Derleme
Review

Investigation of the effects of Age-Related Changes in the vestibular system on balance: A Review

VESTİBÜLER SİSTEMDE YAŞA BAĞLI DEĞİŞİKLİKLERİN DENGE ÜZERİNE ETKİLERİNİN ARAŞTIRILMASI: BİR DERLEME

Aygül KÖSEOĞLU KURT[1], **Mehmet Kaan ALTUNOK**[1], **Mustafa Oğuz KETHÜDAOĞLU**[1], **Suzan AYDIN**[1], **Havva Ezgi ALBAYRAK**[1], **Hande Besna GÖÇEN**[1], **Bülent Abut ÖZSEZİKLİ**[1,2]

[1]Bahçeşehir Üniversitesi Lisansüstü Eğitim Enstitüsü Fizyoterapi ve Rehabilitasyon Doktora Programı, İstanbul, Türkiye
[2]Bahçeşehir Üniversitesi Lisansüstü Eğitim Enstitüsü Fizyoterapi ve Rehabilitasyon Anabilim Dalı, İstanbul, Türkiye.

Abstract

The vestibular system (VS) undertakes vital tasks for the survival of the individual by perceiving the movement of the head according to gravity and adjusting on balance, autonomic function, spatial perception, and orientation. In addition to being the first system to develop in the intrauterine period, the VS continues to develop with childhood. Although the onset time varies depending on various factors, it is known that VS degenerates with aging. It has also been shown in the literature that the number of sensory vestibular hair cells decreases by approximately 6% per decade from birth to old age. In addition, neurons in the vestibular nuclei are known to decrease by about 3% per decade between the ages of 40 and 90. These age-related changes in VS may cause dizziness, loss of balance, unsteady gait, increased falls and even agitation, loneliness, and loss of self-confidence in elderly individuals. In addition, it is reported in the literature that falls due to vestibular disorder are among the third to tenth leading causes of death among older adults. In this sense, it is very important to determine age-related VS dysfunctions in the healthy aging action plans of the health systems of the countries and in the development of strategies to prevent age-related falls. At the same time, it is very valuable for physiotherapists working in the field of geriatric rehabilitation to know well the age-related changes of VS and its effects on balance in the creation of possible vestibular rehabilitation programs. We think that virtual reality applications applied in addition to vestibular rehabilitation for vestibular disorders are promising, especially hearing problems in the elderly population should not be overlooked and hearing aids should be prescribed if needed.

Keywords: Balance, geriatric rehabilitation, vestibular dysfunction, vestibular rehabilitation.

Ayşegül KÖSEOĞLU KURT
Bahçeşehir Üniversitesi Lisansüstü Eğitim Enstitüsü Fizyoterapi ve Rehabilitasyon Doktora Programı, İstanbul, Türkiye
E-posta:aygulkoseoglu@gmail.com
orcid.org/ 0000-0001-7180-3693

DEU Tıp Derg 2023;37(3):309-321
J DEU Med 2023;37(3):309-321
doi:10.18614/deu.tip1330102

Gönderim tarihi/Submitted: 21.07.2023
Kabul tarihi/Accepted: 19.12.2023

ÖZ

Vestibüler sistem (VS), başın yer çekimine göre hareketini algılayıp denge, otonomik fonksiyon, uzaysal algı ve oryantasyon üzerine düzenlemeler yaparak bireyin hayatta kalabilmesi için hayati görevler üstlenir. VS'nin intraüterin dönemde gelişmeye başlayan ilk sistem olmasının yanı sıra çocukluk dönemiyle birlikte gelişimine devam etmektedir. Başlangıç zamanı çeşitli faktörlere bağlı olarak değişmekle birlikte yaşlanmayla VS dejenere olduğu bilinmektedir. Literatürde duyusal vestibüler tüylü hücre sayısının doğumdan yaşlılığa her on yılda yaklaşık %6 oranında azaldığı da gösterilmiştir. Bunun yanı sıra vestibüler çekirdeklerdeki nöronlar, 40 ila 90 yaşları arasında her on yılda yaklaşık %3 oranında azaldığı da bilinmektedir. VS'deki yaşa bağlı bu değişiklikler yaşlı bireylerde baş dönmesi, denge kaybı, dengesiz yürüme, artan düşmeler ve hatta ajitasyona, yalnızlık ve özgüven kayıplarına neden olabilmektedir. Bunun yanı sıra literatürde vestibüler bozukluğa bağlı düşmelerin yaşlı yetişkinler arasında ölüm sebepleri arasında üçüncü ila onuncu önde gelen ölüm nedeni arasında olduğu da bildirilmektedir. Bu anlamda ülkelerin sağlık sistemlerinin sağlıklı yaşlanma eylem planlamalarında ve yaşa bağlı düşmeleri engelleyici stratejilerin geliştirilmesinde yaşa bağlı VS disfonksiyonlarının belirlenmesi oldukça önemlidir. Aynı zamanda özellikle geriatrik rehabilitasyon alanında çalışan fizyoterapistlerin muhtemel vestibüler rehabilitasyon programlarının oluşturulmasında VS'nin yaşa bağlı değişimlerini ve denge üzerine olan etkilerini iyi bilmeleri oldukça değerlidir. Vestibüler bozukluklar için vestibüler rehabilitasyona ek olarak uygulanan sanal gerçeklik uygulamalarının ümit vadettiği, yaşlı popülasyonda özellikle işitme problemlerinin gözden kaçırılmaması ve ihtiyaç halinde işitme cihazlarının reçete edilmesi gerektiğini düşünmekteyiz.

