Effect of age and sex on maturation of sensory systems and balance control

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Maintenance of postural balance requires an active sensorimotor control system. Current data are limited and sometimes conflicting regarding the influence of the proprioceptive, visual, and vestibular afferent systems on posture control in children. This study investigated the development of sensory organization according to each sensory component in relation to age and sex. A total of 140 children (70 males, 70 females; mean age 10y [SD 4y]; age range 3y 5mo–16y 2mo) and 20 adults (10 males, 10 females; mean age 30y 6mo [SD 8y 4mo]; age range 17y 2mo–49y 1mo) were examined using the Sensory Organization Test. Participants were tested in three visual conditions (eyes open, blindfolded, and sway-referenced visual enclosure) while standing on either a fixed or a sway-referenced force platform. Mean equilibrium scores for the six balance conditions showed rapid increases and maturation ceiling levels for age-related development of the sensorimotor control system. Proprioceptive function seemed to mature at 3 to 4 years of age. Visual and vestibular afferent systems reached adult level at 15 to 16 years of age, revealing differences between young males and females. Characterizing balance impairments can contribute to the diagnostic evaluation of neuromotor disorders.

Maintenance of postural balance requires an active sensorimotor control system. Afferent information from the proprioceptive, visual, and vestibular systems, as well as from the cognitive system, is integrated and evaluated to generate motor responses that keep the body inside its limits of stability (Nashner et al. 1982, Black et al. 1983, Black 1985).

In adults, the sensory systems are well organized and act in a context-specific way (Shumway-Cook and Woollacott 1985). In children, however, the sensory systems are not completely developed, although their anatomical structures are detectable and mature early in life (Ornitz 1983). The three afferent sensory systems (proprioceptive, visual, and vestibular) develop more slowly than the hierarchically lower automatic motor processes that mature early in childhood (Forssberg and Nashner 1982).

Although there is limited data on the influence of proprioceptive, visual, and vestibular afferent systems on posture control in children, several studies have been conducted on the development of sensory organization. Brandt et al. (1976) and Hirabayashi and Iwasaki (1995) reported that development and calibration of the three sensory subsystems occur sequentially. When evaluating the proprioceptive system, Riach and Hayes (1987) and Aust (1996) reported that the Romberg quotient, a measure of somotosensory function, increased to adult values by 9 to 11 or 12 years of age. In contrast, Hirabayashi and Iwasaki (1995) found that maturation of the proprioceptive function occurred by approximately 3 to 4 years of age. The visual influence on standing stability is reported to be established at adult levels by the age of 15 years, whereas the vestibular system is still developing at that age (Hirabayashi and Iwasaki 1995, Aust 1996).

Investigations into standing stability in response to intersensory conflict have produced different results. Forssberg and Nashner (1982) reported that children younger than 7 years 6 months could not suppress the influence of sensory input providing inappropriate orientation information. Shumway-Cook and Woollacott (1985) suggested that 7- to 10-year-old children were able to resolve intersensory conflict like adults. In contrast, Peterka and Black (1990), Hirabayashi and Iwasaki (1995), and Cherng et al. (2001) found that optimal stance stability was reached by the age of 15 years.

Because data on maturation of the proprioceptive, visual, and vestibular functions are conflicting, this study aimed to compare the sensory organization of posture control in children and adolescents with that of adults. Analysis of posture mechanisms is necessary to produce standard values which, in turn, allow detection of pathological results in balance control. This allows differentiation of neurological and orthopaedic diagnoses.

The significance of each sensory component was determined using computerized dynamic posturography.

Method

The child participants were healthy children from kindergarten and school, and in-patient children awaiting adenotomies or tonsilectomies. Apart from the underlying illness, the in-patient children were healthy. Information on the children was based on medical records and parent interview. Adult participants were healthy colleagues from the Department of Otorhinolaryngology, Innsbruck Medical University. A total of 140 children (70 males, 70 females; mean age 10y [SD 4y]; age range 3y 5mo–16y 2mo) and a reference group of 20 adults

(10 males, 10 females; mean age 30y 6mo [SD 8y 4mo]; age range 17y 2mo–49y 1mo) were examined at Innsbruck Medical University Hospital, Austria, using the Sensory Organization Test (SOT; Nashner et al. 1982) which is a component of the EquiTest (Stoll 1985, Nashner 1993). The study was approved by the appropriate local ethics committee and consent was given by parents and participants.

