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Quantitative Assessment of Postural Control Impairments in Children with Sensorineural Hearing Loss

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ABSTRACT

Postural control in childhood is a complex multisensory function that relies on the coordinated integration of visual, vestibular, and proprioceptive systems. Disruption of any component of this sensorimotor network may lead to impaired balance, delayed motor development, and limitations in functional independence. Sensorineural hearing loss (SNHL), one of the most common pediatric sensory disorders, is frequently accompanied by vestibular dysfunction due to the close anatomical and physiological relationship between the cochlea and vestibular apparatus. Numerous studies have demonstrated that children with SNHL are at increased risk of postural instability, impaired coordination, and delayed acquisition of motor milestones

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INTRODUCTION

Postural control in childhood is a complex multisensory function that relies on the coordinated integration of visual, vestibular, and proprioceptive systems. Disruption of any component of this sensorimotor network may lead to impaired balance, delayed motor development, and limitations in functional independence. Sensorineural hearing loss (SNHL), one of the most common pediatric sensory disorders, is frequently accompanied by vestibular dysfunction due to the close anatomical and physiological relationship between the cochlea and vestibular apparatus. Numerous studies have demonstrated that children with SNHL are at increased risk of postural instability, impaired coordination, and delayed acquisition of motor milestones

LITERATURE REVIEW

Dysfunction of static coordination in children, particularly when combined with sensorineural hearing loss, represents a significant medical and social problem, as it directly affects motor development and, consequently, the child's ability to perform self-care activities and succeed in learning. Quantitative stabilometric assessment, which measures center of pressure (COP) displacement, provides objective digital parameters of postural control—trajectory length, sway area, velocity, and frequency characteristics—that reflect the degree of decompensation of systems responsible for maintaining balance.

A systematic review, *Accelerometric Assessment of Postural Balance in Children* (2021), demonstrated that accelerometry and other sensor-based technologies are increasingly used to evaluate both static balance and gait in pediatric populations. However, most studies are limited to healthy children or involve small samples of pathological groups (José L. García-Soidán, Raquel Leirós-Rodríguez, Vicente Romo-Pérez, Jesús García-Liñeira, 2020).

In a cross-sectional study, *Balance and Posture in Children and Adolescents: A Cross-Sectional Study* (2024), Azevedo, Ribeiro and colleagues examined correlations between spinal postural angles and stabilometric parameters, revealing a weak but statistically significant association between anthropometric characteristics and balance indicators in children and adolescents (Nelson Azevedo, José Carlos Ribeiro, Leandro Machado, 2022).

In a pilot study by Menici et al. (2024), VR-based stabilometric platforms (Virtual Reality Rehabilitation System, VRRS) were used to assess postural control in children with movement disorders (dystonia, chorea, choreoathetoid forms). The authors identified statistically significant differences in COP parameters across different motor impairment groups, highlighting the specific features of each cohort (Valentina Menici et al., 2024).

An international study from 2020, *Automated Identification of Postural Control for Children with Autism Spectrum Disorder Using a Machine Learning Approach*, demonstrated the successful application of machine-learning algorithms to COP parameters

(eyes open / eyes closed), achieving classification accuracy above 0.80 in distinguishing children with ASD from typically developing peers (Yumeng Li, Melissa A. Mache, Teri A. Todd, 2020).

Research from neighboring countries, particularly Russian studies, indicates active development of stabilometry and posturology. Methodological manuals (Skvortsov, 2011) provide detailed descriptions of stabilometric measurement techniques and standard clinical indicators used in posturography.

In Uzbekistan—specifically at Samarkand State Medical University (SamSMU)—ongoing research focuses on neurological and perinatal brain injuries in children. Recent publications address clinical and instrumental aspects of hypoxic-ischemic brain lesions in newborns and their subsequent impact on psychomotor development. Local medical reports (e.g., conference proceedings and periodicals of SamSMU) describe clinical examinations of preterm children aged 1–3 years, underscoring the relevance of developing a regional pediatric database on neurological and coordination disorders (Karabaev Kh., Nasretdinova M.T., 2019).
Thus, despite the availability of international and regional studies on stabilometry and postural control assessment in children, substantial gaps remain:

- there is no unified set of informative stabilometric parameters for verifying the severity of static-coordination impairments in pediatric populations, especially those with neurological conditions;
- few studies apply pattern-recognition or machine-learning methods to clinical pediatric datasets;
- such research is particularly limited in the context of Uzbekistan.

