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Stabilometry in Children with Neurological Conditions

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Abstract

Balance in children relies on the integration of visual, vestibular, and proprioceptive systems with central motor processing. In neurological conditions such as cerebral palsy, developmental coordination disorder, and acquired brain injury, these systems are often compromised, resulting in instability that may not be detected by standard clinical assessments. Stabilometry provides a means of quantifying subtle postural fluctuations through the measurement of center-of-pressure shifts, offering insights into both developmental trajectories and pathological deviations. Research shows that sway magnitude and variability decline with age in typically developing children, while those with neurological conditions display increased sway and less efficient control. Stabilometry has proven useful for complementing clinical scales, tailoring interventions, and monitoring progress, though its application depends on reliable protocols, normative data, and functional interpretation. Emerging technologies, including motion capture systems such as Qualisys QTM, portable platforms, and wearable sensors, are expanding the scope of assessment. With continued refinement, stabilometry has the potential to strengthen both clinical practice and research in pediatric neurology.

Keywords: Stabilometry; Postural control; Cerebral palsy; Developmental coordination disorder; Pediatric neurology

1. Introduction

The ability to stand upright and maintain balance is something most of us take for granted, but in children it represents a complex developmental achievement. Postural control depends on the seamless integration of sensory inputs—vision, vestibular signals from the inner ear, and proprioceptive feedback from muscles and joints—together with central processing in the brain and coordinated motor output. This intricate system allows the body to remain stable while adapting to constant challenges, whether it is a subtle shift in weight, an uneven surface, or the removal of visual cues. (1)

For children with neurological conditions such as cerebral palsy, developmental coordination disorder, genetic syndromes, or acquired brain injury, these systems often do not interact in the expected way. Damage to motor pathways, altered muscle tone, delayed sensory integration, or impaired central processing can each disrupt the delicate balance required for stability. The result may be increased sway, clumsiness, reduced confidence in movement, or difficulty participating in daily activities that demand postural control.

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Stabilometry, sometimes referred to as static posturography, provides a means of quantifying these balance disturbances. By recording the movement of the body's center of pressure while a child stands on a force platform, stabilometry translates what might appear to be small and almost invisible wobbles into measurable data. Parameters such as sway amplitude, sway velocity, and the area of displacement can reveal how efficiently the nervous system is managing postural control, and how well different sensory systems are contributing to stability. (2)

The aim of this review is to bring together what is known about stabilometry in pediatric populations, with a focus on children who present with neurological conditions. First, I will describe how balance develops in typically developing children and how stabilometric findings change across age groups, providing a sense of what "normal" looks like. I will then move on to discuss what happens when this developmental trajectory is altered, summarizing stabilometry findings in children with conditions such as cerebral palsy, developmental coordination disorder, and brain injury. Because the interpretation of sway data is not straightforward, I will also examine methodological issues: how reliable these measures are in children, how different protocols influence outcomes, and what limitations researchers and clinicians need to be aware of. From there, I will consider what these findings mean for clinical practice and for ongoing research, highlighting how stabilometry can be used to guide therapy, monitor progress, and refine interventions. Finally, I will identify the gaps that remain in our knowledge and suggest directions for future work, with the goal of situating stabilometry as a valuable but carefully interpreted tool in the broader landscape of pediatric neurology and rehabilitation. Several systems are available for stabilometric assessment, ranging from laboratory-grade force platforms to portable and wearable solutions. High-resolution force plates, such as those from AMTI or Bertec, remain the gold standard for center-of-pressure measurement. Computerized dynamic posturography systems, including the NeuroCom SMART EquiTest, extend assessment by manipulating the visual field and support surface. Motion capture platforms, such as Qualisys Track Manager (QTM), allow three-dimensional tracking of body sway and segmental movements, providing a richer picture of postural strategies. More accessible options include portable stabilometric platforms (e.g., Tecnobody, GeaMaster) and adaptations of the Wii Balance Board, while wearable inertial sensors and VR-based systems are emerging as complementary tools.