Participants were divided into seven age groups: 3–4 years (mean age 3y 9mo [SD 4mo]); 5–6 years (5y 7mo [5mo]); 7–8 years (7y 8mo [7mo]); 9–10 years (9y 6mo [5mo]); 11–12 years (11y 4mo [5mo]); 13–14 years (13y 6mo [6mo]); and 15–16 years (15y 6mo [6mo]), after exclusion of peripheral, central vestibular, proprioceptive, and visual disorders, as well as medication influencing the balance system. Inclusion was determined from medical histories and by questioning the parents. Children who were unable to cooperate and professional athletes were also excluded.

The EquiTest is designed to analyze the participant's interaction of sensory systems to maintain balance. The SOT, a component of the EquiTest protocol, assesses quantitatively vestibular, visual, and proprioceptive contributions to balance, including the ability to suppress inaccurate information from each of these senses by systematically manipulating somatosensory and visual input (Baloh et al. 1994, 1998). The force plate, visual surround, or both can be sway-referenced (i.e. foot pressure is used to control the pitch angle of the surround or platform with the aim of keeping the ankle angle constant (see Table I).

During the SOT participants were asked to stand upright and centre each foot directly on the stripe of the dual force plate while paying attention to the lateral foot placement, which is dependent on height. Participants faced a visual surround that could also tilt to be sway-referenced. The visual surround included a colour, child-friendly picture to enhance attention. Participants' safety was ensured by the operator who stood within reaching distance of the participants; no safety harness was worn.

The posturographic platform included dual force plates, which could be angled up, down, or moved in the anterior–posterior direction. Each plate consisted of a flat, rigid surface supported at four points by independent force-measuring devices to record the pressure on the right and left anterior and posterior plantar surfaces.

The SOT evaluates the equilibrium score for postural stability comparing anterior–posterior sway to a theoretical sway stability limit of 12.5° in six test conditions (C1–C6). Test conditions varied depending on whether eyes were open or blindfolded, the surround was fixed or sway-referenced, and whether the platform was fixed or sway-referenced. The equilibrium score provides a non-dimensional percentage. Equilibrium scores near 100% indicate the highest standing stability, while scores approaching 0% indicate a participant swaying at the limits of stability (Nashner 1993). A composite score was calculated by taking the mean equilibrium

Table I: Sensory test conditions (C1–C6) of Sensory Organization Test (Nashner et al. 1982)

Test conditions	*Eyes*	*Surround*	*Platform*
C1	Open	Fixed	Fixed
C2	Blindfolded	Not applicable	Fixed
C3	Open	Sway-referenced	Fixed
C4	Open	Fixed	Sway-referenced
C5	Blindfolded	Not applicable	Sway-referenced
C6	Open	Sway-referenced	Sway-referenced