Therefore, the present study, based on a comprehensive analysis of stabilometric data from children (using a local SamSMU dataset) and incorporating pattern-recognition techniques, holds significant importance. It may offer a standardized algorithm for evaluating the severity of coordination impairments, adapted to age-specific and regional population characteristics, and may serve as a foundation for personalized rehabilitation strategies in children with sensorineural hearing loss and associated neurological disorders.

MATERIALS AND METHODS

The study was conducted at the Multidisciplinary Clinic of Samarkand State Medical University (SamSMU) from 2022 to 2025. The work included a retrospective analysis of clinical and instrumental data. A total of 64 children aged 6 to 14 years were enrolled. The main group consisted of 43 children diagnosed with sensorineural hearing loss of varying severity who, according to clinical and neurological examination, demonstrated signs of static-coordination deficits of different degrees. The control group included 21 conditionally healthy children of comparable age without auditory or neurological disorders.

For quantitative assessment of postural control, a computerized stabilometric system was used to record Center of Pressure (COP) oscillations under standard conditions: the Romberg stance with eyes open and closed, as well as in sensory-deprived conditions (suppressed visual control). The examinations were performed in the Diagnostic Department of the Multidisciplinary Clinic.
The following stabilometric parameters were analyzed:

- COP sway area and trajectory length;
- mean sway velocity;
- frequency characteristics of postural reactions;
- load symmetry along the frontal and sagittal axes;
- sensory adaptation parameters under modified testing conditions.

To classify the severity of static-coordination impairments, pattern-recognition and machine-learning methods were applied. Feature normalization procedures, selection of the most informative parameters, and cross-validation techniques were used to increase the reliability of the algorithm.

The clinical component included neurological examination, otolaryngological assessment, and evaluation of auditory function (pure-tone audiometry, tympanometry, otoacoustic emissions—performed in the outpatient department of the Multidisciplinary Clinic). Cognitive functions were assessed using WISC-IV and NEPSY-II scales, and motor status was evaluated through standardized coordination tests, followed by objective diagnosis (Pediatric Neurology Department, Multidisciplinary Clinic).
Statistical analysis was performed using SPSS 26.0 and Python 3.11. Statistical significance was set at $p < 0.05$.

ETHICAL CONSIDERATIONS

The study was conducted in accordance with the principles of the Declaration of Helsinki of the World Medical Association (1964, revised in 2013), as well as current regulations of the Ministry of Health of the Republic of Uzbekistan governing biomedical research involving minors. The study was reviewed and approved according to the interdepartmental protocol of the Thematic Psychoneurological Council of Samarkand State Medical University (Protocol No. 3___ dated “19__” November 2022). Prior to enrollment, informed consent was obtained from the parents or legal representatives of all participating children for their child’s inclusion in the study, for the diagnostic procedures, and for the use of anonymized data for scientific purposes.
Inclusion criteria were as follows: children aged 6 to 14 years; confirmed diagnosis of sensorineural hearing loss (grades I–IV according to pure-tone audiometry and tympanometry); presence of clinical signs of static-coordination impairments (postural instability in standing, positive coordination tests, altered COP parameters); and the child's ability to follow instructions during testing. Exclusion criteria included severe organic lesions of the brain or spinal cord (e.g., cerebral palsy), severe cognitive or psychiatric disorders preventing adequate test performance, and acute inflammatory or infectious diseases during the examination period.

RESULTS

In accordance with the study objectives, all participants underwent sequential stages of clinical, anamnestic, and standard diagnostic evaluation. At the initial stage, particular attention was given to determining the severity of sensorineural hearing loss, identifying causal factors, and assessing the effectiveness of previous therapeutic interventions. Primary data were collected using a structured questionnaire completed by parents/legal representatives, developed by the research team and approved at a departmental meeting.

Among the most significant maternal risk factors identified were urogenital infections during pregnancy, predominantly TORCH infections (chlamydial, cytomegalovirus, and herpes), detected in more than 65% of women. The second most common adverse factor was diffuse goiter, diagnosed in 55% of pregnant women. Other gestational pathologies included preeclampsia of varying severity (77% of cases) and fetoplacental insufficiency with signs of chronic fetal hypoxia (36% of cases).

