Falls among people with bilateral vestibulopathy : a review of causes, incidence, injuries, and methods

Reference:
Herssens Nolan, How Daniella, van den Berg Raymond, McCrum Christopher.- Falls among people with bilateral vestibulopathy : a review of causes, incidence, injuries, and methods
JAMA otolaryngology, head and neck surgery / American Medical Association; American Academy of Facial Plastic and Reconstructive Surgery- ISSN 2168-619X - Chicago, Amer medical assoc, 148:2(2022), p. 187-192
Full text (Publisher's DOI): https://doi.org/10.1001/JAMAOTO.2021.3673
To cite this reference: https://hdl.handle.net/10067/1855090151162165141

Falls among people with bilateral vestibulopathy: a narrative review of causes, incidence, injuries and methodology

Nolan Herssens, PhD[1,2], Daniella How, MSc[3], Raymond van de Berg, MD, PhD[4,5], Christopher McCrum, PhD[6]*

[1] Space Medicine Team (HRE-OM), European Astronaut Centre, European Space Agency, Cologne, Germany

[2] Department of Rehabilitation Sciences and Physiotherapy/MOVANT, Faculty of Medicine and Health Sciences, University of Antwerp, Wilrijk, Belgium

[3] Institute of Sport and Exercise Sciences, Münster University, Münster, Germany

[4] Division of Balance Disorders, Department of Otorhinolaryngology and Head and Neck Surgery, Faculty of Health Medicine and Life Sciences, School for Mental Health and Neuroscience, Maastricht University Medical Centre+, Maastricht, The Netherlands

[5] Faculty of Physics, Tomsk State University, Tomsk, Russia

[6] Department of Nutrition and Movement Sciences, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre+, Maastricht, The Netherlands

*Correspondence:
Christopher McCrum
Department of Nutrition and Movement Sciences
Maastricht University,
PO Box 616, Maastricht, 6200 MD, The Netherlands
chris.mccrum@maastrichtuniversity.nl

Manuscript word count: 2184

Abstract

Importance: People with bilateral vestibulopathy experience severe balance and mobility issues. Fear and anxiety lead to reduced activity which can further affect balance and fall risk. Understanding and intervening on falls in this population is essential. The aims of this narrative review are to provide an overview of current knowledge and applied methodology on fall incidence, causes and injuries in bilateral vestibulopathy.

Observations: A total of ten articles reporting falls incidence in people with bilateral vestibulopathy were deemed eligible, including two prospective and eight retrospective studies, with a total of 317 participants of which 43% experienced a fall over the assessed time period. When reported, the most common perceived causes of falls were loss of balance, darkness and uneven ground. Information on sustained injuries was limited, with bruises and scrapes being the most common, and only four fractures being reported. As most studies included falls as a secondary, descriptive outcome measure, falls data obtained using best practice guidelines was lacking: only five studies reported their definition of a fall, of which two studies explicitly reported the way subjects were asked about fall status; only two studies performed a prospective daily fall assessment using monthly fall diaries (recommended practice) while the remaining studies retrospectively collected fall-related data through questionnaires or interviews; and while most studies reported the number of (non-)fallers, the number of total falls in individual studies was lacking.

Conclusions and Relevance: Findings from this review indicate that falls in people with bilateral vestibulopathy are common but remain an understudied consequence of the disease. Larger prospective studies, following best practice guidelines for fall data collection, with the aim of obtaining and reporting falls data are required to improved current fall risk assessment and interventions in bilateral vestibulopathy.

Introduction

Falls are one of the leading causes of injuries and are related to an important risk of morbidity and mortality.[1,2] Vestibular disorders result in both an increased mortality from all causes[3] and deficits in gait and balance control.[4-10] In particular, people with bilateral vestibulopathy (BVP) are at an increased risk of falls, with one survey showing a 31-fold increased risk over five years compared to the USA national average.[11]

Bilateral vestibulopathy is characterized by a partial, or complete loss of vestibular function due to dysfunction of both vestibular end-organs, the 8th cranial nerve, or a combination of both.[12,13] Although a bilateral loss of vestibular function is fairly uncommon with a prevalence of 28/100,000 US adults in 2008[14] (likely an underestimation due to diagnosis difficulties[12,15,16]), it is a highly disabling disorder. People with BVP often report frequently falling, alongside many other related symptoms such as imbalance, dizziness, oscillopsia, and vertigo, all of which contribute to a decreased quality of life.[17-22] These adverse effects of BVP highlight the impact on function and participation. Alongside the direct consequences of a fall (e.g. injuries and loss of independence), secondary, indirect complications such as limiting activities of daily life, becoming more sedentary, moving more rigidly to reduce symptoms and increased concern about falling may further negatively impact physical and psychological well-being and quality of life.[13,16,23,24] Despite the importance of understanding and intervening on falls in this population, there is a distinct lack of data in the literature that might give actionable insight into the incidence and causes of falls in BVP, as well as the most common fall-related injuries.

The purpose of this narrative review is to provide an overview of current knowledge on the incidence and circumstances of falls in BVP and to determine the gaps in knowledge and the drawbacks of current methods to obtain this information within this population. This would help guide further research on falls incidence and prevention in BVP.

