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Postural balance under normal and altered sensory conditions in normal-weight and overweight children

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ABSTRACT

Background: Little or no research has been done in the overweight child on the relative contribution of multisensory information to maintain postural stability. Therefore, the purpose of this study was to investigate postural balance control under normal and experimentally altered sensory conditions in normal-weight versus overweight children.

Methods: Sixty children were stratified into a younger (7–9 yr) and an older age group (10–12 yr). Participants were also classified as normal-weight (n = 22) or overweight (n = 38), according to the international BMI cut-off points for children. Postural stability was assessed during quiet bilateral stance in four sensory conditions (eyes open or closed, normal or reduced plantar sensation), using a Kistler force plate to quantify COP dynamics. Coefficients of variation were calculated as well to describe intra-individual variability.

Findings: Removal of vision resulted in systematically higher amounts of postural sway, but no significant BMI group differences were demonstrated across sensory conditions. However, under normal conditions lower plantar cutaneous sensation was associated with higher COP velocities and maximal excursion of the COP in the medial-lateral direction for the overweight group. Regardless of condition, higher variability was shown in the overweight children within the 7–9 yr old subgroup for postural sway velocity, and more specifically medial–lateral velocity.

Interpretation: In spite of these subtle differences, results did not establish any clear underlying sensory organization impairments that may affect standing balance performance in overweight children compared to normal-weight peers. Consequently, it is believed that other factors account for overweight children's functional balance deficiencies.

1. Introduction

As an inherent factor of movement, adequate postural stability is crucial for general motor development as well as the performance of daily life activities (Westcott et al., 1997). Even during quiet stance, continuous adjustments of muscle activity and joint position occur in anticipation and response to the integration of sensory information from visual, vestibular, and somatosensory inputs, all of which contribute to postural balance (Horak, 1987; Peterka, 2002; Winter, 1995). Although children are able to resolve sensory conflict situations from an early age, more adaptive and fully mature postural balance responses generally occur later in childhood due to the complexity of context-dependent multisensory reweighting (Bair et al., 2007; Cherng et al., 2001; Rine et al., 1998). Despite clear evidence for non-optimal motor development in overweight and obese children, research examining the impact of excess body mass on children's postural balance function is limited and not yet fully understood (D'Hondt et al., 2009; D'Hondt et al., in press; Okely et al., 2004).

A few studies investigated balance and postural skills in overweight and obese children using standardized field tests. Goulding et al. (2003) reported an inverse relationship between different measures of adiposity and performance scores on the Bruininks–Oseretsky sub-test of balance. Similarly, Deforche et al. (2009) found lower competence in overweight versus normal-weight prepubertal boys when performing several static and dynamic balance tasks related to activities of daily living. Research has also shown that approximately 20% of the variance in Movement Assessment Battery for Children balance sub-scores could

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be explained by children's body mass index (BMI) (D'Hondt et al., 2009). Overall, clinical measures of stability suggest that overweight and obesity impose significant constraints on children's functional balance performance.

Beyond clinical assessment, computerized posturography allows a more detailed analysis of postural stability, using force platforms to quantify centre of pressure (COP) dynamics. However, only a limited number of studies have applied this more comprehensive approach to provide additional information on postural balance control in overweight and obese children. McGraw et al. (2000) demonstrated decreased postural stability in obese versus non-obese prepubertal boys during quiet stance. Significantly greater COP displacement and variability were observed, primarily in the medial–lateral direction. As challenges to the visual system (i.e., conflicting or eliminated visual feedback) accentuated these differences between groups, the authors suggested that obese boys are more dependent on vision to control postural stability than non-obese peers. Conversely, other studies concluded that childhood obesity does not strongly alter postural control and balance impairments are small in magnitude (Bernard et al., 2003; Colné et al., 2008). Bernard et al. (2003) reported no significant differences in postural balance of obese and normal-weight adolescents during modified visual conditions; however, greater COP displacement occurred in obese children when somatosensory input was altered (i.e., foam support surface). In line with other recent research, the above-mentioned findings suggest that the less stable posture observed in overweight and obese children is probably not only the result of their excess body mass, but could also result from an impaired sensory-motor control system (Bernard et al., 2003; Colné et al., 2008; Hue et al., 2007; Wang et al., 2008; Wearing et al., 2006).