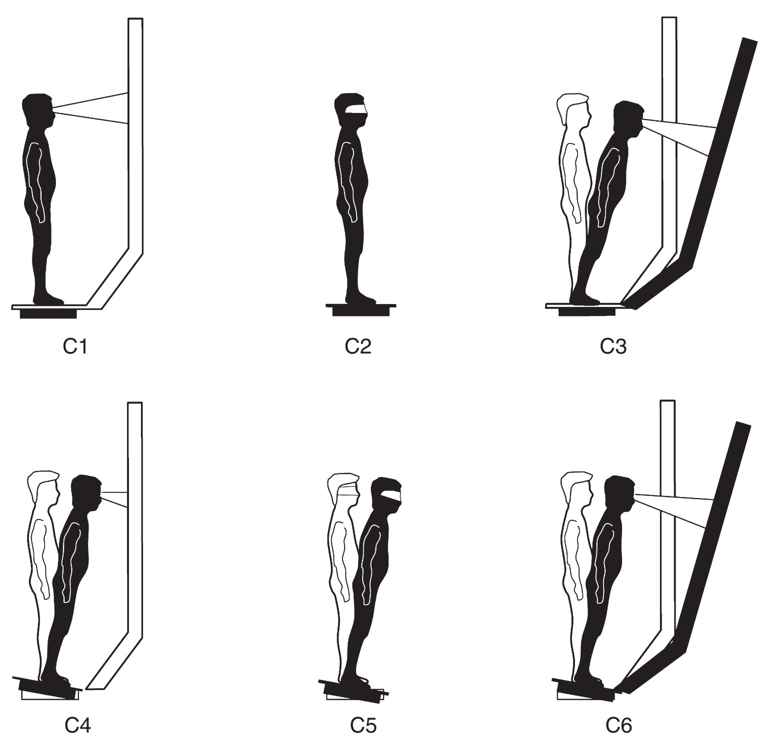

Figure 1: *Test conditions (C1–C6) of Sensory Organization Test (Nashner et al. 1982). C1, eyes open surround fixed, platform fixed; C2, eyes blindfolded, fixed platform; C3, eyes open surround sway-referenced, platform fixed; C4, eyes open, surround fixed, platform sway-referenced; C5, eyes blindfolded, platform sway-referenced; C6, eyes open, surround sway-referenced, platform sway-referenced.*

score of the six different test conditions. Each test condition was examined twice for 20 seconds with a 20-second break between tests. Sensory conditions were presented in random order.

Figure 1 and Table I summarize the test conditions that systematically vary the visual and somatosensory cues available to participants. No manipulation of vestibular input was attempted. Conditions C1–C3 presented accurate somatosensory cues: C1 and C2 were eyes-open and eyes blindfolded Romberg tests. Condition C3 provided inaccurate visual information: if the participant swayed to anterior or posterior, the visual surround moved with the participant. Conditions C4–C6 presented inaccurate somatosensory input by tilting the platform by an amount equal to the participant's anterior–posterior sway. Subsequently, the same visual variations in C1–C3 were tested in C4–C6. Thus, in C5 and C6 only the vestibular input was accurate.

Sensory analysis reflects the sensory ratios computed from mean equilibrium scores obtained from specific pairs of sensory test conditions. The ratio C2:C1 presents the participant's ability to use input from the somatosensory system to maintain balance, C4:C1 input from the visual system, and C5:C1 input from the vestibular system (Nashner 1993).

A low C2:C1 ratio is interpreted as dysfunction of the somatosensory input, which normally dominates the control of balance during eye closure. Although vestibular input presents a second alternative in this case, the vestibular system is substantially less sensitive than somatosensory input in controlling sway. The ratio C4:C1 quantifies the extent of stability loss when the normally dominant somatosensory input is disrupted by sway-referencing of the support surface. The increase in sway is minimal when the alternative visual input functions normally. The ratio C5:C1 reflects a relative reduction in stability when somatosensory and visual inputs are simultaneously disrupted. Although sway increases significantly in C5, healthy participants maintain their balance well within the limits of stability using the remaining vestibular input.

The mean equilibrium score for each test condition, composite scores, and ratios were calculated and compared between neighbouring age groups and between sexes using *t*-tests (SPSS version 11.0.1). Statistical significance was set at $p \leq 0.05$, and high significance was set at $p \leq 0.01$.

Results

AGE-RELATED CHANGES IN STANCE STABILITY FOR TEST CONDITIONS C1–C6

Posture control showed different progress throughout C1 to C6 with an age-increase from 5–6 to 15–16 years. This tendency was supported by the composite score for each age group (Table II). Evaluation of each test condition revealed a clear increase in standing stability up to an age of 7–8 years for C1, 9–10 years for C2, and 11–12 years for C3. Only a small improvement in standing stability was demonstrated for these test conditions (C1–C3) with increasing age. For C4 and C5 clear developmental progress occurred up to the age of 7–8 years. Further development was observed between 9–10 and 11–12 years, and 15–16 years and adults for C4; and between 11–12 and 15–16 years for C5. C6 showed an increase in standing stability between the ages of 3–4 and 5 –6 years, 7–8 and 11–12 years, and 13–14 and 15–16 years. Adults showed an improvement in posture

Table II: Mean equilibrium scores and SD for Sensory Organization Test (Nashner et al. 1982) conditions (C1–C6) and composite scores (Com) according to age group (*n*=20 per age group)