Methods

For this review, articles were deemed eligible to include if they reported falls incidence data (using any method) among people with bilateral hypofunction or vestibulopathy (>18 years of age). Note that since the Bárány Society Diagnostic Criteria were only recently published,[25] we did not include or exclude articles on the diagnostic criteria used, but this information was collected from the included studies. Studies were gathered by means of manually screening search results and reference lists from previous projects, including one systematic review,[10] the doctoral theses of authors NH[26] and CM[27] and personal bibliographic databases of the authors. In addition, a broad search was completed in PubMed and Web of Science by CM and DH (PubMed search string: ((bilateral[Title/Abstract] AND vestibul*[Title/Abstract])) AND (gait[Title/Abstract] OR balance[Title/Abstract] OR walk*[Title/Abstract] OR stand*[Title/Abstract] OR stance[Title/Abstract] OR locomot*[Title/Abstract] OR fall*[Title/Abstract])). Finally, CM and NH performed snowball searches for all relevant articles. Note that due to the amount of literature previously obtained by the authors, a new PRISMA-compliant systematic search process was not conducted or deemed necessary. All available data on patient characteristics, BVP aetiology, and falls incidence, causes and injuries (data and methodology) were extracted. When there appeared to be missing or erroneous data in the articles, or when only data on combined groups of patients (e.g., unilateral vestibulopathy and BVP data combined) were provided, authors of those articles were contacted by email for further clarification. To evaluate the fall data collection and reporting methods, the recommendations of Lamb, et al.,[28] shown in Table 1, were used for reference as best practice recommendations.

Insert Table 1 here

Observations

In total, ten articles[9,11,29-36] were reviewed, including a total of 317 patients (155 women) with ages ranging between 30 and 90 years old. A total of 135 fallers (43%) were identified (Table 2). The most commonly reported aetiologies were 'idiopathic' (n=115), followed by 'unknown' (n=38) and 'ototoxicity' (n=34) although three studies[29,32,36] did not report any aetiology (n=71). Regarding diagnostic criteria, only one of the included studies[35] used the Bárány Society Diagnostic Criteria, while the other studies most frequently used combinations of caloric testing with varying cut-offs,[9,11,29,31,32,34,36] video head impulse testing[9,29,32,33] and rotary chair testing.[29,30,36] Full details of the criteria used can be found in Supplementary Table 1.

Insert Table 2

Details on how fall assessments were performed in the included studies can be found in Table 3. A total of five studies[29,32-35] reported a definition of a fall the same or similar to that of a fall as proposed by Lamb, et al.[28] (Recommendation 1, Table 1). For the second recommendation, only two studies[34,35] explicitly reported the way participants were asked about fall status, both were in line with the recommendation.

All studies defined a specific timeframe ranging from the previous 4 weeks,[30] to the previous 6 months,[9,31,36] 12 months,[11,32-35] up until the onset of the disease.[29] Only two studies[33,34] performed a prospective fall assessment using monthly fall diaries, with one study[33] using telephone interviews to collect missing data (Recommendation 3). Neither of the two prospective studies used telephone interviews or face-to-face interviews to collect further details on falls and injuries. The remaining studies retrospectively collected fall-related data through questionnaires or interviews. Concerning Recommendation 4, only four studies[9,33-35] reported the total number of fall episodes ranging from 19[33] to 104 falls.[35] Also, the number of single fallers, twice fallers and multiple fallers were lacking in most of the included studies,[11,29-33,36] and none of the included studies reported the fall rate per person year or time to first fall. Where possible, the fall rate per person years was calculated (Table 2), which ranged between 4.16[34] and 0.87.[35] Lastly, none of the studies adjusted for physical activity, which was in line with Recommendation 5.

Insert Table 3

Four studies investigated the causes and locations of the falls, as well as any injuries because of the fall.[29,33-35] One study[9] investigated causes and locations. Two studies[11,32] only investigated the injuries sustained from the fall. The remaining studies[30,31,36] did not report whether they collected additional details of the fall episodes. Specific details on fall episodes can be found in Table 4. Studies investigating the location of falls[9,33-35] reported a total of 87 fall episodes in an indoor setting, such as at home or in a public building, versus 73 falls in an outdoor setting such as the garden or public space. Causes were mostly attributed to a loss of balance,[34,35] darkness,[9,33] or uneven ground.[9,33] Most of the injuries sustained by the subjects were limited to bruises, cuts or scrapes,[34,35] while injuries needing medical attention, such as fractures, or rendering the subject unable to work, were limited.[29,34,35]

Insert Table 4

Discussion

The purpose of this narrative review was to provide an overview of current knowledge on the incidence and circumstances of falls in BVP, to determine the gaps in knowledge and the drawbacks of current methods to obtain this information within the BVP population. Overall, ten studies reporting falls incidence in people with BVP (two prospective[33,34] and eight retrospective[9,11,29-32,35,36]) were considered in this review, with a total of 317 participants with BVP (28 of which from the prospective studies). In this sample, 43% of people experienced a fall over the assessed time period, with loss of balance, darkness and uneven ground being the most common perceived causes in the four studies that assessed these outcomes.[29,33-35] Information on injuries was limited, the most common being bruises and scrapes. Four fractures (two rib and two hip) were also reported. The limited number of severe injuries due to falls may appear positive but people with vestibular disorders are known to reduce social and physical activity participation,[37,38] thereby reducing their exposure to risky situations. In the future, it would be important to evaluate physical activity in relation to falls and fall related injury.

