Clinical balance tests for evaluation of balance dysfunction in children with sensorineural hearing loss

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Aim

Children with hearing impairment may have a potential risk for vestibular dysfunctions. They may undergo a sensory redistribution process whereby visual and somatosensory information becomes more essential for postural control. The aim of the study was to assess the balance ability in children with sensorineural hearing loss (SNHL) compared with normal-hearing controls using clinical balance subset tests. A second aim was to determine the prognostic value of some etiological, audiological, and demographic (age and sex) factors in predicting a possibility for vestibular impairment for the early identification of children with vestibular deficits.

Participants and methods

Thirty children with normal hearing (17 girls and 13 boys) and 50 children with bilateral SNHL of varying degree, aged between 5 and 15 years, were recruited from the Audiology Unit of Assiut University Hospital. All of them were subjected to the following: basic audiological evaluation (pure tone, speech audiometry), immittancemetry and auditory brainstem responses, clinical balance subset tests of the standardized Bruininks-Oseretsky Test of motor proficiency (BOT-2), modified Clinical Test of Sensory Interaction for Balance (mCTSIB), one-leg stand (OLS), and tandem stand.

Results

Hearing-impaired (HI) children showed bilateral SNHL of varying degree, ranging from moderate to profound hearing loss (moderately–severe 32%, severe 18%, and profound 50%) and of different etiologies (heredofamilial 46%, acquired 38%, not known 16%).

Balance abilities as measured in this study were significantly poorer in HI children compared with normal-hearing children. HI children with acquired cause and profound degree of SNHL had the highest abnormal score in these clinical tests compared children with other etiologies and degrees of SNHL (although this difference did not reach statistical significance).

In most clinical balance tests that were done in this study, the youngest children in the HI group achieved scores that were almost lower than the scores obtained by the older age groups; the most significant difference was observed for tests performed with eyes closed.

Conclusion

Balance dysfunction occurs in a significant percentage of HI children and may have significant detrimental effects on motor development mainly in very young children. Therefore, information on the identification and treatment of these balance dysfunctions is crucial.

Keywords:
balance dysfunction, prognostic factors, sensorineural hearing loss

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Introduction

Disturbances in cochlear function, which can result in sensorineural hearing loss (SNHL), could accompany vestibular impairment because the cochlea and the vestibule share the continuous membranous labyrinth of the inner ear. Therefore, injury or trauma prenatally, perinatally, or postnatally may cause damage to one or both systems [1–3]. As damage to vestibular structures is known to cause balance deficit, which may interfere with normal motor development, it has been postulated as the primary cause of motor deficit [4,5]. Balance control is a fundamental prerequisite for motor development in children [6].

Newborns are screened for auditory capability before discharge from the hospital. As a result, congenital and early-onset SNHL in children is usually well managed and most parents are prepared for the choices at hand for communication purposes during this most important period of development [7]. Early intervention programs allow HI children approach with their normal-hearing (NH) peers with respect to speech, language skills, cognitive and social development, and academic performance. Those who are identified late often never reach the same level of skill. The critical period of postural control development is between 4 and 6 years of age; hence, intervention addressing the motor deficits in this population should be initiated before this age [8,9].

Teachers and parents of these children often report coordination difficulties, clumsiness, and balance deficits, which may hinder the child's optimal performance [10]. Moreover, many pediatric healthcare providers are often too busy or inadequately trained to conduct elaborate developmental screening tests during regular clinic visits. There are a variety of reasons why vestibular evaluation is not routinely performed in the pediatric population [11–14], with one reason being the lack of feasible and effective procedures for clinical use. Moreover, in developing countries early detection poses a significant practical challenge.

The labyrinths are known to play a role in postural responses. Therefore, it can be believed that their hypofunction would lead to delays in the acquisition of gross motor milestones. Whereas failure to acquire language skills alerts us to hearing disorders, failure to achieve motor milestones should alert us to potential vestibular dysfunction [15].

Postural or balance control is an essential prerequisite for most daily life activities in children. It is the complex ability to maintain, achieve, or restore a state of balance while a person is stationary, preparing to move, in motion, or preparing to stop moving [16–18]. Afferent input from the visual, vestibular, and proprioceptive systems are integrated and evaluated by central processing systems to generate motor responses that keep the body in balance [19].

Several studies on motor skills in children with hearing impairments have shown deficits in balance, general dynamic coordination, physical fitness, and ball-catching abilities, as well as clear differences in reaction times and speed of movements [20–24]. Another study reported that the onset of hearing impairment (congenital vs. delayed) has an impact on balance and manual skills and overall motor development [25]. Children with hearing impairments, with a potential risk for vestibular dysfunctions, may undergo a sensory redistribution process whereby visual and somatosensory information becomes more essential for postural control, as their vestibular input may be disturbed or even absent [26–28].

In clinical practice, assessment of postural stability typically involves evaluation of functional tasks with balance constraints such as standing on one foot or walking on a balance beam. These tasks are often part of a more general motor test such as Bruininks-Oseretsky Test of motor proficiency (BOT-2) [29]. The balance subset of BOT-2 (Table 1) appears to be particularly well suited to identify vestibular dysfunction in children with SNHL compared with a number of other clinical tests [30]. Several studies agree that deaf individuals display inferior static and dynamic balance compared with NH individuals [31,32].

Table 1 Balance Subtest scores of the Bruininks-Oseretsky Test of motor proficiency

Balance Subtest scores	Raw score maximum	Point score
(1, 2) Standing with feet apart on a line		
Eyes open	10 s	0–4
Eyes closed	10 s	0–4
(3) Walking forward on a line		
Eyes open	6 steps	0–4
(4,5) Standing on one leg on a line		
Eyes open	10 s	0–4
Eyes closed	10 s	0–4
(6) Walking forward heel to toe on a line		
Eyes open	6 steps	0–4
Score for 1–6		0–24
(7,8) Standing on one leg on a balance beam		
Eyes open(imp)	10 s	0–4
Eyes close(imp)	10 s	0–4
(9) Standing heel-to-toe on a balance beam		
Eyes open(imp)	10 s	0–4
Total score (1–9)		0–36

The balance subset of BOT-2 is a simple and cost-effective tool requiring only 10 min to administer; however, one concern is that the minimum age of administration is 4 years. Computerized dynamic posturography is certainly an alternative to BOT-2 and likely provides additional information; however, it is more costly and does not allow the assessment of very young children. BOT-2 has allowed us to accurately identify which children with SNHL suffer from concurrent abnormalities in balance [33].

The modified Clinical Test of Sensory Interaction for Balance (mCTSIB), [34,35] unilateral stance, and tandem stance on a force platform were selected to be able to evaluate sensory and motor strategies under conditions of increasing balance constraints. The duration of one-leg stand (OLS) in most motor assessment tools [29,36,37], is used as a static balance measure and has shown good reliability in a well-designed protocol [6,38]. In a clinical setting, without the opportunity to use posturography, assessment of postural stability typically involves evaluation of functional tasks with balance constraints. The mCTSIB, unilateral stance, and tandem stance were selected to be able to evaluate sensory and motor strategies under conditions of increasing balance constraints [34,35].

The mCTSIB [33,39] allows evaluation of the influence of various sensory conditions on postural sway. By closing the eyes or by standing on a cushion, inaccurate visual and somatosensory input is provided to the central nervous system. A previous study [34] showed moderate reliability for mCTSIB, whereas another study [35] demonstrated excellent reliability for mCTSIB. These motor strategies can be evaluated not only in stance but also under more challenging conditions with a narrow base of support such as OLS or tandem stand.

