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Faculteit Revalidatiewetenschappen

master in de revalidatiewetenschappen en de
kinesitherapie

Masterthesis

The effect of vestibular perturbations on spatiotemporal gait parameters in healthy adults

Gianluca Mirisola

Warre Wouters

Scriptie ingediend tot het behalen van de graad van master in de revalidatiewetenschappen en de kinesitherapie,
afstudeerrichting revalidatiewetenschappen en kinesitherapie bij musculoskeletale aandoeningen

PROMOTOR :

Prof. dr. Pieter MEYNS

COPROMOTOR :

Mevrouw Esma Nur KOLBASI DOGAN



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We are also grateful to Professor Pieter Meyns for serving as our promoter. His critical questions, constructive criticism, and high standards consistently pushed us to strengthen our methodology and sharpen our analyses. The level of rigour he demanded inspired us to continuously improve our thesis and pursue excellence in our research.

Our sincere thanks go to Joke Spildoren, whose specialist advice illuminated key aspects of our study and helped us interpret complex findings with greater clarity.

Finally, we wish to thank our families and friends for their patience and support during the many long hours of writing and revision. Undertaking this work alongside the daily demands of internships and other commitments was a significant challenge, but with the encouragement of our mentors and loved ones, we were able to persist and deliver a thesis of which we are truly proud.

- Warre Wouters & Gianluca Mirisola -

Research Context

This master's thesis is situated within the broader domain of geriatric rehabilitation and is part of the "*Gait & Balance*" theme of REVAL.

Maintaining dynamic balance during gait is a complex sensorimotor task that relies critically on vestibular inputs to detect head movements and gravitational forces, integrate multisensory feedback, and generate timely postural adjustments (Khan & Chang, 2013; Ertl & Boegle, 2019). Although numerous experimental paradigms have applied vestibular perturbations—such as galvanic vestibular stimulation (GVS), mastoid vibration (MV), and stochastic vestibular stimulation (SVS)—to probe balance mechanisms, their collective impact on spatiotemporal gait parameters in healthy adults remains incompletely characterised. Individual studies offer valuable insights (e.g. Chien et al., 2016; Sun et al., 2023; Li et al., 2025), but differences in study protocol, stimulation modality, intensity, timing, and outcome measures have so far prohibited a unified understanding.

The scope of the review was limited to spatiotemporal parameters only, as advised by the promoter team, in order to ensure feasibility within the one-year timeframe of this master's thesis. Alternative approaches to characterising gait, such as Margins of Stability and Center of pressure displacements, were not included in the analysis but are briefly addressed in the discussion, where relevant to the interpretation of our findings.

This thesis addresses that gap by systematically reviewing and meta-analysing cross-sectional studies of vestibular perturbations administered during straight-line walking in adults without known balance or neurological disorders. With this meta-analysis, this thesis aimed to quantify how each form of vestibular perturbation influences spatiotemporal gait parameters. Such a quantitative synthesis is needed to (1) determine the magnitude and direction of perturbation-induced changes, (2) assess heterogeneity attributable to protocol differences or participant characteristics, and (3) inform the design of future intervention studies and clinical assessments of dynamic balance.

Under the supervision of Dr. Esma Kolbasi Dogan and the promotion of Prof. Pieter Meyns, this thesis was conducted independently within the REVAL research centre and is not part of an ongoing doctoral project, funded programme, or clinical collaboration. It does not serve

as a pilot study for a prospective grant application. The research consisted solely of a systematic review and meta-analysis. No experimental testing or clinical data collection was involved in this thesis. Our work aims to enhance both fundamental knowledge and practical applications in balance rehabilitation.

The research topic “sensory integration in walking and its association with falls” was provided by the supervisor. The precise research question was proposed by the students themselves and approved by the supervisor and promoter.

This work was carried out as a duo master’s thesis by students Gianluca Mirisola and Warre Wouters. Both students contributed equally to all components of the thesis, working together throughout each phase of the research process.

1. Abstract

Background: Gait relies on vestibular inputs to maintain balance during locomotion. While numerous cross-sectional studies have applied vestibular perturbations during walking, their collective impact on spatiotemporal gait parameters in healthy adults remains unclear. This study is the first systematic review and meta-analysis assessing how vestibular perturbations alter spatiotemporal parameters during gait in healthy adults.

Methods: Following Cochrane and PRISMA guidelines, PubMed, Scopus, and Web of Science were screened for cross-sectional studies in English. Eligible studies applied vestibular perturbations during straight-line walking in healthy adults and reported spatiotemporal outcomes. Two reviewers independently screened titles/abstracts and full texts, extracted data, and assessed study quality. Pooled effects reported in at least three studies using random-effects models (REML) with Hartung–Knapp–Sidik–Jonkman (HKSJ) adjustment, calculating standardised mean differences (SMDs) and 95 % confidence intervals (CIs).

Results: Seven studies ($n = 125$, aged between 19 and 41 years) were included.

Meta-analyses did not show significant effects of vestibular stimulation on step length (SMD = 0.08; 95 % CI -0.47 to 0.63 ; $I^2 = 0\%$), step length variability (SMD = 0.32; 95 % CI -0.21 to 0.85 ; $I^2 = 0\%$), step width (SMD = 0.04; 95 % CI -0.15 to 0.23 ; $I^2 = 0\%$), and step-width variability (SMD = 0.35; 95 % CI -0.88 to 1.57 ; $I^2 = 55\%$).

Conclusions: Acute vestibular perturbations during gait do not significantly produce measurable alterations in spatiotemporal parameters in healthy young adults.

Keywords: Locomotion, Spatiotemporal gait parameters, Healthy, Adults, Vestibular, Balance, Perturbation

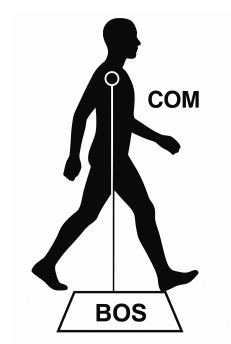
2. Introduction

Falls are the second leading cause of unintentional injury deaths worldwide. (World Health Organisation, 2024). Falls often cause fractures, especially in the hip, wrist, and spine, which may lead to long-term disability, ongoing pain, and a reduced ability to live independently. They can also impact mental well-being, leading to increased anxiety, fear of future falls, and withdrawal from social activities (Søgaard et al., 2022). Falls pose significant problems not only for individuals and their immediate environment but also for society as a whole. The financial burden from fall-related injuries is considerable. The health care expenditure for treating fall-related injuries in the European Union is estimated to be 25 billion Euros each year (European Public Health Association, 2015).

Falls can result from various causes, many of which are complex. A crucial factor is the individual's ability to respond effectively to a balance disturbance. In our everyday lives, we frequently encounter these disturbances or perturbations through actions such as slipping, tripping, and colliding with objects. Every intentional movement we make creates a perturbation to our postural balance. Postural balance is the ability to maintain equilibrium by keeping the body's center of mass (COM) over the base of support (BOS) (Hrysomallis et al., 2007). Postural balance can be divided into two categories: static and dynamic balance. Static balance refers to maintaining equilibrium while standing or sitting, with the BOS remaining stationary and only the COM moving (Hrysomallis et al., 2007). In function of gait, dynamic balance during steady-state gait is defined as the ability to stabilise an individual's COM within a series of alternating unilateral stances above the BOS, while both are moving (Figure 1) (Siragy et al., 2018). In addition, the COM never stays within the BOS during periods of single-limb support (Woollacott et al., 1997). Balance control is achieved through a continuous feedback system that processes inputs from the somatosensory (including proprioception), vestibular, and visual systems, eliciting appropriate neuromuscular responses (Hrysomallis et al., 2007). Perturbations in these systems can make it more challenging to maintain balance (Huxham et al., 2001).

Figure 1

Person maintaining dynamic balance while walking/ COM in BOS.



Various gait impairments can negatively impact young and older adults' ability to maintain dynamic balance while walking. For example, Parijat and Lockhart (2008) showed that acute quadriceps fatigue in healthy young adults significantly altered multiple spatiotemporal gait parameters and has been identified as one of multiple intrinsic factors contributing to slip and fall accidents. An increase in postural sway was noted after fatigue, which seems to be linked to a higher risk of falling (Hsiao & Simeonov, 2001; Nardone et al., 1997). With advancing age, even in the absence of overt pathology, spatiotemporal gait parameters deteriorate in ways that compromise dynamic balance and elevate fall risk. Ambrose et al. (2013) report that preferred gait speed declines by approximately 1 % per year after age 60, primarily driven by a reduction in step and stride length. Concurrently, older adults spend a greater proportion of the gait cycle in double-support, an adaptive safety strategy that slows down locomotion, and exhibit increased stride-to-stride variability in timing, length, and width. Such variability undermines the consistency required to rapidly correct for perturbations, directly eroding the ability to maintain the body's COM over its BOS (Ambrose et al., 2013).

Despite previous biomechanical and age-related gait impairments, the capacity to maintain dynamic balance also relies on the integrity and integration of multiple sensory inputs. The sensory systems in the human body enable individuals to interpret their environment and are a complex network of sensory components that includes the vestibular system, the ocular system, the proprioceptive system, the brainstem, the cerebellum, and the cerebral cortex. Sensory receptors are found in multiple organs, such as the eyes, ears, nose, mouth,

joints, and internal organs. Each receptor type processes a specific sensory modality, which is then integrated into a unified perceptual experience (Marzvanyan & Alhawaj, 2023). The different sensory modalities include hearing, taste, smell, vision, equilibrium, and the somatosensory system (touch, pressure, vibration, pain, temperature, proprioception). As first described by Ayres (1972), sensory integration is defined as “the organisation of sensory information for use”. It is a neurological process that enables us to make sense of our surroundings by receiving, registering, modulating, organising, and interpreting brain information originating from our receptors (Pollock, 2009, p. 6).