2. Normative Stabilometry in Children

Any interpretation of stabilometry in children with neurological conditions has to begin with an understanding of what is typical. Balance does not arrive fully formed in early childhood; rather, it develops gradually as the nervous system matures and the child learns to coordinate sensory inputs with motor responses. In very young children, postural sway is relatively large and irregular. As they grow older, these movements become smaller, slower, and more consistent, reflecting the refinement of sensory integration and motor control. (3)

Several studies have mapped this developmental trajectory using stabilometry. Hsu and colleagues studied children between the ages of three and twelve under four different sensory conditions: standing on a firm surface with eyes open, standing on a firm surface with eyes closed, standing on foam with eyes open, and standing on foam with eyes closed. They reported that sway measures such as velocity and sway area declined with age, gradually approaching adult values. Interestingly, maturation was not uniform across conditions. On a firm surface with eyes open, children reached near-adult stability by about seven years old. Under more challenging conditions, particularly when standing on foam with their eyes closed, improvements continued until around twelve years, suggesting that the ability to integrate vestibular and proprioceptive cues develops later than reliance on vision. (4)(5)(6)

Other cross-sectional studies support these observations, consistently showing that younger children sway more and with greater variability, while older children display reduced sway magnitude and velocity. The "envelope" of stability shrinks as children age, reflecting a more efficient and confident control of posture. Large normative datasets, such as those published by Voss and colleagues, have provided reference values for sway across a wide range of sensory and stance conditions in children and adolescents, making it possible to quantify what falls within typical limits. More recently, Darr and colleagues in 2024 expanded on this by publishing normative values for five different static standing tasks, including unsupported stance, feet together, tandem, and single-limb standing. Their work covered children as young as two years old up to thirteen, and included variations across surfaces and vision conditions, thereby offering one of the most detailed developmental maps to date. (5) (7) (8)

Normative data, however, are only as useful as they are reliable. The repeatability of sway measures in children has been a subject of investigation, and the results underscore several challenges. Test–retest reliability tends to be acceptable under stable conditions, but measurement error grows in more difficult situations, such as when children stand on foam or keep their eyes closed. Younger children are particularly prone to variability. They may struggle to stand still for the required duration, fail to comply with instructions, or grow restless and disengaged, leading to noisy data or incomplete trials. Even small inconsistencies in cooperation can significantly affect sway metrics. (9) (10)

Anthropometric factors also complicate interpretation. Height, weight, and body mass index are known to influence postural control, and because these factors change so dramatically with age, disentangling their independent contributions is difficult. Some studies suggest that children at the extremes of BMI may show greater instability, while others find weaker or inconsistent associations. This highlights the importance of age-matched and, ideally, size-matched comparisons when judging whether an individual child's performance falls within expected limits. (10)

The protocols themselves also shape what counts as "normal." Many studies use 30-second trials as the standard, which is practical but may not capture the full extent of postural control. In older children, particularly those with good balance, shorter trials can lead to ceiling effects, where performance appears uniformly stable and subtle differences are masked. To address this, Darr and colleagues extended some trials to two minutes, which allowed them to detect more nuanced variations in postural sway. Choices about stance, vision, surface, and trial duration all influence the results, meaning that normative values are highly protocol-specific and cannot always be generalized from one study to another. (10)

Taken together, these findings paint a clear picture of normative stabilometry in childhood: sway decreases with age, the trajectory of improvement depends on the sensory demands of the task, and reliable measurement requires both careful protocol design and thoughtful interpretation. This foundation is essential, because without it, comparisons with children who have neurological conditions risk being misleading. Only by understanding the typical developmental course can we identify where and how balance control diverges. (5) (7) (10)

3. Stabilometry Findings in Children with Neurological Conditions

When the nervous system is affected by disease or injury, the smooth integration of sensory and motor systems that underpins balance becomes disrupted. Stabilometry makes these disruptions visible by quantifying the patterns of sway that emerge under different testing conditions. A considerable body of research has examined how these patterns differ in children with neurological conditions compared with typically developing peers. (11)

One of the best-studied groups is children with cerebral palsy. Across many investigations, these children consistently show greater sway areas, higher sway velocities, and less regular sway trajectories. Their postural control is less stable and more variable, reflecting the challenges imposed by abnormal muscle tone, impaired coordination, and altered sensory integration. The spatial and temporal features of their sway often reveal frequent corrective movements and irregular patterns, suggesting that the postural system is working harder and less efficiently to maintain stability. Importantly, stabilometry findings have been linked with clinical outcomes: children who demonstrate reduced sway tend to perform better on gross motor function measures and walking tests, underscoring the relevance of these measurements to everyday function. At the same time, cerebral palsy is a heterogeneous condition. The degree and pattern of postural instability vary widely depending on the subtype, the severity of motor involvement, and whether both sides of the body are affected. This variability makes it challenging to generalize but also highlights the value of stabilometry as a tool for capturing individual differences. (11) (12)

