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Children achieve adult-like sensory integration during stance at 12-years-old

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Abstract

This study examined balance control in children to determine at what age the integration of sensory information in unperturbed stance is comparable to that of adults. In addition, it examined whether overall performance was related to age, gender and specific physical characteristics, such as height, weight and body mass index (BMI). Seventy-four female and 80 male children between the ages of 6 and 12 years participated in the study, as well as 20 adults, aged 20–22 years. The Sensory Organization Test (SOT), a component of computerized dynamic posturography, was used to assess overall balance as well as the use of specific sensory information in maintaining stability. Analyses of variance revealed significant differences between equilibrium scores of 7- and 8-year-old and 11- and 12-year-old ($p < .01$), with only the 12-year-old participants achieving scores comparable to those of the adult group. A repeated-measures analysis of variance comparing the use of different sensory information across age and gender groups revealed that while all groups demonstrated mature use of somatosensory information, children under 11 did not use visual information as effectively as adults, and only the 12-year-old group demonstrated adult-like use of vestibular information. Correlational analyses revealed a moderate correlation between composite balance scores and age, $r(152) = .38$, $p < .001$, but poor correlations between the composite equilibrium score and height, weight and BMI ($r < .13, p > .15$). Multiple regression analysis revealed that while physical characteristics accounted for approximately 20% of the variability in the composite equilibrium score, age alone accounted for the largest single contribution to the variance (16%). These results support recent findings suggesting that children do not demonstrate adult-like use of sensory information prior to age 12 years.

Keywords: Postural control; Balance; Development; Sensory organization

1. Introduction

The nature of the development of postural control has intrigued researchers for many years. A better understanding of balance and how and why postural control develops is important for many reasons. This knowledge would enable earlier detection of atypical postural development in children, provide better understanding and appreciation of the differences seen between individual and groups of children, and might also lead to improved interventions for children and adults with pathological balance impairments.

Postural control is a broad term used to describe a complex mixture of various abilities. Adequate postural control requires not only the ability to maintain quiet stance, but also the ability to maintain stability when perturbed or when actively moving a limb or the entire body, such as when reaching or when walking [1]. In order to coordinate the forces required for these tasks, an individual also must be able to organize sensory information, including visual, somatosensory and vestibular information.

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The different components of postural control have been studied extensively in children. Hayes and Riach [2] assessed quiet stance in children aged 2–14 years and found that amplitude of postural sway decreased with age, as did the variability of postural responses. Taguchi and Tada [3] reported that spontaneous sway during quiet stance was comparable to that of adults in children aged 9–12 with eyes open. Several studies have been conducted to assess compensatory postural control to perturbations to balance [4–6]. In general, these studies documented that children exhibited well-organized muscular responses to perturbations by 7–10 years of age, although the amplitude, latency and duration of the responses were greater than those of the adults.

Investigators have also examined how children use sensory information. Initial studies were conducted using a "moving room" in which the responses of sitting and standing infants and children were observed as the walls around them moved [7,8]. These methods were later replaced by computerized dynamic posturography (CDP). CDP is a tool used to assess the sensory and motor components of postural control, and includes different testing protocols, including the Sensory Organization Test (SOT), Motor Control Test (MCT) and the Adaptation Test (ADT) [9]. The Sensory Organization Test assesses use of sensory information by measuring postural sway during quiet stance while systematically manipulating sensory input, such as by eliminating visual input or by distorting somatosensory or visual information by sway-referencing the platform or visual surround. The method of sway-referencing involves tilting the platform or visual surround in an anterior–posterior direction in response to the individual's center of pressure movement in the anterior–posterior direction [9]. Sway-referencing provides inaccurate sensory input to the visual and somatosensory systems, enabling assessment of vestibular function and determination of how the three sensory inputs are weighted by the individual.

Using procedures similar to the SOT, Shumway-Cook and Woollacott [6] reported data that has for several years served as the standard timeline for postural development for educators, clinicians and researchers alike. After assessing 21 children ranging in age from 15 months to 10 years, they determined that children in the 7–10 years age group demonstrated mature postural control as evident by the presence of adult-like response synergies and the ability to resolve sensory conflict. Children younger than 7 years were unable to balance effectively when input from both the visual system and the somatosensory system was removed or altered.

In recent years, however, several studies have demonstrated that mature responses do not appear until much later in childhood or adolescence. Peterka and Black [10], in their investigation of 214 individuals ranging in age from 7 to 81 years, found that children younger than age 15 years demonstrated increased postural sway compared to adults when all sensory information was available and accurate. This sway was more pronounced in conditions of altered somatosensory cues. In their study of 112 Japanese children, Hirabayashi and Iwasaki [11] proposed that generalized postural stability had not reached adult level by age 15 years, nor had vestibular function for resolving sensory conflict. Three years later, Rine et al. [12] reported similar findings in that the oldest children in their study (age 7.5 years) swayed more than the adults, and scores measuring visual and vestibular function were significantly lower, as well.

