Chapter 14

Development of Balance Functions in Childhood and the Importance of Balance Impairments

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Abstract

Balance is a fundamental skill that enables the performance of daily living activities. Balance skills are critical at every stage, from a baby learning to sit to an elderly person preventing falls. Maintaining balance control is related to three sensory systems: the vestibular, visual and somatosensory systems. These systems change and develop over time, from infancy to adulthood. As a result of this change, postural control becomes more stable and reaches adult levels. However, postural control is not regulated solely by sensory inputs. Many factors, such as motor responses, adaptive skills and cognitive status, also contribute to this process. Childhood is a critical period in which motor skills develop rapidly and the balance system begins to mature. Balance functions directly affect a child's interaction with their environment, safe movement and healthy neuromotor development. Detailed knowledge of the developmental stages of balance functions in childhood is critical for early detection of any unusual conditions. Accordingly, this chapter will discuss the development of balance functions and the importance of balance disorders in childhood.

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1. Components of the Balance System

Balance is a complex function achieved by the integration of sensory information from the vestibular, visual and somatosensory systems by the central nervous system (1). This integration provides postural control, enabling individuals to maintain their balance in various environments (2). The vestibular system provides fundamental information about head position, linear and angular movement to maintain balance and plays a crucial role in this process. The information provided by this system is decisive in postural regulation. The visual system supports postural stability by providing information about the environment (3). The somatosensory system provides information about the body's position in space through proprioceptive feedback from musculoskeletal structures (4). The appropriate processing of sensory inputs from these three systems and their integration with motor outputs forms the basis of static and dynamic balance performance. Since the maturation rates of these components differ during childhood, balance development also follows an age-dependent course.

2. Neurodevelopment of Postural Control in Childhood

2.1. Maturation of the Vestibular System and Reflexes

The maturation and integration of sensory systems play a critical role in the development of balance control. The vestibular system is a sensory system that begins to develop rapidly in the prenatal period and can perform its basic functions some time after birth. The vestibular organ begins to develop around the 3rd week and completes its development around the 25th week of gestation (5). Peripheral vestibular structures such as the semicircular canals, utricle and saccule begin to form in the 7–8th weeks of the embryonic period; they are largely morphologically complete by the 20th week of gestation. Differentiation of vestibular hair cells and projection of peripheral afferents to the brainstem intensify in the third trimester and reach functional activity just before birth (6, 7).

In the postnatal period, the basic reflexes of the vestibular system become functional. However, the gain values, fine adjustments and central integration processes of these reflexes continue to develop (8). While the vestibuloocular reflex, which ensures the stability of the visual field during head movement, generally approaches adult levels around 2–3 years of age, it may take until the preschool period for the reflex to reach full accuracy and stability. In this process, the plasticity between the flocculonodular lobe of the cerebellum and the vestibular nuclei is particularly critical for the development of the vestibuloocular reflex (9, 10). The vestibulospinal reflex,

another important reflex of the vestibular system, is one of the fundamental reflexes that stabilizes postural control and helps maintain posture. It has a more complex neural mechanism than the vestibuloocular reflex. The effectiveness of the vestibulospinal reflex mechanism in postural control of the vestibular system continues to develop until the age of 15-16 (11). Another important reflex is the vestibulocolic reflex, which helps stabilize the visual system by ensuring the stability of the head and neck during movement. The reason for weak head control in newborns is that the vestibulocolic reflex and the neck extensor muscles are not yet fully mature. From the 3rd month onwards, the vestibulocolytic reflex becomes more consistent in parallel with the development of the neck muscles and from the 6th month onwards, it undergoes a significant functional maturation phase (12-14).

The central maturation of the vestibular system is crucial not only at the reflex level but also in terms of the development of postural control. The ability to integrate vestibular inputs with proprioceptive and visual information allows children to adapt more effectively to environmental changes as they age. Multisensory integration skills show significant development, particularly between the ages of 4 and 6 and during this period, children begin to use strategies such as ankle and step strategies. This development is related to the myelination of the vestibulospinal pathways and the maturation of connections between the cerebral cortex and the brainstem (15, 16).

