was funded by Cochlear, a company that develops implantable hearing solutions for individuals with deafness and vestibular disorders. Cochlear provided support for the study design but had no involvement in the analysis or interpretation of the data. There are no other conflicts of interest to disclose.

Author contributions

Conceptualization: DK, MM; Methodology: MJB, DK, MM; Formal analysis and investigation: MJB, HO, BJ, MM; Writing - original draft preparation: MJB, HO, MM; Writing - review and editing: MJB, HO, BJ, DK, MM; Funding acquisition: MM, DK; Supervision: MJB, DK, MM.

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References

1. Brandt T, Strupp M, Benson J (1999) You are better off running than walking with acute vestibulopathy. *Lancet* 354:746. [https://doi.org/10.1016/S0140-6736\(99\)03179-7](https://doi.org/10.1016/S0140-6736(99)03179-7)
2. Chen P-Y, Jheng Y-C, Wang C-C et al (2021) Effect of noisy galvanic vestibular stimulation on dynamic posture sway under visual deprivation in patients with bilateral vestibular hypofunction. *Sci Rep* 11:4229. <https://doi.org/10.1038/s41598-021-83206-z>
3. Chow MR, Ayiotis AI, Schoo DP et al (2021) Posture, Gait, Quality of Life, and Hearing with a Vestibular Implant. *N Engl J Med* 384:521–532. <https://doi.org/10.1056/NEJMoa2020457>

4. Cowie D, Limousin P, Peters A, Day BL (2010) Insights into the neural control of locomotion from walking through doorways in Parkinson's disease. *Neuropsychologia* 48:2750–2757. <https://doi.org/10.1016/j.neuropsychologia.2010.05.022>
5. Dakin CJ, Son GML, Inglis JT, Blouin J-S (2007) Frequency response of human vestibular reflexes characterized by stochastic stimuli. *J Physiol* 583:1117–1127. <https://doi.org/10.1113/jphysiol.2007.133264>
6. Eder J, Kellerer S, Amberger T et al (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>
7. El-Gohary M, Pearson S, McNames J et al (2014) Continuous Monitoring of Turning in Patients with Movement Disability. *Sensors* 14:356–369. <https://doi.org/10.3390/s140100356>
8. Ellmers TJ, Kal EC (2024) Exploring the role of attention towards balance in chronic dizziness: Development of the Balance Vigilance Questionnaire. *Eur J Neurol* 31:e16148. <https://doi.org/10.1111/ene.16148>
9. Fitzpatrick RC, Day BL (2004) Probing the human vestibular system with galvanic stimulation. *Journal of applied physiology* (Bethesda, Md: 1985) 96:2301–16. <https://doi.org/10.1152/japplphysiol.00008.2004>
10. Forbes PA, Vlutters M, Dakin CJ et al (2017) Rapid limb-specific modulation of vestibular contributions to ankle muscle activity during locomotion. *J Physiol* 595:2175–2195. <https://doi.org/10.1113/JP272614>
11. Fujimoto C, Egami N, Kawahara T et al (2018) Noisy Galvanic Vestibular Stimulation Sustainably Improves Posture in Bilateral Vestibulopathy. *Front Neurol* Volume. <https://doi.org/10.3389/fneur.2018.00900>. 9-2018
12. Fujimoto C, Kawahara T, Kikkawa YS et al (2025) Multicenter randomized double-blind placebo-controlled crossover study of the effect of prolonged noisy galvanic vestibular stimulation on posture or gait in vestibulopathy. *PLoS ONE* 20:1–16. <https://doi.org/10.1371/journal.pone.0317822>
13. Fujimoto C, Kawahara T, Kinoshita M et al (2023) Inter-day and intra-day variations in effective intensity of noisy galvanic vestibular stimulation to improve postural stability in bilateral vestibulopathy. *J Vestib Res* 33:423–429. <https://doi.org/10.3233/VES-230060>
14. Fujimoto C, Kinoshita M, Kamogashira T et al (2019) Noisy galvanic vestibular stimulation has a greater ameliorating effect on posture in unstable subjects: a feasibility study. *Sci Rep* 9:17189. <https://doi.org/10.1038/s41598-019-53834-7>
15. Galna B, Lord S, Rochester L (2013) Is gait variability reliable in older adults and Parkinson's disease? Towards an optimal testing protocol. *Gait Posture* 37:580–585. <https://doi.org/10.1016/j.gaitpost.2012.09.025>
16. Gillespie MB, Minor LB (1999) Prognosis in Bilateral Vestibular Hypofunction. *Laryngoscope* 109:35–41. <https://doi.org/10.1097/00005537-199901000-00008>