While significant research has been done to study the timeline of postural control development, there is limited scientific evidence of physiological changes that lead to adult-like postural control in children. Immaturity of the sensory systems would seem a logical explanation for the differences seen between children and adults. However, from a physiological standpoint, the visual and vestibular systems are largely mature well before balance performance is adult-like. The components of the vestibular system, including the semicircular canals, otolith organs and the degree of myelination of the vestibular nerve are reported to be equivalent to those of adults at birth [13,14]. The degree of maturity of the visual system is more variable. While binocular vision is mature by 4–5 months of age and stereoacuity adult-like by 6–7 months [15], myelination of the visual pathway is not complete until around 2 years, and the retina is not mature until at least age 4 years [16]. This relative maturity of the sensory systems suggests that differences in postural control between children and adults are most likely attributable to other factors, such as processing or integration of visual, vestibular and somatosensory information.

In further efforts to explain the nature of postural control development, researchers have begun to investigate the influence of anthropometric characteristics, such as height, weight and body mass index (BMI) in addition to previously studied factors of chronological age and gender. Lebiedowska and Szcyewska [17] investigated the roles played by age, gender, body height and body mass on ability to maintain static stance for children aged 7–18 years. They found no difference for any of the variables between males ($n = 25$) and females ($n = 32$) in their sample. Furthermore, they reported no correlation between sway parameters (total path, length of sway sagitally and laterally, and velocity) and anthropometric characteristics when children were asked to maintain static stance with or without visual feedback, and only weak correlations negative correlations between age and sway parameters when children were given feedback [17]. In a similar study of postural sway with static stance, Odenrick and Sandstedt found greater sway amplitude in males ($n = 11$) than females under age 10 years ($n = 10$) [18]. Height and weight were not related to sway in females, and explained only 20% of the variability of sway in males.

As childhood obesity becomes more of a problem, with 15% of children between the ages of 6 and 19 years reporting a (BMI) at or above the 95th percentile [19], researchers have begun to question whether children with higher body mass indices mature from a postural control standpoint differently than children with lower body mass indices Currently, this relationship remains unclear. In their investigation of gait and postural stability in boys aged 8–10 years, McGraw et al. [20] reported greater sway in both the anterior–posterior and medial–lateral directions in obese boys ($n = 10$) as compared to age-matched non-obese boys ($n = 10$). These differences were greatest during conditions in which vision was absent or altered and when both vision and the base of support were changed. Non-obese boys demonstrated increased sway only during trials in which both vision and the base of support were altered. In contrast, Goulding et al. [21] found no significant differences between Equitest SOT scores or BalanceMaster limits of stability (LOS) scores for their sample of 25 overweight boys and 68 boys with healthy BMI, all aged 10–21 years.

Overall, there is a lack of consensus regarding the influence of age, gender and anthropometric characteristics on the development of postural control. Because the nature of this development remains largely undetermined, further study of the roles played by these variables is warranted. The objectives of the current study were to determine at what age children's postural sway in quiet stance, as well as their ability to use sensory information to maintain balance during unperturbed standing was comparable to adults' abilities, and to what extent physical characteristics, such as gender, height, weight and body mass index influenced these abilities.

2. Methods

2.1. Participants

Seventy-four female and 80 male children between the ages of 6 and 12 years participated in the study. All of the children were recruited from a Summer Sports Fitness Camp conducted by the Department of Kinesiology at the University of Illinois. This day camp is held each summer and is open to the general public. The population at the camp is comprised of a diverse group of children ages 6–12 years, including children of university faculty and staff, children living within the community and children living in outlying communities. Skill level is diverse as well, ranging from children involved in school athletics to children less skilled hoping to increase motor abilities. Twenty healthy young adults ($M = 21$, range=20–22 years, 11 females, 9 males) recruited from the university undergraduate population volunteered to participate in the study, as well (see Table 1 for participant demographics). Approval by the Institutional Review Board was obtained prior to data collection, and parental consent was obtained for all children at the beginning of the camp.

Table 1
Demographic information for gender and age groups

Age (years)	Females	Males	Total
6	4	5	9
7	14	12	26
8	14	21	35
9	20	16	36
10	9	11	20
11	7	11	18
12	5	4	9
Adult	11	9	20
Total	84	89	173

2.2. Procedure

The Equitest computerized dynamic posturography system (Clackamas, OR) was used in this study and has been shown to be reliable [22,23]. It consists of a force platform that can be sway-referenced (rotated around the ankle joints in response to an individual's postural adjustments measured by changes in center of foot pressure) as well as translated forward or backward. This device includes a visual surround that also can be sway-referenced. By systematically altering the movement of the visual surround, force platform and visual information (by having participants open or close their eyes), or in any combination of these, this device assesses an individual's ability to utilize information received by the somatosensory, visual and vestibular systems.