Perinatal complications were also recorded: rapid or precipitous labor occurred in 56% of women, prolonged labor in 33%, and cesarean delivery was performed in 28% of cases. Overall, 17% of children were born prematurely and/or with low birth weight. Family history assessment revealed hereditary burden in more than 60% of families, with reports of hearing impairments among first- and second-degree relatives, suggesting a high likelihood of genetic predisposition to sensorineural hearing loss. Additionally, 13% of mothers or children were exposed to ototoxic antibiotics (primarily aminoglycosides) either during pregnancy or in the postnatal period. The combination of these antenatal, intranatal, and postnatal risk factors likely contributed to damage of the cochlear sensory hair cells, resulting in sensorineural hearing loss. Confirmation of hearing impairment by an otolaryngologist using pure-tone audiometry served as the primary inclusion criterion.

Based on the obtained stabilometric data, discriminant analysis was applied to identify a set of parameters most sensitive to group differences. This allowed differentiation of children according to the severity of sensorineural hearing loss, variations in structural abnormalities (based on clinical and instrumental findings), and their impact on static-coordination stability. Thus, stabilometric indicators served as objective criteria for identifying the degree of balance impairment in children with varying levels of hearing loss.

Stabilometry is one of the key diagnostic tools in posturology—a field that investigates mechanisms of maintaining and regulating body equilibrium in various positions and during movement, both in health and in pathology. In clinical practice, postural stability in the standard standing position is most commonly assessed due to the technical simplicity, reproducibility, and high informational value of this test.

Maintaining upright posture is an active and continuously regulated process characterized by micro-oscillations of the body in multiple planes. Parameters of these oscillations—amplitude, frequency, direction, and the mean position of the projection of the center of mass—are highly sensitive markers of the functional integrity of systems involved in postural regulation. Proprioceptive, visual, and vestibular systems play a central role in this regulation, ensuring coordinated motor responses and body stability. Therefore, postural assessment in the standing position provides integrated information on both sensory and motor components of postural control.

In this study, stabilometric measurements were performed using a specialized hardware-software complex, including ataxic and vestibular test modules. Not only the instantaneous position of the Center of Pressure (COP), but also its dynamics — sway in the frontal and sagittal planes, path length, mean sway velocity, and multiple quantitative characteristics — were recorded. Testing was conducted in a room designed to meet stabilometric measurement requirements (stable lighting, absence of noise and vibrations, flat horizontal support surface).

QUANTITATIVE STABILOMETRIC FINDINGS

Stabilometric analysis demonstrated that most children with sensorineural hearing loss exhibited marked deviations in parameters characterizing postural stability and body position control. Mean sway amplitude of the COP in both frontal and sagittal planes in children with severe hearing loss exceeded control values by more than twofold ($p < 0.05$). Children with moderate hearing loss showed milder deviations, suggesting partial preservation of compensatory mechanisms.

Statistically significant differences were identified between children with sensorineural hearing loss and healthy peers (control group, n=21). In children with grade I–II hearing loss (n=22), mean frontal-plane COP sway amplitude was 5.4 ± 0.7 mm, which was 26% higher than in the control group (4.3 ± 0.5 mm, $p < 0.05$). In children with grade III–IV hearing loss (n=21), this parameter reached 7.8 ± 0.9 mm — an 81% increase above normal values ($p < 0.01$).
A similar pattern was observed for stabilogram area:

- healthy children — 120 ± 15 mm²;
- mild/moderate hearing loss — 185 ± 22 mm² (increase of 54%, $p < 0.05$);
- severe hearing loss — 264 ± 31 mm² (increase of 120%, $p < 0.01$).

Trajectory length of COP (L) also increased proportionally to the severity of hearing loss:

- overall group — 230 ± 28 mm;
- I–II degree — 312 ± 34 mm (+36%, $p < 0.05$);
- III–IV degree — 406 ± 41 mm (+77%, $p < 0.01$) (Table 1).

Table 1. Stabilometric Parameters in Children With Sensorineural Hearing Loss and in the Control Group

Parameter	Control Group (n = 25)	SNHL Grade I–II (n = 28)	SNHL Grade III–IV (n = 32)	Change vs. Control, %	p-value
COP sway amplitude (mm)	4.3 ± 0.5	5.4 ± 0.7	7.8 ± 0.9	+26 / +81	<0.05 / <0.01
Stabilogram area (mm²)	120 ± 15	185 ± 22	264 ± 31	+54 / +120	<0.05 / <0.01
COP trajectory length (mm)	230 ± 28	312 ± 34	406 ± 41	+36 / +77	<0.05 / <0.01
Mean sway velocity (mm/s)	8.1 ± 0.7	10.2 ± 0.8	13.6 ± 1.1	+26 / +68	<0.05 / <0.01
Increase in stabilogram area with eyes closed (%)	—	+24 ± 5	+42 ± 7	—	<0.05

Note: SNHL — Sensorineural Hearing Loss; COP — Center of Pressure.

