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Vestibular dysfunction in people who fall: A systematic review and meta-analysis of prevalence and associated factors

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Abstract

Objectives: To evaluate the prevalence and factors associated with vestibular dysfunction in people who fall.
Data Sources: All electronic records from MEDLINE, CINAHL, Embase and psycINFO databases were searched to 9 December 2022.
Review Methods: Participants were adults with at least one fall within the previous year who were exposed to at least one vestibular function test. Any published peer reviewed trial designs were accepted. Included studies were assessed for risk of bias using a modified Epidemiological Appraisal Instrument. The quality of each meta-analysis was assessed using modified Grading of Recommendations Assessment, Development and Evaluation (GRADE).
Results: Ten trials (468 participants) were identified, six of which had high methodological quality. Vestibular dysfunction was found in 61% (48.01–72.32) $I^2 = 78\%$ of participants. The most prevalent type of dysfunction was from tests of vestibulo-ocular reflex at 61% (49.79 to 70.49) $I^2 = 68\%$, followed by benign paroxysmal positional vertigo at 22% (10.30–40.32) $I^2 = 87\%$ and central dysfunction at 11% (2.24–37.76) $I^2 = 50\%$. People who fall with vestibular dysfunction had reduced walking function compared to those without dysfunction −0.51 (−0.85 to −0.16) $I^2 = 11\%$. Dizziness was not related to vestibular dysfunction in people who fall 0.25 (−0.10 to 0.60), $I^2 = 0\%$. The quality of the body of evidence ranged from very low to high.
Conclusion: More than one in two people who fall have vestibular dysfunction. Clinicians cannot rely on dizziness report to indicate need for vestibular screening in those who fall. A vestibular screen should be incorporated into a comprehensive falls assessment.

Keywords

vestibular diseases, accidental falls, vestibular function tests, risk factors, adult

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Introduction

Falls are common among older adults with up to 38% of people over the age of 65 sustaining a fall each year.[1] The impacts of falls are considerable, not only are they a leading cause of injury-related death,[2] but the consequences of falls can significantly impact on physical function, activities of daily living and quality of life.[3–5] With the population aging globally, there is a need to reduce the burden attributable to falls by identifying and targeting modifiable factors.

The vestibular system is recognised as a potential contributor to falls risk.[6] When functioning appropriately, somatosensory, visual and vestibular inputs generate eye movements to keep our vision stable and ensure accurate postural reactions.[7] Three categories of vestibular dysfunction can be examined: central (changes to the brain, e.g., stroke), benign paroxysmal positional vertigo (dislodged otoconia triggering nystagmus in specific head positions) and vestibulo-ocular reflex (also known as vestibular asymmetry or hypofunction, resulting from conditions such as neuritis or Meniere's disease). It is common practice for clinicians to diagnose based on a thorough subjective history and a combination of assessments.

Guidelines for the prevention and management of falls advocate for the use of multifactorial assessments for those deemed at risk.[8] Currently expert consensus states that clinicians should routinely ask about dizziness.[8] However, older adults are known to under-report dizziness and imbalance perceptions.[9] This may lead clinicians to deprioritise vestibular examinations as part of a fall assessment. A synthesis of current literature on overall prevalence and common diagnostic categories, would highlight both the need for vestibular screening, and the techniques it is relevant to prioritise for people who fall. Commonalities between risk factors for vestibular dysfunction and risk factors for falls are found in the literature. These include but are not limited to, older age, female sex, reduced balance and impaired gait.[10–15] Clarification of which demographic, physical performance and subjective reports are more frequently associated with vestibular dysfunction in individuals who fall, could assist in refining the selection of individuals requiring further investigation. Identifying these individuals is important since there are effective interventions available.[8,16] Therefore, the research questions in this review were:

(i) What is the proportion of vestibular dysfunction in people who fall, and which diagnostic category is most prevalent?
(ii) What risk factors are associated with vestibular disorder diagnosis in fallers?
(iii) Is vestibular dysfunction associated with physical function or self-report outcomes (e.g. balance confidence and dizziness) in people who fall?

Methods

This study protocol was registered with PROSPERO (reference CRD42016052182). The protocol was modified to remove one secondary analysis which aimed to compare vestibular prevalence in fallers and non-fallers. This analysis was removed due to limited available data.

A systematic search of MEDLINE, CINAHL, Embase and psycINFO databases was performed from inception until 9 December 2022. The search strategies from previous Cochrane Reviews were adopted and terms modified according to the databases selected.[16,17] In each database, synonyms from the two major concepts, 'Accidental falls' and 'Vestibular disorders' were mapped to medical subject headings (MeSH terms) and searched under 'titles' or 'abstracts'. Results within each major concept were combined with the 'OR' Boolean operator and results between each major concept were combined with the 'AND' Boolean operator (Appendix 1). To be eligible, studies had to report on general adult populations who reported at least one fall within 1 year of vestibular testing. All included adult fallers were tested with at least one assessment in which corrective saccades or nystagmus were indicative of vestibular dysfunction. See Box 1 for full eligibility criteria.

The study yield was exported into Endnote (X6.0.2). Two reviewers (2017: A-L (GP and JD), M-Z (HC and JD), 2021: A-L (GP and LD),

M-Z (HC and LD), 2022: (JD and LD)) screened titles and abstracts, then full text articles using eligibility criteria and Covidence reference management software. Discrepancies were resolved by discussion between two reviewers, or a third reviewer (AS), was consulted for more complex decisions. Included articles and systematic reviews at full text were manually searched for additional relevant articles. The study selection process is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement.[18]

Data from eligible studies were extracted using a template by one reviewer and cross-checked by a second reviewer. Information collected from the selected trials detailed: demographics (study setting, study population and participant characteristics), methods (recruitment process, fall inclusion criteria, fall to vestibular assessment timeframes and vestibular assessment technique) and results (proportion of fallers with vestibular disorders, comparisons with controls who were non-fallers, any listed risk factors, as well as any physical function or patient reported outcomes). A request for information was sought from any study authors who collected relevant datasets which were not presented within their article.

Risk of bias was assessed using a modified version of the Epidemiological Appraisal Instrument.[19] The original 43 item tool was modified to score

Box 1. Inclusion and exclusion criteria.