Standard protocol for administering the Sensory Organization Test was followed. For safety purposes, each

Table 2
Means and standard deviations of composite equilibrium scores

Age	SOT total			Standard deviation			Sample size		
	Males	Females	All	Males	Females	All	Males	Females	All
6	48.5	63	55.8	8.89	17.5	15	5	4	9
7	50.08	56.57	53.58	11.71	9.26	10.76	12	14	26
8	54.86	57.07	55.74	8.22	9.28	8.6	21	14	35
9	58.89	63.3	61.33	12.64	10.26	11.43	16	20	36
10	60.45	57.89	59.3	12.14	13.08	12.3	11	9	20
11	61.91	71.29	65.56	12.95	9.23	12.28	11	7	18
12	74.25	74.4	74.33	5.91	7.23	6.26	4	5	9
Adult	82.33	79.36	80.7	5.33	5.85	5.66	9	11	20

participant wore a harness attached to an overhead bar throughout testing. The SOT includes six different conditions: (1) normal vision, fixed support; (2) eyes closed, fixed support; (3) vision sway-referenced, fixed support; (4) normal vision, support sway-referenced; (5) eyes closed, support surface sway-referenced; (6) vision and support surface both sway-referenced. Each trial lasts 20 s and is repeated twice with the exception of conditions 1 and 2, which are repeated only once. The first condition serves as a baseline from which other conditions are compared. For a complete description of the Equitest procedures, see Nashner [9].

For this investigation, composite equilibrium scores and sensory analysis scores were examined. The composite equilibrium score measures the overall level of performance on the SOT and is the weighted average of the six conditions, with greater emphasis placed on conditions 3 through 6 [9]. This score represents postural stability based on how close an individual sways in relation to his or her stability limits. (Ranges = 0–100, 0 indicates a fall and 100 indicates no postural sway.) The sensory analysis scores represent the influence of each sensory system on the individual's stability, and quantify the relative difference in scores between two conditions. The somatosensory ratio compares condition 2 to condition 1 and measures postural stability when vision is removed. The visual ratio compares condition 4 to condition 1 and measures the ability of the visual system to function when somatosensory input is removed by sway-referencing. The vestibular ratio compares condition 5 to condition 1, assessing the stability of the individual when both somatosensory and visual input have been removed by sway-referencing or eye closure, respectively. Finally, the visual preference ratio compares conditions 3 and 6 to conditions 2 and 5, and measures the degree to which the individual relies on visual information, regardless of its accuracy.

Table 3
Means and standard deviations for sensory subscores

	6	7	8	9	10	11	12	Adult
N	9	27	35	36	20	18	9	20
Somatosensory ratio								
Mean	1.01	.91	.95	.95	.99	1.00	.99	.96
S.D.	.19	.2	.06	.06	.29	.17	.04	.03
Vision ratio								
Mean	.72	.55	.62	.7	.69	.75	.87	.90
S.D.	.29	.22	.11	.19	.18	.22	.07	.89
Vestibular ratio								
Mean	.42	.37	.37	.45	.37	.49	.65	.77
S.D.	.27	.19	.18	.21	.22	.22	.10	.08
Preference ratio								
Mean	1.00	.91	.96	.96	.96	1.00	.96	.95
S.D.	.11	.23	.14	.15	.17	.15	.10	.05