These tests, one-leg stand with eyes open (OLS EO) and one-leg stand with eyes closed (OLS EC), cannot be relied upon as ideal measures of postural mechanisms. Interpretation of the results of these tests is complicated by the interplay between activity from proprioceptors, cutaneous receptors, activity from the labyrinth, and the optical righting reflex in the case of standing balance with eyes open. Less influence from nonlabyrinthine receptors occurs with standing balance with eyes closed, which eliminates the effects of visual perception. Ayres [40] found that OLS EC loaded more strongly than OLS EO on posturalocular factors [12].

As routine screening in HI children does not include assessment of balance and motor deficits, physical therapy services are not included in the education program, unless obvious neurological or orthopedic disorders are diagnosed [41].

Despite reports that, as a consequence of vestibular deficits, children have poor gaze stability that affects reading [28] and causes impairment of motor development and balance [30,42,43], children are typically not screened or evaluated for vestibular deficits. Consequently, vestibular dysfunction in childhood is an overlooked entity [20], and intervention to ameliorate these impairments is not provided. Hence, we aim to provide a concise description of balance and motor performance in HI children.

Aim of this work

The aim of the study was to evaluate the balance abilities of children as measured in this study using clinical tests such as the balance subset of BOT-2, mCTSIB, OLS, and tandem stand and determine the prognostic value of some etiological, audiological, and demographic(age and sex) factors associated with SNHL in predicting a possibility for balance impairment for very early identification of children with vestibular deficits, thus allowing proper counseling and recommendation for their parents.

Participants and methods

Participants

Control group

The control group comprised 30 children with NH, of whom 17 were girls and 13 were boys.

Study group

The study group comprised 53 children with a bilateral hearing loss of more than 45 dB hearing level (HL) with varying degrees and etiology of hearing impairment (hereditary, acquired, and unknown). Three of them did not complete the battery of tests and hence only 50 children (27 girls and 23 boys) were included. Forty-two children had been fitted with bilateral conventional hearing aids, five with monaural hearing aids, and three children had no hearing aids.

All children were between 5 and 15 years of age and of average intelligence (a score of 80 or higher on a standard Stanford–Binet test of intelligence). They were recruited from the Auditory Department, Assiut Medical University, with bilateral hearing impairment.

Exclusion criteria

Children with neuromotor or orthopedic dysfunctions or who were taking medication affecting the central nervous system were excluded from the study. Informed consent was obtained from the parents of all participants. The study was approved by the Ethics Committee of Assiut Medical University.

Methodology

Each child was submitted for:

(1) Each child was submitted to a careful systematic history-taking procedure with focus on vestibular and hearing complaints and physical otoneurological development.
(2) They also underwent a basic audiological evaluation with an audiogram made available recently for all children with hearing impairment. Behavioral (pure-tone) audiometry, which included air and bone conduction thresholds, speech audiometry, and tympanometry were performed to confirm normal middle ear pressure and mobility before VEMP testing. Auditory brainstem responses was also used when deemed necessary to establish or confirm hearing loss. The examination was carried out in a standard sound-proof room. SNHL was classified according to the degree of hearing loss [44]. A previous study [45] had proposed an etiologic classification that clarifies the interaction between time of insult, cause, and time of expression of hearing loss [46].

Clinical evaluation of vestibular function

The ability to remove and alter sensory inputs such as vision and proprioception allows for the assessment of the relative contributions of different sensory inputs and maintenance of balance in a given patient [47]. A number of clinical maneuvers exist to assess static and dynamic balance ability and sensory organization ability:

(1) The standardized BOT-2.
(2) The mCTSIB.
(3) The OLS test.
(4) The Tandem stand test.

Testing instructions were explained using total communication to ensure understanding of the activities required. Total communication consisted of sign and oral language, as well as demonstration. Instructions were repeated until the child knew what was expected of him or her, as outlined by Long [48]. The investigator initially demonstrated the stance position directly in front of the child and then moved to the child's left side. As verbal clues could not be optimally used, the investigator had to stay within the child's visual field.

The standardized Bruininks-Oseretsky Test of motor proficiency

The balance subset of BOT-2 assesses static and dynamic balance.

A number of balance subtests of the motor proficiency test (BOT-2) [29] contain nine balance-related tasks performed either with eyes open (EO) or with eyes closed (EC) (Table 1).

The following tests comprise the group of balance subtests of BOT-2:

(1, 2) The participant stands with feet apart on a line while looking at a target on the wall and then repeats the exercise with EC. The test is stopped after 10 s.

(3) The participant walks forward on a line drawn on the floor using a normal stride and with both hands on the hips. This test is scored in a maximum of six steps. If the participant places one foot or both feet completely off the line before covering the six steps, the test is stopped and the number of successful steps is recorded (raw score).

(4, 5) The participant stands on his or her preferred foot on a line drawn on the floor while looking at a target on the wall. Both hands are on the hips, and the free (not preferred) leg is flexed at the knee; these steps are then repeated with EC. The raw score is typically the timed duration for which the child maintains the position for a maximum of 10 s.

(6) The participant walks forward on a line on the floor, heel-to-toe. Both hands are on the hips.

In tests 4–5 the trial is stopped after 10 s and the time is recorded. The trial is stopped before 10 s if the participant touches the free leg to the floor, drops the free leg below a 45° angle, hooks the free leg behind the supporting leg, or shifts the supporting foot out of place.

P is incorrect if one foot or both feet are placed completely off the line or beam, the heel of the front foot fails to touch the toe of the rear foot, or the toe of the rear foot is moved forward to touch the heel of the front foot.

The balance subtests of BOT-2 are carried out in a room free from distractions [21].

In this work, children with NH and those with SNHL were assessed only with tests 1–6. Tests 7–9 were not carried out as equipment was not available.

Raw scores were converted to point scores as described in the BOT-2 manual. Point scores are used in BOT-2 to convert raw scores (i.e. seconds vs. steps) to a common set of values. To determine the presence of a balance deficit, the mean point score of each age group was compared with the mean point score of the appropriate normative data from the BOT-2 [33].

Due to lack of equipment it was marked (imp) standing for impossible [49].

The total point score and the participant's age are used to obtain an age-matched scale score based on the scores obtained by NH children on the test (0–36 points) (Table 1). This normal group overlapped with a previously published study [27].

The modified Clinical Test of Sensory Interaction for Balance

General instructions: the participants have to remove their shoes, stand erect without moving, and look straight ahead as long as possible or until the trial is over.

The mCTSIB is performed with the individual's feet placed side by side with ankle bones touching, arms across his/her chest, and hands touching his/her shoulders. The mCTSIB consists of four standing positions: on a firm surface with EO, on a firm surface with EC for 30 s [49], on a foam cushion with eyes open to assess the patient's ability to use input from the somatosensory system to maintain balance (visual aids lacking), and on a foam cushion with eyes closed to assess the patient's ability to use input from the visual system to maintain balance (incorrect somatosensory information). The patient's ability to use input from the vestibular system to maintain balance (other information lacking or incorrect) was also assessed. The same $45 \times 45 \times 18$ cm, high-density, viscoelastic foam cushion was used for the last two conditions.

For the EO trials, the participants were instructed to look at a target placed at eye level in front of the platform. For the EC trials, they were asked to look at the same target before firmly closing their eyes. The safety of the children was ensured by an observer. The timing of the task was stopped when the participant's arms moved from the original position, or when their foot moved, or when they opened their eyes during EC trial.

One-leg stand

The OLS is a frequently used clinical assessment tool for balance to test the integrity of some postural mechanisms. In the present study a standardized protocol was used [38]. The children were instructed to stand on one leg (OLS) as long as possible for a maximum of 10 s for each trial. They were barefoot, had their hands on their hips, and were made to look straight ahead. The child was then instructed to lift the right foot.