Nevertheless, little or no research has been done in the overweight or obese child to elucidate possible deficiencies in the integration of multisensory information and its relative contribution to standing balance. Therefore, the purpose of the present study was to investigate the effect of normal and experimentally altered sensory conditions on postural balance control during quiet bilateral stance in normal-weight versus overweight children. It was hypothesized that overweight children would have greater difficulty maintaining postural stability during more challenging sensory conditions with altered visual and/or somatosensory inputs.

2. Methods

2.1. Participants

Sixty children (aged 7–12 yr) participated in this study. Participants were stratified into a younger (aged 7–9 yr, n = 19) and an older age group (aged 10–12 yr, n = 41). The total sample was further classified as normal-weight (n = 22) or overweight (n = 38), according to international BMI cut-off points relative to age and gender (Cole et al., 2000). The overweight group consisted of both overweight (n = 8) and obese (n = 30) participants. They were recruited from a local medical treatment centre (Zeepreventorium VZW, De Haan, Belgium) and assessed during the first month of a multidisciplinary inpatient weight management program (6–10 months). Written informed consent was obtained from all participants and their guardians. The experimental protocol of this study was approved by the Ethical Committee of the Ghent University Hospital.

2.2. Materials and procedure

2.2.1. Anthropometry

Participants were barefoot and wore minimal clothing. Height (0.1 cm) was measured using a stadiometer (Harpenden; Holtain Ltd., Crymych, UK). Body weight (0.1 kg) and percentage body fat (0.1 %) were computed using a digital balance scale, with bioelectrical impedance analysis indirectly measuring body composition (Tanita BC-420; Weda B.V., Naarden, Holland). BMI was calculated as body weight divided by square height (kg/m^2). Using a large sliding calliper (Campbell 20; Rosscraft Innovations Inc., Vancouver, Canada), foot length (0.1 cm) was determined as the distance between the most posterior aspect of the calcaneus and the tip of the most distal phalange. Using a small sliding bone calliper (Campbell 10; Rosscraft Innovations Inc., Vancouver, Canada), foot width (0.1 cm) was determined as the distance between the most external points of the first and fifth metatarsal head. Measurements of left and right foot were averaged together.

2.2.2. Postural balance

A Kistler force platform (Kistler 9281-B11, 0.6 m × 0.4 m; Kistler Instruments Corp., Winterthur, Switzerland) was used to assess postural balance control in quiet bipedal stance. Participants were instructed to stand as still as possible in a relaxed upright position with their feet parallel on predetermined marks (10 cm apart) and with their arms hanging against the thighs. The experiment consisted of four sensory conditions, with varied combinations of visual and somatosensory input: (1) normal plantar sensation with eyes open (EO_{normal}), (2) normal plantar sensation with eyes closed (EC_{normal}), (3) reduced plantar sensation with eyes open ($EO_{reduced}$), and (4) reduced plantar sensation with eyes closed ($EC_{reduced}$). In the eyes open conditions, participants were asked to look at a target 2.5 m in front of them. In the eyes closed conditions, a blindfold was used to assure the absence of visual feedback. Considering the differences in weight status of our participants, preference was given to an ice immersion desensitization protocol rather than increasing the compliance of the supporting surface using foam to alter the function of the somatosensory system. Prior to the reduced plantar sensation conditions, participants immersed the plantar surface of both feet in an ice water bath (0–5 °C) for 5 min. The reduced plantar sensation conditions were completed consecutively so that participants were only required to complete one 5-min ice immersion. This resulted in eight possible series of conditions that were presented in a randomized order. Participants completed three successive 30-s trials in each sensory condition. An audible signal was generated by the computer to announce the start and the end of each measurement period. In between trials participants stepped off the platform, allowing them an opportunity to refocus.