Inclusion criteria

Design
- Peer reviewed studies

Participants
- General adult (>18 years old) population
- At least one fall within the preceding 12 months (fall with fracture included)

Assessment
- Assessment of vestibular dysfunction completed following the fall
- Eligible tests include Head Impulse Test (video / manual), electronystagmography, caloric, Hallpike-Dix or any other assessment where nystagmus or abnormal corrective saccades are indicative as a disorder

Language
- All languages included until full text review

Exclusion criteria

Design
- Non-peer-reviewed journals, case studies, dissertations, conference abstracts participants
- <18 years old
- Fall is not documented
- Derived from a specific disease or condition which is linked with potential for higher rates of falls and vestibular dysfunction (i.e. multiple sclerosis, Parkinson's disease, stroke, cognitive impairment, or cohorts with persistent imbalance dizziness)

Location of recruitment is linked with potential for higher rates of vestibular dysfunction (i.e. a vestibular clinic)

Assessment
- Assessment of vestibular dysfunction is completed by survey, interview or test that does not induce nystagmus or corrective saccades (i.e. Rhomberg)

Language
- Non-English excluded at full text

Table 1. Included study characteristics and results.

Study	Population	Falls criteria (timeframe)	Outcome measure (vestibular test used and procedure)	Results: number of positive vestibular tests and diagnostic category
Abbott (2016) UK	n = 37 (25 female) Mean age = 82 Recruitment: Hospital medical admission. Records were screened to identify all eligible participants	Admission that may be consistent with falls, including 'falls', 'dizzy', 'collapse' and 'off legs' (<3 weeks)	*Hallpike-Dix* (Manual test, nystagmus indicative of benign paroxysmal vertigo)	*Benign paroxysmal positional vertigo:* n = 20
Agrawal (2013) USA	n = 18 (11 female) Mean age = 74 Recruitment: Registry of older individuals interested in participating in clinical studies and from outpatient geriatric clinics	A slip or a trip in which the participant lost their balance and landed on the floor or ground or lower level (<12 months)	*Head Impulse Test (HIT)* (Manual HIT (mHIT), overt corrective saccade indicates vestibulo-ocular reflex dysfunction. Eye movement velocities were not quantified)	*Vestibulo-ocular reflex dysfunction:* n = 12
Baldursdottir (2018) Iceland	n = 98 (85 female) Mean age = 62 Recruitment: Emergency department records were screened for fallers with wrist fracture	Falls related to slips and trips, sport and sudden head movement included (2–5 months)	*Head Shake Test (HST)* (Eye movements were recorded in supine using infra-red goggles, ≥ 3 beats indicated vestibular asymmetry)	*Vestibulo-ocular reflex dysfunction:* n = 56
Ekvall Hansson (2014) Sweden	n = 56 (53 female) Mean age = 72 Recruitment: Orthopaedic clinic patients with wrist fractures as the result of a fall	Not specified (<12 months)	*HST* (Eye movements were recorded in supine using infra-red goggles, ≥ 3 beats indicated vestibular asymmetry)	*Vestibulo-ocular reflex dysfunction:* n = 44
Honaker (2011) USA	n = 16 (12 female) Mean age = 68 Recruitment: Community dwelling adults recruited from a tertiary care hospital	Individuals with an accidental fall (i.e. slips or trips). Syncope events causing a fall were excluded from participation (<12 months)	*Caloric test* (Bithermal caloric irrigation with unilateral vestibular hypofunction defined as >25% slow phase eye velocity asymmetry between left and right ear) *Oculomotor testing* (Smooth pursuit, saccades or gaze holding	*Vestibulo-ocular reflex dysfunction:* n = 4 *Central:* n = 3

(Continued)

Table 1. (Continued)

Study	Population	Falls criteria (timeframe)	Outcome measure (vestibular test used and procedure)	Results: number of positive vestibular tests and diagnostic category
			with fixation, where abnormalities or nystagmus indicated dysfunction)	
Kristinsdottir (2001) Sweden	n = 66 Mean age = 68 Recruitment: Patients presenting to emergency department with wrist fracture as the result of a fall	Accidental fall including slips, trips and 'other' (<8 weeks)	*HST* (Eye movements were recorded in supine using infra-red goggles, ≥ 3 beats indicated vestibular asymmetry)	*Vestibulo-ocular reflex dysfunction:* n = 38
Liston (2014) UK	n = 25 (21 female) Mean age = 77 Recruitment: Falls clinic	At least 2 non-syncopal falls clinically attributed to postural instability not due to significant hazards (i.e. blindness, violent blow, medical episodes) (<12 months)	*Caloric test* (Bithermal caloric testing as measured by the duration parameter using the Jongkees' formula of >8% in the absence of optic fixation) *Rotary Chair & Horizontal Direct Current Electronystagmography (ENG)* (Sinusoidal rotation and 60°/s fixed chair velocity, assessed vestibulo-ocular reflex and its suppression. ENG assessed gaze evoked nystagmus with/without optic fixation, saccades, smooth pursuit, and optokinetic response to a striped curtain)	*Vestibulo-ocular reflex dysfunction:* Combined methods (caloric, rotary chair & ENG) n = 19 (Unilateral vestibular hypofunction n = 9, Bilateral vestibular hypofunction n = 2) *Central:* n = 1
Oghalai (2016) USA	n = 39 (female not specified) Mean age = not specified Recruitment: Patients attending a geriatric clinic for regular outpatient care	Not specified (<3 months)	*Hallpike-Dix* (Manual test, nystagmus indicative of benign paroxysmal positional vertigo)	*Benign paroxysmal positional vertigo:* n = 7
Varriano (2021) Canada	n = 29 (20 female) Mean age = 81 Recruitment: Falls prevention programme	Not specified (<12 months)	*Hallpike-Dix* (Not specified) *HST* (Eye movements were recorded in sitting using infra-red goggles, ≥ 3 beats indicated vestibular asymmetry)	*Benign paroxysmal positional vertigo:* n = 4 *Vestibulo-ocular reflex dysfunction:* Combined Methods

(Continued)

Table 1. (Continued)