Children with developmental coordination disorder, sometimes described as having a "motor coordination disorder," represent another group where stabilometry has provided insight. At first glance, many of these children appear to manage standing balance reasonably well, at least under simple conditions. However, when visual input is removed or when they are placed on an unstable surface such as foam, their sway becomes much larger than that of age-matched peers. This pattern suggests that their balance difficulties may not be obvious in everyday situations but become clear when the sensory system is challenged. The findings align with a broader understanding of developmental coordination disorder as involving immature or less flexible strategies for weighting and integrating sensory input. In other words, the difficulty lies not only in motor execution but also in how the child's nervous system decides which information to rely on to maintain stability. (12) (13)

Stabilometry has also been used to study children recovering from acquired neurological conditions such as traumatic brain injury, stroke, or central nervous system infection. In these cases, the deficits in postural control are often subtle and may not be picked up by routine clinical assessments or gross motor tests. Stabilometry can detect residual impairments, offering a more sensitive measure of balance dysfunction. In rehabilitation contexts, stabilometric parameters have been used as endpoints to track changes over time, providing objective evidence of whether therapies are shifting sway patterns toward greater stability. The fact that stabilometry is being incorporated into clinical trials—such as those using force platforms to evaluate rehabilitation outcomes in neuropathy—illustrates the growing recognition of its value as both a research and clinical tool. (12) (14)

Beyond these more common conditions, stabilometry has also been applied, though less extensively, to children with genetic syndromes, cerebellar disorders, neuromuscular diseases such as spinal muscular atrophy, and other rare conditions. The logic is consistent: when motor control is weak, delayed, or inconsistent, postural sway tends to increase. The main challenge in these groups is not whether stabilometry can detect instability—it usually can—but rather that the rarity and heterogeneity of the conditions make it harder to build large datasets for normative comparison. As a result, many studies rely on comparisons with healthy reference groups to classify the degree of impairment. (15)

Overall, the literature shows that stabilometry is sensitive to a wide spectrum of postural control problems in children with neurological conditions. Whether the issue arises from motor deficits, impaired sensory integration, or central processing delays, the body's sway tells the story. The task now is to interpret these findings in ways that are meaningful for therapy, prognosis, and everyday function.

4. Methodological Considerations and Interpretation

The value of stabilometry lies not only in the data it generates but also in the way those data are collected and interpreted. Designing a protocol for children is not as straightforward as asking them to stand still on a force platform. Every decision—from how long the trial lasts to the stance and surface chosen—shapes the results, and missteps at this stage can make findings unreliable or misleading. (16)

One of the most fundamental issues is standardization of protocol. The type of stance has a significant effect on sway measurements. A wide stance offers greater stability and can mask subtle balance problems, while narrower stances, tandem standing, or single-limb tasks increase the challenge and reveal deficits that might otherwise remain hidden. The surface is another variable: firm ground predominantly tests the integration of proprioceptive and visual input, whereas standing on a compliant surface such as foam shifts the demand toward vestibular control. Similarly, vision conditions matter greatly. Trials with eyes open reflect typical postural strategies, but removing visual input or adding dynamic visual stimuli can uncover overreliance on vision or weaknesses in sensory reweighting. Duration also needs careful consideration. Trials should be long enough to capture representative sway patterns but not so long that children lose focus, fatigue, or become restless. While 30 seconds is often used as a standard, some researchers extend trials to one or two minutes, particularly with older children, to reduce ceiling effects. To improve reliability, multiple trials are usually averaged, which helps to smooth out random fluctuations. (16) (17)

Beyond the protocol, another layer of complexity lies in the parameters chosen for analysis. The most commonly reported measures are sway amplitude in both the medial–lateral and anterior–posterior directions, sway velocity as an indicator of how quickly the center of pressure moves, and sway area, often represented as a confidence ellipse covering most of the trajectory. Each captures a slightly different aspect of postural control. Frequency measures, which examine the regularity and timing of corrections, provide further insight into whether adjustments are slow and deliberate or rapid and erratic. More recently, nonlinear measures such as entropy or Lyapunov exponents have been introduced. These approaches attempt to capture the complexity of the postural control system, moving beyond the simple magnitude of sway to assess adaptability and dynamic stability, though they remain less common in pediatric work.

Interpreting these numbers is not always straightforward. A larger sway area or higher velocity might suggest instability, but the relationship to functional ability is not perfectly linear. Some children who sway more still perform well in walking, running, or play activities, while others with relatively modest sway may have significant difficulties in daily life. Age is another confounding factor. Because sway decreases with development, comparisons must always be made against age-matched norms or adjusted for developmental stage. Context also matters: a child may appear stable when standing on a firm surface with eyes open but reveal pronounced instability when vision is removed or the surface is unstable. Without testing multiple conditions, deficits may be underestimated.