Anahtar Kelimeler: Denge, geriatrik rehabilitasyon, vestibüler disfonksiyon, vestibüler rehabilitasyon.

The sense of balance uses sensory info from vision, touch, proprioception, and vestibular input to influence motor neurons and their associated spinal-level motor output (1). The proprioceptive and vestibular system (VS) coordination is particularly important for keeping movements, body posture, and balance. The incidence of vestibular dysfunction (VD) increases with age, which can cause falls, agitation, loneliness, fear of falling, and lack of self-confidence in the elderly population. At the same time, VD is accepted as an important differential diagnosis that causes clinically unexpected falls (2-4). While VD is at the level of 35% in adults over 40 years of age (5), it is reported to be between 29 and 45% in individuals over 70 years of age (6). One-third of adults who report loss of balance also report having symptoms of dizziness (7). It is stated in the literature that falls due to vestibular disorders are among the 3rd to 10th leading causes of death among older adults (8). Age-related falls are among the most important problems of elderly populations (over 65 years of age). It is thought that the increase in fall frequency and fall-related injuries in elderly individuals will increase costs to approximately 65 billion dollars by 2035 in the United States (9). In this sense, it is very important to develop strategies to prevent age-related falls in the health systems of countries. Physiotherapists working with geriatric rehabilitation should be well aware of the age-related changes of VS, which plays an important role in balance, and its effects on balance, in order to develop possible prevention strategies, and it will be valuable in the development of treatment approach and fall prevention action plans.

Vestibular System

The VS has five sensory epithelium made up of hairy cells surrounded by supporting cells (10), a sensory organ located in the inner ear that attends critical functions vital to survival (11, 12). Aristotle's core classification of the five senses does not include VS as one of them. With the exploration of the vestibular organ in the mid-19th century, it was found that the VS contributes sensory info to the brain about the movement and position of the head. For this reason, it has been defined as the sixth sense in the literature (13). The literature indicates that the development of the vestibular apparatus occurs during the 49th day in the womb, while the neural connections between the labyrinths and the oculomotor nuclei in the brain stem take place between the 12th and 24th weeks of pregnancy. During intrauterine life, the vestibular nerve attains myelination before any other cranial nerve, and the vestibular system becomes operational in the 8th and 9th months of development (14). It is the first sensory system to enlarge in humans, and although it has completed its morphological development at birth, it continues its developmental maturation. It helps the child's ability to develop balance, control and movement by making his developmental maturation most evident in the pre-school period (15).

Hair cells in its structure are specialized to convert mechanical energy into electrical energy. Hair cells in the vestibular sensory epithelium are responsible for sensing head rotations (causing endolymph fluid flow in the semicircular canals) and head tilt or linear head movements (causing the movement of the otoconia in otolith organs), and is an important system include in keeping the balance and orientation of the person in space (16).

In general terms, VS, which is responsible for both sensory and motor functions, uses the brain to control eye movement in mammals; it coordinates spatial orientation and balance by sending signals to the muscles to allow the body to maintain a vertical position. It also activates a number of reflex pathways responsible for regulatory movements in order to compensate for the position of the body. Vestibulo-ocular (VOR) reflex, which is one of the fastest reflex mechanisms of the human body in establishing and maintaining quality locomotor function, belongs to VS reflexes. Thanks to the VOR, the visual environment is stabilized during movement (17). People with vestibular disorders often experience dizziness due to blurring or marked oscillation of the visual world, as the eyes cannot compensate for head movements quickly enough with the VOR (18). Another important reflex of the VS is the vestibulo-spinal reflex (VSR). The VSR plays important role in supporting the vertical position of the body to the ground during dynamic movement (13). Vestibular inputs also drive vestibulo-spinal responses that provide postural control (19). Vestibular damage causes loss of balance due to poor postural stabilization during changes in head position and orientation, which can lead to falls (20). Furthermore, the vestibular system triggers vestibulo-autonomic responses, indicating that the vestibular signal regarding head position is also utilized for maintaining homeostasis in various processes like blood pressure, respiratory rate, and gastrointestinal activity when undergoing positional changes (19, 21). In addition to providing inputs to these important brainstem reflexes, the VS also sends information about head orientation and movement to projections to subcortical and cortical structures used for higher-order cognitive operations such as spatial memory and navigation. Consequently, individuals with vestibular disorders may experience spatial disorientation and a decline in spatial memory and navigation skills (22). When the literature is examined, it is seen that vestibular losses are used as vestibular dysfunction, vestibular hypofunction, or vestibular disorder.