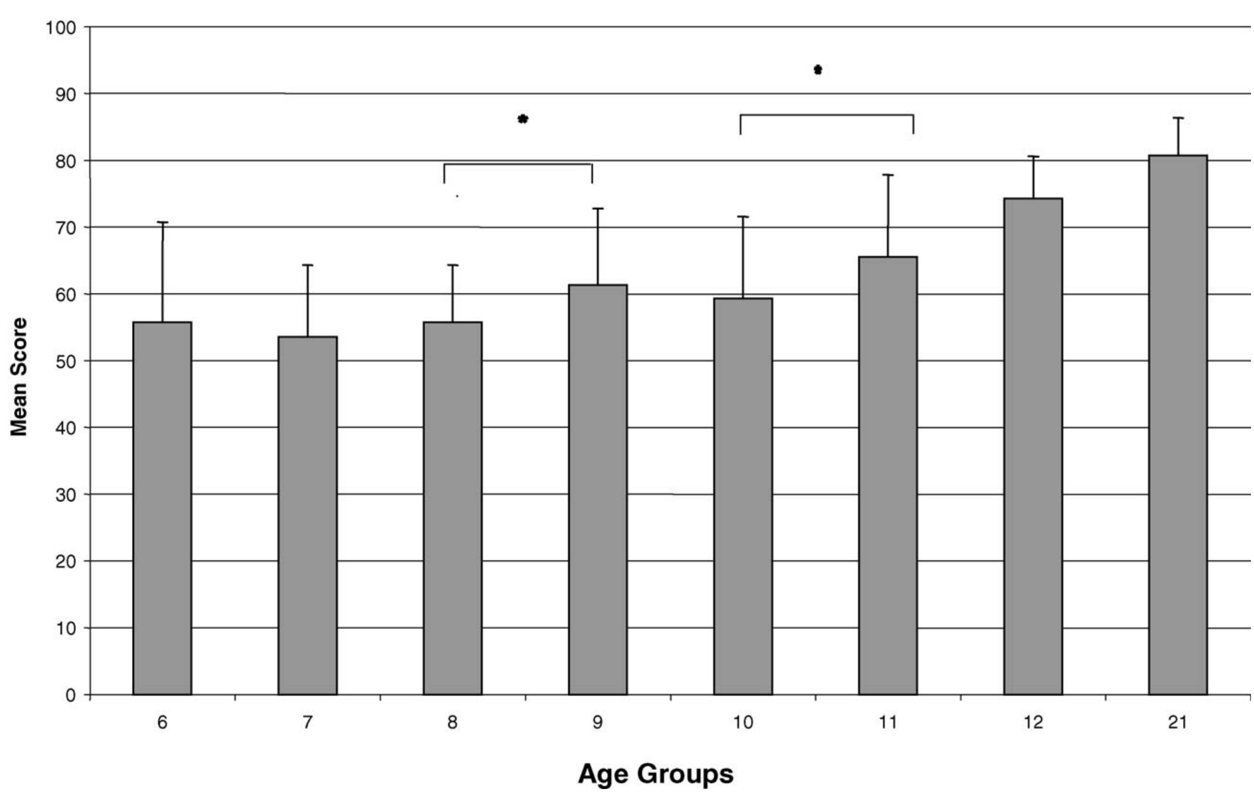

Fig. 1. Mean Equitest composite equilibrium scores (+S.E.) for each age group. Asterisks denote significant differences ($p < .01$) between neighboring age groups. Mean scores are based on a maximum score of 100.

3. Data analysis

A series of analyses were conducted to examine whether there were age and sex effects for overall balance performance and for the use of perceptual information. An eight (age: 6–12 years and adult) by two (gender: male, female) analysis of variance was conducted to examine the overall performance on the Equitest. This analysis was followed by a mixed eight (age) by two (gender) by four (subscore: somatosensory, visual, vestibular, preference) analysis of variance with repeated measures on subscores to examine differences in use of perceptual information across age and gender. Post hoc Tukey (HSD) tests were used to decompose significant main effects. Separate one-way analyses of variance were conducted to determine whether any difference in Equitest equilibrium scores existed when individuals were grouped in tertiles based on height, weight and body mass index percentiles. Simple correlations were calculated comparing variables including age in days, height, weight, BMI, composite equilibrium score and subscores, and partial correlations were run comparing the same variables while controlling for age. A standard multiple regression analysis was conducted to evaluate how well physical characteristics predicted the composite equilibrium score. Additional regression analyses were performed to determine the extent to which these same characteristics predicted each sensory subscore. An alpha level of .05 was used for all statistical tests.

4. Results

Means and standard deviations for all variables are presented in Tables 2 and 3. Fig. 1 shows mean composite equilibrium scores for each age group, as well as groupings based on statistical differences. The homogeneity of variance assumption was met for overall composite scores ($F = 1.63$, $p = .07$). There was a significant main effect for age group on composite equilibrium scores ($F(7,164) = 16.7$, $p < .01$). The 7- and 8-year-old had significantly lower equilibrium scores than the 11-, 12- and 21-year-old. Only the 12-year-old had scores similar to the 21-year-old (adults). A significant main effect for gender was obtained on the composite scores ($F(1,170) = 4.77$, $p = .03$). Overall, females outperformed males ($M_F = 65.4$, S.D. = 1.3; $M_M = 61.4$, S.D. = 1.3). No significant interactions between age and gender were obtained ($F(7,156) = 1.19$, $p = .31$).

Use of sensory information across age groups and gender is shown in Figs. 2a–d. There was a significant main effect for use of sensory information across all groups ($F(3,155) = 281.0$, $p < .01$). In addition, there was a significant interaction between use of sensory information and age ($F(21,471) = 3.46$, $p < .01$) and between use of sensory information and gender ($F(3,155) = 3.42$, $p = .019$), but no significant interaction was seen between use of sensory information, gender and age ($F(21,471) = .144$, $p = .310$). All of the younger groups demonstrated the ability to use somatosensory information comparable to the adults (Fig. 2a). Use of visual and vestibular information was different across age groups, however. The 7- and 8-year-old groups differed from the 11, 12 and adult groups in visual function (Fig. 2b), and differed from the 12 and adult groups in use of vestibular information (Fig. 2c). The 11- and 12-year-old groups demonstrated use of visual information comparable to adults, but only the 12-year-old showed similar vestibular function. The 7- and 8-year-old females demonstrated better use of vestibular information than their male peers, as evident by higher scores during conditions 3 and 6 on the SOT. There were no differences in visual preference scores between the age groups, indicating that no age group was more likely to be influenced by inaccurate visual input.

Although participants completed three trials within each condition, learning across trials was not evident for the most part. A comparison of the means for each trial in all conditions for each age group and gender revealed minimal differences between trials. One exception was condition 6, where the overall means increased from 33.4 (25.2) for trial 1 and 43.5 (25.7) for trial 3.

Correlational analyses were conducted to investigate the relationship between age, physical characteristics, composite scores and subscores on the Equitest (see Table 4). A moderate correlation was seen between age and composite equilibrium score, $r(154) = .38$, $p < .001$. However, when partial correlations were run to control for age, physical characteristics correlated poorly with the various Equitest scores, with r-values ranging from less than $-.01$ to .13 (see Table 5).