Only two studies that reported prospective falls incidence data were found, and these had small samples of participants with BVP (28 in total).[33,34] Prospective falls monitoring is considered the gold standard method for obtaining reliable information related to falls due to, among other issues, difficulty in recalling falls and their consequences, especially if not severe.[28,39] Lamb, et al.[28] introduced consensus-driven recommendations for research on falls and related to the methods to obtain falls information, these included using a standard definition of a fall, collecting falls data prospectively with daily recording (i.e., diary or calendar) and monthly reporting (a monthly questionnaire) with additional telephone or face-to-face interviews to complete missing data and obtain further details of falls and injuries. While the two prospective studies included in this review used the standard definition and daily diaries and monthly questionnaires in accordance with these guidelines, neither study mentioned telephone or face-to-face interviews to obtain additional information. Most of the included studies reported the number of fallers and non-fallers within their samples. However, the majority did not report the number of falls or the fall rate per person year (where the required information was available in the articles, we have calculated this and included it in the results). In addition to the recommendations for obtaining information on falls, Lamb, et al.[28] also recommend reporting these outcome measures as standard. Similarly, they provide guidelines for the standardised reporting of injury data. The lack of application of best practice in obtaining falls data may be because no studies used falls as their primary outcome or tested the effects of an intervention on falls, with most studies including falls as a secondary, descriptive outcome measure. In summary, in order to obtain a more extensive and reliable picture of falls incidence, cause and injuries in BVP, larger, prospective studies following the recommendations of Lamb, et al.[28] are needed. Three articles were identified, but not included in our results, that presented relevant information on falls incidence but combined data from patients with unilateral vestibulopathy with data from patients with BVP.[40-42] As the prognosis of the two categories of vestibulopathy are quite different, the information cannot necessarily be combined and used to draw conclusions specific to BVP, as was the goal of this review. These studies reported that 74%, 41% and 55% of included participants had experienced at least one fall in the last 12, 6 and 12 months, respectively. Six-month prospective monitoring in Schniepp, et al.[42] also found that 36% of 69 patients fell at least once over a six-month period. We strongly recommend that future research provide as much disease-specific data as possible and avoid presenting data for combined groups. A related matter to note is that only one of the included studies[35] used the Bárány Society Diagnostic Criteria. This may be attributed to the fact that many of the included studies collected data prior to the publication of these criteria. As it is not known how slight differences in diagnostic criteria might impact balance and fall risk, this results in a less precise picture of falls in BVP.

Four articles reported some information about the participants' perceived causes and locations of falls.[29,33-35] The most common causes were loss of balance, darkness and uneven ground. These common causes represent a different profile than that seen in healthy adults, for whom trips and slips are frequently reported to be the most common causes.[27,43-49] The locations of falls were roughly evenly split between inside and outside locations with two studies reporting a high proportion of falls on stairs, whereas one study did not find stairs to be particularly common.[34] Based on this limited data, the only general recommendation that can be made currently is that adequate lighting in the homes of people with BVP should be confirmed. Other home modifications to reduce fall risk like those for the general older adult population may also be worth considering,[50,51] but have not yet been evaluated in the BVP population. In addition to the causes mentioned above that imply a pathological vestibular-ocular reflex and/or visual dependence as a contributing factor to falls in BVP, a number of potential physiological mechanisms may also be considered in future research, including attention deficits,[52] increased walking variability[9,34] and altered stability control during steady state[53] and perturbed walking[7] which may contribute to increased risk of stability loss and decreased ability to recover stability, once lost.

Regarding other potential interventions to reduce falls in BVP, no study was identified with falls as a primary outcome. Exercise, physical therapy and vestibular rehabilitation interventions have generally not been very successful in BVP.[54-56] Emerging technical therapeutic interventions using vibrotactile feedback and noisy galvanic vestibular stimulation may hold some promise.[57-59] Recent advances in the vestibular implant in humans are promising, with partial or complete restoration of various vestibular reflexes and functions having already been demonstrated (for further details, see: Perez Fornos, et al.,[60] Guinand, et al.,[61] McCrum, et al.,[62] Perez Fornos, et al.,[63] van de Berg, et al.,[64] Chow, et al.,[65]). However, the evaluation of the effectiveness of such interventions, in particular in relation to falls and improving patients' mobility in daily life, requires more investigation.

Conclusions

Falls are more common and have different causes in people with BVP compared to the healthy population but remain a relatively understudied consequence of the disease. To better guide improvements in fall risk assessment and interventions in BVP, larger prospective studies following best practice recommendations[28] for obtaining and reporting falls data are required.

Acknowledgements

This work was supported by the Young European Research Universities (YERUN) Research Mobility Awards (2020) obtained by NH and by the NUTRIM Graduate Programme Grant awarded to CM. The authors thank Prof. dr. Vincent Van Rompaey, Prof. dr. Ann Hallemans, Dr. Kenneth Meijer, Dr. Angélica Pérez Fornos, Dr. Nils Guinand and Florence Lucieer, MD for their feedback on an earlier version of the manuscript.