2.2.3. Plantar cutaneous sensation

Using Semmes–Weinstein monofilaments (SWMF; Benefitsnow Ltd., Isle of Wight, UK), plantar cutaneous sensation was assessed as a baseline measurement prior to balance testing. A second set of measurements was taken at the completion of the desensitized conditions, immediately following an additional min of ice immersion. Five plantar sites of the right foot were tested, including the heel, the plantar aspect of the first and fifth metatarsal head, the hallux, and the fifth toe using a set of five nylon filaments (index numbers 6.65, 4.56, 4.31, 3.61, and 2.83) designed to produce a specific application force proportional to their diameters (theoretical values of 447 g, 3.63 g, 2.06 g, 0.408 g, and 0.068 g, respectively) (Bell-Krotoski, 2002; Semmes et al., 1960; Weinstein, 1993). Filaments were presented in a descending order to gradually increase task difficulty with decreasing application force, testing each of the five plantar sites three times in a random order. Participants were blindfolded and asked to indicate the site where the filament touched the skin. If the verbal response was correct for at least two times, participants were awarded a positive score (1). If participants gave only one correct answer or did not sense the filament at all, they received a negative score (0). The number of sites per filament with intact sensation were added to produce a final SWMF score (range 0–25) (Hong et al., 2007; Kamei et al., 2005).

2.3. Data analysis

The force platform data were collected at a sampling rate of 240 Hz for 30 s. Orthogonal components of the ground reaction force and coordinates of the COP in the horizontal plane were stored. Data were filtered at 6 Hz with a second-order Butterworth filter (Robertson and Dowling, 2003). After the filtering process, only the middle 20 s of each trial were retained for further analysis to prevent poor preparation, loss of attention, or fatigue from affecting measurement outcome (Le Clair and Riach, 1996).

Using Matlab 7.8 software (The Mathworks Inc., Natick, MA, USA), the following COP parameters were calculated to analyze postural sway. Mean velocity of sway was calculated as total COP displacement divided by the duration of the trial for overall COP (V), as well as in medial–lateral (V_{ML}) and anterior–posterior (V_{AP}) directions. Sway area of the COP ($SWAY_{AREA}$) was estimated by fitting an ellipse to the data covering 85.35% of the COP displacement, using the method provided by Duarte and Zatsiorsky (2002). Mean sway amplitude of the COP ($SWAY_{AMPL}$) was defined as the divergence relative to the mean COP coordinate. Maximal excursion of the COP was calculated as the distance between the extreme COP data points in the medial–lateral (MAX_{ML}) and anterior–posterior (MAX_{AP}) directions. Additionally, coefficients of variation (CVs) were calculated as the percent ratio of the standard deviation to the mean (SD/mean × 100 (%)) to estimate intra-individual variability of COP parameters based on the participants' three trials per condition.

SPSS 16.0 software (SPSS Inc., Chicago, IL, USA) was used for statistical analyses. Independent samples t-tests were conducted to compare anthropometric characteristics between normal-weight and overweight participants. SWMF scores were assessed in a 2 × 2 [BMI group (normal-weight, overweight) × plantar sensation (normal, reduced)] repeated measures analysis of variance (ANOVA) to investigate BMI group differences, as well as to verify the effectiveness of our ice immersion desensitization protocol. Intra-class correlation coefficients (ICCs) were used to establish inter-trial reliability for each COP parameter across the three trials per condition. ICC (2,1) values ranged between 0.72 and 0.95, demonstrating good reliability and allowing the use of mean COP values per sensory condition as the dependent variables in the subsequent analyses. A 2 × 2 × 4 [BMI group (normal-weight, overweight) × age group (7–9 yr, 10–12 yr) × sensory condition (EO_{normal}, EC_{normal}, $EO_{reduced}$, $EC_{reduced}$)] repeated measures ANOVA was applied to both COP and CV parameters to study BMI group and age group differences in postural sway and variability during quiet bilateral stance across sensory conditions. When significant effects of sensory condition were shown, pairwise comparisons (LSD method) were used to determine differences among sensory conditions. Finally, Pearson correlation coefficients were calculated for both normal-weight and overweight participants to examine the relationship between plantar cutaneous sensation (SWMF scores) and postural sway (mean COP values per condition). Values of $P<0.05$ were considered statistically significant.