Study	Population	Falls criteria (timeframe)	Outcome measure (vestibular test used and procedure)	Results: number of positive vestibular tests and diagnostic category
			HIT (mHIT: Overt corrective saccade indicated positive result for peripheral vestibular hypofunction. Video HIT (vHIT): ICS impulse Video Goggles, impulses performed in horizontal plane only. Positive result included gain of 0.8 or lower with corrective saccades, or an observable overt/covert saccade that measured 50% or greater than that of the head velocity)	(HST, mHIT, vHIT) n = 23 (HST n = 5, mHIT n = 20, vHIT n = 20)
Zur (2006) Israel	n = 84 (69 female) Mean age = 81 Recruitment: Patients within an inpatient rehabilitation unit following a fall requiring hip surgery	Not specified (<3 weeks)	*Hallpike-Dix* (Manual test, nystagmus indicative of benign paroxysmal positional vertigo) *HIT* Participant in a seated position, head manually rotated 20°–30° at high velocity overt saccade was indicative of unilateral hypofunction *HST* Tested in sitting, dark room with internally lit Frenzel glasses, > 3 beats were considered positive for vestibular asymmetry	*Benign paroxysmal positional vertigo:* n = 10 *Vestibulo-ocular reflex dysfunction:* HIT n = 52 HST n = 17

Table 2. Modified Epidemiological Appraisal Instrument assessment of risk of bias for included studies.

Criteria	Abbott, 2016	Agrawal, 2013	Baldursdottir, 2018	Ekvall hansson, 2014	Honaker, 2011	Kristinsdottir, 2001	Liston, 2014	Oghalai, 2000	Varriano, 2021	Zur, 2006
Hypothesis/aim/objective is clearly described	y	y	y	y	y	y	y	y	y	y
Methods of assessing the outcome variables is clearly described	y	y	y	y	y	y	y	p	y	y
Study design is clearly described	p	y	y	y	p	p	y	y	p	y
Source of the sample is clearly described	p	p	y	y	y	y	y	y	y	p
Eligibility criteria is clearly defined	p	y	p	p	y	p	y	p	y	p
Excluded sample is clearly defined	y	p	y	y	p	y	p	n	p	y
Characteristics of participants is described (age, gender, number of falls in 12 months)	p	y	y	y	y	p	y	y	y	p
Important covariates or confounders are described	p	y	y	y	y	n	y	y	y	y
Statistical methods are clearly described	n	y	y	y	y	y	y	y	y	y
Main findings of the study are clearly described	y	y	y	y	y	y	y	y	y	y
Study provides estimates of random variability	n	y	n	y	n	n	y	n	y	n
Study provides estimates of statistical parameters	n	y	y	n	y	n	y	y	y	y
Sample size calculations are performed and reported	n	n	n	y	n	n	n	n	n	n
Vestibular assessment assessor was blinded to the group	n	n	y	y	n	n	n	n	n	n
Included vestibular assessment tools are reliable	n	n	n	n	n	n	n	n	y	n
Included vestibular assessment tools are valid	n	y	n	p	n	n	n	y	y	p

(Continued)

Table 2. (Continued)

Criteria	Abbott, 2016	Agrawal, 2013	Baldursdottir, 2018	Ekvall hansson, 2014	Honaker, 2011	Kristinsdottir, 2001	Liston, 2014	Oghalai, 2000	Varriano, 2021	Zur, 2006
Outcomes are reported by subgroup	n	y	p	y	n	p	n	p	y	n
Results can be applied to the population as assessed by the participation rate	n	n	n	p	n	p	n	y	n	p
Total (%)	13 (36)	26 (72)	24 (67)	29 (81)	20 (56)	17 (47)	23 (64)	23 (64)	28 (78)	21 (58)

n: no; y: yes; p:partial.

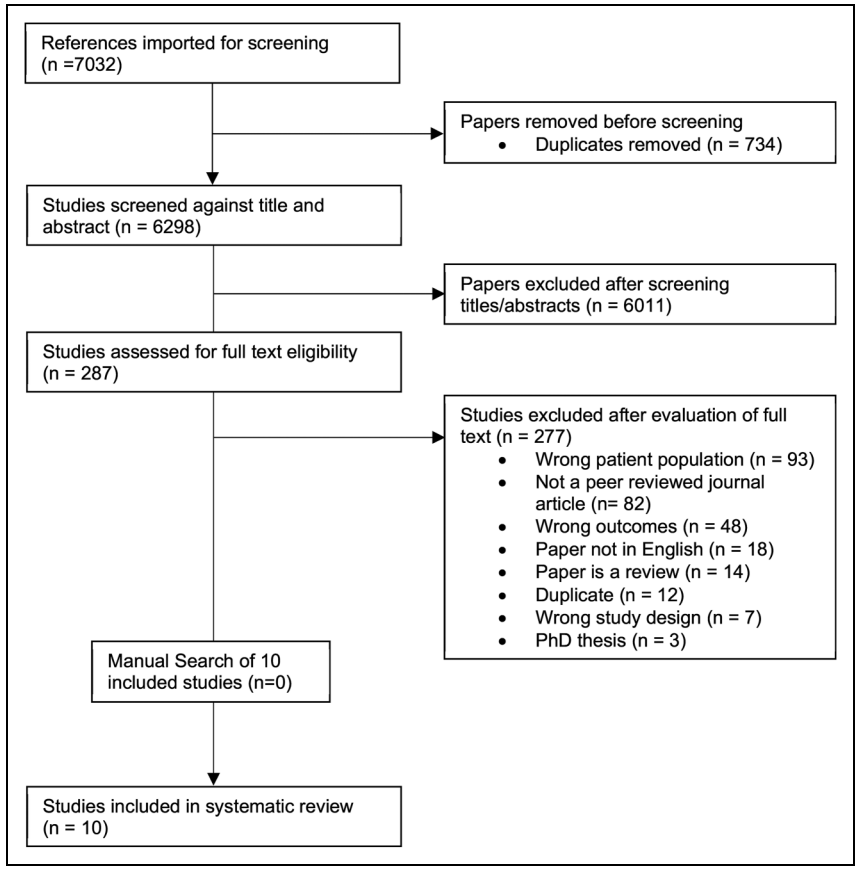

Figure 1. Flow of studies through the systematic review.

only those items deemed relevant to risk of bias associated with the purpose of this review. The final tool was compared to other risk of bias assessments used in epidemiology to ensure no key domains were neglected. Each included article was assessed using the final 18 item tool on reporting, subject selection, measurement quality, data analysis and generalisation of results (full criteria can be sourced from Supplemental Table 1). The total possible score was 36 where 'yes' = 2, 'partial' = 1 and 'no' = 0. Where the article scored ≥60%, a high-quality rating was applied based on methodology reported by other authors.[20] Two reviewers independently rated the study quality (HC and JD). Where consensus could not be confidently agreed a third reviewer (AS) was consulted to make a final judgement.