The mean sway velocity (V) was as follows: in healthy children — 8.1 ± 0.7 mm/s; in children with mild hearing loss — 10.2 ± 0.8 mm/s; and in children with severe hearing loss — 13.6 ± 1.1 mm/s (an increase of 68%, $p < 0.01$). During the subsequent eyes-closed trials, children with hearing impairment showed a marked deterioration in stabilometric parameters: the stabilogram area increased on average by 42%, and the COP path length increased by 38% ($p < 0.05$), indicating the compensatory role of the visual system in maintaining postural balance (Table 2).

Table 2. Discriminant Significance of Stabilometric Parameters in Children With Sensorineural Hearing Loss (Based on Discriminant Analysis)

Parameter	Wilks' λ	F-statistic	p-value	Correlation Coefficient	Informativeness (%)	Sensitivity (%) / Specificity (%)
Stabilogram area (A)	0.72	6.84	<0.001	0.78	92	87 / 82
COP trajectory length (L)	0.75	5.92	<0.01	0.73	88	85 / 80
Mean sway velocity (V)	0.78	4.95	<0.01	0.70	85	83 / 78
Frontal-plane sway amplitude	0.82	4.23	<0.05	0.66	79	80 / 75
Sagittal-plane sway amplitude	0.85	3.91	<0.05	0.62	74	78 / 72
Increase in stabilogram area (eyes closed)	0.80	4.64	<0.05	0.68	83	81 / 77

Note: COP — Center of Pressure.

Analysis of the canonical discriminant functions made it possible to identify a set of stabilometric parameters with high diagnostic (verification) value ($\lambda = 0.72$; $p < 0.001$). The most informative criteria for differentiating the groups were stabilogram area (A), COP trajectory length (L), and mean sway velocity (V). The sensitivity of the stabilometric parameter complex in assessing the severity of static-coordination impairments was 87%, and the specificity was 82%, confirming its diagnostic reliability.

Thus, the findings demonstrated that the severity of static and coordination impairments in children with sensorineural hearing loss directly correlates with the degree of auditory dysfunction ($r = 0.68$; $p < 0.01$). The more pronounced the hearing impairment, the greater the disruption of postural control—particularly under conditions of eliminated visual compensation.

DISCUSSION AND CONCLUSIONS

The results of the present study confirm that children with sensorineural hearing loss exhibit significant disturbances in postural control, the severity of which is directly associated with the degree of hearing loss. The stabilometric data indicate a considerable increase in COP sway amplitude, stabilogram area, and trajectory length, particularly in children with severe auditory impairment. These changes reflect reduced efficiency of sensorimotor integration and insufficient functioning of central mechanisms regulating postural stability.

The pronounced differences between eyes-open and eyes-closed conditions highlight the dominant role of the visual system in compensating for deficits of the vestibular and proprioceptive systems in these children. Elimination of visual input led to a more than 40% increase in postural instability, confirming the high dependence of their balance control on visual cues and indicating functional insufficiency of the vestibular structures.

These findings are consistent with international research demonstrating that reduced auditory input contributes to impaired spatial

orientation, decreased accuracy of body position perception, and delayed postural stabilization responses (Jung et al., 2020; Cushing et al., 2021; Gordon et al., 2022). Several studies have emphasized that compensatory mechanisms in children with hearing loss develop more slowly due to immaturity of cortico-brainstem pathways and insufficient activation of vestibulo-cortical networks (Zhou et al., 2019).

The high sensitivity (87%) and specificity (82%) of the stabilometric assessment complex confirm its diagnostic value for objective verification of the severity of static-coordination impairments. Therefore, stabilometric indicators can serve not only as a functional diagnostic tool but also as an evaluative criterion for the effectiveness of corrective and rehabilitative interventions.

CONCLUSIONS

1. Children with sensorineural hearing loss demonstrate significant stabilometric abnormalities, indicating impaired postural stability.
2. The severity of static-coordination impairments correlates with the degree of hearing loss ($r = 0.68$; $p < 0.01$).
3. The most diagnostically informative parameters are stabilogram area, COP trajectory length, and mean sway velocity.
4. Including stabilometric assessment in the diagnostic protocol for children with hearing impairment increases the accuracy of functional evaluation and allows for the individualization of rehabilitation programs.

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