Imbalance was defined and the test was discontinued if the child placed the lifted foot on the floor, removed either hand from hips to regain balance, hopped, or moved the weight-bearing foot [50]. The child was allowed one training trial before data collection. The test was then performed twice both with EO and with EC. The interval between trials for both OLS EO and OLS EC was sufficient; the child assumed a stable position with both feet on the ground and hands at his or her sides before attempting a second trial.

Two trials were performed for the left foot and the right foot both with EO (OLS EO) and with EC (OLS EC) (the scores of the two trials were added up and the average was obtained) [38].

Test manuals suggest that the outcomes of these tests (e.g. the length of time the child can SOL) provide information on the child's general 'balance ability' [34,35,51].

Tandem stand

The children were instructed to stand with a heel-to-toe gait and both hands on the hips. A step is incorrect if one foot or both feet are placed completely off the line, the heel of the front foot fails to touch the toe of the rear foot, or if the toe of the rear foot is moved forward to touch the heel of the front foot.

The tandem stand test was performed in two trials of 10 s each. The participants were tested barefoot or wearing soft-soled shoes and were instructed to stand as steady as possible with their arms by their sides. During each trial, the foot position remained the same because the foot position was marked.

The child's balance ability on the mCTSIB, OLS EO, OLS EC, and tandem stand tests was determined to be normal or abnormal by comparison with standardized norms. The results of these tests were broken down according to their different cutoff limits (cutoff limit or the lowest score defined as normal = mean of the number of seconds that the normative sample was able to balance on one leg − 2 SD) into children who showed scores at or above the cutoff limit and thus considered successful in these tests, and children who failed to pass the test if they scored below this cutoff limit.

All test sessions took place in the same quiet room to minimize any noise or other disturbances. At least one break was offered to the children between tests.

Equipment

(1) Dual channel clinical audiometer (Madsen OB 922, GN Otometrics, Cobenhagen, Denmark).
(2) Immitancemeter (impedance audiometer AZ 26, Interacoustics AZ 26, Denmark).
(3) Sound-treated booth (industrial acoustic company IAC model 1602-A-t, USA).
(4) Nicolit Spirit equipment (USA) for electrophysiological testing (auditory brainstem responses).
(5) Four-channel electronystagmograph (ENG version Micromedical ENG device, version 8.1 R, USA) for the electronystagmography test.
(6) Navigator Pro evoked potential system manufactured by Bio-Logic (Mundelein, Illinois, USA) for the VEMP test.

Statistical analysis

Data collected were analyzed using computer program SPSS 'version 17' (SPSS Inc, Chicago, Illinois, USA) and expressed as mean ± SD. The *t*-test was used to determine significance for quantitative variables and the χ^2-test to determine significance for qualitative variables. The Pearson correlation test was used for the numeric variables in the same group and the analysis of variance test for numeric values with other qualitative variables.

P values greater than 0.05 were considered nonsignificant, *P* values less than 0.05 were considered significant, and *P* values less than 0.001 were considered highly significant.

Table 2 Demographic information of children with sensorineural hearing loss

Features	*n* (%)
Age (years)	
Group 1 (5–7)	12 (24)
Group 2 (8–10)	15 (30)
Group 3 (11–15)	23 (46)
Sex	
Male	22 (44)
Female	28 (56)
Degree of SNHL	
Moderate to moderately severe	16 (32)
Severe	9 (18)
Profound	25 (50)
Etiology of sensorineural hearing loss	
Heredofamilial	23 (46)
Nonsyndromic	21 (42)
Syndromic	2 (4)
Acquired	19 (38)
Prenatal	2 (4)
Perinatal	6 (12)
Postnatal	12 (24)
Unknown	8 (16)
Hearing aid fitting	
Binaural	42 (84)
Monaural	5 (10)
Not fitted	3 (6)
History of delayed motor development, clumsiness, or unsteadiness	11 (22)

SNHL, sensorineural hearing loss.

Results

Results of the basic audiological evaluation

All the children in the control group had normal developmental milestones and displayed bilateral NH. In contrast, 11 of 50 HI children had delayed milestones as their parents reported that they showed a delay in walking of more than 18 months. They showed bilateral SNHL of various degrees ranging from moderate to profound hearing loss on audiometry and with various etiologies (Table 2).

Results of clinical evaluation of vestibular function

The results of the present work indicate that when children with SNHL are challenged by sufficiently difficult balance tasks that emphasize the contribution of the peripheral vestibular system, as when vision and surface inputs are eliminated and/or inaccurate, they experience difficulty in maintaining balance compared with NH children of the same age.

As noticed in Table 3 there are statistically significant differences between NH children and HI children on using different tests for clinical evaluation of vestibular function (BOT-2, mCTSIB, OLS, and tandem stand) mainly when vision is eliminated. Meanwhile, no statistically significant differences were found in subtest 3 of BOT-2 and in the tandem stand test with EO.

The impact of etiology of hearing level on the results of clinical tests for vestibular system assessment: Bruininks-Oseretsky Test of motor proficiency, modified Clinical Test of Sensory Interaction for Balance, stand on one leg, and tandem stand

Generally, children with hearing loss of acquired etiology displayed poorer balance performance scores compared with their counterparts with hearing loss of unknown or heredofamilial etiologies in some items of BOT-2 (Table 4), as well as in mCTSIB, OLS, and tandem stand tests, although this difference did not reach a statistically significant level between various etiologies of SNHL when compared with the results of different tests for clinical evaluation of the vestibular system.

Table 3 Comparison between the mean ± SD of balance subtest scores of Bruininks-Oseretsky Test of motor proficiency (point score), modified Clinical Test of Sensory Interaction for Balance, one-leg stand, and tandem stand in normal-hearing and hearing-impaired children

	NH children	HI children	*P* value
BOT-2			
Standing with feet apart on a line			
Eyes open			
Row	10 ± 0.00	10 ± 0.00	–
Point	4.0 ± 0.00	4 ± 0.6	–
Eyes closed			
Row	9.06 ± 1.4	7 ± 1.4	0.000**
Point	3.9 ± 0.58	2.9 ± 0.36	0.000**
Walking forward on a line			
Eyes open			
Row	6 ± 0.0	5.6 ± 0.6	0.372
Point	4.0 ± 0.00	3.75 ± 0.4	0.423
Standing on one leg on a line			
Eyes open			
Row	9.7 ± 1.7	7 ± 1.2	0.001**
Point	3.9 ± 0.69	2.3 + 0.49	0.02*
Eyes closed			
Row	8.6 ± 2.4	4.4 ± 0.7	0.001**
Point	3.6 ± 0.39	1.8 ± 0.5	0.000**
Walking forward heel to toe on a line			
Eyes open			
Row	6 ± 0.5	4.0 ± 0.7	0.01*
Point	4 ± 0.7	2.7 ± 0.4	0.01*
Total point score	22.8 ± 2.7	17.4 ± 3.5	0.01*
mCTSIB			
Standing on a firm surface			
Eyes open	10 ± 0.00	10 ± 0.00	–
Eyes closed	9.00 ± 1.4	6.1 ± 1.3	0.02*
Standing on a foam cushion			
Eyes open	9.5 ± 2.5	7.3 ± 1.8	0.04*
Eyes closed	8.3 ± 2.6	4.5 ± 0.6	0.001**
Stand on one leg			
Eyes open	9.03 ± 1.7	6.8 ± 1.2	0.01*
Eyes closed	8.6 ± 2.4	4.4 ± 0.7	0.001**
Tandem stand			
Eyes open	9.9 ± 2.04	8.2 ± 1.8	0.372
Eyes closed	9.2 ± 0.62	5.17 ± 1.5	0.04*

BOT-2, Bruininks-Oseretsky Test of motor proficiency; HI, hearing impaired; mCTSIB, modified Clinical Test of Sensory Interaction for Balance; NH, normal hearing.
*Significant.
**Highly significant.