The R statistical software package (https://www.r-project.org/, metafor package v 2.0) was used to calculate the proportion of fallers with vestibular dysfunction and subgroupings (% with 95% confidence interval (CI)). Review Manager 5.4 was used to describe risk factors and associations with physical or self-reported outcomes. Risk factors for vestibular dysfunction in fallers were presented as odds ratios (OR, 95% CI) where the risk factor was dichotomous (e.g. gender), or standardised mean differences (SMD, 95% CI), where risk factors were continuous (e.g. age). To describe the association of vestibular dysfunction in fallers with physical function and subjective reported outcomes, continuous data were extracted and compared between fallers with and without vestibular

dysfunction using SMD (95% CI). Medians and inter-quartile ranges were converted to means and standard deviations using methods described elsewhere.[21]

A random effects meta-analysis was completed for each outcome where two or more studies provided clinically homogeneous data. Statistical heterogeneity was assessed using the 'I^2' statistic. For the total prevalence meta-analysis, where studies completed multiple vestibular tests but provided no overall prevalence, the highest reported value across all diagnostic methods was used. In this analysis subgroups were presented for each vestibular assessment used. The 'mixed' subgroup encapsulated all studies which provided a total vestibular dysfunction value using more than one test. Three additional clinically relevant subgroups based on diagnostic categorisation were developed by consensus of the team: (a) central vestibular dysfunction, which included oculomotor assessments such as gaze holding, smooth pursuit, saccades and vestibulo-ocular reflex suppression, (b) benign paroxysmal positional vertigo, which included Hallpike-Dix tests and (c) vestibulo-ocular reflex dysfunction, where assessments such as; caloric, rotary chair, head impulse test and other general tests of vestibular

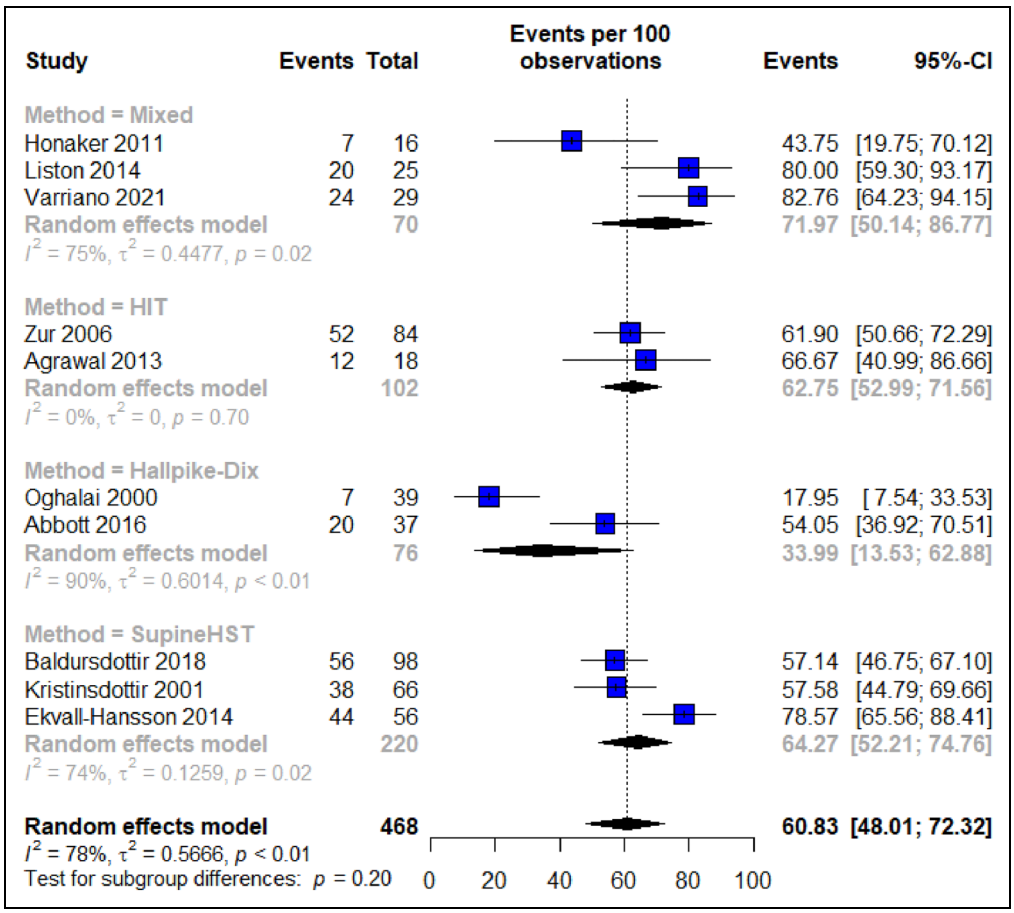

Figure 2. Meta-analysis of total episodes of vestibular dysfunction in adults who fall, grouped by type of vestibular asssessment. Mixed: vestibular dysfunction by two or more methods; HIT: head impulse test; supineHST: supine head shake test.

asymmetry such as the head shake test were combined. Where a study provided data for two outcomes within the diagnostic subgroup (with no combined total), the outcome with the highest specificity was selected (i.e. head impulse over the head shake test).[22] Where heterogeneity was moderate or more (>50%),[23] and combined outcomes were used, we explored further by subgrouping for individual vestibular test types. For studies which used head shake test, only participants with three or more saccades were considered positive for vestibular dysfunction.[24] In the context of neuro-otological testing, directional preponderance alone was not considered positive for vestibular dysfunction in subgroup analyses.[25] For outcomes with multiple measures, (i.e. balance and physiological profile) only studies with a combined total score (i.e. Sensory Organisation Test, or Physiological Profile Assessment) were eligible for pooling.