This maturation process, which continues until adolescence, also strengthens the contribution of the vestibular system to tasks related to motor and cognitive processes. The accuracy and consistency of vestibular inputs gradually increase in higher-level functions such as motor planning, spatial awareness and orientation. Therefore, early and orderly development of the vestibular system is a fundamental determinant of postural control, motor coordination and movement safety in childhood.

2.2. Developmental Stages of Balance Functions

The components of the balance system develop over time during childhood. These systems are in a constant state of development to perform daily living activities, produce responses and develop motor skills (17). The development of neurological processes involved in balance is rapid during childhood and adolescence (18). Children develop various balance strategies from the first years of life. In early childhood, postural control in sitting and walking is largely based on biomechanical references (19). Over time, more complex systems come into play in line with changing postural needs

and in increasingly challenging conditions. At this stage, head and neck stabilization and coordination of the trunk and extremities are provided through multisensory integration (20).

2.2.1. Neonatal Period (0-1 month)

Development in children progresses cephalocaudally, with the head, trunk and feet developing first. Although the vestibular system is functional after birth, it is not yet developed and has limited functionality. Muscle tone is the primary determinant of postural stability in the early stages of life. During this period, muscle development has not yet reached the level required to provide stability (5).

2.2.2. Infancy Period (2-12 months)

A normal baby can hold its head straight at 6 weeks old and can lift it above the horizontal line around 12 weeks. By 16 weeks, it can move its head horizontally to observe its surroundings (5). Head control becomes significantly better around 4-6 months. A more stable posture is achieved in a sitting position at 6 months and by 9 months, it can sit unsupported for a few minutes. These processes occur thanks to the integration of vestibular information and proprioceptive information received from the cervical system. Around 12 months, it can crawl and stand with support (21, 22).

2.2.3. Early Childhood Period (1-3 years)

During this period, the child begins to walk without support. Parameters of walking such as speed, stride length and foot span develop over time. In order to adapt to changing conditions, he/she begins to use strategies such as ankle, hip and stepping. Towards the end of this period, swing decreases, but full maturation has not yet occurred (23).

2.2.4. Preschool Period (3-6 years)

This period is when postural control develops rapidly. It is reported that the somatosensory system is fully developed at 3-4 years of age (24) and at the latest at 6 years of age (25). However, some studies indicate that children at this age have not yet completed their motor development and do not have enough motor experience (26). Between the ages of 4-5, children can use rapid and large posture adjustment strategies under changing conditions (27). However, full adaptation may not yet be observed.

2.2.5. School Age (6-12 years)

Children can now maintain stabilization even under challenging conditions that disrupt the balance system (5). Improvements in postural performance are more pronounced between the ages of 8-10 because integration is better (27, 28). Increased physical activity during school age contributes to the development of balance performance during this period.

2.2.6. Adolescence (12-18 years)

Adolescence is the period when balance performance and postural control come closest to adult levels. Balance performance improves with the maturation of the musculoskeletal system, the development of sensory systems, multisensory integration and motor planning (29). However, evidence exists in the literature that it does not fully reach adult levels. Adults can maintain postural control even with incorrect visual input because they have a well-developed vestibular system. However, children around 12 years of age cannot adapt to incorrect visual input. This indicates that the vestibular system is still in the developmental stage (5).