Age groups, y	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*Com*
3–4							
Mean	82.1	80.3	75.1	54.2	25.4	22.5	49
SD	6.4	7	9.3	10.4	15.7	17.7	7.2
5–6							
Mean	87.9	83.8	78.5	59.8	45.7	49	61.6
SD	4.3	7.6	12.5	13	9.9	8.4	6
7–8							
Mean	91.2	87.3	84.4	69.6	50.1	42.4	64
SD	2.1	4.1	9	11	15.8	18.4	6.1
9–10							
Mean	91.9	89.8	86.1	71.4	50.7	51.9	67.2
SD	2.3	3.1	5.4	13.1	16.4	15.5	7.4
11–12							
Mean	91.5	90	90.6	80.2	59.3	66.3	75.5
SD	2.8	3	5	8.3	17.3	12.6	6.7
13–14							
Mean	93.1	91.5	91	79.4	61.7	58.2	74.2
SD	3.1	3.6	3.7	11.9	10.2	15.6	5.8
15–16							
Mean	92.3	91	91.6	83.9	69.9	66.9	78.7
SD	2.6	3	2	11.3	9.3	11.9	4.5
Adults							
Mean	94.5	91.9	92.2	86	65.8	70.10	78.9
SD	1.5	2.8	2.4	5.8	7.8	13.9	6.8

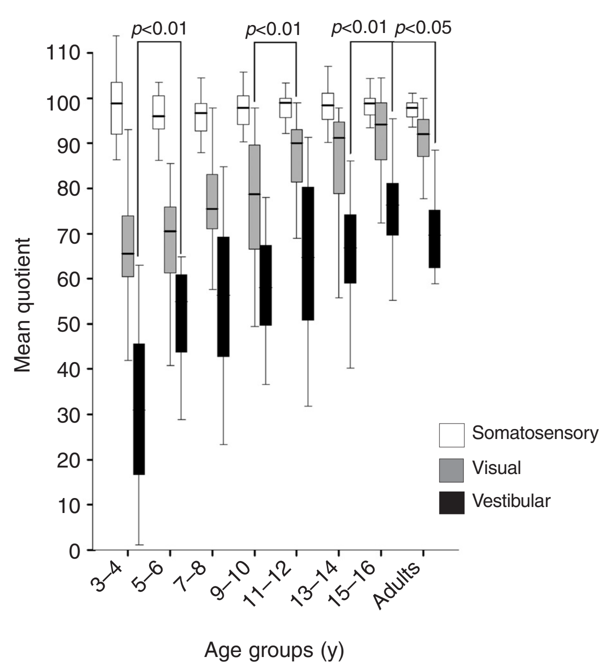

Figure 2: *Influence of sensory systems on postural control. Comparison of mean ratio C2:C1 (somatosensory), ratio C4:C1 (visual), and ratio C5:C1 (vestibular) according to age group (p≤0.05; p≤0.01).*

control for C1–C4 and C6 compared with adolescents (15–16y); for C5 adult standing stability decreased significantly.

Comparison of mean equilibrium scores between neighbouring age groups showed high statistical significance ($p\leq0.01$) between the 3–4 and 5–6 year age groups for C1, C5, C6, and the composite score; between 5–6 and 7–8 year age groups for C1; between 9–10 and 11–12 year age groups for C3, C6, and the composite score; and between 13–14 and 15–16 year age groups for the composite score (Table III). These results reflect the developmental progress of balance control in childhood and adolescence. Furthermore, statistical significance ($p\leq0.05$) was demonstrated between 5–6 and 7–8 year age groups for C4, between 7–8 and 9–10 year age groups for C2, between 9–10 and 11–12 year age groups for C4, and between 13–14 and 15–16 year age groups for C5.

When evaluating the standing stability of females and males, the six test conditions showed that females up to the age of 11–12 years developed sensory systems earlier than males; results were statistically significant ($p\leq0.05$) for C5 in the 9–10 year olds. Only in the 5–6 year age group did males score higher for C4 and C6. Males also showed higher scores at the age of 13–14 years for all test conditions except C4 and at the age of 15–16 years, with statistical significance ($p\leq0.05$) for C6. In the adult group no sex difference was detected.

Analysis of the composite score showed that females were able to maintain balance more accurately than males in the age groups below 11–12 years, with the exception of the 5–6 year age group. The 3–4 year age group showed statistical significance ($p\leq0.05$) for females when analyzing the composite score between the sexes. At the age of 13–14 years there was no sex difference, although males scored higher in the 15–16 year age group. Adult results showed no sex difference.

INFLUENCE OF SENSORY SYSTEMS ON STANDING STABILITY

Figure 2 summarizes the analysis of each sensory system with regard to posture control. The C2:C1 ratio accounted for 98% (i.e. high standing stability) in the 3–4 year age group and changed negligibly until adulthood. This indicates that the proprioceptive system is fully developed at this early age. The C4:C1 ratio shows the visual influence on balance control. A highly significant difference was detected between 9–10 and 11–12 years. Visual afference showed no further development after 15–16 years.