Attention and fatigue present additional hurdles. Younger children in particular may struggle to remain engaged, especially during longer or repeated trials. Variability in attention can inflate sway measures or produce inconsistent results. Finally, there is the issue of individual variability. Even within the same diagnostic category—two children with spastic cerebral palsy, for example—sway profiles can look quite different due to variations in severity, distribution of motor involvement, compensatory strategies, or comorbid conditions. This makes stabilometry a powerful tool for capturing individualized profiles but a challenging one for drawing broad generalizations. (19)

For stabilometry to be clinically meaningful, it must demonstrate both validity and responsiveness. Validity requires that the measurements align with real-world function. A sway metric is only useful if it correlates with clinically relevant outcomes such as walking ability, performance on standardized balance scales, or participation in daily activities. Responsiveness refers to the ability of stabilometry to detect change over time, particularly after an intervention. If a therapy program genuinely improves balance, the platform should register a measurable difference. Without these qualities, stabilometry risks becoming an exercise in collecting data without actionable significance. (20)

In short, stabilometry in children demands careful protocol design, thoughtful choice of parameters, and cautious interpretation. Numbers alone do not tell the story; they need to be understood in the context of age, task demands, attention, and functional ability. When handled carefully, however, these measurements provide a unique and valuable window into the workings of postural control.

5. Clinical and Research Implications

The growing body of evidence on stabilometry in children raises an important question: how can these findings be applied in practice, and what role should they play in research? The answer lies in using stabilometry not as a replacement for clinical judgment but as a complementary tool that can refine assessments, guide interventions, and deepen scientific understanding of postural control. (3)

In clinical practice, stabilometry adds a layer of precision to balance assessment that traditional scales cannot always capture. Tools such as the Pediatric Balance Scale or the Gross Motor Function Measure are valuable for evaluating gross abilities, but they may overlook subtle impairments that nonetheless affect a child's safety and participation. Stabilometry can detect these finer disturbances, highlighting instability that might only emerge under specific sensory conditions. For example, if a child demonstrates a marked increase in sway when asked to stand with eyes closed, this may point to an overreliance on vision and underuse of proprioceptive or vestibular input. Knowing this allows therapists to design interventions that target proprioceptive or somatosensory training, thereby addressing the underlying weakness rather than the surface symptom. (4)

Another practical use is in monitoring progress over time. Clinical impressions and parental reports can be subjective, but stabilometry provides objective data. By comparing sway patterns across weeks or months, clinicians can determine whether therapy is reducing sway amplitude, lowering sway velocity, or improving consistency of postural control. This kind of evidence not only helps refine treatment plans but can also reassure families by making improvement visible in measurable terms. Stabilometry may also have a role in risk stratification. Children with consistently high sway values or highly unstable patterns may be at greater risk of falls, low mobility, or difficulties in community participation. Identifying these risks early could inform decisions about orthotic support, safety strategies, or additional therapies.

The implications for research are equally significant. One of the main challenges in the field has been the lack of standardized protocols, which makes it difficult to compare results across studies. Establishing common testing conditions—stance types, trial durations, surface challenges, and vision tasks—would allow researchers to pool data and build more robust conclusions. Normative databases are another priority. Large, population-specific reference values are essential for interpreting children's results in context, especially given the strong developmental trajectory of sway measures.

Beyond these basics, there is potential for methodological innovation. Most pediatric studies rely on linear measures such as sway amplitude or velocity, but nonlinear metrics like entropy or Lyapunov exponents may capture aspects of postural control that simple averages cannot. These advanced analyses could reveal how adaptable or complex a child's balance strategies are, opening the door to new insights into neurological function. (9)

Longitudinal research is also needed. Rather than simply comparing groups at one point in time, following children over years would show how stabilometry evolves with growth, development, and therapy. Intervention trials are an obvious extension, using stabilometry as an outcome measure to test the effectiveness of different rehabilitation strategies, balance training programs, or assistive devices. Finally, subgroup analyses are important for teasing out the diversity within neurological conditions. Children with the same diagnostic label may display very different stabilometric profiles, depending on etiology, lesion type, or severity. Identifying these subgroups can refine both clinical management and research design.

In sum, stabilometry offers clinicians a way to look beneath the surface of postural control, while giving researchers a reliable, quantitative tool to explore how balance develops and responds to therapy. Its full potential will be realized only when protocols are standardized, data are interpreted alongside functional outcomes, and findings are consistently tied back to the real-world experiences of children and their families.