17. Guinand N, Boselie F, Guyot J-P, Kingma H (2012) Quality of Life of Patients with Bilateral Vestibulopathy. *Ann Otol Rhinol Laryngol* 121:471–477.
<https://doi.org/10.1177/000348941212100708>
18. Hall CD, Herdman SJ, Whitney SL et al (2022) Vestibular Rehabilitation for Peripheral Vestibular Hypofunction: An Updated Clinical Practice Guideline From the Academy. of Neurologic Physical Therapy of the American Physical Therapy Association
19. Inukai Y, Masaki M, Otsuru N et al (2018a) Effect of noisy galvanic vestibular stimulation in community-dwelling elderly people: a randomised controlled trial. *J Neuroeng Rehabil* 15:63.
<https://doi.org/10.1186/s12984-018-0407-6>
20. Inukai Y, Miyaguchi S, Saito M et al (2020a) Effects of Different Stimulation Conditions on the Stimulation Effect of Noisy Galvanic Vestibular Stimulation. *Front Hum Neurosci* 14:581405.
<https://doi.org/10.3389/fnhum.2020.581405>
21. Inukai Y, Otsuru N, Masaki M et al (2018b) 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>
22. Inukai Y, Otsuru N, Saito K et al (2020b) The after-effect of noisy galvanic vestibular stimulation on postural control in young people: A randomized controlled trial. *Neurosci Lett* 729:135009.
<https://doi.org/10.1016/j.neulet.2020.135009>
23. Iwasaki S, Yamamoto Y, Togo F et al (2014) Noisy vestibular stimulation improves body balance in bilateral vestibulopathy. *Neurology* 82:969–975. <https://doi.org/10.1212/WNL.0000000000000215>
24. Kremmyda O, Hüfner K, Flanagan VL et al (2016) Beyond Dizziness: Virtual Navigation, Spatial Anxiety and Hippocampal Volume in Bilateral Vestibulopathy. *Front Hum Neurosci* 10.
<https://doi.org/10.3389/fnhum.2016.00139>
25. Lindemann U, Najafi B, Zijlstra W et al (2008) Distance to achieve steady state walking speed in frail elderly persons. *Gait Posture* 27:91–96. <https://doi.org/10.1016/j.gaitpost.2007.02.005>
26. Lord S, Galna B, Verghese J et al (2013) Independent domains of gait in older adults and associated motor and nonmotor attributes: validation of a factor analysis approach. *Journals Gerontol Ser A: Biomedical Sci Med Sci* 68:820–827
27. Lucieer F, Vonk P, Guinand N et al (2016) Bilateral Vestibular Hypofunction: Insights in Etiologies, Clinical Subtypes, and Diagnostics. *Front Neurol* 7. <https://doi.org/10.3389/fneur.2016.00026>
28. Macfarlane PA, Looney MA (2008) Walkway Length Determination for Steady State Walking in Young and Older Adults. *Res Q Exerc Sport* 79:261–267.
<https://doi.org/10.1080/02701367.2008.10599489>
29. Mahmud M, Hadi Z, Prendergast M et al (2022) The effect of galvanic vestibular stimulation on postural balance in Parkinson's disease: A systematic review and meta-analysis. *J Neurol Sci* 442:120414. <https://doi.org/https://doi.org/10.1016/j.jns.2022.120414>
30. Mahmud M, Hadi Z, Sohail I et al (2026) Effects of noisy galvanic vestibular stimulation on reactive postural and neuromuscular responses to surface perturbations. *J Neurophysiol*.