3. Results

Descriptive characteristics for both BMI groups are presented in Table 1. Compared to the normal-weight participants, overweight participants had significantly higher values for weight, BMI, and percentage of body fat ($P<0.001$), as well as foot width ($P<0.01$). No significant group differences were found for age, height, and foot length.

Table 1
Descriptive characteristics according to BMI group: mean (SD).

Characteristics	BMI group		Independent samples *t*-test	
	NW	OW	t value	*P* value
Age (yr)	11.1 (1.5)	10.6 (1.9)	1.215	0.229
Height (cm)	147.2 (11.0)	147.7 (12.3)	0.187	0.852
Weight (kg)	38.16 (7.92)	63.95 (17.95)	7.661	<0.001
Body fat (%)	18.67 (5.27)	37.54 (8.37)	9.521	<0.001
BMI (kg/m²)	17.41 (1.65)	28.81 (4.98)	12.954	<0.001
Foot length (cm)	22.7 (1.6)	23.2 (2.2)	0.869	0.389
Foot width (cm)	8.6 (0.7)	9.2 (0.8)	3.176	0.002

BMI: body mass index; NW: normal-weight group; OW: overweight group.

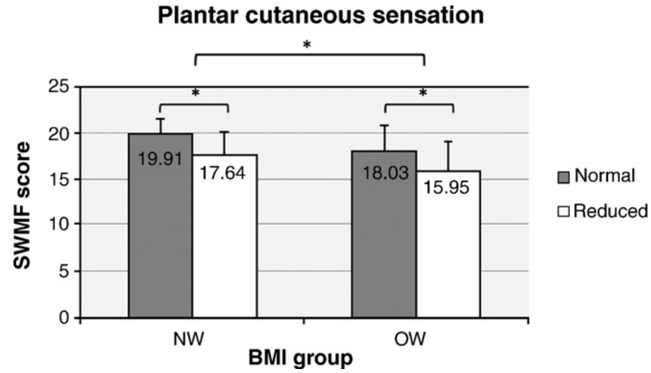

Fig. 1. Mean Semmes–Weinstein monofilaments scores (SWMF scores) observed in normal-weight (NW, gray blocks) and overweight (OW, white bocks) participants, before (normal) and after (reduced) a plantar desensitization protocol by means of ice immersion. Vertical bars represent standard deviation.

As shown in Fig. 1, ice immersion of the plantar surface of both feet resulted in a significant reduction of plantar cutaneous sensation for all participants ($F_{(1,58)} = 40.796$, $P<0.001$). Additionally, a main effect of BMI group revealed that overweight participants obtained significant lower mean SWMF scores compared to the normal-weight participants ($F_{(1,58)} = 7.512$, $P<0.01$). No BMI group × plantar sensation interaction effect was found ($F_{(1,58)} = 0.081$, $P = 0.777$).

Table 2 presents mean values and standard deviations of the total group for the COP parameters analyzed. The alteration of sensory condition had a significant effect on all COP parameters ($F_{(1,53)} = 2.845$–23.028, $P<0.05$). Pairwise comparisons revealed no significant differences between EO_{normal} and $EO_{reduced}$ conditions, or between EC_{normal} and $EC_{reduced}$ conditions. Hence, COP parameters mainly varied across sensory conditions due to the change in visual feedback. Regardless of desensitization, systematically higher COP values were found in EC versus EO conditions for all participants. No interaction effects or significant differences between BMI groups and age groups were observed.

Tables 3 and 4 show the mean values and standard deviations for the calculated CVs of the COP parameters. Looking at intra-individual variability, a three-way interaction was found for CV of MAX_{ML} ($F_{(1,53)} = 3.151$, $P = 0.033$). Subsequently, separate 2 × 4 (BMI group × sensory condition) repeated measure ANOVAs were computed for each age group. No BMI related effects were found in either age group. Only a significant effect of sensory condition was shown in the 10–12 yr old group ($F_{(1,38)} = 12.160$, $P<0.001$), with pairwise comparisons again revealing that differences between conditions were primarily based on the alteration of vision. Regardless of BMI group,

Table 2
COP parameters according to sensory condition for the total group: mean (SD).