References

1. WHO, Ageing WHO, Unit LC. *WHO global report on falls prevention in older age.* World Health Organization;2008. 9241563532.
2. James SL, Lucchesi LR, Bisignano C, et al. The global burden of falls: global, regional and national estimates of morbidity and mortality from the Global Burden of Disease Study 2017. *Inj Prev.* 2020;26(Supp 1):i3-i11.
3. Cao C, Cade WT, Li S, et al. Association of Balance Function With All-Cause and Cause-Specific Mortality Among US Adults. *JAMA Otolaryngol Head Neck Surg.* 2021;147(5):460-468.
4. Marchetti GF, Whitney SL, Blatt PJ, Morris LO, Vance JM. Temporal and spatial characteristics of gait during performance of the Dynamic Gait Index in people with and people without balance or vestibular disorders. *Phys Ther.* 2008;88(5):640-651.
5. Sevilla-Garcia MA, Boleas-Aguirre MS, Perez-Fernandez N. The limits of stability in patients with Meniere's disease. *Acta Otolaryngol.* 2009;129(3):281-288.
6. Peterka RJ, Statler KD, Wrisley DM, Horak FB. Postural compensation for unilateral vestibular loss. *Front Neurol.* 2011;2:57.
7. McCrum C, Eysel-Gosepath K, Epro G, et al. Deficient recovery response and adaptive feedback potential in dynamic gait stability in unilateral peripheral vestibular disorder patients. *Physiol Rep.* 2014;2(12):e12222.
8. Eysel-Gosepath K, McCrum C, Epro G, Bruggemann GP, Karamanidis K. Visual and proprioceptive contributions to postural control of upright stance in unilateral vestibulopathy. *Somatosens Mot Res.* 2016;33(2):72-78.
9. Schniepp R, Schlick C, Schenkel F, et al. Clinical and neurophysiological risk factors for falls in patients with bilateral vestibulopathy. *J Neurol.* 2017;264(2):277-283.
10. Herssens N, Verbecque E, McCrum C, et al. A Systematic Review on Balance Performance in Patients With Bilateral Vestibulopathy. *Phys Ther.* 2020;100(9):1582-1594.
11. Ward BK, Agrawal Y, Hoffman HJ, Carey JP, Della Santina CC. Prevalence and impact of bilateral vestibular hypofunction: results from the 2008 US National Health Interview Survey. *JAMA Otolaryngol Head Neck Surg.* 2013;139(8):803-810.
12. Hain TC, Cherchi M, Yacovino DA. Bilateral vestibular loss. *Semin Neurol.* 2013;33(3):195-203.
13. Lucieer F, Vonk P, Guinand N, et al. Bilateral Vestibular Hypofunction: Insights in Etiologies, Clinical Subtypes, and Diagnostics. *Front Neurol.* 2016;7:26.
14. Sun DQ, Ward BK, Semenov YR, Carey JP, Della Santina CC. Bilateral Vestibular Deficiency: Quality of Life and Economic Implications. *JAMA Otolaryngol Head Neck Surg.* 2014;140(6):527-534.
15. Jen JC. Bilateral vestibulopathy: clinical, diagnostic, and genetic considerations. *Semin Neurol.* 2009;29(5):528-533.
16. van de Berg R, van Tilburg M, Kingma H. Bilateral Vestibular Hypofunction: Challenges in Establishing the Diagnosis in Adults. *ORL J Otorhinolaryngol Relat Spec.* 2015;77(4):197-218.
17. Gillespie MB, Minor LB. Prognosis in bilateral vestibular hypofunction. *Laryngoscope.* 1999;109(1):35-41.
18. Calder JH, Jacobson GP. Acquired bilateral peripheral vestibular system impairment: rehabilitative options and potential outcomes. *J Am Acad Audiol.* 2000;11(9):514-521.
19. Janssen M, Stokroos R, Aarts J, van Lummel R, Kingma H. Salient and placebo vibrotactile feedback are equally effective in reducing sway in bilateral vestibular loss patients. *Gait Posture.* 2010;31(2):213-217.
20. Suarez H, Sotta G, San Roman C, et al. Postural response characterization in elderly patients with bilateral vestibular hypofunction. *Acta Otolaryngol.* 2013;133(4):361-367.
21. Wenzel A, Ward BK, Schubert MC, et al. Patients with vestibular loss, tullio phenomenon, and pressure-induced nystagmus: vestibular atelectasis? *Otol Neurotol.* 2014;35(5):866-872.
22. Lucieer F, Duijn S, Van Rompaey V, et al. Full Spectrum of Reported Symptoms of Bilateral Vestibulopathy Needs Further Investigation—A Systematic Review. *Front Neurol.* 2018;9:352-352.
23. Guinand N, Boselie F, Guyot JP, Kingma H. Quality of life of patients with bilateral vestibulopathy. *Ann Otol Rhinol Laryngol.* 2012;121(7):471-477.
24. Fell D, Fell DW, Lunnen KY, Rauk R. *Lifespan Neurorehabilitation: A Patient-Centered Approach from Examination to Interventions and Outcomes.* F.A. Davis Company; 2018.