<https://doi.org/10.1152/jn.00235.2025>

31. Mahmud M, Kaski D (2024) Vestibular neurology for the generalist. *J Neurol Neurosurg Psychiatry* 95:1196–1206. <https://doi.org/10.1136/jnnp-2024-333580>
32. McLaren R, Smith PF, Taylor RL et al (2022) Efficacy of nGVS to improve postural stability in people with bilateral vestibulopathy: A systematic review and meta-analysis. *Front Neurosci* Volume. <https://doi.org/10.3389/fnins.2022.1010239>. 16-2022
33. McLaren R, Smith PF, Taylor RL et al (2023) Scoping out noisy galvanic vestibular stimulation: a review of the parameters used to improve postural control. *Front Neurosci* Volume. <https://doi.org/10.3389/fnins.2023.1156796>. 17-2023
34. McLaren R, Smith PF, Taylor RL, Taylor D (2025) Optimizing noisy galvanic vestibular stimulation (nGVS) for postural control: methodological considerations when individualizing the signal for people with bilateral vestibulopathy. *Front Neurol* Volume. <https://doi.org/10.3389/fneur.2025.1609123>. 16-2025
35. Miller CA, Verstraete MC (1996) Determination of the step duration of gait initiation using a mechanical energy analysis. *J Biomech* 29:1195–1199. [https://doi.org/10.1016/0021-9290\(96\)00033-4](https://doi.org/10.1016/0021-9290(96)00033-4)
36. Muir BC, Rietdyk S, Haddad JM (2014) Gait initiation: The first four steps in adults aged 20–25 years, 65–79 years, and 80–91 years. *Gait & Posture* 39:490–494. <https://doi.org/10.1016/j.gaitpost.2013.08.037>
37. Nguyen TT, Lee S-B, Kang J-J, Oh S-Y (2023) Optimal Design of Galvanic Vestibular Stimulation for Patients with Vestibulopathy and Cerebellar Disorders. *Brain Sci* 13:1333. <https://doi.org/10.3390/brainsci13091333>
38. Osler CJ, Reynolds RF (2026) Age-related decline in vestibulo-ocular reflex gain is associated with an increased sway response to electrical vestibular stimulation. *J Neurophysiol* 136:1359–1368. <https://doi.org/10.1152/jn.00110.2026>
39. Porciuncula F, Johnson CC, Glickman LB (2012) The effect of vestibular rehabilitation on adults with bilateral vestibular hypofunction: A systematic review. *J Vestib Res* 22:283–298. <https://doi.org/10.3233/VES-120464>
40. Rice D, Hannan KB, Ewer M, Dakin CJ (2026) When noise isn't simply noise: deterministic postural drive during noisy galvanic vestibular stimulation. *J Neurophysiol* 136:405–411. <https://doi.org/10.1152/jn.00177.2026>
41. Schniepp R, Schlick C, Schenkel F et al (2017) Clinical and neurophysiological risk factors for falls in patients with bilateral vestibulopathy. *J Neurol* 264:277–283. <https://doi.org/10.1007/s00415-016-8342-6>
42. Schniepp R, Wuehr M, Neuhaeusser M et al (2012) Locomotion speed determines gait variability in cerebellar ataxia and vestibular failure. *Mov Disord* 27:125–131. <https://doi.org/10.1002/mds.23978>

43. Strupp M, Kim J-S, Murofushi T et al (2017) Bilateral vestibulopathy: Diagnostic criteria Consensus document of the Classification Committee of the Bárány Society¹. *J Vestib Res* 27:177–189. <https://doi.org/10.3233/VES-170619>
44. Sun DQ, Ward BK, Semenov YR et al (2014) Bilateral Vestibular Deficiency: Quality of Life and Economic Implications. *JAMA Otolaryngol Head Neck Surg* 140:527–534. <https://doi.org/10.1001/jamaoto.2014.490>
45. Ulrich B, Santos AN, Jolles BM et al (2019) Gait events during turning can be detected using kinematic features originally proposed for the analysis of straight-line walking. *J Biomech* 91:69–78. <https://doi.org/10.1016/j.jbiomech.2019.05.006>
46. Ward BK, Agrawal Y, Hoffman HJ et al (2013) Prevalence and Impact of Bilateral Vestibular Hypofunction: Results From the 2008 US National Health Interview Survey. *JAMA Otolaryngol Head Neck Surg* 139:803–810. <https://doi.org/10.1001/jamaoto.2013.3913>
47. Wrisley DM, Marchetti GF, Kuharsky DK, Whitney SL (2004) Reliability, internal consistency, and validity of data obtained with the functional gait assessment. *Phys Ther* 84:906–918
48. Wuehr M, Decker J, Schniepp R (2017) Noisy galvanic vestibular stimulation: an emerging treatment option for bilateral vestibulopathy. *J Neurol* 264:81–86. <https://doi.org/10.1007/s00415-017-8481-4>
49. Wuehr M, Nusser E, Decker J et al (2016) Noisy vestibular stimulation improves dynamic walking stability in bilateral vestibulopathy. *Neurology* 86:2196–2202. <https://doi.org/10.1212/WNL.0000000000002748>
50. Zeni JAJ, Richards JG, Higginson JS (2008) Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait Posture* 27:710–714. <https://doi.org/10.1016/j.gaitpost.2007.07.007>