In this study, the etiology of HL was not significantly correlated with balance as estimated by the BOT-2 score. Hence, the differences in balance abilities across various etiologies revealed that etiology may not be considered a predictor of balance abilities in HI children. It could be explained by age at onset – whether since birth or after 2 years.

Impact of the degree sensorineural hearing loss on the results of clinical tests for balance evaluation

Children with a profound degree of HL had poorer balance performance scores in the BOT-2 balance subtests compared with their counterparts with hearing loss with other degrees of SNHL (Table 5).

The lowest success rates in mCTSIB, OLS, and tandem stand were achieved in HI children with a profound degree of HL compared with children with other degrees of SNHL. There were no statistically significant difference in the results of different tests for balance evaluation on the basis of degree of SNHL.

Impact of age on the results of clinical tests for balance evaluation

To study the effect of age the control group was divided according to age (5–7, 8–10, and 11–15 years) into subgroups 1, 2, and 3. The study group was also divided into three subgroups 4, 5, and 6.

HI children achieved statistically significantly poorer scores in some balance subtests of BOT-2 compared with NH children of the same age group. Meanwhile, the youngest children in both the NH and HI groups (6–7.5 years) achieved the lowest balance subtest scores and the lowest score in OLS with EO and with EC. The older age groups achieved better scores. There were statistically significant differences only in HI children with respect to the results obtained on OLS with EO ($P = 0.02$), SOL with EC ($P = 0.01$), and walking forward heel-to-toe on a line ($P = 0.01$) (Table 6).

Table 4 Comparison between the mean ± SD of balance subtest scores of Bruininks-Oseretsky Test of motor proficiency (point score) in hearing-impaired children according to various etiologies of hearing loss

	Etiologies of HI (*N* = 50) Point score			
Balance Subtest scores	Heredofamilial (*n* = 23)	Acquired (*n* = 19)	Unknown (*n* = 8)	*P* value
Standing with feet apart on a line				
Eyes open	4 ± 0.00	4 ± 0.00	3.9 ± 0.4	0.899
Eyes closed	2.9 ± 0.3	2.6 ± 0.28	3.02 ± 0.3	0.367
Walking forward on a line				
Eyes open	3.7 ± 0.3	3.7 ± 0.3	3.8 ± 0.3	0.899
Standing on one leg on a line				
Eyes open	2.3 ± 0.3	2.1 ± 0.5	2.8 ± 0.3	0.249
Eyes closed	1.8 ± 0.22	1.6 ± 0.2	2.0 ± 0.43	0.371
Walking forward heel-to-toe on a line				
Eyes open	2.7 ± 0.3	2.1 ± 0.34	2.7 ± 0.3	0.741
Total point score	17.4 ± 3.1	16.1 ± 2.1	18.22 ± 3.7	0.408

HI, hearing impaired.

Table 5 Comparison between the mean ± SD of balance subtest scores of Bruininks-Oseretsky Test of motor proficiency (point score) in hearing-impaired children according to various degrees of hearing loss

Balance Subtest scores	Degree of SNHL (*N*=50) Moderate–severe (*n*=16)	Severe (*n*=9)	Profound (*n*=25)	*P* value
Standing with feet apart on a line				
Eyes open	4 ± 0.00	4 ± 0.00	4 ± 0.00	–
Eyes closed	3.0 ± 0.3	3.0 ± 0.3	2.9 ± 0.4	0.290
Walking forward on a line				
Eyes open	4 ± 0.00	3.8 ± 0.2	3.0 ± 0.4	0.788
Standing on one leg on a line				
Eyes open	2.4 ± 0.2	2.5 ± 0.17	1.9 ± 0.6	0.688
Eyes closed	2.1 ± 0.2	1.9 ± 0.12	1.6 ± 0.45	0.183
Walking forward heel-to-toe on a line				
Eyes open	2.3 ± 0.6	2.5 ± 0.5	2.3 ± 0.36	0.307
Total point score	17.8 ± 0.35	18 ± 3.4	16.5 ± 2.8	0.470

SNHL, sensorineural hearing loss.

Table 6 Comparison between the mean (SD) of balance subtest scores of Bruininks-Oseretsky Test of motor proficiency (point score) in normal-hearing and hearing-impaired children according to age

Balance Subtest scores	NH children (*N*=30) Group 1 (5–7) (*n*=6)	Group 2 (8–10) (*n*=13)	Group 3 (11–15) (*n*=11)	*P* value	HI children (*N*=50) Group 4 (5–7) (*n*=12)	Group 5 (8–10) (*n*=15)	Group 6 (11–15) (*n*=23)	*P* value
Standing with feet apart on a line								
Eyes open	4 ± 0.00	4 ± 0.00	4 ± 0.00	–	4 ± 0.00	4 ± 0.00	4 ± 0.00	–
Eyes closed	3.8 ± 0.3	4 ± 0.00	4 ± 0.00	–	3.2 ± 0.1	3.6 ± 0.3	3.8 ± 0.4	0.395
Walking forward on a line								
Eyes open	4 ± 0.00	4 ± 0.00	4 ± 0.00	–	3.8 ± 0.2	3.9 ± 0.3	4 ± 0.00	0.421
Standing on one leg on a line								
Eyes open	3.8 ± 0.3	4 ± 0.00	4 ± 0.00	0.421	2.0 ± 0.2	3.1 ± 0.3	3.6 ± 0.1	0.02*
Eyes closed	3.1 ± 0.3	3.7 ± 0.3	3.7 ± 0.4	0.254	1.6 ± 0.3	2.1 ± 0.2	2.8 ± 0.4	0.01*
Walking forward heel-to-toe on a line								
Eyes open	3.6 ± 0.1	3.9 ± 0.2	3.9 ± 0.1	0.421	1.9 ± 0.4	3.1 ± 0.3	3.4 ± 0.3	0.01*
Total point score	22.3 ± 1.3	23.6 ± 0.3	23.6 ± 2.5	0.385	16.5 ± 0.3	19.8 ± 0.3	21.6 ± 0.3	0.02*

HI, hearing impaired; NH, normal hearing.
*Significant.

In mCTSIB, the youngest children in the HI group had the lowest success rate and there were statistically significant differences in HI children only with respect to the results of standing on a firm surface with EC ($P = 0.02$) and standing on a foam cushion ($P = 0.009$) with EC. The same result was observed for the OLS and tandem stand tests (Table 7).

A HI child was considered to have successfully passed the different skill tests of mCTSIB by comparing the results with standardized norms. The cutoff limit in these tests, or the lowest value that was defined as normal, was determined as the mean number of seconds that a normal child could maintain balance −2 SD. Children were considered to have failed the test if their score was below this cutoff limit.

The impact of visual cues on performance in different clinical tests for vestibular system assessment

All HI children performed poorly in different balance skill tests and experienced greater difficulty on an identical task with their EC versus EO. The most significant effect of vision was seen in the youngest age group among both NH and HI children (groups 1 and 4) but only for tests of BOT-2 (Table 6), mCTSIB (Table 7), OLS, and tandem stand performed with EC (Table 8). This indicates the importance of visual cues in the maintenance of balance at this young age, which seemed to apply not only for HI children but also for NH children.

Further, there were low success rates in the balance subtest that were almost lower than the success rates achieved by older HI children when compared with NH children.