Vestibular losses occur with age and are manifested by decreased vestibular function in healthy older adults. Within the clinical context, balance issues frequently observed among older adults manifest as dizziness, impaired balance, an unsteady gait, and an elevated risk of falling (23-25). Although both peripheral and central vestibular disorders are a common cause of these signs; other sensory problems such as vision, somatosensory, and hearing; neuromotor and musculoskeletal problems such as arthritis and weakness; cognitive problems such as attentional control (26); sensory integration (26,27); motor coordination/planning disorders; psychological disorders such as fear of falling (28, 29) may also pave the way for balance-related disorders. In addition, common pathological effects of some systemic conditions, such as vascular disease and diabetes, whose prevalence increases with age, such as cerebral hypoperfusion - orthostatic hypotension, sensory loss - peripheral neuropathy, may also affect balance control (30). These risk factors can potentially influence the impact of vestibular disorders on balance control in older individuals, or they may interact with vestibular impairments to result in a distinct balance phenotype.

Primary changes in cellular size in peripheral VS with aging are associated with loss of neurons and hair cells in both the otolith and semicircular canals. Rauch et al. (2001) showed hair cell loss in 67 temporal bone samples from 49 individuals aged 1-100 years. They also showed a firm and statistically substantial decrease with age, consistent with the linear regression model over time (31). Although the evidence in the literature is not unanimous, some studies indicate age-related reductions in vestibular cell populations, both peripheral (e.g., hair cells) and central (e.g., vestibular afferent nerve, brain stem vestibular nucleus neurons) (32-34). In addition, age-related changes in clinical vestibular function in the literature vary according to the type of tests used for evaluation, making the evidence suspicious (35, 36).

Wan et al. (2019) showed that synaptic loss may be an early and significant subscriber to the vestibular loss associated with aging (37). Given that hair cells and neurons are not regenerated in humans, it is believed that these losses are irreversible or permanent. In addition to this view, Tighilet et al. (2019) in their study on rats suggested that under certain conditions, strong synaptic plasticity can occur in the vestibular sensory organs, and this reactive plasticity can gradually restore peripheral sensory input, which may contribute to the repair of damaged contacts between hair cells and vestibular nerve fibers (38). If this process can be demonstrated in humans, a broad range of therapeutic approaches for pharmacological interventions could be demonstrated in the future.

Nevertheless, further research is required to investigate the cellular and molecular mechanisms that underlie the spontaneous peripheral repair process. In addition, it is also known that these developments will be critical in the light of emerging therapies that specifically target the VS, such as vestibular hair cell regeneration and prosthetic electrical vestibular stimulation. It should be noted, however, that an individual's balance problem is at least partially due to vestibular disorder rather than other co-existing disorders, but in such a case, balance function can be developed following vestibular therapy.

Daniel et al. (2019) conducted a retrospective cohort study of 76 elderly participants, aged 66-99 years (mean 80.5 years), who had a history of loss of balance, dizziness, and falls due to loss of balance, who completed vestibular rehabilitation treatment, using computerized instruments to objectively determine the degree of adaptive improvement in balance control. They used a dynamic posturography. Results revealed a 42.1% improvement ($p < .0001$) in balance function with a mean post-treatment composite sensory organization score of 74.2. The data confirm that vestibular therapy programs can significantly improve balance loss, if not restore it to a normal level by the age of 99 (39).

Balance or postural control is an intricate process that arises from the dynamic interplay between the particular tasks related to posture, the individuals' physiological system functioning, and the surrounding environment. Different postural goals are conducted by different central and peripheral nervous system networks and can be divided into three types: (i) steady-state posture (40, 41); (ii) reactive postural responses to unexpected, external postural disturbances (41-43) ; and (iii) proactive postural control (44). The sensory, motor, cognitive, psychological, and cardiovascular health of an aging individual forms the basis for how the individual performs postural tasks in each setting. The brain plays a crucial role in integrating diverse sensorimotor cues for balance control. Numerous studies have suggested that the integration of multiple sensory inputs, such as visual and somatosensory inputs, is a significant predictor of balance function and the likelihood of experiencing falls (45, 46). In addition, cognitive load, environmental and emotional conditions involve the balance control of the individual (47-49). One of the most important abilities of the body in daily life is the ability to stand upright against gravity dynamically and statically, both at rest and on the go. This skill is very important in the physical and social participation of the person in life. Elderly individuals generally prefer to restrict physical activity, travel, and social interactions to avoid or minimize the symptoms and possible consequences of balance and/or VS disorders (50, 51). Therefore, rehabilitation of VS disorders will play an important role in returning the person to activities of daily living.