COP parameter	Sensory condition			
	EO_{normal}	EC_{normal}	$EO_{reduced}$	$EC_{reduced}$
V (cm/s)	1.50 (0.56)*	1.76 (0.63)*	1.43 (0.54)*	1.84 (0.79)*
V_{ML} (cm/s)	0.81 (0.32)	0.90 (0.38)#	0.76 (0.30)*	0.96 (0.44)*,#
V_{AP} (cm/s)	1.08 (0.41)*	1.30 (0.45)*	1.03 (0.41)*	1.34 (0.56)*
$SWAY_{AREA}$ (cm²)	2.72 (2.72)	3.46 (2.34)	2.61 (1.84)*	3.74 (3.31)*
$SWAY_{AMPL}$ (mm)	6.03 (2.50)*	6.81 (2.50)*	6.02 (2.13)*	6.84 (2.56)*
MAX_{ML} (mm)	20.13 (8.44)*	22.89 (8.06)*	19.71 (7.50)*	24.69 (10.86)*
MAX_{AP} (mm)	24.85 (10.08)*	28.49 (9.81)*	24.68 (8.44)*	29.04 (10.04)*

*Significant difference between visual stimuli ($P<0.05$).
#Significant difference between somatosensory stimuli ($P<0.05$).
COP: centre of pressure; EO: eyes open; EC: eyes closed; V: velocity; V_{ML}: medial-lateral velocity; V_{AP}: anterior-posterior velocity; $SWAY_{AREA}$: sway area; $SWAY_{AMPL}$: sway amplitude; MAX_{ML}: maximal medial-lateral excursion; MAX_{AP}: maximal anterior-posterior excursion.

Table 3
CV parameters (V, V_{ML}, and V_{AP}) according to sensory condition, BMI group and age group: mean (SD).

CV parameter	BMI group	Age group	Sensory condition			
			EO_{normal}	EC_{normal}	$EO_{reduced}$	$EC_{reduced}$
CV of V (%)	NW	7–9 yr	8.52 (2.57)†	10.94 (3.03)	6.07 (2.39)†	9.41 (5.57)
		10–12 yr	14.75 (10.15)	13.05 (8.85)	14.48 (8.06)	15.04 (9.49)
	OW	7–9 yr	14.90 (6.37)†	14.13 (8.96)	18.22 (10.52)†	16.41 (12. 65)
		10–12 yr	12.64 (7.50)	14.02 (8.43)	12.78 (6.11)	14.81 (8.20)
CV of V_{ML} (%)	NW	7–9 yr	10.23 (1.00)†	13.53 (5.97)†	12.87 (4.17)	10.24 (6.15)†
		10–12 yr	17.82 (11.73)	17.67 (6.90)	19.07 (11.52)	16.45 (10.25)
	OW	7–9 yr	20.25 (9.48)†	24.68 (14.60)†	23.03 (16.79)	23.69 (14.90)†
		10–12 yr	17.27 (11.07)	14.67 (7.72)	17.12 (7.72)	18.94 (13.69)
CV of V_{AP} (%)	NW	7–9 yr	9.94 (3.95)	11.68 (2.53)	6.68 (1.93)	12.02 (5.83)
		10–12 yr	13.94 (10.06)	15.72 (7.35)	13.62 (9.09)	16.22 (10.15)
	OW	7–9 yr	14.77 (7.51)	14.21 (6.27)	15.65 (7.94)	13.44 (12.25)
		10–12 yr	13.17 (7.66)	17.20 (8.89)	13.61 (5.92)	14.06 (6.48)

†Significant difference between BMI groups ($P<0.05$).
CV: coefficient of variation; BMI: body mass index; NW: normal-weight group; OW: overweight group; EO: eyes open; EC: eyes closed; V: velocity; V_{ML}: medial-lateral velocity; V_{AP}: anterior-posterior velocity.