25. Strupp M, Kim JS, Murofushi T, et al. Bilateral vestibulopathy: Diagnostic criteria Consensus document of the Classification Committee of the Barany Society. *J Vestib Res.* 2017;27(4):177-189.
26. Herssens N. *LOSING THE SENSE OF BALANCE - Gait Stability in Healthy Adults and Patients with Bilateral Vestibulopathy* 2020. doi: 10.13140/RG.2.2.33546.08647
27. McCrum C. *A Trip to Remember: Assessing and Improving Walking Stability in Older Adults*. Gildeprint Drukkerijen, Maastricht University; 2019. doi: 10.26481/dis.20191219cm
28. Lamb SE, Jorstad-Stein EC, Hauer K, et al. Development of a common outcome data set for fall injury prevention trials: the Prevention of Falls Network Europe consensus. *J Am Geriatr Soc.* 2005;53(9):1618-1622.
29. Herdman SJ, Blatt P, Schubert MC, Tusa RJ. Falls in patients with vestibular deficits. *Am J Otol.* 2000;21(6):847-851.
30. Brown KE, Whitney SL, Wrisley DM, Furman JM. Physical therapy outcomes for persons with bilateral vestibular loss. *Laryngoscope.* 2001;111(10):1812-1817.
31. Karapolat H, Celebisoy N, Kirazli Y, et al. Is vestibular rehabilitation as effective in bilateral vestibular dysfunction as in unilateral vestibular dysfunction? *Eur J Phys Rehabil Med.* 2014;50(6):657-663.
32. Schlick C, Schniepp R, Loidl V, et al. Falls and fear of falling in vertigo and balance disorders: A controlled cross-sectional study. *J Vestib Res.* 2016;25(5-6):241-251.
33. Swanenburg J, Zurbrugg A, Straumann D, et al. A pilot study investigating the association between chronic bilateral vestibulopathy and components of a clinical functional assessment tool. *Physiother Theory Pract.* 2017;33(6):454-461.
34. McCrum C, Lucieer F, van de Berg R, et al. The walking speed-dependency of gait variability in bilateral vestibulopathy and its association with clinical tests of vestibular function. *Sci Rep.* 2019;9(1):18392.
35. Dobbels B, Lucieer F, Mertens G, et al. Prospective cohort study on the predictors of fall risk in 119 patients with bilateral vestibulopathy. *PLoS One.* 2020;15(3):e0228768.
36. Grove CR, Whitney SL, Pyle GM, Heiderscheit BC. Instrumented Gait Analysis to Identify Persistent Deficits in Gait Stability in Adults With Chronic Vestibular Loss. *JAMA Otolaryngol Head Neck Surg.* 2021. doi:10.1001/jamaoto.2021.1276. Accessed Jul 1.
37. Alghwiri A, Alghadir A, Whitney SL. The vestibular activities and participation measure and vestibular disorders. *J Vestib Res.* 2013;23(6):305-312.
38. Alshebber KM, Dunlap PM, Whitney SL. Reliability and Concurrent Validity of Life Space Assessment in Individuals With Vestibular Disorders. *J Neurol Phys Ther.* 2020;44(3):214-219.
39. Ganz DA, Higashi T, Rubenstein LZ. Monitoring falls in cohort studies of community-dwelling older people: effect of the recall interval. *J Am Geriatr Soc.* 2005;53(12):2190-2194.
40. Sankarpandi SK, Baldwin AJ, Ray J, Mazza C. Reliability of inertial sensors in the assessment of patients with vestibular disorders: a feasibility study. *BMC Ear Nose Throat Disord.* 2017;17(1):1.
41. Grill E, Heuberger M, Strobl R, et al. Prevalence, Determinants, and Consequences of Vestibular Hypofunction. Results From the KORA-FF4 Survey. *Front Neurol.* 2018;9:1076.
42. Schniepp R, Huppert A, Decker J, et al. Fall prediction in neurological gait disorders: differential contributions from clinical assessment, gait analysis, and daily-life mobility monitoring. *J Neurol.* 2021. doi:10.1007/s00415-021-10504-x. Accessed Mar 13.
43. Sheldon JH. On the Natural History of Falls in Old Age. *Br Med J.* 1960;2(5214):1685-1690.
44. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med.* 1988;319(26):1701-1707.
45. Lord SR, Ward JA, Williams P, Anstey KJ. An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study. *Aust J Public Health.* 1993;17(3):240-245.
46. Berg WP, Alessio HM, Mills EM, Tong C. Circumstances and consequences of falls in independent community-dwelling older adults. *Age Ageing.* 1997;26(4):261-268.
47. Niino N, Tsuzuku S, Ando F, Shimokata H. Frequencies and circumstances of falls in the National Institute for Longevity Sciences, Longitudinal Study of Aging (NILS-LSA). *J Epidemiol.* 2000;10(1 Suppl):S90-94.
48. Talbot LA, Musiol RJ, Witham EK, Metter EJ. Falls in young, middle-aged and older community dwelling adults: perceived cause, environmental factors and injury. *BMC Public Health.* 2005;5:86.