Quality of the body evidence across the studies in each meta-analysis was assessed using a modified version of the Grading of Recommendations Assessment, Development and Evaluation (GRADE).[26–28] The modification was due to the epidemiological nature of the review (rather than assessing interventions), as well as the inclusion of data from a range of study designs (rather than randomised controlled trials alone). The level of evidence was rated as high, moderate, low, and very low quality, and was downgraded based on: (1) risk of bias (downgrade where mean Epidemiological Appraisal Instrument < 60%), (2) inconsistency (downgrade if $I^2 > 50\%$),[27] (3) precision (for proportion data CI spans more than a quartile (or 12.5 points in either

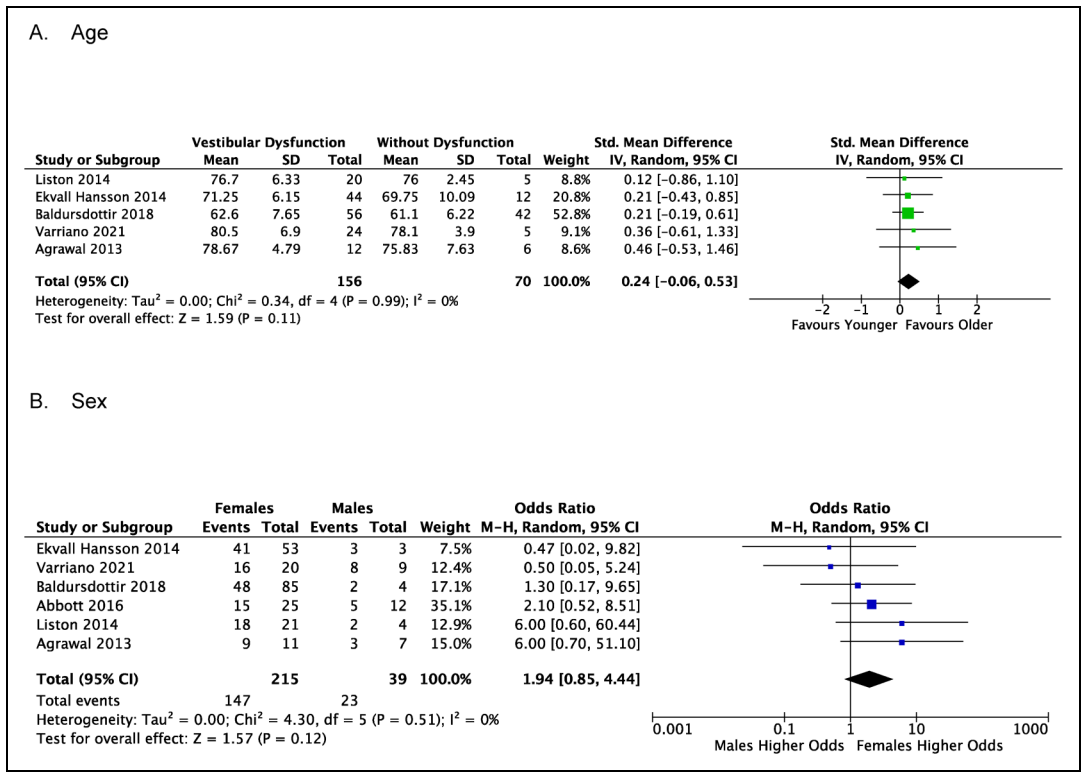

Figure 3. Risk factors. (A) Standardised mean difference (95% confidence interval) indicating effect of age on vestibular dysfunction in people who fall and (B) odds ratio comparing vestibular dysfunction prevalence between males and females who fall.