closing the eyes appeared to increase variability of MAX_{ML} in the 10–12 yr old sub-group. A significant BMI group × age group interaction for CV of V ($F_{(1,53)}=8.250$, $P=0.006$) and CV of V_{ML} ($F_{(1,53)}=10.994$, $P=0.002$) indicated higher intra-individual variability for the overweight participants compared to the normal-weight children within the 7–9 yr old sub-group, whereas both normal-weight and overweight 10–12 yr old participants demonstrated comparable CVs. Further, an age group × sensory condition interaction for CV of $SWAY_{AMPL}$ ($F_{(1,53)}=2.799$, $P=0.049$) revealed that all children in the younger group (7–9 yr) showed higher values compared to those in the older group (10–12 yr) during the $EO_{reduced}$ condition.

Finally, the overweight group produced significant correlations in the EO_{normal} condition for V ($r=-0.37$, $P=0.022$), V_{ML} ($r=-0.40$, $P=0.012$), V_{AP} ($r=-.33$, $P=0.041$), and MAX_{ML} ($r=-0.42$, $P=0.009$), with lower plantar cutaneous sensation (SWMF score) being associated with higher values for those COP parameters. No significant correlations were found in the altered sensory conditions, or for participants in the normal-weight group.

4. Discussion

The purpose of this study was to investigate postural balance control and the relative contribution of sensory information to the maintenance of stability during quiet bilateral stance under normal and experimentally altered sensory conditions in normal-weight versus overweight children.

Our results demonstrated that a 5-min ice immersion desensitization protocol effectively reduced sensation to the plantar surface of the feet in all participants. To our knowledge, ice immersion techniques were previously only conducted in adults (Hong et al., 2007; McKeon and Hertel, 2007; Stal et al., 2003). Therefore, the present research is the first published study to similarly alter the somatosensory input from the mechanoreceptors of children's feet. SWMF assessment also revealed a baseline difference in plantar cutaneous sensation between BMI groups, with overweight participants displaying lower scores before and after the plantar desensitization protocol. This finding confirms what has been suggested in previous research. Due to the continuous increased loading of the feet as a result of the excess body mass, childhood overweight and obesity cause substantial changes in foot structure (Dowling et al., 2001; Riddiford-Harland et al., 2000). Even from an early age, overweight and obese children display significantly larger foot dimensions, a more flattened medial longitudinal arch, larger contact areas with the ground, and increased plantar pressure values (Dowling et al., 2001; Mickle et al., 2006). The structural changes associated with excessive weight-bearing may also affect the functional capacities of the foot, characterized by a decrease in the quality of sensory information from the mechanoreceptors within the plantar surface, which could contribute to the maintenance of postural stability (Bernard et al., 2003; Hue et al., 2007).

In the present study, analysis of the dynamics of the COP indicated no marked differences in postural sway between overweight and normal-weight participants in any of the sensory conditions. All participants had systematically higher values for each calculated COP parameter while standing upright with eyes closed versus eyes open, indicating that the removal of vision had a more pronounced effect on postural balance performance than the experimental alteration of plantar cutaneous sensation. Therefore, our findings offer support for the important role of vision to control children's postural stability. As opposed to the assumption of McGraw et al. (2000), no increased visual dependency was revealed in the overweight group. Instead, we

Table 4
CV parameters ($SWAY_{AREA}$, $SWAY_{APMPL}$, MAX_{ML}, and MAX_{AP}) according to sensory condition and age group: mean (SD).

CV parameter	Age group	Sensory condition			
		EO_{normal}	EC_{normal}	$EO_{reduced}$	$EC_{reduced}$
CV of $SWAY_{AREA}$ (%)	7–9 yr	36.36 (14.27)	30.55 (19.38)	43.57 (24.95)	39.20 (23.67)
	10–12 yr	36.64 (22.57)	35.02 (17.20)	31.67 (15.14)	31.61 (20.58)
CV of $SWAY_{AMPL}$ (%)	7–9 yr	21.42 (12.12)	16.83 (8.96)	26.92 (13.05)‡	21.40 (10.54)
	10–12 yr	21.73 (13.17)	20.00 (9.31)	18.50 (9.32)‡	18.15 (11.55)
CV of MAX_{ML} (%)	7–9 yr	22.07 (8.05)	24.44 (8.13)	21.22 (7.16)	24.65 (8.20)
	10–12 yr	19.30 (8.44)*	22.23 (8.04)*	19.07 (7.63)*	24.71 (11.91)*
CV of MAX_{AP} (%)	7–9 yr	24.79 (11.47)	18.68 (9.13)	24.42 (12.05)	24.36 (14.74)
	10–12 yr	23.04 (12.51)	23.61 (15.01)	22.25 (12.01)	20.15 (8.70)