In order to investigate whether postural sway varied by height and/or weight, separate analyses were run, dividing participants by tertiles. Specifically, analyses were conducted on the total equilibrium score for percentile height (low, average, high), percentile weight (low, average, high) and BMI percentile (low, average, high) for each gender. The ''low'' tertile was comprised of children with a percentage between 0% and 25%, the ''medium'' was comprised of those between 26% and 74%, and the ''high'' group was comprised of those falling at or above the 75th percentile for height, weight or BMI, respectively. Separate comparisons were made for males and females; no significant differences in Equitest composite scores were seen between individuals in different tertiles for height, weight or BMI.

The standard multiple regression analysis for Equitest composite score revealed that physical characteristics, including age, gender, height, weight and BMI, accounted for a significant amount of the variability in the composite equilibrium score, $R^2 = .201$, adjusted $R^2 = .174$, $F(5,146) = 7.35$, $p < .001$ (see Table 6). The sample multiple correlation coefficient was .45, indicating that the combination of the above physical characteristics accounts for approximately 20% of the variability in score. Regarding the relative strength of the individual predictors, only the partial R-squares

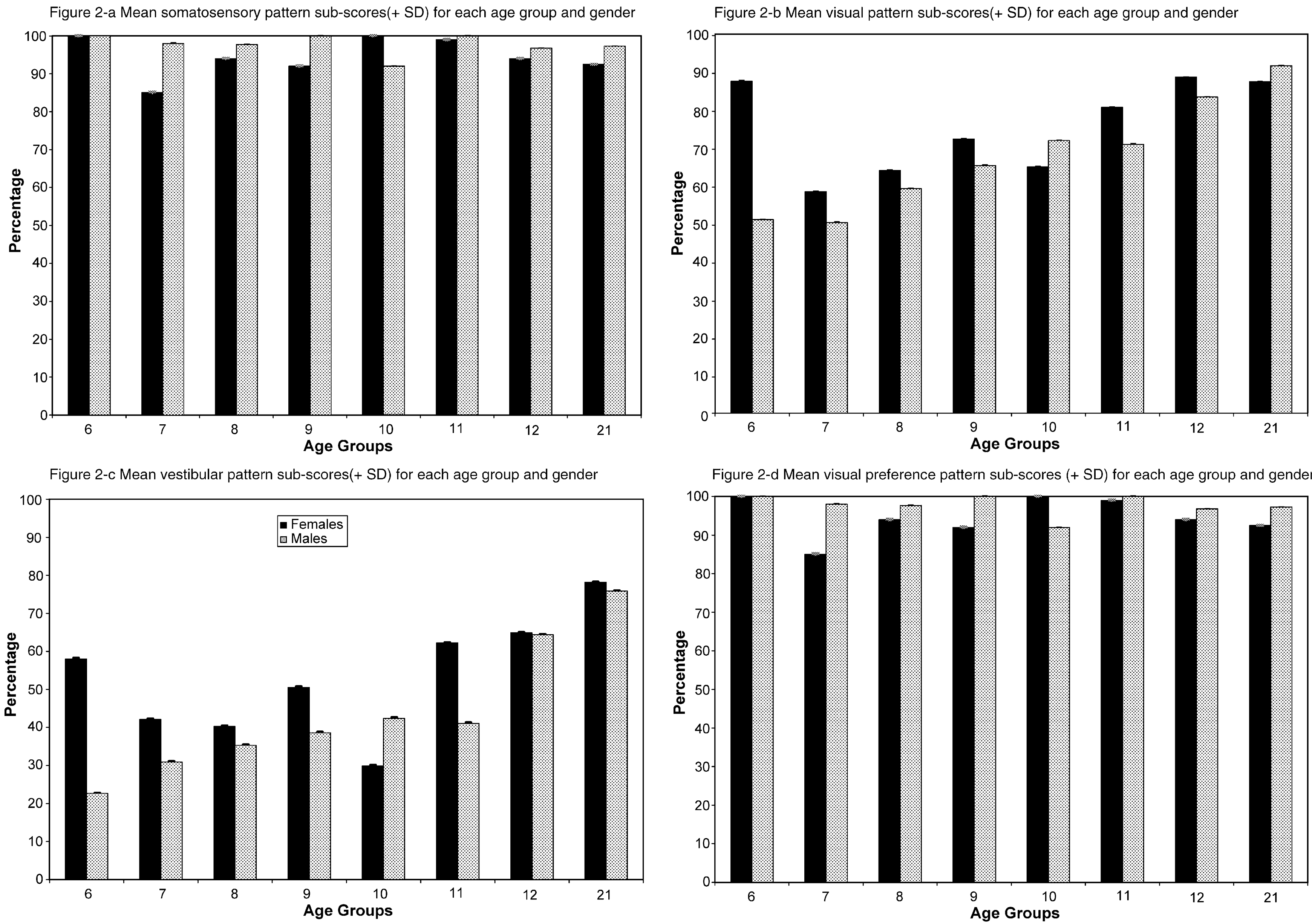

Fig. 2a–d. Use of perceptual information based on sub-scores for somatosensory, visual, vestibular, and visual preference patterns for each age group and gender. Standard deviations may be difficult to see, but are included as error bars for each value.