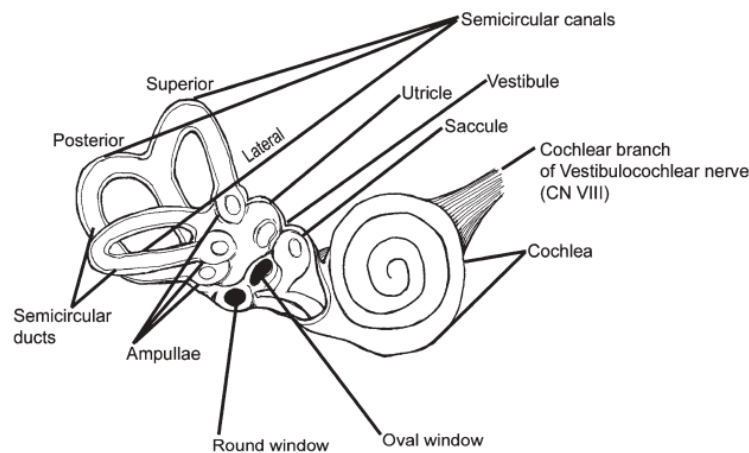
The vestibular organs, located in the inner ear, are responsible for detecting head movements and gravitational forces (Khan & Chang, 2013). The vestibular system has many other specific functions that could play an important role in balance and gait. The vestibular system plays a crucial role in maintaining a stable gaze during head movements, for example, during walking. This stability is achieved through rapid vestibulo-ocular reflexes (VORs)(Tian, 2001, as cited in Agrawal et al., 2020). Impairment in this system can lead to dizziness characterised by blurring or apparent oscillation of the visual world, as the eyes struggle to adapt timely during head movements (Minor, 1998, as cited in Agrawal et al., 2020). Additionally, the vestibular system plays a role in vestibulo-autonomic responses (VARs), where signals about head position help regulate homeostatic processes such as respiratory rate, blood pressure, and gastrointestinal activity during position changes (McCall et al., 2017 & Gagliuso et al., 2019; as cited in Agrawal et al., 2020). Impairments here can lead to lightheadedness due to insufficient stabilisation of intracranial blood flow during these changes (Jian et al., 1999, as cited in Agrawal et al., 2020). Furthermore, the vestibular system contributes to a person's perception of self-motion and self-orientation in space, often referred to as vestibular perception or spatial orientation (Agrawal et al., 2020). This is facilitated by projections from the vestibular system to the thalamus and cortex (Smith, 2013, as cited in Agrawal et al., 2020). When this is impaired, it can lead to spatial disorientation and difficulties with spatial memory and navigation (Agrawal et al., 2019, as cited in Agrawal et al., 2020). Notably, the vestibular inputs also connect to the cerebellum, which is believed to play a crucial role in adapting and calibrating behavioural response (motor, autonomic, or perceptual) in response to vestibular sensory input. A loss of vestibular inputs to the cerebellum can result in dysmetria and a lack of adaptive control

over these responses (Goldberg, 2012, as cited in Agrawal et al., 2020). Most importantly, in the function of this research, the vestibular system is responsible for driving vestibulo-spinal responses (VSRs) that help maintain postural control (McCall, 2017, as cited in Agrawal et al., 2020). Impairments in this system can result in loss of balance, as inadequate postural stabilisation occurs during changes in head position and orientation, which increases the risk of falls (Murray, 2018, as cited in Agrawal et al., 2020). In conclusion, perturbations of the vestibular system can have an influence on gait.

The process within the vestibular organs, when a perturbation occurs, is very detailed. When the vestibular system is perturbed, hair cells within the vestibular organs (utricle, saccule, and semicircular canals) detect these mechanical disturbances. Perturbations cause deflection of hair cell stereocilia, tiny hair-like projections on their surface. Each hair bundle is mechanically coupled by fine protein filaments called tip links, connecting stereocilia at their tips. When the stereocilia bend due to head movements or accelerations, tension in the tip links changes, rapidly opening mechanoelectrical transduction (MET) channels located at the tips. Opening of these channels allows positively charged ions (primarily potassium and calcium) to flow into the hair cell from the surrounding endolymph, generating a receptor potential. This receptor potential modulates neurotransmitter release from the base of hair cells onto vestibular afferent nerve fibers, altering their firing rates. The altered signals travel via the vestibular nerve to the brainstem, providing real-time information about head movement and orientation. Additionally, calcium influx through MET channels initiates adaptation mechanisms, resetting channel sensitivity to continuous stimuli and maintaining responsiveness to future perturbations. Through these precise and rapid biophysical processes, vestibular hair cells convert mechanical perturbations into neural signals crucial for balance, gaze stabilisation, and spatial orientation (Müller & Gillespie, 2009).

Figure 2

Anatomy of the vestibular system



Reprinted from Khan, S., & Chang, R. (2013). Anatomy of the vestibular system: A review. *NeuroRehabilitation*, 32(3), 437–443. <https://doi.org/10.3233/NRE-130866>. © 2013 IOS Press. Reprinted with permission.

Vestibular perturbation techniques provide controlled means to evoke and characterise vestibular afferent activity, thereby illuminating the contributions of vestibular inputs to balance, spatial orientation, and multisensory integration (Ertl & Boegle, 2019). The following vestibular perturbation techniques are most common during gait: galvanic vestibular stimulation (GVS), mastoid vibration (MV), stochastic vestibular stimulation (SVS), and head turns.

GVS, applied bilaterally or unilaterally, employs small direct or alternating currents applied via electrodes on the mastoid processes to modulate the activity of the vestibular end organs without head movements, in sinusoidal, square-wave, or stochastic (“noisy”) waveforms (Ertl & Boegle, 2019). MV, applied bilaterally or unilaterally, utilises small vibrators placed on the bony mastoid processes located behind each ear. It employs high-frequency oscillations, often at 100 Hz, either in a continuous or burst pattern, with an amplitude that is often 130% above the suprathreshold level. This mechanical stimulation targets irregular vestibular afferents in the otolith organs and semicircular canals (Lu et al., 2022). SVS, applied bilaterally or unilaterally, employs small bipolar electrodes over the mastoid processes and is connected to a constant-current stimulator that delivers a continuous, zero-mean “white-noise” electrical waveform with a bandwidth from 0 to 25 Hz and peak amplitude of ± 5.0 mA (Magnani et al., 2021; Magnani et al., 2023). Regarding head turns, there is considerable variability across studies.

For example, Fitzgerald et al. (2020) had participants make rapid, visually cued yaw head turns as quickly as possible towards targets located approximately 60° to the left or right. This method produced abrupt, high-velocity stimulation that affected balance. In contrast, Huppert et al. (2024) used active head-turn challenges where participants performed controlled rotations to specific angles ($\pm 45^\circ$) at a fixed cadence dictated by an auditory metronome. Besides previous forms of vestibular perturbation techniques, other forms include caloric vestibular stimulation (CVS), sound-induced vestibular stimulation (SiVS), impulsive acceleration stimulation (IAS), magnetic vestibular stimulation (MVS), rocking bed, rotatory chair, and hexapod (Ertl & Boegle, 2019).

Visual, proprioceptive, and vestibular inputs in most common environments work together and provide consistent information. When one of the three sensory subsystems is impaired or disrupted, the remaining two systems must compensate for the loss or dysfunction. This explains the concept of sensory weighting, namely, how much “weight” the central nervous system places on each individual system at any time (Assländer & Peterka, 2014, as cited in Bronstein, 2016). For example, if a person walking is pushed from the right, the brain integrates three signals: visual cues indicate movement to the left, proprioceptive feedback detects stretch in muscles on the right, and the vestibular system senses the head’s acceleration to the left. However, in the absence of visual input, such as in complete darkness, the brain places greater emphasis on vestibular and proprioceptive information, enhancing their role in maintaining balance (Bronstein, 2016). However, this is context dependent (Nashner, Black, & Wall, 1982).

Besides previous evidence surrounding the vestibular role and functions, evidence surrounding the contribution of the vestibular system to dynamic balance in healthy adults remains scarce. Further research on this topic could help address the following gaps in the current literature: infrequent measurement of all factors contributing to balance control (e.g., vestibular function, vision, somatosensory function, cognition) in both clinical and research contexts; lack of large datasets with extensive assessments covering multiple dimensions of balance, including thorough characterisation of contributors to balance control (e.g., vision, vestibular function, cognition) (Agrawal et al., 2020).

Xie et al. (2024) conducted a systematic review of 55 cross-sectional studies that examined both GVS (50 studies) and vibration-based vestibular stimulation (VVS; 5 studies) during gait in healthy adults. Across these studies, supra-threshold GVS and VVS consistently impaired gait performance and postural control. Bilateral vestibular perturbations led to greater gait and postural deviations than unilateral applications, and VVS was generally better tolerated, with fewer adverse effects compared to GVS. While this review provides a broad qualitative synthesis of various perturbation modalities and their different protocols, it does not offer a quantitative synthesis, nor does it explore the heterogeneity across participant characteristics, stimulation parameters, and outcome measures. A meta-analysis would enable the calculation of weighted mean effects, assessment of between-study variability, and investigation of potential moderators (e.g., stimulus amplitude, waveform, age, or walking task). This would strengthen the evidence surrounding the contribution of the vestibular system to dynamic balance in healthy adults and guide the development of standardised protocols for vestibular perturbation during gait.

This systematic review and meta-analysis focus on various types of vestibular perturbations and their effects on gait in healthy adults. The aim of this review is to compare the impact of different vestibular perturbations during walking on healthy individuals and to examine their influence on various gait parameters. This will help to enhance the understanding of the vestibular system's role in dynamic balance. The study hypothesises that supra-threshold stimulation of the vestibular system will significantly disrupt spatiotemporal gait parameters.

3. Methods

The Cochrane Handbook for Systematic Reviews of Interventions and PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines served as the primary frameworks for conducting this systematic review and meta-analysis (Higgins et al., 2024; Page et al., 2021).

3.1. Research Question

This review aims to synthesise current evidence on how perturbing the vestibular system during walking influences human gait in healthy adults. Guided by the PICO framework (see Table 1), this review addresses the following research question:

What is the influence of vestibular perturbations applied during gait on spatiotemporal parameters in healthy adults?

Table 1

PICO

Component	Definition
Population (P)	Adults (≥ 18 years) with no disorder known to influence gait or vestibular function.
Intervention (I)	Any externally applied or self-generated vestibular perturbation delivered during the walking trial. Modalities include: direct or stochastic galvanic vestibular stimulation (GVS); magnetic vestibular stimulation (MVS); mastoid vibration or other vibration-induced vestibular stimulation; sound-induced vestibular stimulation; voluntary head turns, tilts, rotations, or deviations applied concurrently with gait.
Comparator (C)	Straight-line walking without concurrent vestibular perturbation, performed overground or on a treadmill at preferred or fixed speed.
Outcome (O)	Quantitative spatiotemporal gait metrics: speed, cadence, stride/step length, stride/step time, step width, stance, swing, and double-support time, and variability of these parameters.

3.2. Literature Search

A preliminary search on PubMed was conducted to ensure the validity of the proposed research idea, identify relevant articles, and avoid duplication of previous research. A simple search was conducted in Pubmed using following syntax: *((Gait[Mesh]) OR (Locomotion[Mesh]) OR (walk*[Title/Abstract])) AND ((sensory integration*[Title/Abstract]) OR (Multisensory Integration[Title/Abstract]) OR (sensory organization[Title/Abstract]) OR (integration[Title/Abstract]) OR (interaction[Title/Abstract]) OR (Processing[Title/Abstract]) OR (sensor*[Title/Abstract])) AND ((vestibular[Title/Abstract]) OR (galvanic stim*[Title/Abstract]) OR (mastoid[Title/Abstract]) OR (Visual[Title/Abstract]) OR (eyes open[Title/Abstract]) OR (eyes closed[Title/Abstract]) OR (somatosensory[Title/Abstract]) OR (insole[Title/Abstract]) OR (Proprioception[Mesh]).*

The following steps were taken during the screening process:

Two final-year master's students in Rehabilitation Sciences and Physiotherapy conducted the screening process for this review. A PhD holder with domain expertise, employed at the REVAL Rehabilitation Research Centre, provided supervision during this process. EndNote 20 was used as a reference manager.

In the first screening phase, articles were screened by title and abstract using PubMed, Scopus, and Web of Science. Duplicates were removed with EndNote 20 to form a pool of eligible articles. The articles were evenly divided between two reviewers, who screened each article for inclusion or exclusion. Uncertain articles were included for further assessment. The search strategies for each database are presented in Table A in the Appendix.