The Effect of Vestibular Rehabilitation Modifications on Balance in the Elderly

With vestibular rehabilitation, it is aimed to increase gaze stability and postural stability, thereby improving vertigo, activities of daily living (52), and psychological factors such as anxiety, depression, fear of moving and fear of falling (53). According to the Current Clinical Practice Guideline published by the American Academy of Physical Therapy Neurological Physical Therapy in 2022 (54), vestibular rehabilitation applied to individuals with peripheral vestibular hypofunction; It should be recommended to individuals with vestibular disorders, regardless of age, gender, duration of illness (acute - chronic). However, abnormal cognitive function, comorbidities such as depression, anxiety, and drugs that suppress VS may adversely affect the rehabilitation process. It is important for individuals with both bilateral and unilateral vestibular hypofunction to begin rehabilitation as soon as possible. According to this guideline, the rehabilitation program should consist of targeted exercise techniques, gaze fixation exercises, vibrotactile exercise programs, progressive static-dynamic balance and gait exercises, and should be administered in a supervised manner in individuals with cognitive impairment (54).

As new technologies continue to advance in the field of rehabilitation and their usage becomes more widespread, many researchers are investigating the effectiveness of virtual reality applications in both assessment and rehabilitation. Virtual reality is defined as technology that combines computer graphics to create a realistic world, responds to the user's verbal and non-verbal responses, and can change the virtual world (55). Virtual reality technology reflects interactive simulations of the real world created by computers and presented to users through various virtual environments and allows users to feel present in these environments (56). According to research, the use of virtual reality in vestibular rehabilitation is becoming more widespread day by day (57, 58) .

In a study, it was reported that 36% of 70-year-old geriatric females and 29% of males suffer from dizziness, and this figure rises to 50% in advanced ages (59) . Therefore, new research in this area is gaining more and more importance. In a systematic literature review, it was stated that the efficacy of virtual reality use only with a head-mounted screen in individuals over 65 years of age in improving balance and gait is uncertain, but there is great potential here (60). In a randomized controlled trial comparing vestibular rehabilitation with the use of virtual reality in addition to vestibular rehabilitation in individuals with unilateral vestibular disorders, it was found that, at the end of a four-week program, significant improvements in dizziness and balance confidence were demonstrated in addition to VOR and postural control (61) . In a study conducted on individuals with and without cognitive impairment, it was stated that virtual reality use can be safely used to improve VOR, postural control, and quality of life even with cognitive impairment (62) . In another study examining the effectuality of a hybrid virtual reality-based vestibular rehabilitation program, virtual reality application was compared with static posturography education with visual feedback. When the results were examined, no difference was found between the two groups, but the reduction in symptoms was found to be greater in the virtual reality program (63) . A summary of the mentioned studies is given in Table 1. In a different study, lavender oil scent was added to virtual reality use in individuals with multiple sclerosis, and positive results were found in balance and fear of falling compared to the virtual reality group that did not smell lavender (64) . According to these studies, it seems that greater effects can be obtained with virtual reality experiences added to vestibular rehabilitation.

Table 1. Summary table of studies referenced in the review about vestibular rehabilitation

Study	Participants	Intervention Group(s)	Comparison Group(s)	Outcomes	Results
Deems et al. (2019) (39) retrospective cohort study	Age: 66-99 years (mean 80.5 years) Total n = 76 (35 women, 41 men)	The study group performed vestibular therapy (repetitive balance exercises) on average 2 times per week for 7 weeks.	X	1. Computerized dynamic posturography (CDP) 2. Sensory organization test (SOT) 3. Timed up and go test 4. Functional gait assessment 5. The four square-step test of dynamic balance	Balance function, measured by composite sensory organization test CDP scores, improved on average by 35% (P < .0001). Results revealed an improvement in balance function of 42.1% (P < .0001), with an average posttherapy SOT score of 74.2.
Micarelli et al. (2017) (61) randomized controlled pilot trial	Age: 39-60 years (mean 50,1 years) Total n = 47 (20 women, 27 men) Intervention group (IG) = 39-60 years (mean 49.72 years), n =23 (9 women, 14 men) Comparison group (CG) = 41-60 years (mean 50.48 years), n = 24 (11 women, 13 men)	The IG performed a head-mounted device (HMD) --based gaming procedure when combined with a classical vestibular rehabilitation and underwent a 4-week rehabilitation protocol.	The CG performed only a vestibular rehabilitation program and underwent a 4-week rehabilitation protocol.	1. VOR gain and postural arrangement. 2. Italian Dizziness Handicap Inventory 3. Activities Specific Balance Confidence scale 4. Zung Instrument for Anxiety Disorders 5. Dynamic Gait Index 6. Simulator Sickness Questionnaire	The findings indicated notable enhancements in the CG, with significant improvements observed in areas such as VOR gain on the impacted side, parameters related to postural stability, low-frequency body oscillations, and scores on both the Italian Dizziness Handicap Inventory and Activities-specific Balance Confidence scale (P < .0001).IG reported fewer symptoms associated with the gaming tasks, as evidenced by decreased scores on the Simulator Sickness Questionnaire (P < .0001).
Micarelli et al. (2019) (62)	Age: 69-82 years (mean 75 years) Total n = 47 (26 women, 21 men) Group 1: IG without mild cognitive impairment (MCI)= 72-80 years (mean 76.9 years), n	The IGs underwent vestibular rehabilitation with virtual reliability (HMD). They	The CGs underwent only vestibular rehabilitation. They followed in the clinic twice a week for 4 weeks for 30–45 min. Between	1. VOR gain and postural arrangement.	Despite all groups showing a significant improvement ($p < 0.05$) in posturography parameters, dizziness-related symptoms, and quality of life scores through within-subjects analysis, the HMD