For vestibular afference, results showed a high statistical significance between 3–4 and 5–6 years, as well as between 13–14 and 15–16 years, following the developmental tendency of the previously described visual system. After a plateau phase, standing stability again improved at 11–12 years for C5:C1. A comparison between the 15–16 year age group and the adults showed a statistically significant decrease in the vestibular influence on posture control.

The vestibular system developed earlier in females than males until 9–10 years and again at 13–14 years. Statistical significance ($p\leq0.05$) was given for the 9–10 year age group females, while the 15–16 year males were more stable. Adults showed no sex difference.

With regard to the visual system, females scored higher until age 9–10 years, with the exception of the 5–6 year group. In the age groups over 9–10 years, males scored higher with the exception of the 13–14 year age group.

When analyzing the proprioceptive system no sex-related developmental tendency was observed.

Discussion

To maintain postural control, sensory input from accurate external spatial orientation references are provided by the vestibular, visual, and somatosensory systems. This information is processed by the central nervous system to generate adequate muscle response, especially of the trunk and lower extremities (Scholtz et al. 2001).

Information about the interaction of cervico-proprioceptive and vestibular information can be found in Pompeiano (1972) and Maeda et al. (1979), and the interaction of vestibular and visual inputs is outlined in Cohen (1974) and Dichgans and Brandt (1978).

The complex system of standing stability supported by various compensatory mechanisms raises the question of how sensory organization develops in children and adolescents when considering each sensory component in relation to age and sex. There is conflict of data, and several studies report a large developmental variability between individuals (Lee and Aronson 1974, Butterworth and Hicks 1977, Forssberg and Nashner 1982, Shumway-Cook and Woollacott 1985, Peterka and Black 1990, Aust 1991, Hirabayashi and Iwasaki 1995, Cherng et al. 2001).

AGE-RELATED CHANGES IN STANDING STABILITY

During sensorimotor processing the proprioceptive system is of significant importance because it dominates balance control under fixed support surface conditions, i.e. conditions C1 to C3 (Diener et al. 1986, Diener and Dichgans 1988). Evaluation of proprioceptive function using the mean equilibrium score

Table III: Significant differences in age groups for Sensory Organization Test (Nashner et al. 1982) conditions (C1–C6) and composite scores (Com)

Age groups, y	*Test conditions*						
	C1	*C2*	*C3*	*C4*	*C5*	*C6*	*Com*
3–4 to 5–6	$p\leq0.01$	–	–	–	$p\leq0.01$	$p\leq0.01$	$p\leq0.01$
5–6 to 7–8	$p\leq0.01$	–	–	$p\leq0.05$	–	–	–
7–8 to 9–10	–	$p\leq0.05$	–	–	–	–	–
9–10 to11–12	–		$p\leq0.01$	$p\leq0.05$	–	$p\leq0.01$	$p\leq0.01$
11–12 to 13–14	–	–	–	–	–	–	–
13–14 to 15–16	–	–	–	–	$p\leq0.05$	–	$p\leq0.01$
15–16 to adult	–	–	–	–	–	–	–

for the six test conditions showed a great increase in standing stability in children from 5 to 10 years of age. Standing stability reached adult levels at the age 7–8 years for C1. C2 and C3 showed a smaller increase in standing stability in older children; adult-like patterns were observed by the age of 9–10 years (C2), and 11–12 years (C3). The same results were reported by Hirabayashi and Iwasaki (1995). Other authors, like Riach and Hayes (1987), suggested that standing stability in C1 and C2 reached adult level by the age of 9 to 11 years; Aust (1996) reported this to be 12 years.

Using the Romberg quotient, calculated as the ratio of C2:C1, the current results, like those of Hirabayashi and Iwasaki (1995), showed nearly no change after age 3–4 years. Therefore, maturation of the proprioceptive function of standing stability can be assumed at this age.

Visual input plays a significant role in posture control, especially when the support surface is unstable (Lee and Lishmann 1975, Bles and de Jong 1986). The influence of gaze fixation was clearly demonstrated in the current study, as children in each age group showed better posture control when standing with their eyes open than with their eyes closed (C2; Odenrick and Sandstedt 1984, Aust 1996). Focusing on a colour picture enhanced attention. Riach and Hayes (1987) reported contrary behaviour in children younger than 8 years of age and attributed this to reduced vigilance and an inability to make effective use of a fixed retinal image. However, the current study did not show similar results.