In the second phase, both reviewers independently screened the full texts of the articles for eligibility. Their decisions were compared, and any discrepancies were resolved with input from the supervisor. A manual search was also conducted using the reference lists of the included articles and the Google Scholar search engine.

3.3. Selection Criteria

The PICO framework (Table 1) was used as a general guideline to determine the inclusion and exclusion criteria. The inclusion and exclusion criteria are outlined in Table 2. Vestibular stimulation had to be applied during the gait task to assess direct, real-time effects on locomotor control.

Only cross-sectional studies were included in this review, as they enable the assessment of real-time effects of vestibular stimulation. Intervention studies were excluded because vestibular stimulation was generally not administered during gait assessments, which limited the ability to evaluate immediate effects. Studies involving caloric vestibular stimulation, cerebellar Transcranial Magnetic Stimulation (TMS) or repetitive TMS (rTMS) were excluded, as these forms of stimulation are not administered concurrently with walking tasks and do not reflect real-time vestibular input during gait.

Table 2

Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
1. Healthy adults (≥ 18 yrs) without any illness, pathology, or disability affecting gait or vestibular function (e.g., Parkinson's, Meniere's, BPPV).	1. Vestibular stimulation administered outside of the gait task, or more than one vestibular/sensory perturbation applied simultaneously in a single trial.
2. Vestibular stimulation/manipulation applied during walking (e.g., GVS, MV, head turns), supra-threshold to perturb gait.	2. Use of cerebellar transcranial magnetic stimulation (TMS).
3. Straight-line walking ≥ 3 m (preferred or set speed; may include head movements).	3. Study designs that are case reports, systematic reviews, or meta-analyses.
4. Reported spatiotemporal gait outcomes (e.g., gait speed, stride length, step width, cadence).	4. Raw outcome data for effect-size calculation not available in the publication and unobtainable after author contact and Datadryad search.

- | | |
|---|---|
| 5. Published in English with full-text available. | 5. Designs or analyses that do not isolate straight-line walking results (i.e., outcomes only from turns/complex gait tasks). |
|---|---|
-

3.4. Quality & Risk of Bias Assessment

The NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (National Heart, Lung, and Blood Institute [NHLBI], 2021) was used to evaluate methodological quality, based on the cross-sectional design of the included studies and recommended by Ma et al. (2020). Following the NIH recommendations, no numeric summary scores were assigned, as the tool is designed to support domain-based judgment rather than additive scoring. Instead, studies were categorised as “Good”, “Fair”, or “Poor” based on the presence or absence of bias in four predefined critical domains: population specification (Q2), validity of exposure measurement (Q9), validity of outcome measurement (Q11), and control for confounding (Q14)(NHLBI, 2021). This decision was guided by NIH guidance stating that: "Critical appraisal involves considering the risk of potential for selection bias, information bias, measurement bias, or confounding (the mixture of exposures that one cannot tease out from each other)" (NHLBI, 2021). Studies with no concerns in these domains were rated as “Good”; those with serious concerns in one critical domain were rated as “Fair”; and studies with two or more critical concerns, or any fatal methodological flaw, were rated as “Poor”. Questions regarding Temporal precedence of exposure (6), sufficiency of timeframe (7), repeated exposure assessment (10) and blinding of outcome assessors (12), related to temporality and timeframe, were excluded from judgment. These items are structurally inapplicable to cross-sectional designs and, therefore, consistently rated 'No' by default. Two independent reviewers assessed the quality of each individual study. The reviewers rated each of the 14 items into dichotomous variables: yes, no, or not applicable (NA).

3.5. Data Extraction

Data were extracted using a standardised form in Google Sheets, developed based on Chapter 5 of the *Cochrane Handbook for Systematic Reviews of Interventions* (Higgins et al., 2024). Two reviewers independently piloted the form on a sample of three included studies to assess clarity, consistency, and usability. Revisions were made following the pilot phase. Data extraction was structured into three main categories:

- **Study, participant, and task characteristics**

Extracted information included first author, year of publication, study design, inclusion and exclusion criteria, participant details (total number, sex distribution, mean age), conditions or groups tested, characteristics of the vestibular perturbation (type, duration, frequency, intensity), and a description of the walking task, including task type (ground vs. treadmill walking), environment, and walking speed.

- **Outcome measures and results**

For each study, outcome measures related to spatiotemporal gait parameters were extracted, along with the instrument used to measure them, the timing of the measurements, and the reported results (group means, standard deviations or standard errors). A combined effect summary (including confidence intervals and p-values, where reported) was also collected.

Two researchers independently extracted data. Reviewer 1 screened and extracted data from the first half of the included studies and checked the second half, which was screened by Reviewer 2. Conversely, Reviewer 2 verified the first half. Discrepancies were addressed through discussion, and a third reviewer was consulted if needed.

3.6. Data Analysis

To explore the effects of different forms of vestibular perturbation on gait, a meta-analysis with a subgroup analysis for the different perturbation methods was performed using the “meta” package in RStudio (version 2024). Both reviewers wrote their own code in RStudio for every analysis. Afterwards, differences were compared to create the final code. Standardised Mean Difference (SMD) was used as the test statistic with its corresponding Standard deviation (SD) to compare the vestibular perturbation and control conditions. A random-effects model (REML) was used to account for between-study heterogeneity. The

Hartung-Knapp-Sidik-Jonkman (HKSJ) method was used because, according to a research article by Inthout et al. from 2014, the HKSJ method consistently yields more accurate error rates compared to the DerSimonian and Laird (DL) approach, especially when there are differences in sample sizes between studies.

The included articles are ranked by perturbation type and outcome measurements.

Articles are included in the meta-analysis when identical outcome measurements are used in at least three articles.

A subgroup analysis within the same perturbation type was performed once at least three articles with the same perturbation type and outcome measurement are eligible.

4. Results

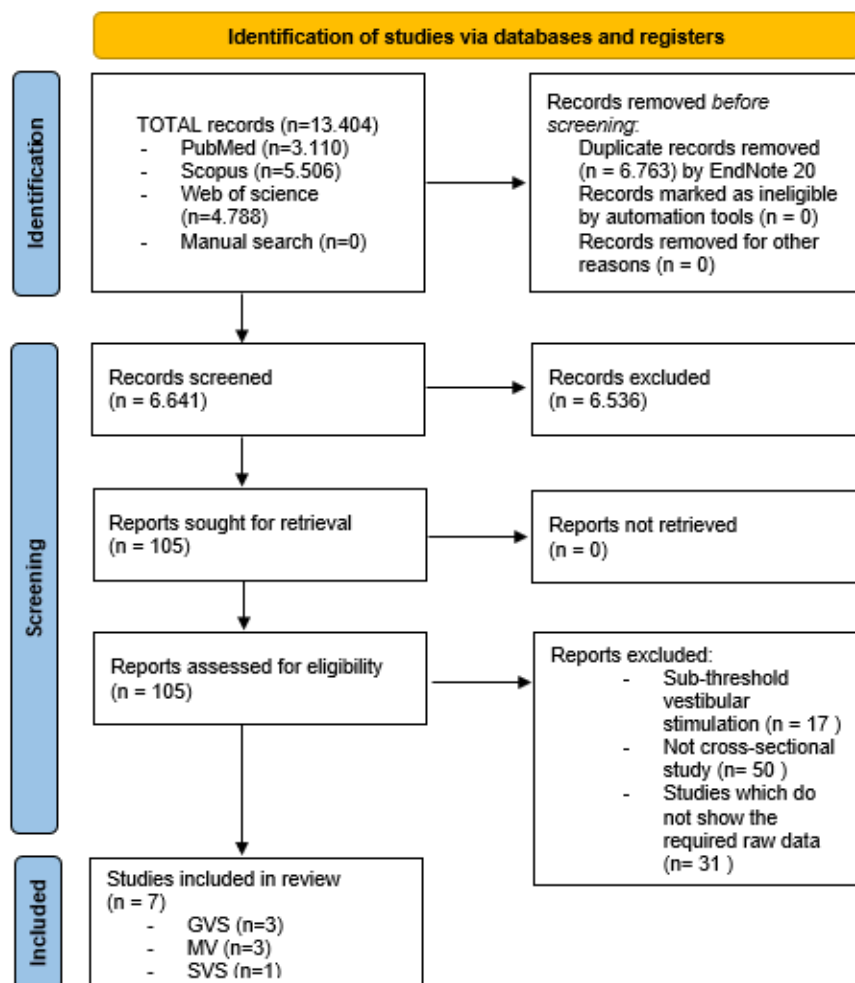
4.1. Results Study Selection

A total of 13,404 studies were retrieved from the database searches: 3,110 from PubMed, 5,506 from Scopus, and 4,788 from Web of Science. After removing 6,763 duplicates, 6,641 unique studies remained for title and abstract screening. No studies were excluded by automation tools or for other reasons.

The screening and selection process is summarised in the PRISMA 2020 flow diagram (Figure 3). Ultimately, seven studies met the inclusion criteria and were included in the systematic review.

Figure 3

PRISMA flow diagram study selection



4.2. Quality & Risk of Bias Assessment

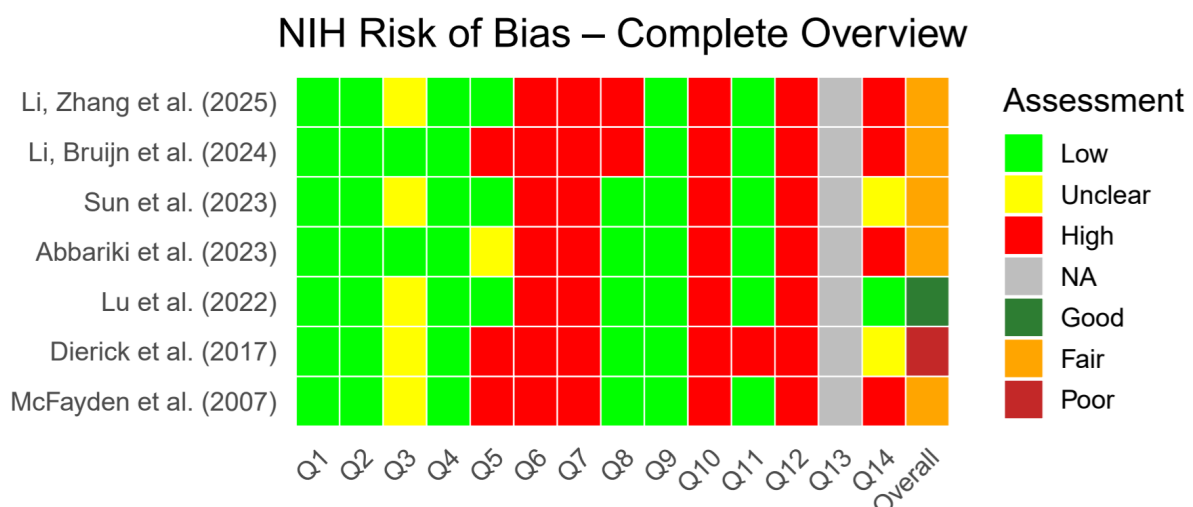
The complete assessment of the NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies for each study can be found in Table B in the Appendix.