49. Crenshaw JR, Bernhardt KA, Achenbach SJ, et al. The circumstances, orientations, and impact locations of falls in community-dwelling older women. *Arch Gerontol Geriatr.* 2017;73:240-247.
50. Pynoos J, Steinman BA, Nguyen AQD, Bressette M. Assessing and Adapting the Home Environment to Reduce Falls and Meet the Changing Capacity of Older Adults. *J Hous Elderly.* 2012;26(1-3):137-155.
51. Keall MD, Pierse N, Howden-Chapman P, et al. Home modifications to reduce injuries from falls in the home injury prevention intervention (HIPI) study: a cluster-randomised controlled trial. *Lancet.* 2015;385(9964):231-238.
52. Dobbels B, Mertens G, Gilles A, et al. Cognitive Function in Acquired Bilateral Vestibulopathy: A Cross-Sectional Study on Cognition, Hearing, and Vestibular Loss. *Front Neurosci.* 2019;13:340.
53. Herssens N, Saeys W, Vereeck L, et al. An exploratory investigation on spatiotemporal parameters, margins of stability, and their interaction in bilateral vestibulopathy. *Sci Rep.* 2021;11(1):6427. doi:10.1038/s41598-021-85870-7. Accessed Mar 19.
54. Herdman SJ, Hall CD, Schubert MC, Das VE, Tusa RJ. Recovery of dynamic visual acuity in bilateral vestibular hypofunction. *Arch Otolaryngol Head Neck Surg.* 2007;133(4):383-389.
55. Porciuncula F, Johnson CC, Glickman LB. The effect of vestibular rehabilitation on adults with bilateral vestibular hypofunction: a systematic review. *J Vestib Res.* 2012;22(5-6):283-298.
56. Herdman SJ, Hall CD, Maloney B, et al. Variables associated with outcome in patients with bilateral vestibular hypofunction: Preliminary study. *J Vestib Res.* 2015;25(3-4):185-194.
57. Wuehr M, Decker J, Schniepp R. Noisy galvanic vestibular stimulation: an emerging treatment option for bilateral vestibulopathy. *J Neurol.* 2017;264(Suppl 1):81-86.
58. Herssens N, McCrum C. Stimulating balance: recent advances in vestibular stimulation for balance and gait. *J Neurophysiol.* 2019;122(2):447-450.
59. Kingma H, Felipe L, Gerards MC, et al. Vibrotactile feedback improves balance and mobility in patients with severe bilateral vestibular loss. *J Neurol.* 2019;266(Suppl 1):19-26.
60. Perez Fornos A, Guinand N, van de Berg R, et al. Artificial balance: restoration of the vestibulo-ocular reflex in humans with a prototype vestibular neuroprosthesis. *Front Neurol.* 2014;5:66.
61. Guinand N, van de Berg R, Cavuscens S, et al. Vestibular Implants: 8 Years of Experience with Electrical Stimulation of the Vestibular Nerve in 11 Patients with Bilateral Vestibular Loss. *ORL J Otorhinolaryngol Relat Spec.* 2015;77(4):227-240.
62. McCrum C, Willems P, van de Berg R, et al. Preliminary observations of the acute effects of vestibular nerve stimulation on stride length and time in two patients with bilateral vestibular hypofunction. *Gait Posture.* 2016;49(Supp 2):124.
63. Perez Fornos A, Cavuscens S, Ranieri M, et al. The vestibular implant: A probe in orbit around the human balance system. *J Vestib Res.* 2017;27(1):51-61.
64. van de Berg R, Guinand N, Ranieri M, et al. The Vestibular Implant Input Interacts with Residual Natural Function. *Front Neurol.* 2017;8:644.
65. Chow MR, Ayiotis AI, Schoo DP, et al. Posture, Gait, Quality of Life, and Hearing with a Vestibular Implant. *N Engl J Med.* 2021;384(6):521-532.

Tables

Table 1. Recommendations to assess daily life falls as proposed by the 'Prevention of Falls Network Europe' (ProFaNe)[28]

1.	A fall should be defined as ''an unexpected event in which the participants come to rest on the ground, floor, or lower level.''
2.	Ascertainment must consider the lay perspective of falls. Participants should be asked, ''In the past month, have you had any fall including a slip or trip in which you lost your balance and landed on the floor or ground or lower level?''
3.	Falls should be recorded using prospective daily recording and a notification system with a minimum of monthly reporting. Telephone or face-to-face interviews should be used to rectify missing data and to ascertain further details of falls and injuries.
4.	Fall data should be summarized as number of falls, number of fallers/non-fallers/frequent fallers, fall rate per person year, and time to first fall (as a safety measure).
5.	Primary analysis of fall data should not be adjusted for physical activity, and reporting should include the absolute risk difference between groups.