Table 4
Pearson correlations between physical characteristics and SOT scores ($N = 154$)

	Age (day)	Height (in.)	Weight (lb)	BMI	Height (%)	Weight (%)	BMI (%)	Equil. score	SOM	VIS	VEST	VIS PREF
Age (days)	1	.833**	.728**	.441**	.038	.091	.186*	.377**	.215*	.325**	.245**	.047
Height (in.)		1	.793**	.433**	.457**	.351**	.194**	.368**	.149	.322**	.184*	.198*
Weight (lb)			1	.882**	.295**	.580**	.584**	.330**	.139	.294**	.183	.205*
BMI				1	.085	.645**	.769**	.206*	.087	.192*	.128	.170*
Height (%)					1	.520**	.095	−.028	.032	.033	−.103	.149
Weight (%)						1	.776**	.085	−.019	.088	.012	.184*
BMI							1	.091	−.036	.078	.058	.120
Equil. score								1	.158	.826**	.859**	.151
SOM									1	.436**	.249**	.275**
VIS										1	.653**	.278**
VEST											1	−.104
VIS PREF												1

* $p < .05$.
** $p < .01$.

Table 5
Partial correlations, controlling for age, for physical characteristics and SOT scores ($N = 154$)

	Height (in.)	Weight (lb)	BMI	Height (%)	Weight (%)	BMI (%)	Equil. score	SOM	VIS	VEST	VIS PREF
Height (in.)	1	.495**	.156	.973**	.490**	.071	.129	−.088	.103	−.030	.152
Weight (lb)		1	.927**	.541**	.759**	.665**	.091	−.116	.090	−.008	.189
BMI			1	.280*	.722**	.790**	.022	.029	.053	.013	.144
Height (%)				1	.581	.194	.097	−.198	.063	−.098	.153
Weight (%)					1	.721**	.082	−.078	.068	−.001	.171
BMI (%)						1	.024	−.083	−.019	−.013	.117
Equil. Score							1	.125	.809**	.856**	.151
SOM								1	.415**	.230*	−.002
VIS									1	.625**	.180*
VEST										1	−.226
VIS PREF											1
Mean	53.6	78.7	18.9	68.2	76.7	71.6	59.4	.960	.668	.422	.966
S.D.	4.28	24.32	3.66	26.3	21.6	26.7	12.0	.11	.210	.211	.143

* $p < .05$.
** $p < .01$.

between gender and equilibrium score and age and equilibrium score were statistically significant. Age alone accounted for 16% of the overall 20% of variance, while gender accounted for 3.24%. Thus, height, weight and BMI accounted for almost none of the variance.

The regression analyses for the sensory subscores revealed mixed findings. Physical characteristics accounted for essentially none of the variability in the somatosensory subscore, $R^2 = .031$, adjusted $R^2 = -.002$, $F(5,148) = .936$, $p = .46$. In contrast, these variables accounted for 14% of the variability in the vision score ($R^2 = .141$, adjusted $R^2 = .112$, $F(5,147) = 4.83$, $p < .01$) and 12% of the vestibular score ($R^2 = .116$, adjusted $R^2 = .086$, $F(5,147) = 3.8$, $p < .01$) (see Table 7). However, for both of these subscores, age was again responsible for all but 3% of the variability.

Table 6
Standard multiple regression predicting Equitest composite score from physical characteristics ($N = 151$)

Predictor variables	Partial r	B	S.E. B	β	t	p
Age	.205	2.39	.94	.32	2.5	.01
Sex	−.192	−4.25	1.80	−.16	−2.4	.02
Height (in.)	−.022	−.26	.98	.09	−.26	.79
Weight (lb)	.046	.18	.32	.36	.56	.58
BMI	−.038	−.67	1.40	−.20	−.47	.64

5. Discussion

In our study, only the 12-year-old children demonstrated use of sensory information comparable to the adults. This was true both for overall performance on the SOT and for the use of vestibular information. These findings differ from earlier research that reported adult-like postural control, including overall amounts of postural sway, response to perturbations and the use of sensory information in children by age 7 years [5,6]. In contrast, our results are more in line with the findings of Peterka and Black [10], and Hirabayashi and Iwasaki [11]. Both groups found greater postural sway under altered sensory conditions for individuals up to 15-year-old when compared with adult participants.