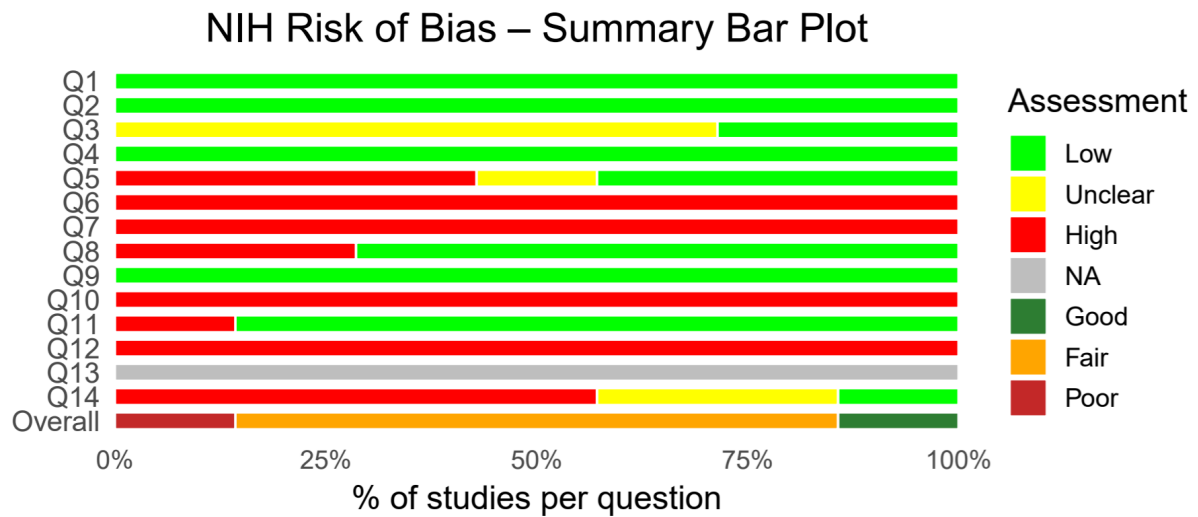
As stated in the methods section, no numeric summary scores were assigned, and the focus was directed towards the predefined critical domains: Q2, Q9, Q11, and Q14. As a result, one study was rated as "Good," one as "Poor," and the remaining five as "Fair". Dierick et al.(2017) did not identify or adjust for potential confounders. They did not differentiate between the various forms of GVS in their results, including binaural (n = 12), unilateral left (n = 11), and unilateral right (n = 11). For these reasons, the study received a "Poor" rating. In contrast, Lu et al. (2022) scored positively on all four critical domains, earning a "Good" rating. The other five studies also failed to define and adjust for possible confounders, resulting in all of them receiving a "Fair" rating.

Other criteria, such as uniform application of eligibility criteria (Q4), consistent measurement of exposures (Q9), and assessment of exposure levels (Q8), were more variably reported across studies. A traffic-light & bar plot (Figure 4) was created to summarise the results.

Figure 4

NIH traffic-light & summary bar plot





High= High RoB, Low= Low RoB, NA= Not Applicable

4.3. Data Extraction

4.3.1. Qualitative Synthesis

Table 3 presents the full details of each included study. This table provides a structured overview of several key elements: study design, participant characteristics (including sample size, age, and sex), the type and parameters of vestibular perturbation (such as modality, frequency, and intensity), the walking task (including type, environment, and speed), experimental conditions or comparison groups, outcome measures and measurement method used, and a concise summary of the main findings for each study.

Table 3

Summary included studies

Study (year)	Study design	Participants	Perturbation (type & characteristics)	Walking task (task, speed, and environment)	Groups/conditions	Outcome measures	Main findings
Dierick et al. (2017)	Cross-sectional study within-group	34 Healthy young adults (18♂/16♀), age 23±2 years	Continuous DC GVS (bilateral/monaural left & right), ~1.4 mA (0.07 mA cm ²), at the highest sensory threshold during the full 15-minute walking trial.	Instrumented treadmill walking at preferred speed 15 min/condition; forward 4.4 ± 0.4 km/h,	Forward treadmill walking; with/without GVS (FWS0, FWS+)	Stride interval, stride interval variability, step width (calculated from medio-lateral COP displacement)	No significant differences in step width were reported. No significant differences in stride interval and stride interval variability were found. No significant differences in step width were reported
Lu et al. (2022)	Cross-sectional study within-group	20 Healthy young adults (10♂/10♀) age 24.6±2.1 yrs	Mastoid vibrotactile stimulation 100 Hz, amplitude 130% threshold; 0.5 s on/off; bilateral or left only	Treadmill walking at preferred speed (mean 1.4 m/s)	No vibration vs bilateral mastoid vibration vs unilateral (left) mastoid vibration, each 3 min with 2 min rest between trials	Step length/width & variabilities.	Unilateral MV significantly decreased step width. Bilateral MV did not alter step width significantly. Both unilateral and bilateral MV significantly increased step width variability. MV did not significantly alter Step length and step length variability.
Abbariki et al. (2023)	Cross-sectional study within-group	12 Healthy young adults (5♂/10♀) aged between 20-41 (27±7) yrs	Binaural bipolar GVS, 200-ms pulse, 1x motoric threshold (T) and 1.5T with left & right cathode conditions for	Treadmill walking at preferred speed (mean = 1.03 ± 0.06 m/s)	Baseline group, RCathode and LCathode, each at 1.0 T and 1.5 T, applied at right heel strike 30	Cycle duration	GVS in RCathode 1.5T condition significantly increased cycle duration compared to baseline data, RCathode 1T,

			both intensities		stimuli/condition		and the Lcathode conditions did not alter cycle duration
Sun et al. (2023)	Cross-sectional study within-group	19 Healthy young adults (10♂/9♀) age 24.4±2.1 yrs	Bilateral mastoid vibrotactile stimulation, 100 Hz, amplitude 130 % threshold, 0.5 s on/0.5 s off cycles	Treadmill walking at preferred speed (mean 1.4 m/s)	Walking with/without bilateral mastoid vibration (8 trials, 3 min each with 2 min rest between trials)	Stance, double support, step length/time/width, foot clearance and variabilities	MV significantly increased step length and step time. MV did not affect step width, step width variability or step time variability.
W. Li. et al. (2025)	Cross-sectional study within-group	18 Healthy young adults (9♂/9♀); age 24.33 ± 2.14 y	Bilateral mastoid vibration, 100 Hz, supra-threshold 130 %, impulse 0.3 s ON/0.7 s OFF	Biodex RTM 600 treadmill, 3-min trials at preferred speed (mean 1.41 ± 0.21 m/s) on each incline	MV vs no-MV	Margin of Stability (MoSap, MoSml) & variability; step length/width & variability	Bilateral mastoid vibration MV did not affect step length. MV did not affect step width or significantly affect step length variability or step width variability.
Y.C. Li et al. (2024)	Cross-sectional study within-group	16 Healthy young adults (7♂/9♀); aged between 19 and 29 (23.5 ± 3.4) yrs	Binaural-bipolar stochastic EVS 0–25 Hz, ±5 mA	Dual-belt treadmill trials at preferred speed with eyes open, 2.8 km/h, cadence 78 steps/min, 8 min/condition	SVS/No-SVS	Cadence & step width	SVS evoked a significantly increased step width and cadence.
McFayden et al. (2007)	Cross-sectional study within-group	6 Healthy young adults (2 ♂/4 ♀); mean age of 26.5 yrs	Binaural, bipolar GVS (1-1,5 mA)	10 m overground walking with PWS	Level walking (L) & level with GV (LS)	Gait speed (m/s)	GVS did not affect walking speed

COP= Center Of Pressure, DC=Direct Current, VSS=Visual Surround Shift, N-VSS=No visual perturbation, SST=Single Support Time, DST=Double Support Time, PWS=Preferred Walking Speed, LDE=Local Divergence Exponent, PSW=Preferred Step width, NSW=Narrow Step Width, min=minutes

Following spatiotemporal gait parameters were extracted from the seven included studies:

step length (m), step length variability (m), step width (m), step width variability (m), cycle duration (s), step time (s), step time variability (s), stance time (s), cadence (steps/min), stride interval (s), double limb support time (s) gait speed (m/s) and foot clearance variability (mm).

Cycle duration was significantly prolonged under GVS (Abbariki et al., 2023), while both step and stance time significantly increased under bilateral MV (Sun et al., 2023). Cadence significantly increased following SVS (Y.C. Li et al., 2024), and foot clearance variability was significantly elevated under MV (Sun et al., 2023).

In contrast, no significant changes were reported in step length variability under unilateral MV (Lu et al., 2022). No significant changes were reported for step time variability under MV (Sun et al., 2023), stride interval under GVS (Dierick et al., 2017), double-support time under MV (Sun et al., 2023), gait speed under GVS (McFayden et al., 2007), or foot clearance under MV (Sun et al., 2023).

The results for step length, step width, and step width variability are further explored in a meta-analysis, with a subgroup analysis for step width under bilateral MV. Figure 5a shows the random-effects forest plot for step length; Figure 5b presents the corresponding plot for step length variability; Figure 5c presents the corresponding plot for step width with subgrouping by perturbation type; Figure 5d presents the corresponding plot for the step width variability.

4.3.2. Quantitative Synthesis (meta-analysis)

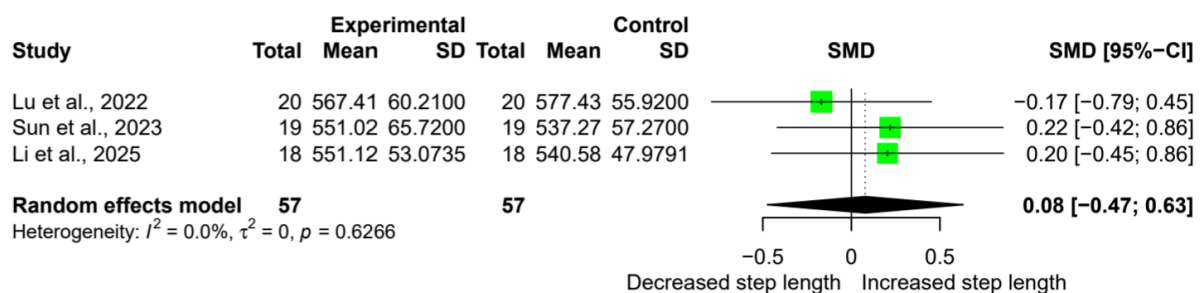
The results for step length, step width, and step width variability are further explored in a meta-analysis, with a subgroup analysis for step width under bilateral MV. Figure 5a shows the random-effects forest plot for step length; Figure 5b presents the corresponding plot for step length variability; Figure 5c presents the corresponding plot for step width with subgrouping by perturbation type; Figure 5d presents the corresponding plot for the step width variability.

The first meta-analysis assessed the effect of MV on step length and included three studies (Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025; $n = 57$). The second meta-analysis assessed step length variability and included three studies (Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025; $n = 57$). The third meta-analysis assessed step width as the outcome measure and included five studies (Dierick et al., 2017; Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025; W. Li et al., 2024; $n = 105$). Within the step width meta-analysis, a subgroup analysis was conducted for studies utilising MV as the vestibular perturbation. This subgroup consisted of three studies (Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025; $n = 57$).

The fourth meta-analysis assessed *Step width variability and included* three studies (Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025).