The impact of sex on performance in different clinical tests for vestibular system assessment

Low success rates were achieved in both sexes of HI children when compared with NH children of the same sex with respect to different clinical tests of balance. There was no statistically significant difference between the number of poorly performing boys and poorly performing girls in both the NH and HI group with respect to the performance in different clinical tests for vestibular system assessment (Tables 7 and 8).

Discussion

Some studies have suggested that the clinical course of SNHL may be aggravated if the vestibular system is also involved [52,53]. It may even result in delayed motor development in children [11].

Table 7 Number and percentage of normal-hearing and hearing-impaired children who successfully passed different skill tests of modified Clinical Test of Sensory Interaction for Balance according to their age and sex

		mCTSIB							
		Standing on a firm surface Successful [*n* (%)]				Standing on a foam cushion Successful [*n* (%)]			
		Eyes open		Eyes closed		Eyes open		Eyes closed	
	Number	Normal (30)	HI (50)	Normal	HI	Normal	HI	Normal	HI
Age (years)									
5–7									
N	6	6 (100)	12 (100)	4 (67)	6 (50)	5 (83)	8 (67)	3 (50)	4 (39)
HI	12								
8–10									
N	13	13 (100)	15 (100)	13 (100)	12 (92)	13 (100)	12 (92)	13 (100)	11 (73)
HI	15								
11–15									
N	11	11 (100)	23 (100)	11 (100)	20 (87)	11 (100)	22 (95.6)	11 (100)	11 (73)
HI	23								
P value		–		0.02*		0.414		0.009*	
Sex									
Male	17 22	(100)	22 (100)	17 (100)	19 (68)	17 (100)	18 (82)	15 (94)	12 (55)
Female	13 28	(100)	28 (100)	11 (85)	22 (79)	12 (92)	23 (82)	11 (85)	14 (64)
P value		0.669		0.512		0.358		0.440	

HI, hearing impaired; N, normal.
*Significant.

Table 8 Number and percentage of normal-hearing and hearing-impaired children who successfully passed different skill tests of one-leg stand and tandem stand tests, according to age and sex

		One-leg stand Successful [*n* (%)]				Tandem stand Successful [*n* (%)]			
		Eyes open		Eyes closed		Eyes open		Eyes closed	
	Number	Normal (30)	HI (50)	Normal	HI	Normal	HI	Normal	HI
Age (years)									
5–7									
N	6	6 (100)	8 (66.6)	5 (83.3)	7 (58.3)	6 (100)	9 (75)	5 (83.3)	6 (50)
HI	12								
8–10									
N	13	13 (100)	13 (86.6)	13 (100)	12 (85.3)	13 (100)	14 (93)	13 (100)	13 (86.6)
HI	15								
11–15									
N	11	11 (100)	19 (82.6)	11 (100)	17 (73.9)	11 (100)	21 (91.3)	13 (100)	19 (82.6)
HI	23								
P value		0.137		0.03		0.195		0.078	
Sex									
Male	17 22	17 (100)	18 (81.1)	17 (100)	15 (68.1)	17 (100)	19 (86.3)	17 (100)	17 (77.2)
Female	13 28	12 (100)	22 (78.5)	27 (96.4)	21 (75)	12 (100)	25 (89.2)	27 (96.4)	21 (75)
P value		0.395		0.378		0.253		0.593	

HI, hearing impaired; N, normal.

This study showed that HI children performed worse in different balance skill tests (BOT-2, mCTSIB, OLS, and tandem stand) compared with NH children (Table 3). This agrees with the study by Lindsey and O'Neal [39], who found that deaf children performed more poorly in static and dynamic balance skill tests compared with NH children.

Further, the results of other investigations [5,6,15, 16,28,39,41,54] have shown that children with hearing loss have a balance and/or motor deficit that may be progressive [15]. As damage to the vestibular structures is known to affect motor and balance ability, many deaf children were found to have poor static balance skills in some studies [34,51].

Gheysen *et al.* [24] showed that NH children performed significantly better than deaf children and that hearing status had a significantly important impact mainly on the OLS test; deaf children were far less skilled than their NH peers in maintaining balance when standing on one leg. The motor skills of NH children were significantly better for all scales of the OLS. In a cross-sectional study it was found that HI children with sensory organization deficits have poor balance and motor deficiency in many areas [29].

Possible explanations for the observed motor deficits in deaf children can be enumerated [20] on the basis of four categories: (a) organic factors – associated vestibular or neurological defects; (b) sensory, auditory deprivation; (c) verbal, language deprivation – lack of verbal representations of motor skills, verbal–conceptual strategies to support execution; and (d) emotional factors – lack of self-confidence or overprotection or neglect on the part of parents, causing the deaf child to be less willing to explore the environment.

Other investigators [39,55,56] have reported impaired balance in deaf children because of the previously described possibility of vestibulocochlear dysfunction causing poor performance in tests on balance ability. Lack of complete comprehension of test instructions by the deaf child may be an additional cause of poor performance on the balance subtests. Hence, this study attempted to minimize the lack of comprehension using total communication and permitting one practice trial for each test.

This was not in accordance with the approach adopted in other studies [57,58], which have emphasized that not every deaf child has a balance deficit. They reported that preimplant motor scores of prelingually deaf infants and children fell within the typical range of variation found in NH children. Rapin [59] also described a delay in motor development in some, but not all, children with limited vestibular function included in her study.

Horak *et al.* [42] found that they could not differentiate the control group from the HI group despite the presence of reduced peripheral vestibular function in HI patients (one-foot stand, both with EO and with EC) [54–56]. A lack of universal findings on balance deficits and deafness suggests that some deaf children simply do not have a deficit, whereas others may have a deficit but use other sensory systems to compensate [60].

Impact of etiology of sensorineural hearing loss on the results of clinical tests for vestibular system assessment

In this study, it was noticed that HI children with acquired etiology of deafness performed poorly in different balance skill tests of BOT-2 (Table 4), mCTSIB, OLS, and tandem stand tests, compared with children with other etiologies.

This result agrees with that of Potter and Silverman [60], who suggested that children born deaf are less likely to have a balance dysfunction compared with those who acquire deafness, usually secondary to meningitis, in infancy or during early childhood. Also, other studies reported that the lower level of balance in deaf children can be attributed to vestibular defects, most often related to cerebral meningitis [50,61,62].

This also agrees with the results of a previous study, which reported that those whose cause of deafness was meningitis suffer from the most serious balance deficits [54].

Cushing *et al.* [33] also found that children with deafness caused by meningitis or cochleovestibular anomalies display poorer balance than those with mutations in the GJB2 encoding connexin 26 gene or with SNHL of unknown etiology, although the latter two groups also contained a number of poor performers. However, this was not in agreement with the results of another study [63] that suggested that the cause of deafness appears to have only a negligible influence on postural stability.

In this study, there was no statistically significant difference in the results of different tests for clinical assessment of the vestibular system on the basis of differences in etiology of SNHL. This agrees with the results of Boyd [63] who also reported no significant differences in static equilibrium ability on the basis of the etiology of deafness. However, this did not agree with the results of other investigators [64] who found that balance ability was significantly correlated with etiology.

Impact of the degree of sensorineural hearing loss on the results of clinical tests for vestibular system assessment

In this study HI children with profound SNHL tended to perform more poorly, as reflected by their low scores in all subtests of BOT-2 (Table 7), compared with children with other degrees of SNHL, although there was no statistically significant difference in the results of different tests for clinical evaluation of the vestibular system assessment on the basis of differences in the degree of SNHL. Also, the lowest success rate was achieved in HI children with profound SNHL in all subtests of mCTSIB, SOLS, and tandem stand tests (Table 5).