6. Gaps, Challenges and Future Directions

Despite the clear promise of stabilometry in pediatric populations, several gaps remain in the literature, and important challenges must be addressed before the tool can reach its full clinical and research potential. (19)

One of the most pressing needs is the development of larger and more diverse normative datasets. Most of the existing reference values have been derived from Western populations, yet anthropometric, ethnic, and cultural differences may influence postural control. Children in different parts of the world grow at different rates, engage in different physical activities, and have varied exposure to environments that challenge balance. Without datasets that reflect this diversity, comparisons risk being skewed, and clinicians may misinterpret whether a child's performance truly falls outside the expected range. Expanding normative research across regions and populations is therefore essential for building a reliable foundation. (9) (20)

Another gap is the limited number of studies that connect stabilometry metrics to real-world functional outcomes. While sway patterns differ between typically developing children and those with neurological conditions, what these differences mean for mobility, independence, and participation in daily life is less well established. To move from laboratory findings to clinically meaningful insights, more work must be done to link changes in sway amplitude, velocity, or variability with tangible outcomes such as walking ability, playground participation, or risk of falls in the home and community.

There are also methodological challenges related to the cooperation of children during testing. Young participants may struggle to remain engaged, especially during repetitive or lengthy trials, which increases measurement error. To address this, researchers are beginning to explore gamified protocols or interactive platforms that keep children motivated while still collecting reliable data. Attention aids, shorter trials with repeated measures, or integrating tasks into playful settings may all improve compliance without sacrificing rigor.

Beyond static stance, the field has only begun to explore the possibilities of dynamic posturography in children. Static measures are valuable but capture only a small portion of postural control. Perturbation-based tests, sway-referenced surfaces, or assessments during active movement could provide richer information about how children respond to real-life challenges. Expanding research into dynamic stabilometry is a logical next step, particularly since many balance problems only emerge under conditions of motion or unexpected change.

New analytic approaches also hold promise. Most current studies rely on conventional metrics such as sway area or mean velocity, but advanced computational techniques are now available. Machine learning and pattern recognition algorithms could identify unique sway signatures associated with specific conditions or even predict progression before clinical symptoms become obvious. These tools could also help classify subtypes within heterogeneous disorders, improving both diagnosis and individualized care.

Finally, the integration of stabilometry with other modalities could deepen our understanding of the mechanisms underlying sway abnormalities. Combining force platform data with electromyography could clarify how muscle activation patterns contribute to instability. Linking it with kinematic analyses might reveal compensatory strategies in joint movement, while neuroimaging could map the central pathways involved in postural control. Multimodal approaches like these would allow researchers to move from describing the "what" of postural instability to explaining the "why."

In short, stabilometry has already proven itself as a valuable tool for quantifying balance in children, but the next phase of research must expand its scope, refine its methods, and strengthen its connection to meaningful outcomes. By addressing these gaps, the field can move toward making stabilometry not only a research instrument but also a practical part of everyday pediatric neurology and rehabilitation.

7. Conclusion

Stabilometry provides a unique window into the mechanisms of postural control in children. By translating subtle shifts in the center of pressure into measurable parameters, it allows clinicians and researchers to see what the naked eye cannot. In typically developing children, stabilometry charts the gradual refinement of balance as sensory systems mature and motor responses become more efficient. In children with neurological conditions, it exposes the ways in which this developmental trajectory is altered—whether through increased sway, irregular corrective strategies, or exaggerated reliance on particular sensory inputs.

The strength of stabilometry lies in its precision and sensitivity. It can highlight impairments too subtle for clinical observation, track progress during rehabilitation, and offer insights into the specific sensory or motor deficits that underlie instability. At the same time, its usefulness depends on careful protocol design, age-appropriate normative data, and thoughtful interpretation. A sway measure in isolation tells us little; its true value comes when it is linked to functional outcomes such as mobility, participation, and quality of life.

For clinical practice, stabilometry can serve as a complement to traditional assessments, guiding individualized therapy and providing objective evidence of change. For research, it offers a rigorous platform for testing interventions, comparing populations, and advancing our understanding of postural control. Looking ahead, the field needs broader normative datasets, stronger connections between laboratory measures and real-world outcomes, and innovative methods—such as dynamic testing, machine learning, and multimodal integration—that push beyond the limits of static sway analysis.

In the end, stabilometry should not be seen as an abstract laboratory exercise but as a practical tool that, when interpreted carefully, can directly inform the care of children with neurological conditions. By capturing the story told in every wobble and correction, it helps clinicians and researchers alike to better understand the challenges these children face—and, most importantly, to design interventions that support their stability, independence, and participation in daily life.

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