Lee and Aronson (1974) and Brandt et al. (1976) suggested that visual proprioception is dominant over mechanical-vestibular proprioception in maintaining postural stability among young children who had recently learned to walk. Both studies demonstrated a decrease in standing stability in children under 5 years of age after exposing them to a moving visual field. Forssberg and Nashner (1982) also reported a destabilizing effect of a moving visual surround on children under 6 years 6 months of age.

However, Butterworth and Hicks (1977) and Forssberg and Nashner (1982) did not interpret their findings as proof of visual dominance but as an inability to establish the appropriate context-dependent weighting among the three senses and, therefore, to accomplish inter-sensory incongruence.

The current results demonstrate maturation of visual afference of posture control at the age of 15–16 years as previously described by Hirabayashi and Iwasaki (1995) and Aust (1996).

INTERSENSORY CONFLICT MANAGEMENT

Intersensory conflict requires vestibular information which is critical for balance as it controls the centre of gravity position (Nashner et al. 1982, 1989). Such conflict emerges when visual and proprioceptive inputs are incongruent, e.g. in C5 and C6 (Bles and de Jong 1986).

Lee and Aronson (1974) and Brandt et al. (1976) assumed vestibular dominance in adolescents and adults when an intersensory conflict occurred. The current study showed neither an increase in standing stability for the 15–16 year group for C5 and C6, nor a change in the ratio C5:C1 (reflecting vestibular afference) after 15–16 years. Thus, maturation of vestibular afference can be assumed in adolescents. Hirabayashi and Iwasaki (1995) performed their study under the same test conditions, but their results showed that the vestibular system was still developing at age of 14 to 15 years. Cherng et al. (2001) examined children from age 7 to 10 years and adults from 19 to 23 years. They reported incomplete vestibular development at age 10 years, whereas vestibular function in the 19 to 23-year-old group was already mature.

According to Shumway-Cook and Woollacott (1985), age 4 to 6 years may represent a period of transition, where children develop more adult-like sensory integration strategies for organizing redundant sensory inputs and resolving multi-modal sensory conflicts. The response patterns of the 7 to 10 year age group under altered sensory conditions were comparable to those of adults, suggesting that by this age maturation of organizational processes means that the integration of sensory inputs occurs in an adult-like fashion.

Foudriat et al. (1993) reported that 3-year-old children suppressed conflicting sensory inputs as the majority of children were able to complete the six test conditions. However, the current results were concordant with those of Forssberg and Nashner (1982), Riach and Hayes (1987), and Peterka and Black (1990). Forssberg and Nashner (1982) reported an increase in sway in children younger than age 7–8 years when they were exposed to conflicting visual and somatosensory information.

Riach and Hayes (1987) suggested that children do not show an adult-like pattern of standing stability until the age of 7 years, whereas Peterka and Black (1990) considered that children younger than 15 years differ from adults in relation to posture control. The current participants showed the same balance responses at the age of 15 years. Thus, maturation of the three sensory systems and the ability to solve an intersensory conflict situation can be assumed in adolescents.

DIFFERENCES IN STANDING STABILITY IN RELATION TO SEX

Females showed a greater rate of improvement in stability until the age of 11–12 years. Results indicated that younger males under the age of 10 years seemed to be less attentive and agitated. Odenrick and Sandstedt (1984) and Riach and Hayes (1987) noted that males younger than 10 years swayed more than females of the same age. Comparable results were described by Hirabayashi and Iwasaki (1995), who considered hyperactivity to be a responsible factor for maturational slowness in posture control seen in young males. Ayres (1978) found that the sensory system is not only important for balance control but also for higher central nervous functions, like attention and cognition, in conjunction with the vestibular system. Hirabayashi and Iwasaki supposed that delayed vestibular development could play a significant role in children with attention-deficit–hyperactivity disorder.

CLINICAL ASPECTS

This study provides normative data on postural balance and the influence of the proprioceptive, visual, and vestibular afferent systems in children from 3 to 16 years of age. Analysis of postural mechanisms in children and adolescents allows a better understanding of sensory system development. Characterizing balance impairments can contribute to the diagnostic evaluation of neuromotor disorders.

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