This agreed with the results of other studies, which reported a high prevalence of poor performance on tasks of standing balance in a profoundly deafened cohort [59,60,65]. Schwab and Kontorinis [64] concluded that the extent of hearing loss alone does not enable conclusions to be drawn about either vestibular function or dynamic balance performance.

Impact of vision on the results of clinical tests for vestibular system assessment

This study demonstrated the impaired balance in HI children as reflected by their lower scores in all subtests of BOT-2 (Table 4) and lower success rate in the mCTSIB, OLS, and tandem stand tests with the elimination of visual input (Tables 5 and 6).

This was consistent with the results of another study [66] that reported that deaf children with vestibular loss could not maintain balance in the standing position when the visual input was removed and the somatosensory input was modified. Yet, when visual and somatosensory input was enabled, these children showed postural control similar to that of deaf children with normal vestibular function and that of hearing children. This suggests a compensation process whereby input from proprioceptive, visual, and other sensory systems substitute for the absent peripheral vestibular input.

This finding also agreed with the findings of researchers [24] who suggested that hearing status had a significantly important impact mainly on the OLS test and that deaf children were far less skilled than their NH peers in maintaining balance when standing on one leg especially with EC. Potter and Silverman [60] showed that many deaf children seemed to compensate for vestibular deficits through nonlabyrinthine systems, such as visual and kinesthetic, to maintain static balance with EO or closed.

Lindsey and O'Neal [39] also agreed that balance ability decreases in the dark and when eyes are closed. Another study [65] indicated that in situations in which vision controls movement deaf children are seen to perform better than healthy children. This is attributed to the better eye–hand coordination of deaf children, which is an outcome of the training they undergo with emphasis on visual stimuli. This disagrees with the findings of Cushing *et al.* [33], who demonstrated that the relative importance of vision on the maintenance of balance is unchanged in the presence of bilateral vestibular loss. This was reflected in the observation that all children, whether NH or deaf, and with or without concurrent vestibular dysfunction, suffered a proportionally identical decrement in performance on certain subtests of the BOT-2 when their eyes were closed.

Impact of age of hearing-impaired children on the results of clinical tests for vestibular system assessment

This study showed that HI children achieved lower scores when compared with NH children in different clinical balance skill tests (BOT-2, mCTSIB, SOL, and tandem stand tests) at all age groups. This agrees with the results of Myklebust [54] and was also consistent with the findings of Boyd [63], who reported that there were differences in static balance between deaf and NH boys at all ages and significant differences in dynamic balance between deaf and NH boys of 9 and 10 years of age.

In this study the success rates for HI children in the different balance subtests of BOT-2, mCTSIB, OLS, and tandem stand tests increased with age (Tables 6–8). This was reflected in the lower scores in young HI children (5–7 years) when compared with the other age groups (8–10 and 11–15 years). This agreed with the results of Siegel *et al.* [21], who found significantly higher scores in the balance tests with increasing age, as seen when the scores of group 1 (40.5–60.5 years.) were compared with those of group 2 (8–10 years) and when balance scores of group 1 were compared with those of group 3 (12.5–14 5 years). No significant difference was found between the scores of groups 2 and 3. They noted that the youngest children achieved balance subtest scores that were almost 50% lower than the mean score of the NH population of the same age in the standardization trials. Groups 2 and 3 each had scores that were ∼20% lower than the mean score of the standardized population of the appropriate age.

This study showed that children with NH and normal vestibular function between the ages of 5–7 years typically display reduced balance ability when vision and surface inputs are eliminated and/or are inaccurate. This is consistent with the results of Shumway-Cook and Woollacott [47] and reflects the defect in the sensory organization system in young children. This was consistent the results of Butterfield [10] and Siegel *et al.* [21], who reported that HI children (hearing loss > 60 dB) aged between 3 and 14 years tested using a version of the BOT-2 that was restricted to balance exercises showed improved postural stability consistently with increase in age.

Rajendran and Roy [67] reported that it is normal for individuals belonging to both sexes in various age groups to have a certain amount of postural sway. However, the child imitates the adult pattern of postural control by the age of 7–10 years. According to the sensory systems, young children depend on the visual system to maintain balance. As they grow older, there is progressive domination of the somatosensory and vestibular systems.

In the study by Morsh [68] an improvement was seen in the balance ability of deaf individuals only until the age of 9 years, after which no clear improvement was seen. The period between the ages of 4 and 6 is a transitional phase before the ability to resolve multimodal sensory conflicts is fully in place. Not until the age of 7 years did the child exhibit adult-like behavior in terms of postural control [48].

Schwab and Kontorinis [64] confirmed the hypothesis that attainment of balance is subject to an age-dependent maturation process. The development of balance requires that all components continually develop and adjust and, above all, that these different sensory impressions are integrated within the central nervous system, although the vestibular organ is already structurally and functionally developed by the time of birth.

Results of previous studies [1,54,60,63,69–72] indicate that, in order to compensate for balance deficits, deaf children use other sensory systems, such as proprioception, kinesthesia, and vision. This disagrees with the findings of Siegel *et al.* [21], who reported that the balance scores of deaf children were equidistant from the scores of NH children across age groups, which strongly suggests that the degree of compensation, when it occurs, is insufficient to diminish the balance deficit in the three age groups we examined.

The significant influence of age appears not only in studies on motor performance of deaf pupils but also of all student populations. Many researchers attributed this improvement to the increasing maturity of the central nervous system and myoskeletal development with age [64,72].

Impact of sex of hearing-impaired children on the results of clinical tests for vestibular system assessment

In this study girls and boys with HI had lower success rates compared with girls and boys with NH in the performance of different balance skill tests. This was in agreement with the results of Boyd [63], who found that deaf boys have less skill than NH boys in maintaining dynamic balance. This was an effect of SNHL and not of sex.

This study demonstrated no difference in balance skills on the basis of sex in the BOT-2, mCTSIB, SOL, and tandem stand tests. This agrees with the results obtained in previous studies [62,73] in which tests of standing balance with eyes open and closed demonstrated no difference in balance skills on the basis of sex. They noted societal trends in which girls were more likely than boys to be physically active when compared with the level of activity in 1927.

A recent study [65] found no difference in performance in terms of static or dynamic balance between deaf girls and deaf boys. This also agrees with the results of some researchers [73,74] who found no difference in the balance abilities of deaf boys and girls. No significant difference was found in standing balance skills with eyes either open or closed between girls and boys [60,68].

This disagrees with the results of several investigators who concluded that the balance ability of deaf boys was superior to the balance ability of deaf girls and they found that deaf girls swayed more than deaf boys. They used either standing balance or beam walking as tests in their studies [48,54]. Some investigators have found deaf girls to sway more than deaf boys [52,74].

Some investigators believed that sex is another factor that affects balance. Deaf boys were thought to have superior balance ability compared with deaf girls, according to studies conducted in the 1930s [53].

Also, Riach and Hayes [75], who studied the maturation of postural stability in children aged between 2 and 14 years, reported that, although boys initially show greater instability than girls, they stabilize better and faster with age. One conceivable cause might be the different patterns of play between girls and boys, with boys' play more dominated by physical activity, which aids in increasing a sense of balance.

Although several investigators [50,56,64] have reported impaired balance in deaf children, others have emphasized that not every deaf child has a balance deficit. Potter and Silverman [60] suggest that children who are born deaf are less likely to have balance dysfunction compared with those who acquire deafness, usually secondary to meningitis, in infancy or during early childhood. A lack of universal findings on balance deficits and deafness suggests that some deaf children simply do not have a deficit, whereas others may have the deficit but use other sensory systems to compensate. A previous study [30] used a very sophisticated system for testing vestibular function in a group of HI children before testing their motor proficiency. They found a group of HI children with normal vestibular function who performed a series of motor tasks as well as, or better than, control groups. The HI children with reduced vestibular function showed poor results on the balance subtest of the BOT-2 [30].