the local longitudinal cohort study	= 11 (6 women, 5 men) Group 2: IG with MCI = 70-81 years (mean 76.3 years), n= 12 (7 women, 5 men) Group 3: CG without MCI = 69-79 years (mean 74.3 years), n =12 (6 women, 6 men) Group 4: CG with MCI =69-76 years (mean 72.5 years), n=12 (7 women, 5 men)	followed in the clinic twice a week for 4 weeks for 30–45 min. Between supervised sessions, patients did a twice-daily home exercise plan for 30–40 minutes/day.	supervised sessions, patients did a twice-daily home exercise plan for 30–40 minutes/day.	2. The Italian Dizziness Handicap Inventory 3. The Activities-specific Balance Confidence scale 4. The Dynamic Gait Index	implementation led to a notable increase ($p < 0.05$) in post-treatment improvements when compared to older adults and participants with MCI who solely underwent vestibular rehabilitation.
Rosiak et al. (2018) (63) A prospective, non-randomized, controlled group	Age: 26-68 years (mean 45 years) Total n = 50 (27 women, 23 men) IG = 26-64 years (mean 46.48 years), n = 25 (14 women, 11 men) CG = 29-68 years (mean 45.20 years) n = 25 (13 women, 12 men)	The IG received ten training sessions lasting 30 minutes for two weeks using a hybrid virtual reliability unit. Also, the group was instructed by physiotherapists on how to perform Cawthorne-Cooksey exercises at home and were asked to exercise three times daily.	The CG received a total of ten sessions of static. posturography training with visual feedback over a two-week period under the supervision of a physiotherapist. The duration of each session was, on average, 25 minutes. Also, the group was instructed by physiotherapists on how to perform Cawthorne-Cooksey exercises at home and were asked to exercise three times daily.	1. The posturographic assessment on a static platform 2. Vertigo Symptom Scale – Short Form (VSS-SF) questionnaire	Both groups showed statistically significant improvements in posturographic parameters. However, there were no significant differences when comparing the results between the two groups. Both groups reported statistically significant improvements in their subjective perception of symptoms on the VSS-SF scale, with the IG showing greater improvement.

n:number; CDP: computerized dynamic posturography; SOT: Sensory organization test; IG: İntervention group; CG:comparison group; HMD: head-mounted device; VOR: Vestibulo-ocular reflex; MCI: without mild cognitive impairment; VSS-SF: Vertigo Symptom Scale – Short Form

Elderly individuals with hearing loss are at greater risk of falling than individuals without (65, 66). The ear, which is responsible for sending information about hearing and balance to the brain via the hippocampus, is also responsible for the vestibular sensation of the acceleration of rotation or translation of the head, in addition to the reception of acoustic stimuli. Therefore, dizziness and loss of balance may also be seen in the elderly with hearing problems (67). In a study comparing children with normal vestibular function without hearing impairment, children with normal vestibular function with hearing impairment, and children with hearing impairment with vestibular dysfunction, significant differences were found in balance and motor performance. While deaf children with vestibular dysfunction showed the worst balance and motor performance, children with normal vestibular function with hearing impairment showed significantly better results than this group. However, this difference was found to be greater in the group with normal hearing and normal vestibular function. The results of this study therefore show that hearing problems added to vestibular disorders result in greater motor losses (68). Therefore, in addition to vestibular rehabilitation to reduce the risk of motor losses and falls in the elderly with hearing impairment; considering that hearing aids should be used to improve postural stability and static balance (69), dual-task training should be provided (65), and considering that hearing problems in the elderly may result in cognitive impairment (70), and this impairment may adversely affect rehabilitation, cognitive rehabilitation may be beneficial.

Conclusion and Suggestions

Many of the elderly population suffer in some way from adverse changes in their vestibular function. Prevention of falls and loss of balance caused by vestibular disorder, regaining the social activity of this population, and making it more independent in daily living activities can only be achieved with vestibular rehabilitation. In addition, countries need to develop their health policies in this sense. With prevention strategies, problems can be prevented before they occur, and health system costs can thus be reduced. More research is needed in the field of vestibular rehabilitation. Studies on hearing-impaired individuals and visually impaired individuals may help to better understand the vestibular system. However, we think that there is a need for innovative studies in the fields of perturbation, virtual reality, and augmented reality.