Figure 5a

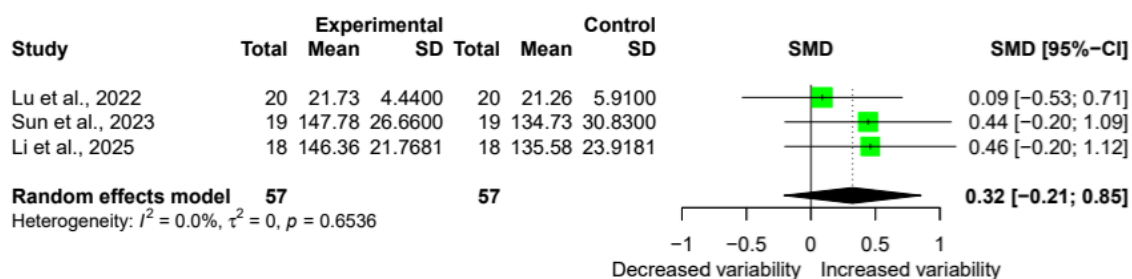
Forest plot for step length



Standardised Mean Differences (SMDs) with 95% Confidence Intervals (CIs) are displayed for each study, and a black diamond represents the pooled effect estimate. Below the figure, heterogeneity statistics are presented, including the I^2 statistic, between-study variance (τ^2), and corresponding p-value. Below the figure, heterogeneity statistics (I^2 , τ^2 , and p-value) are provided for each subgroup and for the overall analysis, along with the χ^2 test results for subgroup differences. Since only one perturbation type (MV) was analysed, no between-group comparison was performed ($\chi^2 = 0.00$, $p = NA$).

Figure 5b

Forest plot for step length variability

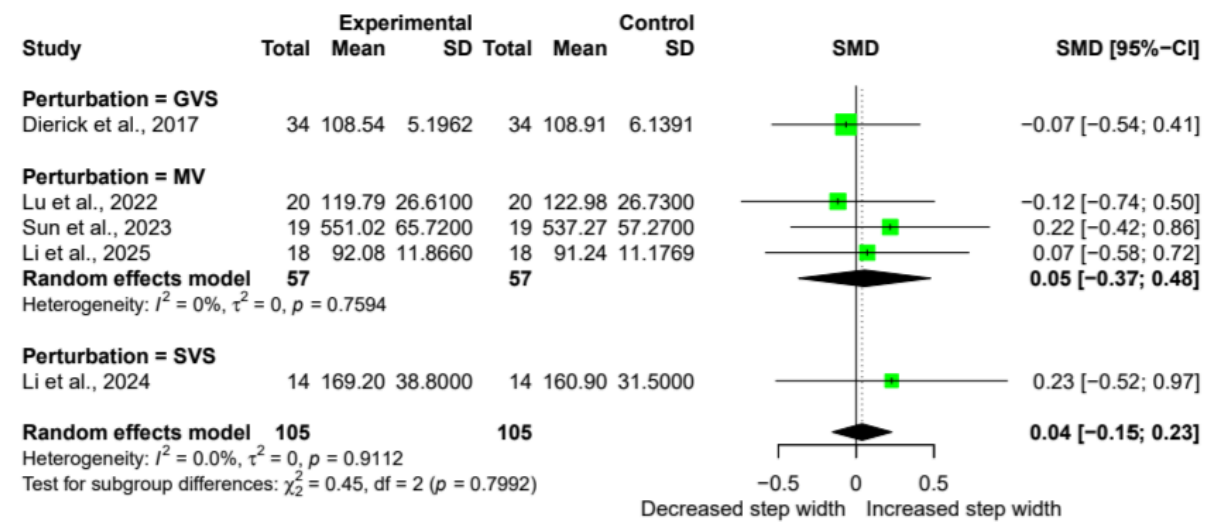


Standardised Mean Differences (SMDs) with 95% Confidence Intervals (CIs) are displayed for each study, and a black diamond represents the pooled effect estimate. Below the figure, heterogeneity statistics are presented, including the I^2 statistic, between-study variance (τ^2), and corresponding p-value. Below the figure, heterogeneity statistics (I^2 , τ^2 , and p-value) are provided for each subgroup and for the overall

analysis, along with the χ^2 test results for subgroup differences, Since only one perturbation type (MV) was analysed, no between-group comparison was performed ($\chi^2_0 = 0.00$, $p = NA$).

Figure 5c

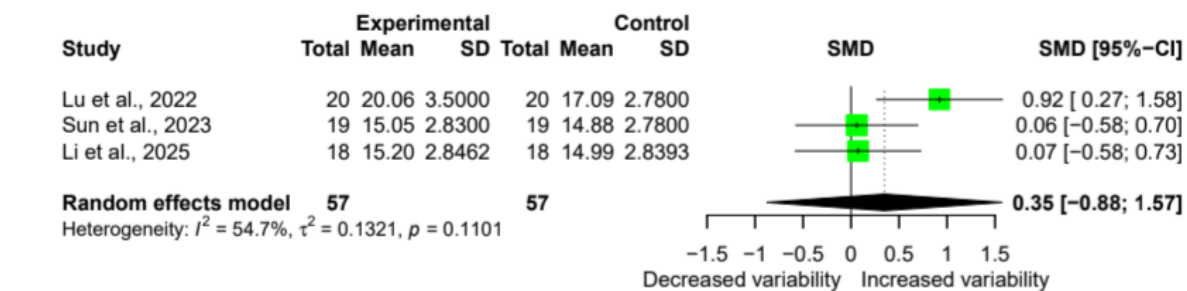
Forest plot for step-width



The studies are categorised by perturbation type: GVS, MV, and SVS. Standardised Mean Differences (SMDs) with 95% Confidence Intervals (CIs) are displayed within each subgroup, while a black diamond represents a pooled effect for each subgroup. The overall pooled effect is shown at the bottom of the plot. Below the figure, heterogeneity statistics (I^2 , τ^2 , and p -value) are provided for each subgroup and the overall analysis, along with the χ^2 test results for subgroup differences.

Figure 5d

Forest plot for step width variability



Standardised Mean Differences (SMDs) with 95% Confidence Intervals (CIs) are displayed for each study, and a black diamond represents the pooled effect estimate. Below the figure, heterogeneity statistics are presented, including the I^2 statistic, between-study variance (τ^2), and corresponding p -value. Below the figure, heterogeneity statistics (I^2 , τ^2 , and p -value) are provided for each subgroup and for the overall analysis, along with the χ^2 test results for subgroup differences, Since only one perturbation type (MV) was analysed, no between-group comparison was performed ($\chi^2_0 = 0.00$, $p = NA$).

For step length, the pooled standardised mean difference (SMD) from the restricted maximum likelihood (REML) was 0.0776 (95 % CI: -0.4750 to 0.6302; $p = 0.607$).

For step length variability, the pooled SMD was 0.3219 (95 % CI: -0.2086 to 0.8524; $p = 0.121$)

For step width, the pooled SMD was 0.0382 (95 % CI: -0.1528 to 0.2292; $p = 0.608$).

For step width variability, the pooled SMD was 0.3482 (95 % CI: -0.8753 to 1.5718; $p = 0.345$).

All the effect sizes were calculated using Hedges' g under a random-effects model with REML estimation, to account for between-study variance and Hartung-Knapp adjustment to mitigate potential overestimation of precision in analyses with small sample sizes.

Both meta-analyses showed no heterogeneity, though the wide confidence intervals indicate uncertainty in these estimates.

A subgroup analysis was performed within the step-width meta-analysis to examine differences between perturbation types (GVS, MV, SVS). No statistically significant effect between subgroups was observed $Q(2) = 0.45$ ($p = 0.80$), with low heterogeneity values $Q(2) = 0.55$ (-0.3695 to 0.4773], $\tau^2 = 0$ and $I^2 = 0$ within the MV subgroup.

Publication bias was not formally assessed due to the small number of studies ($k < 10$), in accordance with Cochrane guidelines (Cochrane Training, 2022). This guideline states that 'tests for funnel plot asymmetry should be used only when at least 10 studies are included in the meta-analysis, because when there are fewer studies, the power of the tests is low (Higgins et al., 2024, Ch. 13 § 13.3.4.4).

5. Discussion

The aim of this systematic review and meta-analysis was to identify, critically appraise, and synthesise key findings in the literature regarding the effect of vestibular perturbations on spatiotemporal parameters during gait in healthy adults. To our knowledge, this is the first study to conduct a systematic review and meta-analysis on this topic.

5.1. Reflection on Study Quality

Six of the seven included studies have a “fair” to “good” methodological study quality. Only Dierick et al. has a “poor” study quality. For the meta-analyses on step length, step length variability, and step width variability, the included articles demonstrated good and fair quality. This indicates that the conclusions drawn from these analyses are reasonably reliable. However, for the meta-analysis on step width, while most included articles exhibited good or fair quality, the study by Dierick et al. was rated as having “poor” quality. Despite this, the overall conclusions drawn from the analyses still remain reasonably reliable. To conclude, the overall quality of all included studies is generally fair.

5.2. Reflection on Findings in Relation to the Research Question

Previous findings indicate that acute vestibular disturbances may induce possible changes in spatiotemporal parameters, which are not significantly measurable. The random effects models did not yield statistically significant results across all four meta-analyses in this study. As a result, the hypothesised disruption of the gait pattern due to vestibular stimulation was not observed.

Bilateral supra-threshold MV did not significantly influence step length

The meta-analysis for step length (three studies, $n=57$) showed no significant difference in step length between perturbed and control walking. No previous studies appear to have examined the influence of bilateral MV on step length in healthy adults.

Several factors could contribute to explaining these non-significant findings.

All participants in this meta-analysis were young, with a mean age between 24 and 25 years across these three studies. Previous research indicates that sensory integration declines with

age (Rosso et al., 2013; Deshpande et al., 2015). Moreover, research indicates that older individuals struggle more with reweighting sensory inputs during vestibular disturbances while walking than younger adults (Deshpande & Patla, 2007; Deshpande & Zhang, 2014; Deshpande et al., 2015). Additionally, studies show that younger adults face fewer challenges when dealing with the effects of vestibular stimulation (Deshpande & Patla, 2007; Deshpande et al., 2015). These findings indicate better sensory integration in young adults, which may have allowed them to rely on information from other sensory inputs, without requiring adjustments in step length to maintain stability. Possibly explaining why there was no significant difference in step length and step length variability during vestibular stimulation in young healthy adults.

Building upon the explanation above, centre of pressure (CoP) displacements have been used to map the stability of the gait pattern. A larger CoP displacement is associated with decreased stability of the gait pattern (Hausdorff 2005; Bizovska et al., 2014; Van Kooten et al., 2018). A larger backwards CoP displacement is associated with a greater propulsive impulse, which leads to an increase in step length (Brenière & Do, 1991; Yiou et al., 2017). Previous studies also indicated that vestibular stimulations can lead to greater CoP displacements in both the frontal and sagittal planes. (Reimann et al., 2017; Chien et al., 2017; Fettrow et al., 2019; Lu et al., 2022; Xie et al., 2024). Larger CoPs were observed in older adults compared to young adults (Chien et al., 2017; Ha et al., 2022; Xie et al., 2024), providing an additional indication that younger adults could be less affected by vestibular stimulation.