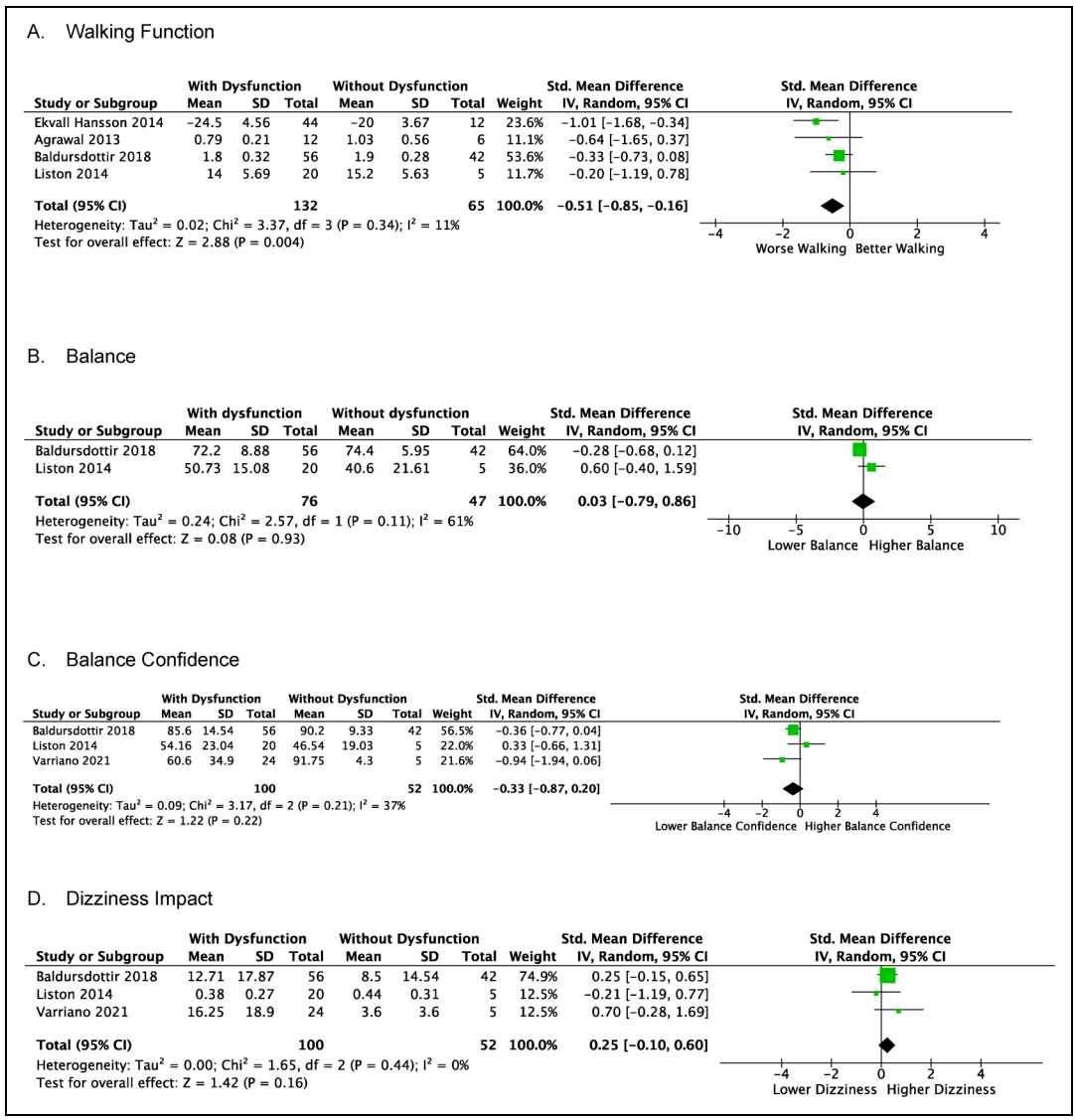

Figure 4. Physical function: standardised mean difference (95% confidence interval) of pooled data. (A) Indicating the effect of vestibular dysfunction on walking performance in people who fall; (B) effect of vestibular dysfunction on balance performance on people who fall. Subjective report: standardised mean difference (95% confidence interval) of (C) effect of vestibular dysfunction on balance confidence in people who fall; and (D) effect of vestibular dysfunction on self-perceived dizziness impact in people who fall.

direction from point estimate),[28] for SMD CI >0.5 in either direction,[27] or for OR CI >2 fold increase or <0.5 decrease).[29] Two reviewers independently assessed the quality of evidence against the criteria (HC and LD). A third reviewer (AS) was consulted and confirmed final agreed results.

Results

The total yield following our search strategy was 7032 articles. Following the removal of duplicates and completion of abstract and title screening, 287 studies were forwarded to full text review.

Of these, 10 studies were eligible for inclusion. See Figure 1 for PRISMA flow diagram.

A total of 468 participants were included across 10 studies. Research designs included one randomised controlled trial,[30] four case-controlled[22,25,31,32] and five cross-sectional investigations.[33–37] Participants were recruited from hospitals (6 studies)[22,30–34] and clinics (4 studies).[25,35–37] Mean age ranged from 62[31] to 82 years.[33] The proportion of female participants ranged from 68%[33] to 95%.[30] The definition of a fall varied across the studies. For example, one trial included participants with two or more falls related to postural instability,[25] while others included falls that resulted in wrist fracture related to slips on ice, and trips on stairs.[34] Five studies relied on retrospective recall of falls,[25,32,35–37] and five recruited directly from a hospital admission due to the occurrence of a fall.[22,30,31,33,34] Time from fall to vestibular assessment varied with two assessing within 3 weeks of a fall,[22,33] two within 3 months[34,35] and six within 12 months.[25,30–32,36,37] A variety of vestibular assessments were selected. Six of 10 studies used only one vestibular test to determine the presence of vestibular dysfunction.[30,31,33–35,37] One study completed a more comprehensive vestibular assessment using a neuro-otological approach with specialist equipment.[25] Two studies assessed for central vestibular dysfunction using various oculomotor procedures.[25,32] Those that assessed for benign paroxysmal positional vertigo used the Hallpike-Dix test only.[22,33,35,36] A number of methods were used to assess the vestibulo-ocular reflex (head impulse test,[22,36,37] head shake test,[22,30,31,34,36] caloric[25,32] and rotary chair[25]). Three studies had participants complete the head shake test supine as opposed to sitting.[30,31,34] Study characteristics are summarised in Table 1.

Six out of 10 research papers were considered high quality (Table 2). Items with poor responses included a lack of sample size calculations, reporting on reliability and validity of vestibular outcomes selected, adjustment for confounders or reporting on subgroups and random variability. Most did not report blinding of their vestibular outcome assessors. Three studies completed video or electronystagmography responses to their vestibular outcome, however only one of these supplied data to an independent assessor.[34] Ability to determine participation rates was also limited across the studies.

Vestibular dysfunction was identified in 61% (48.01, 72.32) $I^2 = 78\%$ of fallers (Figure 2). This meta-analysis was determined to provide moderate quality of evidence with a downgrade applied for inconsistency (see Supplemental Table 2 for all body of evidence decisions). When subgroups were investigated by diagnostic categories, vestibulo-ocular reflex dysfunction (n = 392) was most prevalent in fallers at 61% (49.79, 70.49), $I^2 = 68\%$, followed by benign paroxysmal positional vertigo (n = 183) at 22% (10.30, 40.32), $I^2 = 87\%$ and central dysfunction (n = 41) at 10% (3.29, 25.10), $I^2 = 50\%$ (refer to Supplemental Figure 1). The level of evidence for vestibulo-ocular reflex dysfunction, benign paroxysmal positional vertigo and central dysfunction was moderate (inconsistency), very low (risk of bias, inconsistency and imprecision) and low (inconsistency and imprecision), respectively. Due to the loss of individual test data with pooled findings in 'mixed' categories and >50% heterogeneity of the vestibulo-ocular reflex dysfunction subgroup, a separate analysis of head impulse test, head shake test and caloric stimulation was conducted. The vestibular dysfunction prevalence was highest for head impulse test (n = 128) 66% (57, 73.33) $I^2 = 0\%$ and lowest for caloric (n = 41) 27% (15.54, 42.29) $I^2 = 0\%$. High heterogeneity appears in head shake test (n = 310) 48% (27.54, 68.50) $I^2 = 90\%$ (Supplemental Figure 2).

In people who fall, high-level evidence was found that there is no relationship of age with vestibular dysfunction, SMD 0.24 (−0.06, 0.53) $I^2 = 0\%$ (n = 226) (Figure 3A).[25,30,31,34,36,37] Moderate level evidence (downgrade for imprecision) of no relationship was also found between sex and vestibular function in fallers (OR = 1.94 (0.85, 4.44) $I^2 = 0\%$ (n = 244) (Figure 3B).[25,30,31,33,36,37] Two authors provided data on physiological tests in both fallers with and without vestibular dysfunction. These assessments could not be pooled in a meta-analysis. There was no association found between vestibular dysfunction and each individual outcome (Physiological Profile Assessment[25] or

monofilaments, tuning fork and biothesiometer[31]). See Supplemental Table 3 for details.