REFERENCES

1. Sturnieks DL, St George R, Lord SR. Balance disorders in the elderly. Neurophysiologie Clinique/Clinical Neurophysiology. 2008;38(6):467-78.

2. Kristinsdottir EK, Jarnlo GB, Magnusson M. Asymmetric vestibular function in the elderly might be a significant contributor to hip fractures. Scandinavian journal of rehabilitation medicine. 2000;32(2):56-60.

3. Oghalai JS, Manolidis S, Barth JL, Stewart MG, Jenkins HA. Unrecognized benign paroxysmal positional vertigo in elderly patients. Otolaryngology--head and neck surgery: official journal of American Academy of Otolaryngology-Head and Neck Surgery. 2000;122(5):630-4.

4. Pothula VB, Chew F, Lesser TH, Sharma AK. Falls and vestibular impairment. Clinical otolaryngology and allied sciences. 2004;29(2):179-82.

5. Agrawal Y, Carey JP, Della Santina CC, Schubert MC, Minor LB. Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001-2004. Arch Intern Med. 2009;169(10):938-44.

6. Agrawal Y, Carey JP, Della Santina CC, Schubert MC, Minor LB. Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001-2004. Archives of internal medicine. 2009;169(10):938-44.

7. Lin HW, Bhattacharyya N. Balance disorders in the elderly: epidemiology and functional impact. The Laryngoscope. 2012;122(8):1858-61.

8. Bermúdez Rey MC, Clark TK, Wang W, Leeder T, Bian Y, Merfeld DM. Vestibular perceptual thresholds increase above the age of 40. Frontiers in neurology. 2016;7:162.

9. Fattal D, Hansen M, Fritzsch B. Aging-related balance impairment and hearing loss. The Wiley handbook on the aging mind and brain. 2018:315-36.

10. Lewis ER, Leverenz EL, Bialek WS. Vertebrate inner ear: CRC-Press; 1985.

11. Majeed S, Farooqi S, Jamshed A. Vestibular Disorders and Their Impact on Balance and Mobility. Pakistan Journal of Medical & Health Sciences. 2023;17(03):686-.

12. Wolfe J, KLUENDER K, LEVI D, BARTOSHUK L, HERZ R, KLATZKY R, et al. Sensation and Perception (Sunderland, MA: Sinauer). 2006.

13. Goldberg JM, Wilson VJ, Cullen KE, Angelaki DE, Broussard DM, Buttner-Ennever J, et al. The vestibular system: a sixth sense: Oxford University Press, USA; 2012.

14. Nandi R, Luxon LM. Development and assessment of the vestibular system. Int J Audiol. 2008;47(9):566-77.

15. Ornitz EM, Atwell CW, Walter DO, Hartmann EE, Kaplan AR. The maturation of vestibular nystagmus in infancy and childhood. Acta Oto-Laryngologica. 1979;88(1-6):244-56.

16. Jones SM, Jones TA, Mills KN, Gaines GC. Anatomical and Physiological Considerations in Vestibular Dysfunction and Compensation. Seminars in hearing. 2009;30(4):231-41.

17. Tian J-R, Shubayev I, Baloh RW, Demer JL. Impairments in the initial horizontal vestibulo-ocular reflex of older humans. Experimental brain research. 2001;137:309-22.

18. Minor LB. Gentamicin-induced bilateral vestibular hypofunction. Jama. 1998;279(7):541-4.

19. McCall AA, Miller DM, Yates BJ. Descending influences on vestibulospinal and vestibulosympathetic reflexes. Frontiers in neurology. 2017;8:112.

20. Murray AJ, Croce K, Belton T, Akay T, Jessell TM. Balance control mediated by vestibular circuits directing limb extension or antagonist muscle co-activation. Cell reports. 2018;22(5):1325-38.

21. Mohl JT, Pearson JM, Groh JM. Monkeys and humans implement causal inference to simultaneously localize auditory and visual stimuli. Journal of Neurophysiology. 2020;124(3):715-27.

22. Agrawal Y, Smith PF, Rosenberg PB. Vestibular impairment, cognitive decline and Alzheimer's disease: balancing the evidence. Aging & mental health. 2020;24(5):705-8.

23. Gassmann KG, Rupprecht R. Dizziness in an older community dwelling population: a multifactorial syndrome. The journal of nutrition, health & aging. 2009;13(3):278-82.

24. Barin K, Dodson EE. Dizziness in the elderly. Otolaryngologic clinics of North America. 2011;44(2):437-54, x.

25. Boult C, Murphy J, Sloane P, Mor V, Drone C. The relation of dizziness to functional decline. Journal of the American Geriatrics Society. 1991;39(9):858-61.

26. Redfern MS, Jennings JR, Martin C, Furman JM. Attention influences sensory integration for postural control in older adults. Gait & posture. 2001;14(3):211-6.

27. Westlake KP, Culham EG. Sensory-Specific Balance Training in Older Adults: Effect on Proprioceptive Reintegration and Cognitive Demands. Physical therapy. 2007;87(10):1274-83.