Several possible factors may explain the conflicting findings, including larger sample sizes and advances in technology. For example, the findings of Shumway-Cook

Table 7
Standard multiple regression predicting sensory subscores from physical characteristics ($N = 152$)

Predictor variables	Partial *r*	*B*	S.E. *B*	*β*	*t*	*p*
Somatosensory						
Age	.071	.009	.010	.041	.861	.391
Sex	.018	.004	.019	−.018	.222	.825
Height (in.)	−.037	−.005	.010	−.174	−.454	.651
Weight (lb)	.052	.002	.003	.446	.632	.528
BMI	−.049	−.009	.015	−.288	−.602	.548
Vision						
Age	.126	.026	.017	.199	1.53	.127
Sex	−.159	− .064	.033	−.153	−1.97	.052
Height (in.)	.012	.003	.018	.051	.141	.888
Weight (lb)	.020	.001	.006	.158	.237	.813
BMI	−.009	−.003	.026	−.049	−.108	.914
Vestibular						
Age	.200	.043	.018	.326	2.48	.015
Sex	−.228	−.094	.033	−.224	−2.89	.005
Height (in.)	−.044	−.010	.018	−.198	−.539	.591
Weight (lb)	.022	.002	.006	.181	.267	.790
BMI	−.014	.005	.026	−.079	−.171	.864
Visual preference						
Age	−.089	−.017	.015	−.147	−1.08	.28
Sex	.113	.040	.029	.112	1.38	.169
Height (in.)	.111	.021	.016	.512	1.36	.175
Weight (lb)	−.956	−.003	.005	−.468	−.676	.500
BMI	.074	.021	.023	.421	.897	.371

and Woollacott [6] have been cited widely; however, these findings are based on a sample of 21 children ranging in age from 15 months to 10 years, with six or less children in each age group. In addition to the small sample size, their findings are limited because the experiments did not include conditions that examined the visual (visual surroundings sway-referenced) and vestibular (both the platform and the visual surround sway-referenced) function independently, two of the major contributors of postural control [9]. This omission strengthens the claims of the current study and those of several others [10–12], which report that vestibular maturity for resolving sensory conflict occurs at a later age.

In the present study, the regression analysis attributed approximately 20% of the variability in equilibrium scores to the physical characteristics of age, gender, height, weight and BMI. These results are quite similar to those reported by Odenrick and Sandstedt [18], in which the standard deviation of the sway was explained to 20% by age, height and weight for the males in their sample. However, of these variables only age and gender were found to make significant independent contributions to the variability in equilibrium scores.

As has been reported in previous studies [2,11,18], the females performed better overall on the SOT. In addition, 7- and 8-year-old females performed better in conditions 3 and 6, which were designed to assess ability to use information obtained by the vestibular system. There are several possible explanations for this superior performance. If development of postural control is influenced by activity and experience, it would seem that active children would demonstrate superior performance with testing. However, many observational studies of physical activity in children have reported that males spend more time engaged in physical activity than females [24–26]. The differences between genders observed in this study may be due to the task being studied. The SOT requires the individual to stand quietly while focusing on available sensory information. If males tend to spend more time engaged in moderate-to-vigorous physical activity (MVPA), such as running, jumping and throwing [26], they are less likely to spend time performing static activities that require attention. Female children may choose to spend more time engaged in activities that require integration of sensory information for static activities, such as ballet and gymnastics. Also, these types of activities include rolling, spinning and other rotational movements, which stimulate the vestibular system [27]. This may explain the higher scores for use of vestibular information observed in the 7- and 8-year-old females.

This study presents several points to consider in gaining a better understanding of sensory integration for the maintenance of standing balance. Our results, when considered with those of Peterka and Black [10], Hirabayashi and Iwasaki [11] and Rine et al. [12], provide sufficient data to question the timelines for postural development established previously [5,6]. In these recent investigations, children at the age of 7 years did not show mature postural responses, whether considering postural sway with quiet stance or when evaluating the use of sensory information. Importantly, these conclusions are based on data from significantly larger sample sizes and more specific age ranges. This information is important in setting expectations for what is normal versus delayed in older children; educators, clinicians and parents can use this knowledge for planning appropriate learning activities, designing treatment plans and establishing age-appropriate goals and expectations.

While this study does present with significant strengths, there are limitations, as well. The 6-year-old age group was relatively small ($n = 9$) and showed high variability, thus providing less conclusive data. Although this group was less variable, the 12-year-old group was small, as well. Increasing the size of this group would strengthen the conclusions since this was the "threshold" age for the emergence of mature postural control. It also would be beneficial to include older adolescents in a similar investigation. This would either provide evidence to strengthen the claim that mature postural responses emerge around age 12 years, or it would provide evidence to suggest that these responses mature even later. The most important limitation is that we assessed only children's ability to utilize sensory information to maintain static stance. These results do not predict how individuals of different ages or with different physical characteristics will perform under dynamic conditions, such as with an external perturbation or during gait.

Our results demonstrated that physical characteristics play a small role in postural control during unperturbed stance, but that age is the most significant predictor. However, we have accounted for only 20% of the variability in postural control. The main question arising from these results is that of what factors comprise the remaining 80%. At this time, no one has identified what is truly responsible for the development of integration of sensory information as an individual ages. Perhaps this is because postural control is a process that is more complex than the techniques developed to study it. The lack of explanation offered from either physiological immaturity or physical characteristics does suggest that postural control is not bound by fixed properties, but can be modified through intervention. If individuals perform differently based on the ability to attend to the task or better utilize sensory information, it would seem reasonable that training in these areas would improve performance. This potential for training is evident by the learning effect observed in condition 6—children overall demonstrated significantly less sway over the three trials. This is likely due to the children increasing the attention paid to the task, thereby allowing them to make better use of the sensory information that was being received. The development of a system that truly assesses postural control under numerous and varied conditions that challenge each individual's abilities, rather than only one or two components, will allow a clearer understanding of the factors influencing balance development, as well as the possibilities for influencing this development.