Second, studies described margins of stability (MoS), related to both stability during gait (Hof et al., 2005; Hak et al., 2013; Watson et al., 2021; Kazanski et al., 2022) and step length (Sivakumaran et al., 2017). When the anterior MoS during single support decreases (i.e., the extrapolated center of mass (XCoM) moves farther forward relative to the BoS), a significantly longer subsequent step length follows in healthy adults (Sivakumaran et al., 2017). MoS is calculated out of the XCoM and the BoS (Hof et al., 2005; Hak et al., 2013; Watson et al., 2021; Kazanski et al., 2022), which is linked to step width and step length (Hak et al., 2013; Mahaki et al., 2019). Lu et al. (2022) and W. Li et al. (2025) found larger margins of stability during walking with MV. Increased MoS could be achieved by decreasing step

length, which reduces the XCoM (Bhat et al., 2005; Hak et al., 2012). Because step length in this meta-analysis was not affected under bilateral MV and younger adults show less instability during vestibular stimulations (Deshpande & Patla, 2007; Deshpande et al., 2015), participants could have relied on other methods to control their XCoM (Sivakumaran et al., 2017; Buurke et al., 2019), without requiring a change in step length to restore their stability (W. Li et al., 2025).

Although not significant, notable variations in step length were observed between the three studies. Step length was slightly decreased during MV in Lu et al. (2022), in contrast to the slight increases during MV reported by Sun et al. (2023) and W. Li et al. (2025). Despite comparable samples and methods (stimulation parameters, treadmill walking at preferred speed, measurement methods), several methodological differences could explain the variability in results between studies.

A notable difference among the three studies is that the control mean step length reported by Lu et al. (2022) is significantly higher at 577.43 mm compared to the other two studies, which report mean step lengths of 537.27 mm (Sun et al., 2023) and 540.58 mm (W. Li et al., 2025). This could possibly be explained by the number of trials and randomisation of these trials in Sun et al. (2023) and Li et al. (2025). In Lu et al. (2022), each participant had to perform three trials lasting three minutes each, without any inclines. A mandatory two-minute rest period was required between trials. In contrast, Sun et al. (2023) and W. Li et al. (2025) assessed the effect of bilateral MV on spatiotemporal parameters during gait on 0%, 3%, 6% and 9% inclines, resulting in a total of eight trials lasting three minutes each. Although only data from the level walking trials with and without MV were included in this meta-analysis, the inclined trials could have influenced the performance on the level walking trials. Similar to Lu et al., Sun et al. (2023) and W. Li et al. (2025) also incorporated a mandatory two-minute rest period between trials.

Although the perturbation differs, multiple studies have investigated the retention adaptations in spatiotemporal parameters after split-belt walking. Studies found that the adaptations were still present after ten minutes (Reisman et al., 2005; Roemmich & Bastian, 2015), up to 3 weeks (Buurke et al., 2022) after perturbing the gait pattern. Additionally, relearning speed was increased when a similar task was repeated (Reisman et al., 2005; Malone et al., 2011). Therefore, participants could have adapted their gait pattern during

the inclined MV trials which they could have received prior to the level walking trials, providing a possible explanation for the subtle differences in step width between Lu et al. (2022) and the other two studies (Sun et al., 2023; W. Li et al., 2025).

No studies investigated the retention of gait adaptations after MV, leaving no certainty whether the adaptations from possible previous MV trials affected the spatiotemporal parameters in the level walking trials. In contrast, Lu et al. (2022) only contained a single trial with bilateral MV, making such anticipation impossible for the included participants.

Related to the differences in the number and characteristics of the trials, it may be of importance to consider fatigue, particularly in the studies by Sun et al. (2023) and W. Li et al. (2025). A study conducted by Slider et al. (2012) discovered a higher metabolic cost for the inclined gait trials compared to the level walking trials. Moreover, an experimental study by Hunt and Hatfield (2017) demonstrated a significant increase in cadence during gait after ankle plantar flexor fatigue in healthy adults. Furthermore, research by Dale (2012) shows that step length is influenced by walking speed and cadence, represented by the equation: $\text{step length} = \text{velocity} / \text{cadence}$. These findings suggest an increased cadence due to the metabolic cost of the inclined walking trials. As a result of the fixed speed applied in the walking trials, participants had to compensate for their increased cadence, possibly with a decreased step length. Based on this hypothesis, it can be inferred that the baseline differences in mean step length in the control conditions reported by Sun et al. (2023) and W. Li et al. (2025) may be decreased by ankle plantar flexor fatigue compared to Lu et al. (2022), induced by possibly previous inclined conditions.

In addition to fatigue possibly affecting cadence in the baseline condition, the experimental condition may be modulated by the rhythmic input inherent to mastoid vibration, possibly acting as an external timing signal (Xie et al., 2024). MV was delivered at 1 Hz (W. Li et al., 2025: 0.3/0.7s; Sun et al., 2023 and Lu et al., 2022: 0.5/0.5s). This frequency reflects one complete on–off cycle per second (1Hz) and may serve as an external timing cue. The average cadence in healthy adults is close to 2 Hz (Wu & Harezlak, 2023). Therefore, the frequency of the MV application could have queued participants to lower their already increased cadence during the MV trials in Sun et al. (2023) and W. Li et al. (2025).

In addition to this, the “offset” hypothesis, first described in Séverac Cauquil, Gervet, and Ouaknine (1998), states that bilateral MV neutralises medial–lateral tilt cues but preserves a net anterior–posterior “press-forward” illusion for the subjects receiving MV (Sun et al., 2023). When subjects walk on a treadmill at their preferred speed, this forward-press sensation elicits a compensatory increase in step length, as seen in the raw means reported by Sun et al. (2023) and W. Li et al. (2025), which translates into positive standardised mean differences. The “offset” hypothesis has also been supported by a study done by Chien, Mukherjee, and Stergiou from 2016 (Chien, Mukherjee, & Stergiou, 2016). This hypothesis could be used to explain the slightly increased step length observed in Sun et al. (2023) and W. Li et al. (2025). However, it cannot account for the decreased step length reported in Lu et al. (2022), as all three studies applied bilateral MV.

Bilateral supra-threshold MV did not significantly influence step length variability

The meta-analysis for step length variability (three studies, n=57) showed no significant difference in step length variability during MV. Multiple hypotheses were formed to explain the non-significant results and differences between studies.

As for step length, first, there are significant differences in sensory integration between younger and older healthy adults (Rosso et al., 2013; Deshpande et al., 2015). Additionally, studies show that younger adults significantly show lower step length variability than older healthy adults (Hu & Chien, 2021).

Second, previous research compared spatiotemporal parameters for treadmill and overground walking. Although the mean values for the parameters were not significantly different, the variability of these parameters was significantly lower in treadmill walking. This reduced variability may result from the treadmill’s constant belt speed, constrained walking path, and diminished sensory input, which together promote more uniform and less adaptive gait patterns (Hollman et al., 2016). Although step length variability was not assessed, the significantly lower variability in cadence observed during treadmill walking suggests reduced adaptability in temporal gait control, indicating that reductions in step length variability cannot be excluded, given their established correlation (Hollman et al., 2016).

Third, while none of the SMDs at the level of the overall meta-analysis or the individual studies were significant, step length variability does appear to differ between Lu et al. (2022) and the studies by Sun et al. (2023) and W. Li et al. (2025). Sun et al. (2023) and W. Li et al. (2025) show a larger step length variability in contrast to Lu et al. (2022). The forest plot indicates minor baseline differences for step length variability in both control and experimental groups. While Lu et al. (2022) showed minimal difference, Sun et al. (2023) and W. Li et al. (2025) demonstrated slightly higher variabilities, though none of the effects were statistically significant. The study by Kao and Lomasney (2025) showed no significant effects on step length variability due to fatigue induced by treadmill walking. Their results showed a trend towards a decline in step length variability under fatigue. Contrasting the slight increases in Sun et al. (2023) and W. Li et al. (2025). On the other hand, Castano & Huang (2021) found significantly increased step length variabilities during treadmill walking, which, based on the adaptation retention mentioned in the meta-analysis for step length, could have possibly transferred to the level walking trial if a subject walked an inclined trial prior. Nevertheless, the increase in step length variability was assessed on a self-paced treadmill, while the studies in this meta-analysis used a fixed-speed treadmill. As fixed-speed walking was not systematically examined across slopes in the literature, any interpretation regarding slope-induced effects under fixed-speed conditions remains speculative. In line with the previous two hypotheses regarding step length, the observed differences may be explained by the number of trials and the randomisation of these trials in the studies by Sun et al. (2023) and W. Li et al. (2025). Increased variabilities of spatiotemporal parameters have been reported as a result of fatigue (Barbieri et al., 2013b). However, step length variability was not assessed in young healthy adults, providing no clear evidence to support this hypothesis. Fatigue could thus be an explanatory factor for the slight differences between Lu et al. (2022) and the studies by Sun et al. (2023) and W. Li et al. (2025).

Bilateral supra-threshold vestibular stimulation did not significantly influence step width

The meta-analysis for step width (five studies, n=105) showed no significant difference in step width between perturbed and control walking. Similar to this meta-analysis, previous

studies have shown inconclusive results regarding the relationship between vestibular perturbation and step width during gait (Deshpande et al., 2015; Zhang & Deshpande, 2016; Magnani et al., 2023; Xie et al., 2024).

GVS did not significantly alter step width, only one study assessing this relationship (Dierick et al., 2017) was included in this meta-analysis. Evidence in previous literature on the influence of GVS on step width showed both significant (Deshpande et al., 2015; Xie et al., 2024) and non-significant (Zhang & Deshpande, 2016) results.

MV did not significantly alter step width. No previous studies assessed the influence of bilateral MV on step width in healthy adults.

SVS did not significantly alter step width; only one study assessing this relationship (Y.C. Li et al., 2024) was included in this meta-analysis. Magnani et al. (2023) also examined the impact of SVS on step width during gait. Their findings aligned with the results of this meta-analysis, showing no significant effect of SVS on step width.

Several factors could contribute to explaining these non-significant findings.

First, as for the meta-analysis on step length, all participants in this study were young, with a mean age below 30 years across these five studies. The increased ability to reweigh sensory information (Deshpande & Patla, 2007; Deshpande & Zhang, 2014; Deshpande et al., 2015) and experiencing smaller challenges during vestibular stimulation (Deshpande & Patla, 2007; Deshpande et al., 2015) in younger adults compared to older adults may have allowed them to rely on information from other sensory inputs without requiring adjustments in step width. Possibly contributing to explaining the non-significant findings for step width in this meta-analysis.

The use of CoP displacements and the increase of CoP during vestibular stimulation, as described in the meta-analysis on step length (Reimann et al., 2017; Chien et al., 2017; Fattrow et al., 2019; Lu et al., 2022; Xie et al., 2024), could also add value to explaining the findings in this meta-analysis on step width. Previous studies have explored the relation between CoP displacements and step width, finding that larger CoP displacements are associated with a larger step width (Reimann et al., 2017; van Leeuwen et al., 2021). The larger CoP displacements in older adults compared to younger adults (Chien et al., 2017; Ha

et al., 2022; Xie et al., 2024) could attribute to explain the non-significant findings for step width in this meta-analysis.