Figures

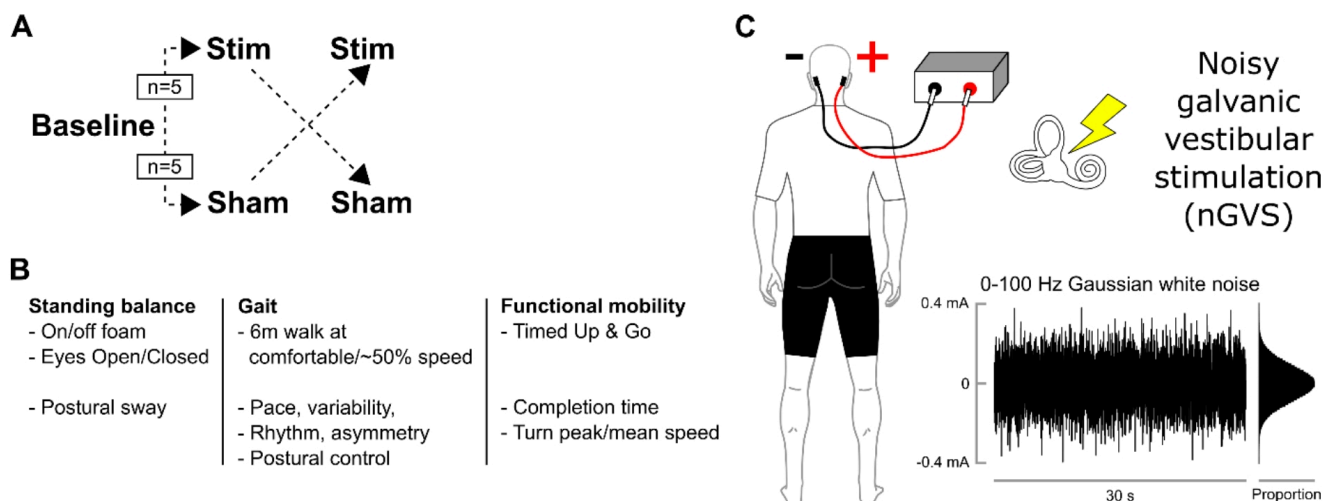


Figure 1

Study Design. (A) Participants first completed a baseline assessment before being randomly assigned to stim-then-sham or sham-then-stim condition orders. (B) Summary of the tasks and outcome measures. (C) An example of the nGVS stimulus. Electrodes were affixed bilaterally to the mastoids and a 0-100 Hz Gaussian white noise $\pm 0.4\text{mA}$ nGVS signal was delivered to the participant.