Walking outcomes (comfortable 4 m, fast 10 m walk test, fast 30 m with x1 turn and Functional Gait Assessment) were pooled from four trials (n = 197).[25,30,31,37] There was high-level evidence for reduced walking function in fallers with vestibular dysfunction compared to fallers without vestibular dysfunction SMD −0.51 [−0.85; −0.16] I^2 = 11% (Figure 4A). Four studies assessed balance and vestibular function in people who fall.[25,30,31,36] Two investigations using computerised posturography were eligible for pooling.[25,31] There is low-level evidence (downgrading occurred for both inconsistency and imprecision) of no relationship between vestibular dysfunction and balance in people who fall (n = 123), SMD 0.03 [−0.79, 0.86] I^2 = 61% (Figure 4B). The two studies which were not able to be pooled found conflicting results with balance performance in the presence of vestibular dysfunction.[30,36]

Balance self-confidence data were available to pool from three studies assessing Activities-specific Balance Confidence Scale.[25,31,36] There was moderate evidence (downgrading due to imprecision) of no significant difference in balance confidence scores between fallers with and without vestibular dysfunction, n = 152 SMD −0.33 [−0.87, 0.20] I^2 = 37% (Figure 4C). Subjective reports of dizziness and its impact were available for pooling from three authors. Two used the Dizziness Handicap Inventory,[31,36] and one the Vestibular Symptom Scale – vertigo subsection.[25] There was high-level evidence from n = 152 of no significant difference between fallers with or without vestibular dysfunction in reports of dizziness impact, SMD 0.25 [−0.10, 0.60] I^2 = 0%, (Figure 4D). One author identified that 70% of fallers with a vestibular dysfunction diagnosis reported no dizziness or vertigo symptoms using the Vestibular Symptom Scale – Vertigo subsection.[25] Another found that in their general elder cohort, almost half of those with benign paroxysmal positional vertigo reported no vertiginous symptoms.[35] Data related to reports of mood was retrieved from one author. No significant association was found between the presence of vestibular dysfunction and anxiety (Hospital Anxiety and Depression scale – anxiety subsection), −0.45[−1.43, 0.54]) or depression (Hospital Anxiety and Depression – depression subsection, 0.05[−0.93, 1.03]).[25]

Discussion

This systematic review identified that more than one in two people who fall have objective signs of vestibular dysfunction using at least one vestibular outcome. Within clinical practice, vestibular screening requires diagnostic interpretation using a battery of assessments. Only one of the included studies in this review came to a cumulative diagnostic decision.[25] Two thirds of the included studies used only one vestibular assessment. This fact, in combination with low sensitivity in some of the vestibular tests used,[24] indicates that the overall prevalence of 60% is likely to be an underestimate.

Across three subgroups, the highest proportion of dysfunction was demonstrated in testing associated with vestibulo-ocular reflex (61%). This percentage is much higher than the 5% to 20% (using head impulse test) reported in other general dizzy and disequilibrium populations.[11,38] The magnitude of our result derived from examinations involving rapid head movements (i.e. head impulse test and head shake test), rather than through caloric stimulation. Due to inconsistency, we examined the pooled vestibulo-ocular reflex tests separately. High heterogeneity was found in results from head shake test, while very low heterogeneity was seen in the head impulse test and caloric analysis. The high variability in this analysis may be related to head shake test being performed in both seated and supine positions.

No significant risk factors for the presence of vestibular dysfunction in fallers were identified by this review. Additional research is unlikely to change our estimate for age as a risk factor, given the high-level evidence. However, there is sufficient uncertainty with our estimates of sex to indicate that further data may change the result. In this analysis the size of effect was large (almost two times greater odds for females than males) although not significant. Other studies provide evidence of a

relationship between sex and vestibular dysfunction.[12,39–42] Researchers speculate that co-morbidities found in older females such as osteoporosis or oestrogen changes, may contribute to the development of vestibular dysfunction.[12,39,42] Data limitations resulted in the inability to investigate the possible contribution of these or other co-morbidities. Collecting demographic information such as co-morbidities and frailty indexing in future work may support further evidence in this area.

The findings in this review seem to substantiate the concept that in the presence of dysfunction, abnormal vestibular sensory information during movement results in the loss of gaze stabilisation and perception of body in space.[43] This may in turn impair rapid motor responses which are necessary for preventing falls. The high prevalence of vestibulo-ocular reflex dysfunction in tests with rapid head movement (head impulse test, head shake test) and impaired walking function found in this review could support this theory. Counterintuitive to this concept, was the finding that balance performance was not related to vestibular dysfunction in fallers. The balance measures used in this analysis did not incorporate head movements or dynamic tasks which are more typical of balance requirements during daily life. In this instance, the impact of vestibular impairment on balance performance may have been underestimated.

There are some limitations to this review. Inclusion criteria for mechanism of fall were not described by all studies. Consequently, participants included in our meta-analyses may not have been specifically exposed to a loss of balance (e.g. collisions, or medical episodes). In addition, included participants had falls up to 12 months prior to their vestibular assessment. The associations in this study are therefore weakened by the fact that time related changes can occur in the vestibular system (both worsening and resolution of function).[44,45] Furthermore, this review was unable to compare to a control group of non-fallers. With population studies demonstrating half of those over 60 having some form of physiological vestibular change this comparison could be important.[9]

Contrary to previously published fall prevention recommendations,[8] when completing a comprehensive fall assessment, we encourage clinicians to objectively screen all people for signs of vestibular dysfunction. This recommendation is based on our high overall prevalence finding, as well as the high confidence that clinicians cannot use verbal reports of dizziness to indicate the need for vestibular assessment. Three assessments which encompass both peripheral and central vestibular dysfunctions may reduce the risk of under diagnosis. Oculomotor, head impulse and Hallpike-Dix tests could be easily incorporated given they do not necessarily require specialist equipment or a significant amount of time to complete. Completing such a screen could assist in effective treatment prioritisation. Further research may determine if vestibular system screening and subsequent intervention can reduce recurrent or future falls. If this is the case, vestibular screening as part of a comprehensive falls management programme could generate significant health and societal cost benefits.

Clinical Message

- More than one in two people who fall have evidence of vestibular dysfunction.
- For a comprehensive fall assessment, an objective screen for vestibular dysfunction is encouraged.
- The use of oculomotor, head impulse and Hallpike-Dix tests may reduce the risk of underdiagnosing vestibular dysfunction as a possible factor contributing to falls.

Author statement Credit

The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

JD contributed to conceptualisation, methodology, investigation, data curation, formal analysis, visualisation, writing – original draft, and project administration. AS was involved in conceptualisation, methodology, formal analysis, supervision, writing – review and editing. LD performed investigation, data curation, formal analysis, writing – review and editing. HC contributed toward

methodology, investigation, data curation, visualisation, writing – review and editing. GP was involved in methodology, investigation, writing – review and editing.