A second explanation for this meta-analysis's non-significant findings for step width could be attributed to the perturbation type or application. Although significant CoP displacements in frontal and sagittal planes were found under vestibular stimulation, studies applying bilateral MV showed significant CoP displacements in the sagittal but not in the frontal plane (Chien et al., 2016, 2017), resulting in inconclusive evidence.

Studies reporting frontal-plane CoP changes often employed GVS rather than MV, suggesting a modality-specific effect. Although GVS and MV have similar effects on gait (Xie et al., 2024), previous research reported that participants stimulated with GVS tend to deviate towards the anode during walking (Bent et al., 2000; Carlsen et al., 2025; Toth et al., 2019; Xie et al., 2024). Because MV was applied with two electromechanical vibrotactile transducers (Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025), participants did not lean towards any of the two transducers.

These findings may account for the limited CoP displacements in the frontal plane and may thus explain the unchanged step width due to its relation with CoP deviations.

Third, comparable to meta-analysis assessing step length, MoS could contribute to explaining the non-significant findings for step width. MoS is related to both stability during gait (Hof et al., 2005; Hak et al., 2012; Hak et al., 2013; Watson et al., 2021; Kazanski et al., 2022) and step width (Mahaki et al., 2019; Watson et al., 2021). MoS was used as a compensatory strategy by participants during perturbed walking (Watson et al., 2021; Kazanski et al., 2022). As described for the meta-analysis on step length, Lu et al. (2022) and W. Li et al. (2025) found larger margins of stability during walking with MV. Increased MoS could be achieved by increasing the BoS with a broader step width and/or reducing the XCoM (Hof et al., 2005; Hak et al., 2013; Mahaki et al., 2019). Because step width in this meta-analysis was not affected under bilateral MV and younger adults show less instability during vestibular stimulations (Deshpande & Patla, 2007; Deshpande et al., 2015), participants could have controlled their XCoM to increase the MoS, without requiring a change in step width to restore their stability (W. Li et al., 2025).

Three studies in this meta-analysis used MV, with very similar study designs (Lu et al., 2022; Sun et al., 2023; W. Li et al., 2025). However, some differences between studies could explain the differences in step width between them. As described for the meta-analysis on step length, Sun et al. (2023) and W. Li et al. (2025) assessed the effect of bilateral MV on multiple inclines, these conditions may also have influenced the results in the meta-analysis on step width. The retention of gait adaptations in previous inclined trials with MV, which participants could have received before the level-walking trials due to the randomisation of the trials, could have affected step width as well. Possibly contributing to explaining the differences between Lu et al. (2022) and the other two studies (Sun et al., 2023; W. Li et al., 2025).

Similar to the meta-analysis for step length as well, fatigue could have played a role in the studies with inclined walking trials due to the higher number of trials combined with their elevated metabolic cost (Slider et al., 2012). Fatigue has been shown to decrease balance and increase step width (Barbieri et al., 2013a), potentially contributing to the variations in step width between these three studies.

Bilateral supra-threshold vestibular stimulation did not significantly influence step width variability

The conducted meta-analysis for step width variability did not show an overall significant result. However, a significantly increased step width variability was observed for Lu et al. (2022).

Consistent with the meta-analysis for step length variability, walking on a treadmill may explain the non-significant result due to the differences with overground walking. Previous research shows that step width variability was significantly smaller in treadmill walking compared to overground walking (Rosenblatt & Grabiner, 2010)

Additionally, the studies in this meta-analysis tested young adults with a mean age below 30 years. Skiadopoulos et al. (2020) found significantly higher step width variabilities in older adults compared to young adults during unperturbed walking. Despite limited evidence on step width variability between these age groups, especially for perturbed gait, the significant differences during unperturbed gait indicate that age may also act as an influencing factor in step width variability during vestibular stimulation.

Similar to step width, the methodological differences in the number of MV conditions and inclines used could explain differences in step width variability. Since there was only one condition with bilateral MV in Lu et al, this was always the first time participants experienced this stimulation. In the other two studies referenced, participants may have already completed a trial with bilateral MV on a slope condition, as they had four trials with bilateral MV. Due to the potential learning effect, participants in the study by W. Li et al. (2025) & Sun et al. (2023) may have demonstrated less variability compared to those in Lu et al. (2022).

Because (Lu et al., 2022) reported both unilateral and bilateral MV, only data for bilateral MV were included in the meta-analysis, making the comparison more homogenous to the other two studies using bilateral MV (Sun et al., 2023; W. Li et al., 2025).

Of note, Lu et al. (2022) found a significant decrease in step-width under unilateral MV, future studies should also focus on this type of perturbation.

No additional studies assessing the effect of unilateral MV on step width were retrieved.

5.3. Strengths and Limitations of the Literature Review

5.3.1. Limitations

Several important limitations of this meta-analysis warrant consideration.

First of all, all the studies included in this systematic review focused exclusively on healthy young adults. Given that age is considered one of the primary factors potentially underlying the non-significant results observed in this meta-analysis, we could not assess the effects of vestibular perturbations on spatiotemporal gait parameters in other adult populations. Therefore, the findings in this study cannot be generalised to older adult groups.

Secondly, the number of eligible articles was low, with only seven studies included. This limited sample size hindered the ability to conduct meaningful meta-analyses subgroup analyses, such as examining average gait speed, average cadence, and average double limb support time, among others. Additionally, six potentially eligible articles could not be included (Deshpande et al., 2015; Fettrow et al., 2019; Magnani et al., 2023; Tran et al.,

2023; Petros et al., 2022; Deshpande & Patla, 2007) due to missing data. The authors were contacted, but no response was received. As a result, the strength and generalizability of the findings across different vestibular perturbations, walking conditions, or demographic groups remains constrained. In addition, most available studies on SVS were treatment articles and often applied subthreshold SVS. These treatment-oriented protocols differ from perturbation interventions such as Y.C. Li et al. (2024), which applied vestibular signals at supra-threshold intensities to perturb the vestibular system. Therefore, only one study using SVS was included in this systematic review and meta-analysis. Not to forget, few studies have leveraged voluntary head-turn perturbations with strict gaze fixation to isolate vestibular inputs from concurrent visual stimulation. Most head-turn protocols allow free gaze, apply fixation on a moving object (Magnani et al., 2021) or do not control for compensatory visual stabilisation, making it challenging to disentangle pure vestibular contributions to changes in spatiotemporal parameters. Future research with larger sample sizes, standardised stimulation intensities/protocols, and uniform reporting of spatiotemporal outcomes is needed to strengthen and refine the following preliminary conclusions.

Third, the Hartung–Knapp–Sidik–Jonkman (HKSJ) method was employed for the random-effects meta-analysis to provide more accurate coverage of confidence intervals in between-study heterogeneity. However, this method resulted in significantly wider confidence intervals for the summary effect sizes than traditional DerSimonian–Laird (DSL) estimates. While the HKSJ method helps reduce the risk of a Type I error, its conservative approach may mask potentially important effects, especially when the number of studies is small and the heterogeneity is moderate.

Fourth, this systematic review focused solely on spatiotemporal gait parameters to examine the influence of vestibular perturbations on gait. According to the Guidelines for Assessment of Gait from the Biomathics and Canadian Gait Consortium Initiatives by Beauchet et al. (2017), essential parameters for gait analysis include walking speed, stride time, swing time, stride width, stride length, stance time, single support time, double support time, stride velocity, and their variabilities. In addition to these parameters, other factors not considered in this review can provide broader insights into the effects of vestibular perturbations on gait. For example, Tran et al. (2023) investigated the effects of GVS on gait speed in healthy

adults during gait. Their findings revealed that unilateral GVS significantly decreased gait speed. In addition, Lu et al.(2022) investigated the effects of MV on the Margin of Stability (MOS) in both anteroposterior and mediolateral directions during gait. Their findings revealed that both unilateral and bilateral vestibular modifications significantly increased the MOS in both directions.

Fifth, there was considerable methodological heterogeneity across studies. The vestibular perturbation modalities differed (GVS, MV, SVS), as did stimulus parameters (intensity, timing, unilateral vs bilateral application). The walking tasks also varied: six studies employed treadmill walking at set speeds, whereas one used overground walking. Notably, treadmill walking itself can constrain natural gait variability and alter spatiotemporal patterns, potentially confounding the results, and treadmill trials tend to exhibit reduced step-to-step variability compared to overground gait, which might mask or dampen the effects of vestibular perturbations on gait variability (Hollman et al., 2016). Despite these concerns, the widespread use of treadmills in both research and clinical settings makes it important to include treadmill studies.

Finally, this review aimed to minimise bias at all stages of this review, yet some potential biases remain. A comprehensive search strategy was used across multiple databases, and study selection was performed independently by two reviewers according to pre-specified inclusion criteria, reducing the risk of selection bias. However, publication bias or selective reporting cannot be excluded in the available literature. With only seven small studies, it was not feasible to formally assess publication bias (e.g. via funnel plot). The inclusion criteria were restricted to English-language publications, so language bias may be present if relevant studies in other languages were missed. Additionally, by focusing on perturbations applied during gait, we excluded studies where vestibular stimulation was applied only before or after walking; this was deliberate for internal validity, but it could bias the context of findings toward immediate effects only. In terms of the review process itself, all data extraction and risk-of-bias assessments were conducted in duplicate; nonetheless, subjective judgments (e.g., study quality (NIH tool)) could introduce bias. We strove to resolve discrepancies by consensus and guidance from a third reviewer, following Cochrane Handbook recommendations and PRISMA guidelines, which strengthens confidence in this review

process.

5.3.2. Strengths

This meta-analysis benefits from several key strengths that bolster confidence in its findings.

First of all, this study is the first meta-analysis to compare different forms of vestibular perturbations and their influence on spatiotemporal gait parameters.

Secondly, the overall methodological quality of the included studies was moderate: five of the seven trials were rated “fair” and one “good” on the NIH Quality Assessment Tool, demonstrating clear research question and population, outcome measures and consistent and reliable exposure measures. Only Dierick et al. (2017) received a “poor” rating.

Third, a strength of this review is that it focused on prospective, controlled experiments where vestibular stimuli were applied during walking, which allows for isolating the immediate effects on gait. All included studies were cross-over or within-subject designs in healthy adults, which reduces between-subject variability and confounding by inter-individual differences.

Additionally, this study adhered to established systematic review protocols (Cochrane guidelines and PRISMA), performed duplicate study selection and data extraction, and used rigorous meta-analytic methods (random-effects with Hartung–Knapp adjustments) to enhance the credibility of the findings in this study. These measures strengthen the internal validity of the evidence synthesis.

Finally, this review serves as a strong foundation for future research. Given that most of the results are not statistically significant, further research on this topic to establish more robust conclusions and clinical implications for practitioners in the field is strongly advocated.

5.4. Recommendations for Future Research

5.4.1. Gap in the Literature

Despite growing interest in how vestibular perturbations alter gait, important gaps remain.