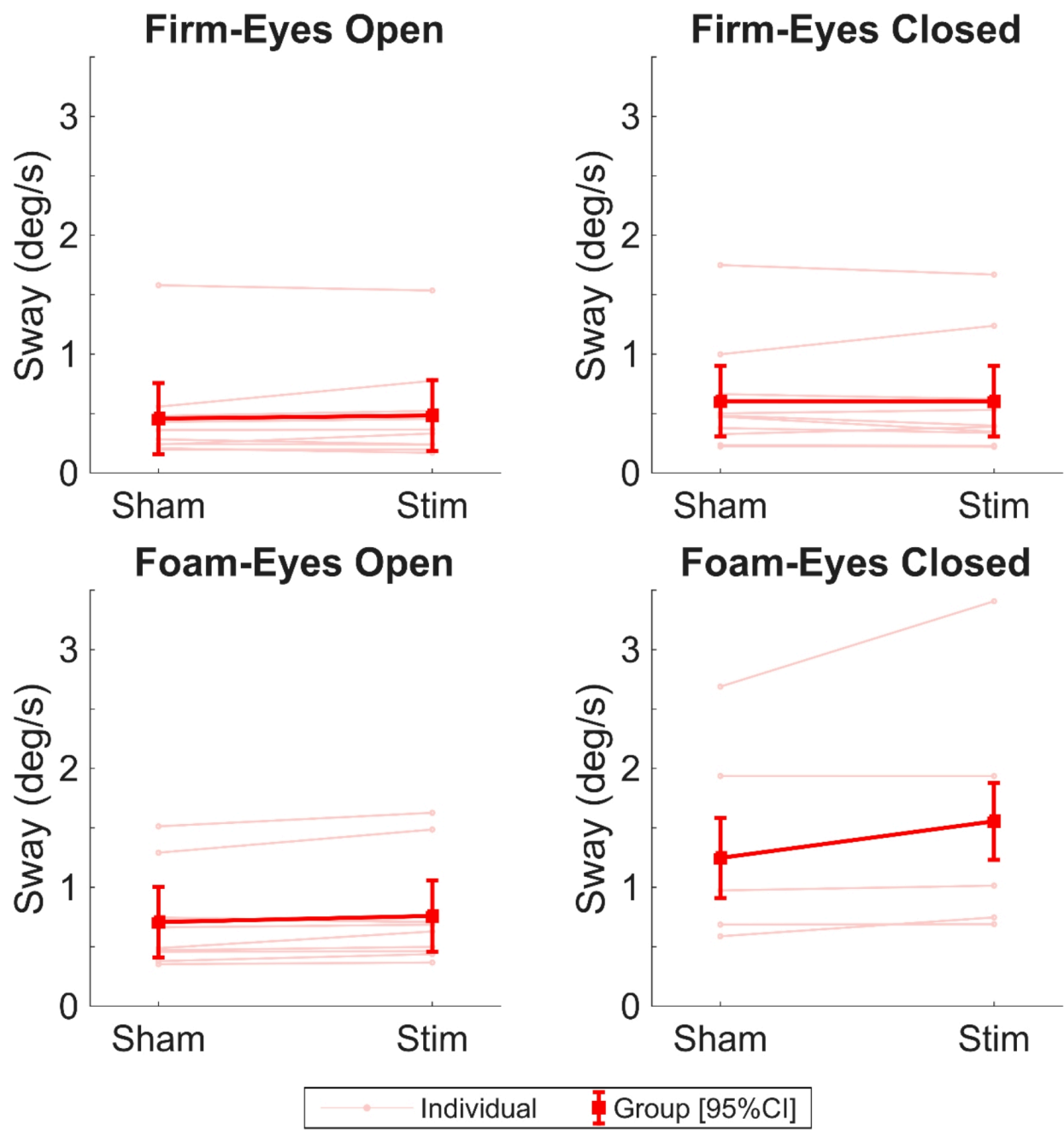


Figure 2

Effect of nGVS on standing balance. Postural sway measured at sacral level in stimulation and sham stimulation conditions. Bold red line is the group mean with 95% confidence intervals; pale red lines are individual participants' mean.



Figure 3

Effect of nGVS on gait at a self-selected comfortable speed. Radar plot showing walking characteristics in stimulation (Stim) relative to sham stimulation (Sham) conditions expressed as standardised (z) scores. Bold red line is the group mean; pale red lines are individual participants; black line is sham stimulation (z=0). Grey lines indicate how many standard deviations the group and each individual differs from sham. Group- and individual-level z scores were computed from within-group and within-individual means and standard deviations, respectively. Note, step time SD, swing time SD, and stance time SD are a pace domain gait characteristics where a higher value is associated with slower pace.