2.3. Critical Periods

Studies in the literature show that postural stability increases over time (30). However, there may be some critical periods in this process. Balance development can generally be divided into 4 stages (5). The first stage is the time between birth and standing. During this process, muscle control begins first in the neck. The baby first tries to keep its head stable, muscle control is in the trunk during the sitting stage and later, during the standing stage, muscle control is provided by the feet. The second stage is the time between standing and 6 years of age. During this period, the visual, vestibular and somatosensory systems mature and sensory weighting mechanisms develop (31). Development shows caudocephalic progression during this period. First, coordination of hip movements is achieved, followed by coordination of the shoulders and neck (5). During this period, the capacity to adapt to environmental changes increases. The third stage is the period from 7 years of age to adolescence. This process is an important one in balance control. Multisensory integration mechanisms begin to approach the adult level and the central processing of vestibular inputs matures significantly. Increased stimulation of the vestibulospinal pathways produces more stable responses under challenging conditions (32, 33). The fourth stage is reached in adulthood and at this stage, all mechanisms are activated and postural control is fully achieved (5).

Many variables influence postural control and balance performance. This is related not only to sensory systems and physiological development, but also to cognitive functions, muscle strength and participation rates in physical activity, as well as the central nervous system's capacity for motor response generation, strategy development and adaptation (34- 36). Each sensory system has individual characteristics in its developmental process and dominance. Therefore, each child should be evaluated on their own individual basis.

3. Balance Disorders Seen in Childhood

Balance disorders in childhood arise from the inability of one or more of the structures responsible for postural control mechanisms to perform their function (37). For this reason, balance disorders should be considered as a multidimensional problem involving the interaction of the vestibular system, visual system, somatosensory inputs and central motor planning processes.

Balance disorders in childhood can result from vestibular pathologies, visual abnormalities, musculoskeletal disorders, neurological or psychological problems. Studies in the literature show that vestibular pathologies are frequently responsible for balance disorders in childhood. The most common diseases are vestibular migraine and benign paroxysmal vertigo of childhood (38). Benign paroxysmal vertigo of childhood is generally characterized by sudden onset, short-term vertigo attacks that usually occur in the preschool period (39). Vestibular migraine, on the other hand, usually appears in the preschool or school-age period and is characterized by attacks of dizziness accompanied by headache (40). The visual system is one of the fundamental components of balance and plays a critical role in the development of balance functions during childhood. A lack of visual input, incorrect visual input, or disorders in the processing of visual stimuli at the central level can lead to significant balance problems in children (41, 42). A disorder in the musculoskeletal system results in incorrect proprioceptive input, which is another factor affecting balance performance in children. In particular, in growing children, the incomplete development of the musculoskeletal system can affect the balance system. Conditions such as flat feet, spinal curvatures, muscle weakness or muscle tone disorders, overweight, or low musculoskeletal mass affect the center of gravity of the body and may be insufficient to produce an appropriate motor response for maintaining balance (43-45). Balance disorders also occur as a result of pathologies affecting the central nervous system, such as cerebral palsy, epilepsy, cerebellar and brainstem lesions, tumors and demyelinating diseases. Therefore, vestibular assessment and early intervention are critically

important for motor development and quality of life in children with neurological disease (46, 47).

4. The Effects of Balance Loss on Children's General Life

4.1. Motor Skills

Balance plays a crucial role in the development of motor skills in children. It forms the basis of skill-based movements and the overall development of motor behavior. By influencing various motor skills, it supports physical development and is important in improving children's ability to participate in complex movements (48). Impairments in postural control mechanisms can lead to delays in acquiring both static and dynamic motor skills such as walking, running, standing on one leg, climbing stairs, jumping and ball control. Children with imbalance have slower movements because they have insufficient proprioceptive feedback. This negatively affects motor learning processes and delays the development of coordination. Long-term balance disorders reduce participation in physical activity, limit the development of muscle strength and can further affect motor performance (49).

4.2. Activities of Daily Living

Children with balance disorders experience greater difficulty performing daily living activities. Many functional tasks such as walking, running, climbing stairs, tying shoelaces, playing, riding a bicycle and engaging in physical activities, as well as dressing and bathing, are related to the balance system. A disorder in the balance system may prevent these activities from being performed or may result in decreased performance (50, 51). This situation limits the child's physical, social and emotional development, reducing their quality of life. In addition, limitations in daily activities lead to decreased physical independence at home, school and in social life.