28. Adkin AL, Frank JS, Carpenter MG, Peysar GW. Fear of falling modifies anticipatory postural control. Experimental brain research. 2002;143(2):160-70.

29. Hadjistavropoulos T, Carleton RN, Delbaere K, Barden J, Zwakhalen S, Fitzgerald B, et al. The relationship of fear of falling and balance confidence with balance and dual tasking performance. Psychology and aging. 2012;27(1):1-13.

30. Wetmore SJ, Eibling DE, Goebel JA, Gottshall KR, Hoffer ME, Magnusson M, et al. Challenges and opportunities in managing the dizzy older adult. Otolaryngology--Head and Neck Surgery. 2011;144(5):651-6.

31. Rauch SD, VELAZQUEZ-VILLASEÑOR L, Dimitri PS, Merchant SN. Decreasing hair cell counts in aging humans. Annals of the New York Academy of Sciences. 2001;942(1):220-7.

32. Alvarez JC, Díaz C, Suárez C, Fernández JA, González del Rey C, Navarro A, et al. Aging and the human vestibular nuclei: morphometric analysis. Mechanisms of ageing and development. 2000;114(3):149-72.

33. Kevetter GA, Leonard RB. Decreased expression of calretinin and calbindin in the labyrinth of old gerbils. Brain research. 2002;957(2):362-5.

34. Taylor RR, Jagger DJ, Saeed SR, Axon P, Donnelly N, Tysome J, et al. Characterizing human vestibular sensory epithelia for experimental studies: new hair bundles on old tissue and implications for therapeutic interventions in ageing. Neurobiology of aging. 2015;36(6):2068-84.

35. Maes L, Dhooge I, D'Haenens W, Bockstael A, Keppler H, Philips B, et al. The effect of age on the sinusoidal harmonic acceleration test, pseudorandom rotation test, velocity step test, caloric test, and vestibular-evoked myogenic potential test. Ear and hearing. 2010;31(1):84-94.

36. Agrawal Y, Zuniga MG, Davalos-Bichara M, Schubert MC, Walston JD, Hughes J, et al. Decline in semicircular canal and otolith function with age. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2012;33(5):832-9.

37. Wan G, Ji L, Schrepfer T, Gong S, Wang GP, Corfas G. Synaptopathy as a Mechanism for Age-Related Vestibular Dysfunction in Mice. Frontiers in aging neuroscience. 2019;11:156.

38. Tighilet B, Bordiga P, Cassel R, Chabbert C. Peripheral vestibular plasticity vs central compensation: evidence and questions. Journal of neurology. 2019;266:27-32.

39. Deems DA, Deems RO, O'Malley Jr BW. Managing challenges in an aging vestibular system: Rehabilitation strategies normalize balance function in a cohort of patients up to 99 years. Ear, Nose & Throat Journal. 2019;98(1):37-43.

40. Mancini M, Salarian A, Carlson-Kuhta P, Zampieri C, King L, Chiari L, et al. ISway: a sensitive, valid and reliable measure of postural control. Journal of neuroengineering and rehabilitation. 2012;9:59.

41. MacKinnon CD. Sensorimotor anatomy of gait, balance, and falls. Handbook of clinical neurology. 2018;159:3-26.

42. Horak FB. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age and ageing. 2006;35 Suppl 2:ii7-ii11.

43. Westlake KP, Johnson BP, Creath RA, Neff RM, Rogers MW. Influence of non-spatial working memory demands on reach-grasp responses to loss of balance: Effects of age and fall risk. Gait & posture. 2016;45:51-5.

44. Horak FB, Wrisley DM, Frank J. The Balance Evaluation Systems Test (BESTest) to differentiate balance deficits. Physical therapy. 2009;89(5):484-98.

45. Mahoney JR, Cotton K, Verghese J. Multisensory Integration Predicts Balance and Falls in Older Adults. The journals of gerontology Series A, Biological sciences and medical sciences. 2019;74(9):1429-35.

46. Mahoney JR, Verghese J. Does Cognitive Impairment Influence Visual-Somatosensory Integration and Mobility in Older Adults? The journals of gerontology Series A, Biological sciences and medical sciences. 2020;75(3):581-8.

47. Patel P, Lamar M, Bhatt T. Effect of type of cognitive task and walking speed on cognitive-motor interference during dual-task walking. Neuroscience. 2014;260:140-8.

48. Woytowicz EJ, Sours C, Gullapalli RP, Rosenberg J, Westlake KP. Modulation of working memory load distinguishes individuals with and without balance impairments following mild traumatic brain injury. Brain injury. 2018;32(2):191-9.

49. Furman JM, Redfern MS, Jacob RG. Vestibulo-ocular function in anxiety disorders. Journal of vestibular research : equilibrium & orientation. 2006;16(4-5):209-15.

50. Han BI, Song HS, Kim JS. Vestibular rehabilitation therapy: review of indications, mechanisms, and key exercises. Journal of clinical neurology (Seoul, Korea). 2011;7(4):184-96.