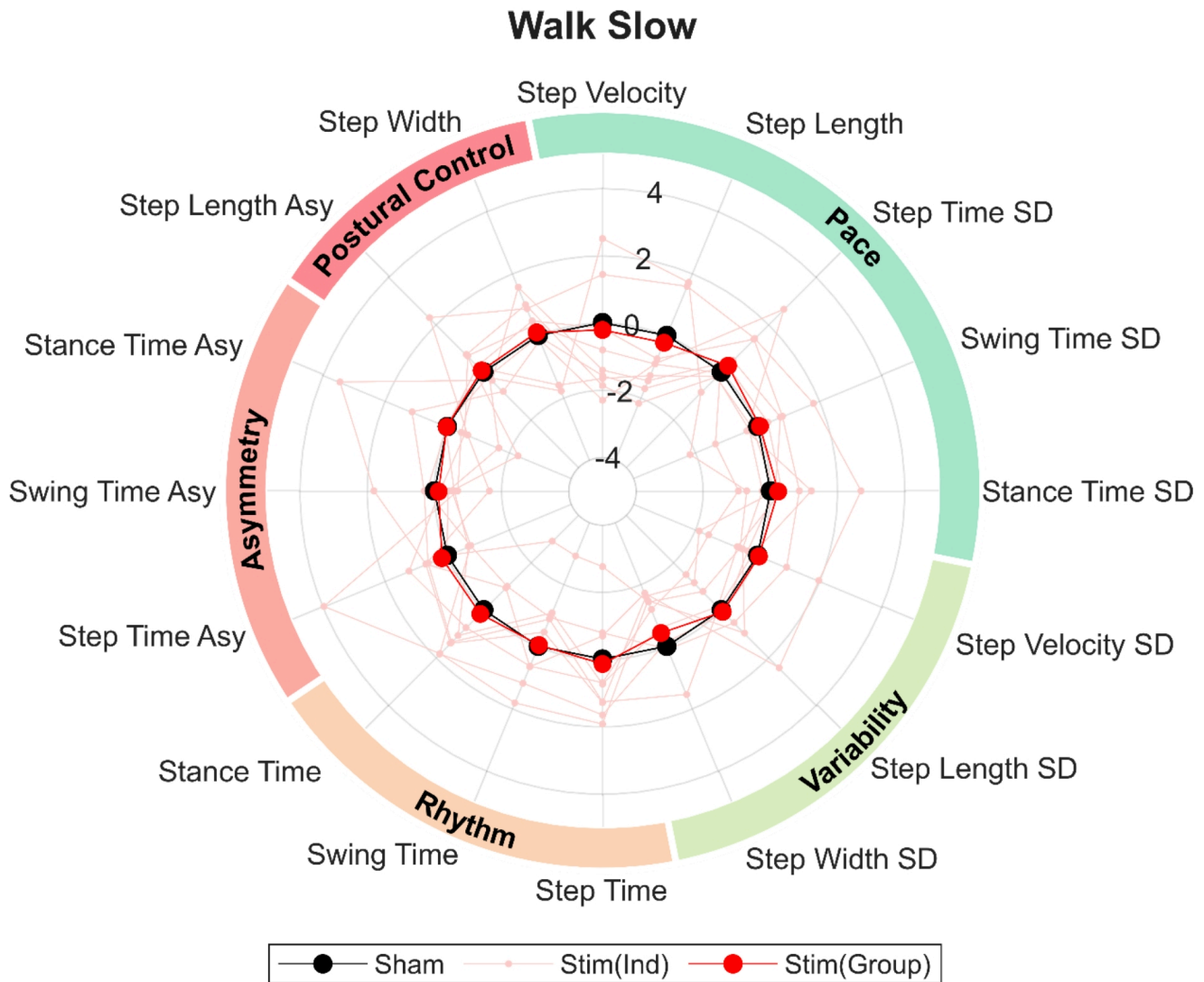


Figure 4

Effect of nGVS on gait at ~50% self-selected comfortable speed. Radar plot showing walking characteristics in stimulation (Stim) relative to sham stimulation (Sham) conditions expressed as standardised (z) scores. Bold red line is the group mean; pale red lines are individual participants; black line is sham stimulation ($z=0$). Grey lines indicate how many standard deviations the group and each individual differs from sham. Group- and individual-level z scores were computed from within-group and within-individual means and standard deviations, respectively. Note, step time SD, swing time SD, and stance time SD are a pace domain gait characteristics where a higher value is associated with slower pace.