4.3. Cognitive Processes

There are connections between balance and cognitive processes. Vestibular information is transmitted to the limbic and cortical regions of the brain and the vestibular system has connections, particularly with the hippocampus. Due to these connections, vestibular disorders affect cognitive processes (52). In particular, executive functions, spatial memory, attention, dual-tasking performance and information processing speed can be affected by balance functions (53). Children with imbalance may experience difficulties in problem-solving, planning, motor-cognitive integration and processing environmental stimuli.

4.4. Academic Performance

Impairments in balance functions can affect academic achievement both directly and indirectly (54). The vestibular system interacts with mechanisms that support learning processes such as eye movement stabilization, attention, memory and spatial positioning. Therefore, children with balance disorders may have difficulty reading books, following the blackboard or teacher and studying. In addition, they may be unable to perform daily living activities due to balance problems, their participation in physical activities may decrease, they may experience social isolation as a result of physical and mental fatigue and psychological problems associated with balance disorders and their school performance may decrease (55). The literature reports that vestibular dysfunction is associated with learning disabilities, reading problems and attention deficit (56).

4.5. Psychosocial Effects

Balance disorders significantly affect not only physical performance but also the psychosocial development of children. Children with balance problems may have difficulty coordinating their movements during play activities with their peers, which can lead to decreased participation in physical activities, lack of self-confidence and social isolation (48). This can create a cycle that exacerbates both physical and emotional difficulties. Experiences of physical failure can create frustration in children, leading to anxiety, shyness and emotional stress (57). Depressive symptoms and behavioral adjustment problems are reported more frequently, especially in children with chronic balance problems (58).

5. Management of Balance Disorders in Children

Diagnosis is the first step in managing balance disorders in children. The pathology causing the balance disorder must be identified and the treatment process should be planned accordingly. Managing this process requires a multidisciplinary approach. As we have mentioned before, the development of balance functions in childhood is multidimensional and each child should be evaluated individually (59, 60). In the evaluation of balance disorders, a detailed history should be taken and a comprehensive assessment of the vestibular system, neurological evaluation, developmental and psychological evaluation should be performed. The treatment protocol should be determined with a multidisciplinary approach, appropriate to the pathology causing the balance disorder. The basic approach in disorders originating from vestibular system pathologies is vestibular rehabilitation (61). Vestibular rehabilitation is a therapeutic approach consisting of a

series of exercises involving eye and head movements. The aim of vestibular rehabilitation is to increase head and eye coordination, improve postural stability and support multisensory integration. Various studies have shown that vestibular rehabilitation is effective in reducing dizziness, imbalance and motor coordination difficulties in children (62, 63).

Play-based therapeutic approaches are intervention methods consisting of play activities to support the development of balance and motor control in children (64). In these approaches, play is used as a fun tool that increases the child's motivation and strengthens sensorimotor integration processes. Rotation, jumping, climbing, ball games, or walking on a balance board, which involve vestibular stimuli, are frequently used examples. Such games aim to improve the child's postural control, dual-task performance and motor planning skills. Research shows that play-based interventions lead to significant improvements in higher-level motor skills, gait stability and daily living functions (65, 66).

6. Conclusion and Recommendations

The development of balance functions in children progresses rapidly from birth. The vestibular system, the mechanism responsible for maintaining balance, processes visual and somatosensory inputs and develops over time. A disruption in these developmental milestones can affect a child's motor development, cognitive functions, psychological state and social life and may impair their quality of life in the long term. Early diagnosis of balance disorders allows for timely intervention, reducing long-term effects. Vestibular rehabilitation and play-based approaches support balance development in children and stabilize postural control. However, for sustainable support of balance development, the involvement of families and teachers is necessary. Regular screening of children with neurodevelopmental disorders, vestibular system pathologies and developmental coordination disorders allows for both early detection of developmental delays and timely application of individualized interventions.

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