Declaration of conflicting interests

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Data sharing

Available on request.

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Trial Registration

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Supplemental material

Supplemental material for this article is available online.

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Appendix 1. Search strategy.

	MEDLINE and CINAHL	psycINFO
S1	MH"vestibular diseases + "	DE "vertigo"
S2	MH"vertigo + "	DE "labyrinth disorders" OR DE "Menieres disease" OR DE "motion sickness"
S3	MH"dizziness + "	
S4	MH"labyrinth diseases + "	
S5	MH "vestibulocochlear nerve diseases + "	
S6	TI (Vertigo OR vestibulopath* OR dizziness OR "vestibular disorder" OR "vestibular hypofunction" OR "vestibular impair*" OR "vestibular patholog*" OR "vestibular disturbance") OR AB (Vertigo OR vestibulopath* OR dizziness OR "vestibular disorder" OR "vestibular hypofunction" OR "vestibular impair*" OR "vestibular patholog*" OR "vestibular disturbance")	TI (Vertigo OR vestibulopath* OR dizziness OR "vestibular disorder" OR "vestibular hypofunction" OR "vestibular impair*" OR "vestibular patholog*" OR "vestibular disturbance") OR AB (Vertigo OR vestibulopath* OR dizziness OR "vestibular disorder" OR "vestibular hypofunction" OR "vestibular impair*" OR "vestibular patholog*" OR "vestibular disturbance")
S7	AB (neurolabyrinthitide* OR neurolabyrinthitis OR "vestibular neuritis" OR "vestibular neuronitis" OR "vestibular neurotide*") OR TI (neurolabyrinthitide* OR neurolabyrinthitis OR "vestibular neuritis" OR "vestibular neuronitis" OR "vestibular neurotide*")	AB (neurolabyrinthitide* OR neurolabyrinthitis OR "vestibular neuritis" OR "vestibular neuronitis" OR "vestibular neurotide*") OR TI (neurolabyrinthitide* OR neurolabyrinthitis OR "vestibular neuritis" OR "vestibular neuronitis" OR "vestibular neurotide*")
S8	AB (vestibular AND (inflammation OR compression)) OR TI (vestibular AND (inflammation OR compression))	AB (vestibular AND (inflammation OR compression)) OR TI (vestibular AND (inflammation OR compression))
S9	TI (acoustic AND (neuroma OR neurilemoma OR neurinoma OR neurilemmoma)) OR AB (acoustic AND (neuroma OR neurilemoma OR neurinoma OR neurilemmoma))	TI (acoustic AND (neuroma OR neurilemoma OR neurinoma OR neurilemmoma)) OR AB (acoustic AND (neuroma OR neurilemoma OR neurinoma OR neurilemmoma))
S10	TI ("vestibular schwannoma" OR "acoustic schwannoma" OR "motion sensitivity" OR meniere* OR BPV OR BPPV OR ANTBPPV) OR AB ("vestibular schwannoma" OR "acoustic schwannoma" OR "motion sensitivity" OR meniere* OR BPV OR BPPV OR ANTBPPV)	TI ("vestibular schwannoma" OR "acoustic schwannoma" OR "motion sensitivity" OR meniere* OR BPV OR BPPV OR ANTBPPV) OR AB ("vestibular schwannoma" OR "acoustic schwannoma" OR "motion sensitivity" OR meniere* OR BPV OR BPPV OR ANTBPPV)
S11	AB ((peripheral AND vestibular) OR (perilymph* AND fistula) OR (labyrinth* AND hydrops) OR (endolymph* AND hydrops) OR (labyrinth* AND syndrome)) OR TI ((peripheral AND vestibular) OR (perilymph* AND fistula) OR (labyrinth* AND hydrops) OR (endolymph* AND hydrops) OR (labyrinth* AND syndrome))	AB ((peripheral AND vestibular) OR (perilymph* AND fistula) OR (labyrinth* AND hydrops) OR (endolymph* AND hydrops) OR (labyrinth* AND syndrome)) OR TI ((peripheral AND vestibular) OR (perilymph* AND fistula) OR (labyrinth* AND hydrops) OR (endolymph* AND hydrops) OR (labyrinth* AND syndrome))
S12	MH "accidental falls"	DE "falls"
S13	TI (fall* OR faller* OR fell OR slip* OR stumble* OR trip* OR tumble*) OR AB (fall* OR faller* OR fell OR slip* OR stumble* OR trip* OR tumble*)	TI (fall* OR faller* OR fell OR slip* OR stumble* OR trip* OR tumble*) OR AB (fall* OR faller* OR fell OR slip* OR stumble* OR trip* OR tumble*)
S14	S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7 OR S8 OR S9 OR S10 OR S11	S1 OR S2 OR S6 OR S7 OR S8 OR S9 OR S10 OR S11

(Continued)

(Continued)

	MEDLINE and CINAHL	psycINFO
S15	S11 OR S12	S11 OR S12
S16	S14 AND S15	S14 AND S15

Embase

('falling'/exp AND [embase]/lim OR ((falls* OR faller* OR fell OR slip* OR trip* OR stumble* OR tumble*:ab,ti) AND [embase]/lim)) AND ('dizziness'/exp AND [embase]/lim OR ('vertigo'/exp AND [embase]/lim) OR ('vestibular disorder'/exp AND [embase]/lim) OR ('vestibulocochlear nerve disease'/exp AND [embase]/lim) OR ('inner ear disease'/exp AND [embase]/lim) OR (vestibular AND (inflammation:ab,ti OR compression:ab,ti) AND [embase]/lim) OR ((peripheral AND vestibular OR (perilymph* AND fistula) OR (labyrinth* AND hydrops) OR (endolymph* AND hydrops) OR (labyrinth* AND syndrome:ab,ti)) AND [embase]/lim) OR (('vestibular schwannoma' OR 'acoustic schwannoma' OR 'motion sensitivity' OR meniere* OR bpv OR bppv OR antbppv:ti,ab) AND [embase]/lim) OR ((vertigo OR vestibulopath* OR dizziness OR 'vestibular disorder' OR 'vestibular hypofunction' OR 'vestibular impair*' OR 'vestibular patholog*' OR 'vestibular disturbance*':ab,ti) AND [embase]/lim))