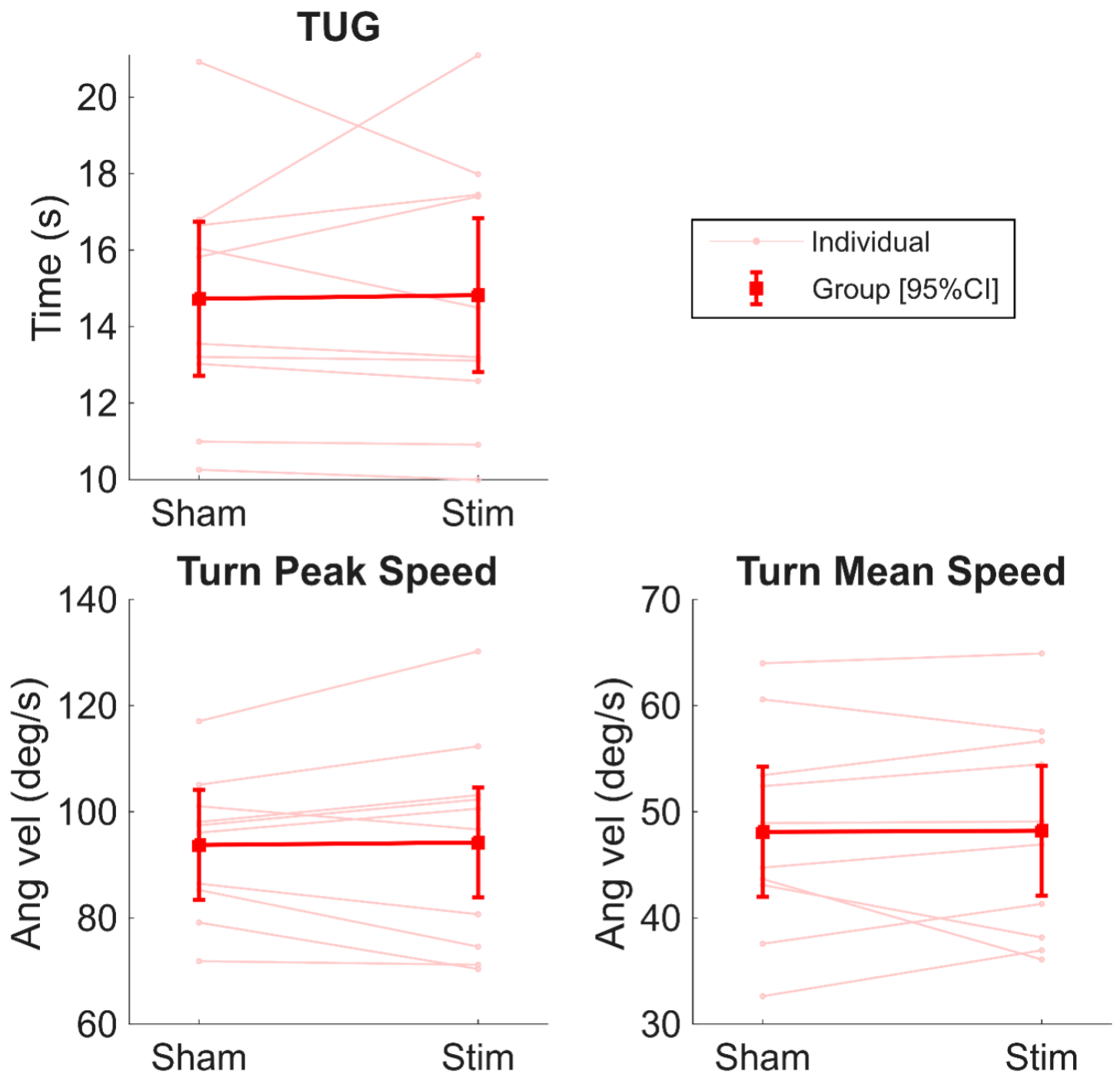


Figure 5

Effect of nGVS on functional mobility. Timed-up-and-go (TUG) test completion time (top left), peak (bottom left) and mean (bottom right) turn speed. Bold red line is the group mean with 95% confidence intervals; pale red lines are individual participants' mean.