First, the overall body of literature remains sparse beyond these two specific limitations. Studies are heterogeneous in stimulation modality (GVS, MV, SVS, voluntary head turns, CVS, ...), outcome measures, experimental setups, and sample sizes tend to be small. This meta-analysis underscores the urgent need for additional, well-powered trials using standardised protocols across a broader age spectrum, testing multiple stimulation parameters with rigorous control of visual confounds and reported spatiotemporal endpoints. Only through such concerted efforts can we build a cohesive evidence base to inform both basic vestibular physiology and clinical applications to improve gait stability.

Second, few studies have leveraged voluntary head-turn perturbations with strict gaze fixation to isolate vestibular inputs from concurrent visual stimulation. Most head-turn protocols allow free gaze, apply fixation on a moving object (Magnani et al., 2021) or do not control for compensatory visual stabilisation, making it challenging to disentangle pure vestibular contributions to changes in spatiotemporal parameters. Carefully designed experiments that enforce gaze fixation during head movements would clarify the unique role of head turns in modulating spatiotemporal gait parameters.

Thirdly, all the eligible studies in this systematic review were on healthy young adults, hindering the capacity to evaluate the effect of vestibular perturbations on gait in other adult populations in this study. Given that age-related declines in vestibular function and balance control were previously demonstrated (Deshpande & Patla, 2007; Deshpande & Zhang, 2014), and supra-threshold GVS tend to have a larger impact in older adults (Deshpande & Patla, 2007; Deshpande et al., 2015; Liu et al., 2019; Xie et al., 2023), the limited availability of data on healthy older adults represents an area of improvement. Without understanding how suprathreshold vestibular stimulation influences gait in an ageing population, whose baseline stability and sensory integration differ substantially from younger groups, findings cannot be generalised to the demographic most at risk for falls.

To conclude, more research in general should be done on this topic, and especially on the above-mentioned topics.

6. Conclusion

In young healthy adults, acute vestibular perturbations do not seem to affect spatiotemporal gait parameters. However, considering the limited number of studies, methodological quality, varying methodologies, and broad confidence intervals, there is a need for further well-designed and adequately powered trials. These should specifically compare different stimulation intensities, isolate vestibular inputs (e.g., head turns with gaze fixation), and include older populations to better understand the actual effects of vestibular challenges on human gait.

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8. Appendix

Table A

Search Strategy

Database (Platform)	Search areas	Hits	Syntax
PubMed (NCBI)	MeSH + Title/Abstract	3110	((Gait[Mesh]) OR (Locomotion[Mesh]) OR (Locom*[Title/Abstract]) OR (walk*[Title/Abstract]) OR (Gait[Title/Abstract]) OR (Ambulat*[Title/Abstract])) AND ((Vestibular stim*[Title/Abstract]) OR (Vestibular manipulation*[Title/Abstract]) OR (GVS[Title/Abstract]) OR (galvanic stim*[Title/Abstract]) OR (galvanic vestibular stim*[Title/Abstract]) OR (Noisy galvanic vestibular stim*[Title/Abstract]) OR (Noisy galvanic stim*[Title/Abstract]) OR (Noisy vestibular stim*[Title/Abstract]) OR (noisy GVS[Title/Abstract]) OR (nGVS[Title/Abstract]) OR (stochastic galvanic vestibular stim*[Title/Abstract]) OR (stochastic vestibular stim*[Title/Abstract]) OR (stochastic electrical vestibular stim*[Title/Abstract]) OR (stochastic electrical stim*[Title/Abstract]) OR (SVS[Title/Abstract]) OR (CVS[Title/Abstract]) OR (Caloric vestibular stim*[Title/Abstract]) OR (Caloric stim*[Title/Abstract]) OR (IAS[Title/Abstract]) OR (Impulsive acceleration stim*[Title/Abstract]) OR (Sound-induced vestibular stim*[Title/Abstract]) OR (vibration-induced vestibular stim*[Title/Abstract]) OR (vibration induced vestibular stim*[Title/Abstract]) OR (Optokinetic Stim*[Title/Abstract]) OR (OKS[Title/Abstract]) OR (Mastoid vibr*[Title/Abstract]) OR (Mastoid stim*[Title/Abstract]) OR (Magnetic stim*[Title/Abstract]) OR (MVS[Title/Abstract]) OR (Magnetic vestibular stim*[Title/Abstract]) OR (head-turn*[Title/Abstract]) OR (head turn*[Title/Abstract]) OR (head tilt*[Title/Abstract]) OR (head-tilt*[Title/Abstract]) OR (head rotation*[Title/Abstract]) OR (head movement*[Title/Abstract]) OR (movement of the head[Title/Abstract]) OR (head deviation*[Title/Abstract]) OR (head perturbation*[Title/Abstract]) OR (head pivot*[Title/Abstract]))

Scopus	TITLE-ABS-KEY	5506	(TITLE-ABS-KEY("gait") OR TITLE-ABS-KEY("locom*") OR TITLE-ABS-KEY("walk*") OR TITLE-ABS-KEY("ambulat*")) AND
(Elsevier)			(TITLE-ABS-KEY("vestibular stim*") OR TITLE-ABS-KEY("vestibular manipulation") OR TITLE-ABS-KEY("GVS") OR TITLE-ABS-KEY("galvanic stim*") OR TITLE-ABS-KEY("galvanic vestibular stim*") OR TITLE-ABS-KEY("noisy vestibular stim*") OR TITLE-ABS-KEY("noisy galvanic stim*") OR TITLE-ABS-KEY("noisy GVS") OR TITLE-ABS-KEY("nGVS") OR TITLE-ABS-KEY("stochastic galvanic vestibular stim*") OR TITLE-ABS-KEY("stochastic vestibular stim*") OR TITLE-ABS-KEY("stochastic electrical vestibular stim*") OR TITLE-ABS-KEY("stochastic electrical stim*") OR TITLE-ABS-KEY("SVS") OR TITLE-ABS-KEY("CVS") OR TITLE-ABS-KEY("caloric vestibular stim*") OR TITLE-ABS-KEY("caloric stim*") OR TITLE-ABS-KEY("IAS") OR TITLE-ABS-KEY("impulsive acceleration stim*") OR TITLE-ABS-KEY("sound-induced vestibular stim*") OR TITLE-ABS-KEY("vibration-induced vestibular stim*") OR TITLE-ABS-KEY("vibration induced vestibular stim*") OR TITLE-ABS-KEY("optokinetic stim*") OR TITLE-ABS-KEY("OKS") OR TITLE-ABS-KEY("mastoid vibr*") OR TITLE-ABS-KEY("mastoid stim*") OR TITLE-ABS-KEY("magnetic stim*") OR TITLE-ABS-KEY("MVS") OR TITLE-ABS-KEY("magnetic vestibular stim*") OR TITLE-ABS-KEY("head-turn*") OR TITLE-ABS-KEY("head turn*") OR TITLE-ABS-KEY("head tilt*") OR TITLE-ABS-KEY("head-tilt*") OR TITLE-ABS-KEY("head rotation*") OR TITLE-ABS-KEY("head movement*") OR TITLE-ABS-KEY("movement of the head") OR TITLE-ABS-KEY("head deviation*") OR TITLE-ABS-KEY("head perturbation*") OR TITLE-ABS-KEY("head pivot*"))

Web of Science (Clarivate)	ALL	4788 ALL=((("walk*" OR "Gait" OR "Locom*" OR Ambulat*) AND ("Vestibular stim*" OR "Vestibular manipulation" OR "GVS" OR "Galvanic stim*" OR "Galvanic vestibular stim*" OR "noisy galvanic stim*" OR "noisy vestibular stim*" OR "nGVS" OR "noisy GVS" OR "stochastic stim*" OR "stochastic galvanic vestibular stim*" OR "stochastic electrical vestibular stim*" OR "stochastic electrical stim*" OR "stochastic vestibular stim*" OR "SVS" OR "CVS" OR "Caloric vestibular stim*" OR "IAS" OR "Impulsive acceleration stim*" OR "Sound-induced vestibular stim*" OR "Vibration-induced vestibular stim*" OR "Optokinetic stim*" OR "OKS" OR "Mastoid vibr*" OR "Mastoid stim*" OR "Magnetic stim*" OR "MVS" OR "Magnetic vestibular stim*" OR "head-turn*" OR "head turn*" OR "Head tilt*" OR "Head-tilt*" OR "Head rotation*" OR "head movement*" OR "Movement of the head" OR "head perturbation*" OR "head deviation*"))
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Table B

NIH Quality & RoB Assessment

NIH Criterion / Study	Lu et al. (2022)			Sun et al. (2023)			Dierick et al. (2023)			Li, Zhang et al. (2025)			Li, Bruijn et al. (2024)			McFadyen et al. (2007)			Abbariki et al. (2023)		
	1	2	C	1	2	C	1	2	C	1	2	C	1	2	C	1	2	C	1	2	C
1. Research question/objective clearly stated?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Population clearly specified and defined?*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

3. <i>Participation rate ≥50%?</i>	NR	NR	NR	NR	NR	NR	NR	NR	NR	Yes	NR	NR	Yes	Yes	Yes	NR	NR	NR	Yes	Yes	Yes
4. <i>Uniform recruitment/inclusion criteria?</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5. <i>Sample-size justification or power analysis provided?</i>	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	No	No	No	No	No	No	NR	NR
6. <i>Exposures measured prior to outcomes?</i>	NA	No	No	NA	NA	No	NA	NA	No	NA	NA	No	NA	NA	No	NA	NA	No	No	No	No

7. <i>Timeframe sufficient to see an effect?</i>	NA	NA	No	NA	NA	No	NA	NA	No	NA	NA	No	NA	NA	No	NA	NA	No	No	No	No
8. <i>Examined different exposure levels?</i>	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
9. Exposure measures valid/reliable/consistent?*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10. <i>Exposures assessed >1× over time?</i>	NA	NA	No	NA	NA	No	NA	NA	No	No	No	No	No	No	No	No	No	No	No	No	No

11. Outcomes clearly defined/valid/reliable /consistent ?*	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
12. Outcome assessors blinded?	NR	NR	No	NR	No	No	No	No	No	NR	NR	No	No	No	No	NR	NR	No	No	NR	No
13. Loss to follow-up ≤20%?	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14. Confounde rs measured/ adjusted?*	Yes	Yes	Yes	No	NR	NR	NR	NR	NR	No	No	No	No	No	No	No	NR	No	No	NR	No

Overall rating	Good	Fair	Good	Fair	Fair	Fair*	Poor	Poor	Poor*	Fair	Fair	Fair*	Fair	Fair	Fair*	Fair	Fair	Fair*	Fair	Fair	Fair*
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1= Rater 1, 2= rater 2, C=consensus, NR= Not Reported, NA= Not Applicable

**Studies with a negative result (“No”/”NR”) in one of the predefined critical domains (Q2/9/11/14) were scored as “Fair” and with >1 were scored as “Poor”*

Table C

Examples of used AI prompts

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1. ***“Can you give me a synonym for the following word?”***
 2. ***“Format following references in APA 7th edition style for in-text citation.”***
 3. ***“Create a table of contents based on these chapter titles.”***
 4. ***“Paraphrase the following sentence and make it sound more academic.”***
 5. ***“Paraphrase this paragraph to reduce wordiness.”***
 6. ***“Can you find the raw data online for the following study?”***
 7. ***“Provide 10 suggestions to improve this paragraph”***
 8. ***“Translate the following terms to academic English”***

+ Variations on the above