51. Tinetti ME, Williams CS, Gill TM. Health, functional, and psychological outcomes among older persons with chronic dizziness. Journal of the American Geriatrics Society. 2000;48(4):417-21.

52. Han BI, Han BI. Vestibular Rehabilitation Therapy: Review of Indications, Mechanisms, and Key Exercises. Simplified Vestibular Rehabilitation Therapy. 2021:1-16.

53. Whitney SL, Sparto PJ, Furman JM, editors. Vestibular rehabilitation and factors that can affect outcome. Seminars in neurology; 2020: Thieme Medical Publishers.

54. Hall CD, Herdman SJ, Whitney SL, Anson ER, Carender WJ, Hoppes CW, et al. Vestibular rehabilitation for peripheral vestibular hypofunction: an updated clinical practice guideline from the Academy of Neurologic Physical Therapy of the American Physical Therapy Association. Journal of Neurologic Physical Therapy. 2022;46(2):118.

55. Valentina M, Ana Š, Valentina M, Martina Š, Željka K, Mateja Z. Virtual reality in rehabilitation and therapy. Acta Clinica Croatica. 2013;52(4.):453-7.

56. Bergeron M, Lortie CL, Guitton MJ. Use of virtual reality tools for vestibular disorders rehabilitation: a comprehensive analysis. Advances in medicine. 2015;2015.

57. Viziano A, Micarelli A, Augimeri I, Micarelli D, Alessandrini M. Long-term effects of vestibular rehabilitation and head-mounted gaming task procedure in unilateral vestibular hypofunction: a 12-month follow-up of a randomized controlled trial. Clinical rehabilitation. 2019;33(1):24-33.

58. Park JH, Jeon HJ, Lim E-C, Koo J-W, Lee H-J, Kim H-J, et al. Feasibility of eye tracking assisted vestibular rehabilitation strategy using immersive virtual reality. Clinical and experimental otorhinolaryngology. 2019;12(4):376-84.

59. Jönsson R, Sixt E, Landahl S, Rosenhall U. Prevalence of dizziness and vertigo in an urban elderly population. Journal of vestibular research. 2004;14(1):47-52.

60. Delgado F, Der Ananian C. The use of virtual reality through head-mounted display on balance and gait in older adults: A scoping review. Games for Health Journal. 2021;10(1):2-12.

61. Micarelli A, Viziano A, Augimeri I, Micarelli D, Alessandrini M. Three-dimensional head-mounted gaming task procedure maximizes effects of vestibular rehabilitation in unilateral vestibular hypofunction: a randomized controlled pilot trial. International Journal of Rehabilitation Research. 2017;40(4):325-32.

62. Micarelli A, Viziano A, Micarelli B, Augimeri I, Alessandrini M. Vestibular rehabilitation in older adults with and without mild cognitive impairment: Effects of virtual reality using a head-mounted display. Archives of gerontology and geriatrics. 2019;83:246-56.

63. Rosiak O, Krajewski K, Woszczak M, Jozefowicz-Korczynska M. Evaluation of the effectiveness of a Virtual Reality-based exercise program for Unilateral Peripheral Vestibular Deficit. Journal of Vestibular Research. 2018;28(5-6):409-15.

64. Seddighi-Khavidak M, Tahan N, Akbarzadeh-Baghban A. Comparing the effects of vestibular rehabilitation with and without lavender oil scents as an olfactory stimulus on balance, fear of falling down and activities of daily living of people with multiple sclerosis: a randomized clinical trial. Disability and rehabilitation. 2022;44(13):3132-8.

65. Wollesen B, Scrivener K, Soles K, Billy Y, Leung A, Martin F, et al. Dual-task walking performance in older persons with hearing impairment: Implications for interventions from a preliminary observational study. Ear and hearing. 2018;39(2):337-43.

66. Gabriel GA, Harris LR, Gnanasegaram JJ, Cushing SL, Gordon KA, Haycock BC, et al. Vestibular perceptual thresholds in older adults with and without age-related hearing loss. Ear and hearing. 2022;43(2):420-35.

67. Alfakir R. Studying subjective hearing loss in older adults measured by speech, spatial, and quality of hearing scale within the framework of the ICF core set for hearing loss. Hearing, Balance and Communication. 2022;20(4):230-9.

68. Maes L, De Kegel A, Van Waelvelde H, Dhooge I. Association between vestibular function and motor performance in hearing-impaired children. Otology & Neurotology. 2014;35(10):e343-e7.

69 .Negahban H, Nassadj G. Effect of hearing aids on static balance function in elderly with hearing loss. Gait & posture. 2017;58:126-9.

70. Wei J, Hu Y, Zhang L, Hao Q, Yang R, Lu H, et al. Hearing impairment, mild cognitive impairment, and dementia: a meta-analysis of cohort studies. Dementia and geriatric cognitive disorders extra. 2018;7(3):440-52.