Table 2. Characteristics of the included study populations

	Origin	# Subjects	# Women	Age (years) – Mean	Age (years) – SD	Time Since Onset (months) - Mean	Time Since Onset (months) - SD	# Non-fallers	# Fallers	Single fall (n)	Two falls (n)	Multiple falls (n)	Fall episodes (n)	Fall rate (falls per person years) [&]
Prospective studies														
McCrum, et al.[34](2019)[$]	Netherlands	10	5	57.3	8.1			4	6	2	0	4	40	4.16
Swanenburg, et al.[33] (2017)	Switzerland	18	6	61.11	15.19			10	8				19	1.06
Retrospective studies														
Brown, et al.[30] (2001)	US	13	7	65	18	13.6	20.3	7	6					
Dobbels, et al.[35] (2020)	Belgium	119	55	59.4	12.5	148.8	135.6	71	45	8/69[‡]	8/69[‡]	14/69[‡]	104	1.51[‡]
Grove, et al.[36] (2021)	US	5	3	58.65	9.39			4	1					
Herdman, et al.[29] (2000)	US	45	27	63.2	13.7			22	23			*		
Karapolat, et al.[31] (2014)	Turkey	19	13	56.95	11.36	44.68	72.66	12	7					
Schlick, et al.[32] (2016)	Germany	21	7	62.8	16.4	90.3	98.2	11	10					
Schniepp, et al.[9] (2017)	Germany	55	20	74	12	31	29	34	21	13	0	8	32	1.16
Ward, et al.[11] (2013)	US	12	11					4	8					

Notes. $: Data concerning falls were not reported within the published manuscript but was obtained via the corresponding author (CM) – questionnaires for one month were not returned for 3 participants ; ‡: Data from Dobbels, et al.[35] (2020) represents a subset of the whole population included within the study.; &: Fall rate calculated as: total # falls / total years assessed; *: a percentage of multiple fallers is reported in the paper, but the percentage does not correspond to other patient numbers in the article. Since the source of the error could not be determined, the value has been excluded.

Table 3. Details on fall assessments

	Assessment Characteristics			Fall-related Data Collected		
	Fall definition	*Assessment method*	*Time Period*	*Cause*	*Location*	*Injuries*
Prospective studies						
McCrum, et al.[34](2019)[$]	"In the past year, have you had any fall including a slip or trip in which you lost your balance and landed on the floor or ground or lower level?"	Diary & Questionnaire	Fixed Timeframe - Following 12 months	x	x	x
Swanenburg, et al.[33] (2017)	"An unexpected event in which the participant comes to rest on the ground, floor, or lower level."	Diary & Questionnaire	Fixed Timeframe - Following 12 months	x	x	x
Retrospective studies						
Brown, et al.[30] (2001)	Not stated	Interview	Fixed Timeframe - Previous 4 weeks			
Dobbels, et al.[35] (2020)	"Have you fallen in the past year due to slipping or tripping, losing balance thereby ending on the floor or another lower level?"	Questionnaire	Fixed Timeframe - Previous 12 months	x	x	x
Grove, et al.[36] (2021)	Not stated	Not stated	Fixed Timeframe - Previous 6 months			
Herdman, et al.[29] (2000)	"A loss of balance in which the person ended up on the floor"	Interview	Since disease onset	x	x	x
Karapolat, et al.[31] (2014)	Not stated	Interview	Fixed Timeframe - Previous 6 months			
Schlick, et al.[32] (2016)	"An unexpected event in which the participant comes to rest on the ground, floor, or lower level"	Questionnaire	Fixed Timeframe - Previous 12 months			x
Schniepp, et al.[9] (2017)	Not stated	Interview	Fixed Timeframe - Previous 6 months	x	x	
Ward, et al.[11] (2013)	Not stated	Questionnaire	Fixed Timeframe Previous 12 months			x

Notes. $: Data concerning falls were not reported within the published manuscript but was obtained via the corresponding author (CM);

Table 4. Specific details on fall episodes.

	Location of falls	Cause of falls	Injuries related to falls
Prospective studies			
McCrum, et al.[34] (2019)[$]	A total of 18 fall episodes were inside the house (i.e., flat surface: n=10, on a staircase: n=6, getting out of bed: n=1, shower/bath: n=1); 7 occurred outside at home (step/stairs: n=1, on a path: n=3, in the garden: n=3); and 9 outdoor away from home (footpath: n=4, getting out of a vehicle: n=3, public building: n=1, on the beach: n=1)	Most falls were attributed to losing balance (n=20), followed by tripping (n=3) or feeling dizzy (n=3)	A total of 13 falls that led to injuries were reported which included 10 instances of bruises, 5 of cuts or grazes and 1 hip fracture.
Swanenburg, et al.[33] (2017)	A total of 19 falls were recorded, of which 10 occurred outside, and 9 inside a building. Nearly half of the fall episodes (n=8) were related to stair negotiation where 6 fall episodes occurred at the last steps when descending the stairs	Sixteen falls were related to lightning conditions: 3 in the morning, 8 at noon and 5 in the afternoon. Five falls were related to head turns during standing (n=2) or running (n=3).	*Inquired, but no information reported.*
Retrospective studies			
Brown, et al.[30] (2001)			
Dobbels, et al.[35] (2020)	A total of 46 fall episodes were inside the house (i.e., stairs: n=11, flat surface: n=11, shower/bath: n=8, chair: n=8, toilet: n=3); 40 in the garden; and 18 away from home (someone else's house: n=5, public building: n=6, car: n=2, gutter: n=5).	Most falls were due to loss of balance (n=23), followed by tripping (n=8), slipping (n=7), or dizziness (n=7).	A total of 33 fall related injuries were reported: bruises: n=17, scrapes: n=8, backache: n=5, rib fracture: n=2; hip fracture: n=1.
Grove, et al.[36] (2021)			
Herdman, et al.[29] (2000)	*Inquired, but no information reported.*[&]	*Inquired, but no information reported.*[&]	None of the injuries related to falls needed medical attention.
Karapolat, et al.[31] (2014)			
Schlick, et al.[32] (2016)			A total of 2 fall episodes required medical attention.