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References

[1] Shumway-Cook A, Woollacott MH. Normal postural control. Motor control: theory and practical applications. Philadelphia, PA: Lippincott Williams, and Wilkins, 2001. p. 163–191.

[2] Hayes KC, Riach CL. Maturation of postural sway in young children. Dev Med Child Neurol 1987;29:650–8.

[3] Taguchi K, Tada C. Change in body sway with growth of children. In: Amblard B, Berthoz A, Clarac F, editors. Posture and gait: development, adaptation, and modulation. Amsterdam: Elsevier; 1988. p. 59–65.

[4] Berger W, Quintern J, Dietz V. Stance and gait perturbations in children: developmental aspects of compensatory mechanisms. Electroencephalog Clin Neurophysiol 1985;61:385–95.

[5] Forssberg H, Nashner LM. Ontogenetic development of postural control in man: adaptation to altered support and visual conditions during stance. J Neurosci 1982;2:545–52.

[6] Shumway-Cook A, Woollacott MH. The growth of stability: postural control from a developmental perspective. J Mot Behav 1985;17(2): 131–47.

[7] Bertenthal BI, Bai DL. Infants' sensitivity of optical flow for controlling posture. Dev Psychol 1989;25:936–45.

[8] Butterworth G, Hicks L. Visual proprioception and postural stability in infancy. A developmental study. Perception 1977;6:255–62.

[9] Nashner LM. Computerized dynamic posturography. In: Jacobson GP, Newman CW, Kantush JM, editors. Handbook of balance function testing. St. Louis, Missouri: Mosby-Year Book; 1993 . p. 280–307.

[10] Peterka RJ, Black FO. Age-related changes in human posture control: sensory organization tests. J Vest Res 1990;1:73–85.

[11] Hirabayashi S, Iwasaki Y. Developmental perspective of sensory organization on postural control. Brain Dev 1995;17:111–3.

[12] Rine RM, Rubish K, Feeney C. Measurement of sensory system effectiveness and maturational changes in postural control in young children. Pediatr Phys Ther 1998;10:16–22.

[13] Dayal VS, Farkashidy J, Kokshanian A. Embryology of the ear. Can J Otolaryngol 1973;2:136–42.

[14] Bergstrom B. Morphology of the vestibular nerve. Part I. Anatomical studies of the vestibular nerve in man. Acta Otolaryngol 1973;76: 162–72.

[15] Neuringer M, Jeffrey BG. Visual development: neural basis and new assessment methods. J Pediatr 2003;87–95.

[16] Brecelj J. From immature to mature pattern ERG and VEP. Doc Opthalmol 2003;107:215–24.

[17] Lebiedowska MK, Syczewska M. Invariant sway properties in children. Gait Posture 2000;12:200–4.

[18] Odenrick P, Sandstedt P. Development of postural sway in the normal child. Hum Neurobiol 1984;3:241–4.

[19] Prevalence of Overweight Among Children and Adolescents: United States, 1999–2000 (n.d). Retrieved December 19, 2003 from: http://www.cdc.gov/nchs/data/hus/tables/20003/03hus069.pdf.

[20] McGraw B, McClenaghan BA, Williams HG, Dickerson J, Ward DS. Gait and postural stability in obese and nonobese prepubertal boys. Arch Phys Med Rehabil 2000;81:484–9.

[21] Goulding A, Jones IE, Taylor JM, Piggot JM, Taylor D. Dynamic and static tests of balance and postural sway in boys: effects of previous wrist bone fracture and high adiposity. Gait Posture 2003; 17:136–41.

[22] Ford-Smith CD, Wyman JF, Elswick RK, Fernandez T, Newton RA. Test–retest reliability of the sensory organization test in noninstitutionalized older adults. Arch Phys Med Rehabil 1995;76:77–81.

[23] Sharpe MH, Bamford E. Test–retest reliability of the sensory organization test in normal adults. In: Woollacott M, Horak F, editors. Posture and gait control mechanisms, 1. 1992. p. 234–7.

[24] Nader PR. Frequency and intensity of activity of third-grade children in physical education. Arch Pediatr Adolesc Med 2003; 157:185–90.

[25] Eaton WO, Yu AP. Are sex differences in child motor activity level a function of sex differences in maturational status? Child Dev 1989;60:1005–11.

[26] Mota J, Santos P, Guerra S, Ribeiro JC, Duarte JA. Patterns of daily physical activity during school days in children and adolescents. Am J Hum Biol 2003;15:547–53.

[27] Bundy AC, Lane SJ, Murray EA. Sensory integration: theory and practice. Philadelphia, PA: F.A. Davis; 2002. p. 71–92.