The discrepancy could be explained by the observation that the studies by Myklebust [54], Morsh [68], and Long [48] were conducted in the 1930s, when girls typically led more protected lives and were less physically active than boys. Consequently, deaf girls may not have had the same opportunities to develop balance ability as did their male counterparts. Our findings support those of the more recent studies. We found no significant difference between male and female subjects. They believed that age-appropriate activities or exercise used to improve balance ability in deaf children did not have to be different between male and female subjects because neither sex is superior.

Butterfield and Loovis [76] found out statistically significant differences between the two sexes. In their effort to justify this difference, they accepted the theory of Greendorfer and Lewko [77] related to the acquisition of increased motion experience by boys as compared with girls, which stipulates that fathers encourage boys more to participate in sports. Anthrop and Allison [78] called this phenomenon the 'Victorian influence' and explained girls' lack of participation in sports as being due to sports being considered a dangerous activity.

Conclusion

Balance abilities as measured in this study with the balance subset of BOT-2, mCTSIB, OLS, and tandem stand were significantly poorer in HI children when compared with NH children.

HI children with acquired cause of hearing loss had observable lowest scores in these clinical tests compared with children with other etiologies. In contrast, those with a profound degree of hearing loss achieved observable poorest scores, although the scores were not statistically significant from those of children with other etiologies and degrees of SNHL. The youngest HI children had the lowest balance scores, and the clearest effect was observed for tests performed with eyes closed. The sex of the participant seems to have a negligible influence on the performance of different clinical tests of vestibular system assessment in HI children.

Recommendation

The high incidence of vestibular dysfunction and problems with balance in HI children without other handicaps is of vital information for therapists concerned with evaluating and treating HI children. Therefore, in order to minimize the adverse effects on normal development, it is crucial to carry out vestibular screening examinations and vestibular testing in all children with SNHL.

Further, once vestibular symptoms or deficits are identified, the children should be referred for testing of balance, motor development, and gaze stability. Appropriate interventions against balance and motor deficits are warranted so that functional improvement can be achieved by participation in vestibular rehabilitation programs focused on substitution and adaptation exercises. However, additional work is needed to examine the long-term effects of intervention.

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Conflicts of interest

There are no conflicts of interest.

References

1 Pajor A, Jozefowicz-korczynsks M. Prognostic factors for vestibular impairment in sensorineural hearing loss. Ear Arch Otorhinolaryngol 2008; 265:403–407.

2 Wilson VJ, Peterson BW. The role of the vestibular system in posture and movement. In: Mountcastle VB, editor. *Medical physiology*. Vol. 1. 14th ed. St Louis, MO: CV Mosby Co.; 1980. pp. 813–836.

3 kaga K. Vestibular compensation in infants and children with congenital and acquired vestibular loss in both ears. Int J Pediatr Otorhinolaryngol 1999; 49:215–224.

4 Jongkees LB, Maas JP, Philipszoon AJ. Clinical nystagmography: a detailed study of electro-nystagmography in 341 patients with vertigo. Pract Otorhinolaryngol 1962; 24:65–93.

5 Jongkees LB. Vestibular tests for the clinician. Arch Otolaryngol 1973; 97:77–80, 1973.

6 De Kegel A, Dhooge I, Cambier D, Baetens T, Palmans T, Van Waelvelde H. Test–retest reliability of the assessment of postural stability in typically developing children and in hearing impaired children gait & posture. J Gait Posture 2011; 33:679–685.

7 Windmill IM. Universal screening of infants for hearing loss: further justification. J Pediatr 1998; 133:318–319.

8 Woollacott MH, Debu B, Mowatt M. Neuromuscular control of posture in the infant and child: is vision dominant? J Mot Behav 1987; 19:167–168.

9 Woollacott MH, Shumway-Cook A. Changes in postural control across the life span – a systems approach. Phys Ther 1990; 70:799–807.

10 Butterfield SA. Gross motor profiles of deaf children. Percept Mot Skills 1986; 62:68–70.

11 Angeli S. Value of vestibular testing in young children with sensorineural hearing loss. Arch Otolaryngol Head Neck Surg 2003; 129:479–482.

12 Goebel JA. Should we screen hearing-impaired children for vestibular dysfunction? Arch Otolaryngol Head Neck Surg 2003; 129:482–483.

13 Snashall SE. Vestibular function tests in children. J R Soc Med 1983; 76:555–559.

14 Valente LM. Adaptation of adult techniques for evaluating vestibular function in children. Hear J 2007; 60:34–44.

15 Mergner T, Rosemeier T. Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions – a conceptual model. Brain Res Brain Res Rev 1998; 28:118–135.

16 Arnvig J. Vestibular function in deafness and severe hardness of hearing. Acta Otolaryngol 1955; 45:283–288.

17 Goldstein R, Landau E, Kleffner F. Neurological assessment of some deaf and aphasic children. Ann Otol Rhinol Laryngol 1958; 67:468–479.

18 Sandberg L, Terkildsen K. Caloric tests in deaf children. Arch Otolaryngol 1965; 81:350–354.

19 Buchman CA, Joy J, Hodges A, Telischi FF, Balkany TJ. Vestibular effects of cochlear implantation. Laryngoscope 2004; 114 (Suppl 103): 1–22.

20 Wiegersma PH, Van der Velde A. Motor development of deaf children. J Child Psychol Psychiatry 1983; 24:103–111.

21 Siegel JC, Marchetti M, Tecklin JS. Age-related balance changes in hearing-impaired children. Phys Ther 1991; 71:183–189.

22 Lieberman LJ, Volding L, Winnick JP. Comparing motor development of deaf children of deaf parents and deaf children of hearing parents. Am Ann Deaf 2004; 149:281–289.

23 Goodman J, Hopper C. Hearing impaired children and youth: a review of psychomotor behavior. Adapt Phys Activ Q 1992; 9:214–236.

24 Gheysen F, Loots G, Van Waelvelde H. Motor development of deaf children with and without cochlear implants. J Deaf Stud Deaf Educ 2008; 13:215–224.

25 Shall MS. The importance of saccular function to motor development in children with hearing impairments. Int J Otolaryngol 2009; 2009:972565.

26 Sechzer JA, Folstein SE, Geiger EH, Mervis RF, Meehan SM. Development and maturation of postural reflexes in normal kittens. Exp Neurol 1984; 86 (no. 3): 493–505.

27 Rine RM, Cornwall G, Gan K, LoCascio C, O'Hare T, Robinson E, Rice M. Evidence of progressive delay of motor development in children with sensorineural hearing loss and concurrent vestibular dysfunction. Percept Mot Skills 2000; 90:1101–1112.

28 Rine RM, Lindblad S, Donovan P, Vergara K, Gostin J, Mattson K. Balance and motor skills in young children with sensorineural hearing impairment: a preliminary study. Pediatr Phys Ther 1996; 8:55–61.

29 Bruininks RH, Broininks BD. *Bruininks-Oseretsky Test of motor proficiency manual*. 2nd ed. Minneapolis, MN: NCS Pearson Inc; 2005.

30 Crowe TK, Horak FB. Motor proficiency associated with vestibular deficits in children with hearing impairments. Phys Ther 1988; 68: 1493–1499.

31 Selz PA, Girardi M, Konrad HR, Huges LF. Vestibular deficits in deaf children. Otolaryngol Head Neck Surg 1996; 115:70–77.