Schniepp, et al.[9] (2017)	Only two fall events took place during ambulation at home.	A total of 28 out of 32 (88%) reported falls were related to darkness or uneven ground.	
Ward, et al.[11] (2013)			Three subjects reported a fall related injury, one subject missed 3 months of work due to bodily injury.

Notes. $: Data concerning falls were not reported within the published manuscript but was obtained via the corresponding author (CM); &. Herdman, et al.[28] (2000) state that “data concerning the circumstances in which the falls occur were incomplete as many patients were not clear as to why they had fallen.”

Online-Only Supplement to:

Falls among people with bilateral vestibulopathy: a narrative review of causes, incidence, injuries and methodology

Nolan Herssens, PhD[1,2], Daniella How, MSc[3], Raymond van de Berg, MD, PhD[4,5], Christopher McCrum, PhD[6]*

[1] Space Medicine Team (HRE-OM), European Astronaut Centre, European Space Agency, Cologne, Germany

[2] Department of Rehabilitation Sciences and Physiotherapy/MOVANT, Faculty of Medicine and Health Sciences, University of Antwerp, Wilrijk, Belgium

[3] Institute of Sport and Exercise Sciences, Münster University, Münster, Germany

[4] Division of Balance Disorders, Department of Otorhinolaryngology and Head and Neck Surgery, Faculty of Health Medicine and Life Sciences, School for Mental Health and Neuroscience, Maastricht University Medical Centre+, Maastricht, The Netherlands

[5] Faculty of Physics, Tomsk State University, Tomsk, Russia

[6] Department of Nutrition and Movement Sciences, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre+, Maastricht, The Netherlands

*Correspondence:

Christopher McCrum

Department of Nutrition and Movement Sciences

Maastricht University,

PO Box 616, Maastricht, 6200 MD, The Netherlands

chris.mccrum@maastrichtuniversity.nl

Contents

eTable 1: Diagnostic Criteria

	Bárány Society Diagnostic Criteria			**Diagnostic Criteria – Other Tests and Cut-Offs**							
	vHIT (Gain <0.6)	*Calorics (SPV <6°/s)*	*Rotatory Chair (Gain <0.1)*	*(v)HIT*	*Cut-Off*	*Calorics*	*Cut-Off*	*Rotatory Chair*	*Cut-Off*	*ENG*	*Other*
<u>Prospective studies</u>											
McCrum, et al.[34](2019)	No	No	No			x	SPV <20°/s				
Swanenburg, et al.[33] (2017)	No	No	No	x	Gain <0.7						
<u>Retrospective studies</u>											
Brown, et al.[30] (2001)	No	No	No					x		x	A moderate or severe loss of vestibular function as rated by a neurologist based on the patient's vestibular function tests (ENG, rotational chair, ocular motor, and positional testing). The rating scale for each ear was as follows: 0 = absent, 1 = severe, 2 = moderate, 3 = mild, and 4 = normal vestibular function. Patients with scores of 2.5 or lower for each ear were included in the analysis.
Dobbels, et al.[35] (2020)	Yes	Yes	Yes								
Grove, et al.[36] (2021)	No	No	No			x	Warm irrigation SPV ≤10°/s, cold irrigation SPV ≤5°/s and total of all four ≤30°/s	x	Abnormally low gain for at least two adjacent frequencies (e.g. 0.01-0.02 Hz) of the slow harmonic acceleration test		
Herdman, et al.[29] (2000)	No	No	No	x		x	<5°/s SPV	x	Gain <0.2		For the head thrust test, the patient’s head was first pitched forward ~30°, and the patient was

									asked to fixate on a stationary target. The patient's head was moved through a small amplitude, first slowly and then rapidly, in the yaw plane. The direction of the rapid head impulses was randomized in order to be unpredictable. Patients were tested on both a near and a far target with appropriate visual correction. When the head thrust resulted in a corrective saccade to refixate on the target, the test result was considered positive for the side of the head thrust (indicating vestibular hypofunction).
Karapolat, et al.[31] (2014)	No	No	No			x (air)	SPV in warm and cold irrigation <12°/s	x	
Schlick, et al.[32] (2016)	No	No	No	x	bilaterally pathological	x	SPV <5°/s in all four tests		
Schniepp, et al.[9] (2017)	No	No	No	x	bilaterally pathological	x	Sum of SPV during warm and cold irrigation <10°/s		
Ward, et al.[11] (2013)	No	No	No			x	SPV <5°/s bilaterally		