32 Lelard T, Jamon M, Gasc J, Vidal P. Postural development in rats. Exp Neurol 2006; 202:112–124.

33 Cushing SL, Papsin BC, Rutka JA, James AL, Gordon KA. Evidence of vestibular and balance dysfunction in children with profound sensorineural hearing loss using cochlear implants. Laryngoscope 2008; 118: 1814–1823.

34 Geldhof E, Cardon G, De Bourdeaudhuij I, Danneels L, Coorevits P, Vanderstraeten G, *et al*. Static and dynamic standing balance: test–retest reliability and reference values in 9- to 10-year-old children. Eur J Pediatr 2006; 165:779–786.

35 Gabriel LS, Mu K. Computerized platform posturography for children: test–retest reliability of the sensory test of the VSR system. Phys Occup Ther Pediatr 2002; 22:101–117.

36 Folio MR, Fewell RR. *Peabody Developmental Motor Scales-2*. Austin, TX: PROED; 2000.

37 Henderson SE, Sugden DA, Barnett AL. Movement assessment battery for children-2: examiner's manual. London, UK: Pearson Assessment Inc; 2007.

38 Atwater SW, Crowe TK, Deitz JC, Richardson PK. Interrater and test–retest reliability of two pediatric balance tests. Phys Ther 1990; 70:79–87.

39 Lindsey D, O'Neal J. Static and dynamic balance skills of eight-year-old deaf and hearing children. Am Ann Deaf 1976; 121:49–55.

40 Bilir S, Guvin N, Bal S, Metin N, Artan I. A comparison study of gross motor developmental skill normal, hearing-impaired and Down syndrome children. Paper presented at the International Congress on education of the deaf Tel Aviv, Israel; 1995. pp. 16–20.

41 Omondi D, Ogol C, Otieno S, Isaac macharia. Parental awareness of hearing impairment in their school-going children and health care seeking behaviour in Kisumu district, Kenya. Int J Pediatr Otorhinolaryngol 2007; 71:415–423.

42 Horak FB, Shumway-Cook A, Crowe TK, Black FO. Vestibular function and motor proficiency of children with impaired hearing or with learning disability and motor impairments. Dev Med Child Neurol 1988; 30:64–79.

43 Krebs DE, Gill-Body KM, Riley PO, Parker SW. Double-blind, placebo–controlled trial of rehabilitation for bilateral vestibular hypofunction: preliminary report. Otolaryngol Head Neck Surg 1993; 109:735–741.

44 American Speech-Language Hearing Association. Degree of hearing loss. Avaliable at: *http://www.asha.org/public/hearing/Degree-of-Hearing-Loss/*.

45 Davidson J, Hyde ML, Alberti PW. Epidemiology of hearing impairment in childhood. Scand Audiol Suppl 1988; 30:13–20.

46 Espeso A, Owens D, Williams G. The diagnosis of hearing loss in children: common presentations and investigations. Curr Pediatr 2006; 16:484–488.

47 Shumway-Cook A, Woollacott MH. The growth of stability: postural control from a development perspective. J Mot Behav 1985; 17:131–147.

48 Long J. Motor abilities of deaf children. Contribution to Education, no. 514. New York, NY: Columbia University Teachers' College; 1932.

49 Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction on balance: suggestion from the field. Phys Ther 1986; 66:1548–1550.

50 Ayres AJ. *Southern California Postrotary Nystagmus. Test Manual*. Western Psychological Services: Los Angeles; 1975.

51 Latash M, Hadders-Algra M. What is posture and how it is controlled? In: Hadders-Algra M, Carlberg EB, editors. *Postural control: a key issue in developmental disorders*. London, UK: Mac Keith Press; 2008. pp. 3–21.

52 Effgen SK. Effect of an exercise program on the static balance of deaf children. Phys Ther 1981; 61:873–877.

53 Doershuk CF, Mathews LW, Tucker AS, Spector S. Evaluation of a prophylactic and therapeutic program for patients with cystic fibrosis. Pediatrics 1965; 36:675–688.

54 Myklebust HR. *The psychology of deafness*. 2nd ed New York, NY: Grune & Stratton Inc.; 1964. pp. 180–201.

55 Scanlon SL, Goetzinger CP. The health rails and Fukuda vestibular tests with deaf and hearing subjects. Eye Ear Nose Throat Mon 1969; 48:8–15.

56 McCarron L, Ludlow G. Sensorineural deafness and neuromuscular dysfunctions: considerations for vocational evaluation and job placement. J Rehabil 1981; 47:59–79.

57 Horn DL, Pisoni DB, Miyamoto RT. Divergence of fine and gross motor skills in prelingually deaf children: implications for cochlear implantation. Laryngoscope 2006; 116:1500–1506.

58 Kutz W, Wright C, Krull KR, Manolidis S. Neuropsychological testing in the screening for cochlear implant candidacy. Laryngoscope 2003; 113:763–767.

59 Rapin I. Hypoactive labyrinths and motor development. Clin Pediatr 1974; 13:922–937.

60 Potter CN, Silverman LN. Characteristics of vestibular function and static balance skills in deaf children. Phys Ther 1984; 64:1071–1075.

61 Shephard Roy J. *Fitness in special populations*. Champaign, Illinois; 1990. p. 350.

62 Brunt D, Broadhead GD. Motor proficiency traits of deaf children. Res Q Exerc Sport 1982; 53:236–238.

63 Boyd J. Comparison of motor behavior in deaf and hearing boys. Am Ann Deaf 1967; 112:598–605.

64 Schwab B, Kontorinis G. Influencing factors on the vestibular function of deaf children and adolescents – evaluation by means of dynamic posturography. Open Otorhinolaryngol J 2011; 5:1–9.

65 Cushing SL, James AL, Papsin BC, Gordon KA. The vestibular olympics: a test of dynamic balance function in children with cochlear implants. Arch Otorhinolaryngol 2007; 134:34–38.

66 Suarez H, Angeli S. Balance sensory organization in children with profound hearing loss and cochlear implants. Int J Pediatr Otorhinolaryngol 2007; 71:629–637.

67 Rajendran V, Roy FG. An overview of motor skill performance and balance in hearing impaired children. Rajendran and Roy Italian Journal of Pediatrics 2011; 37:33.

68 Morsh JE. Motor performance of the deaf. Comp Psychol Monogr 1936; 13:1–51.

69 Gallahue D. *Understanding motor behavior in children*. New York, NY: John Wiley Sons Inc; 1982.

70 Kandel ER, Schwanz JH. *Principles of neural science*. 2nd ed. New York, NY: Elsevier Science Publishing Co. Inc.; 1985. pp. 584–595.

71 Padden DA. Ability of deaf swimmers. Res Q 1959; 30:214–225.

72 Kaga K, Suzuki J, Morsh RR. Influence of labyrinthine hypoactivity on gross motor developmentof infants. Ann NY Acad Sci 1981; 374:412–420.

73 Carlson RB. Assessment of motor ability of selected deaf children in Kansas. Percept Mot Skills 1972; 34:303–305.

74 Gayle GW, Pohlman RL. Comparative study of the dynamic, static, and rotary balance of deaf and hearing children. Percept Mot Skills 1990; 70:883–888.

75 Riach CL, Hayes KC. Maturation of postural sway in young children. Dev Med Child Neurol 1987; 29:650–658.

76 Butterfield SA, Loovis ME. Influence of age, sex, balance, and sport participation on development of throwing by children in grades K-8. Percept Mot Skills 1993; 76:459–464.

77 Greendorfer SI, Lewko JH. Role of the family members in sport socialization of children. Res Q 1978; 49:30–48.

78 Anthrop J, Allison MT. Roll conflict and the high school female athlete. Res Q Exerc Sport 1983; 24:104–111.