* Significant difference between visual stimuli ($P<0.05$).
‡ Significant difference between age groups ($P<0.05$).
CV: coefficient of variation; EO: eyes open; EC: eyes closed; $SWAY_{AREA}$: sway area; $SWAY_{AMPL}$: sway amplitude; MAX_{ML}: maximal medial-lateral excursion; MAX_{AP}: maximal anterior-posterior excursion.

found that childhood overweight did not appear to be associated with adverse postural control capacities during quiet stance, a suggestion made in previous studies (Bernard et al., 2003; Colné et al., 2008). Because overweight children did not show significantly different COP responses to the more challenging sensory conditions when compared to their normal-weight peers, this study could not demonstrate any underlying sensory organization impairments that may affect standing balance performance in overweight children. It therefore suggests that there is another underlying mechanism responsible for the significant constraint of overweight and obesity on children's functional performance, as demonstrated in clinical balance tests.

Although the analysis of COP parameters did not result in significant BMI related differences, inverse relationships between SWMF scores and the amount of postural sway (V, V_{ML}, $V_{AP,}$ and MAX_{ML}) were revealed in the overweight group during EO_{normal}. However, the reported correlations were only low to moderate probably because a single measure of sensory function was associated with overall balance performance. The lack of significant correlations in the altered sensory conditions ($EO_{reduced}$, EC_{normal}, and $EC_{reduced}$) might be explained by a global freezing strategy, which typically occurs when confronted with novel or difficult situations (Bernstein, 1967). The movement amplitude of the joints is minimized by means of increased muscle co-activation, making the body sway as a more stiffened inverted pendulum (Keshner, 1990; Kirshenbaum et al., 2001; Ko et al., 2003). Consequently, this strategy reduces the complexity of the sensory-motor system and maximizes the efficiency to control posture under given task constraints (Ko et al., 2003).

Age-related differences only emerged from the analysis of calculated CV parameters, which described intra-individual variability. Regardless of condition, increased variability was found in the younger (7–9 yr) overweight participants compared to their normal-weight peers for postural sway velocity (CV of V), and more specifically medial–lateral velocity (CV of V_{ML}). This finding is in agreement with the greater variability previously shown in obese versus non-obese prepubertal boys (McGraw et al., 2000). An increased intra-individual variability most likely indicates a less consistent and more immature control strategy. Therefore, it might be suggested that the sensory reweighting capacity of overweight children develops at a somewhat slower pace than in normal-weight peers. It also explains the comparable CVs observed in both normal-weight and overweight 10–12 yr old participants, when postural balance control is supposed to be more mature (Bair et al., 2007; Cherng et al., 2001; Rine et al., 1998). As a result of the reduction in plantar cutaneous sensation by means of ice immersion, all children in the younger group (7–9 yr) demonstrated higher intra-individual variability in sway amplitude relative to the mean COP coordinate (CV of $SWAY_{AMPL}$) when standing upright with their eyes open. The older children (10–12 yr) displayed a more precise control in $EO_{reduced}$ conditions, suggesting an earlier transition to the strategy of global freezing when sensory conditions are more challenging.

Our study is not without limitations. Participants' postural balance control was measured during quiet bilateral stance using a natural base of support. This less challenging foot position might explain the absence of marked BMI group differences in postural sway and balance control in static conditions. Offering a reduced base of support (i.e., feet together, tandem stance, and unilateral stance) may lead to more apparent differences in postural stability between overweight and normal-weight children, as is the case in dynamic balance tasks because of inertia properties (Deforche et al., 2009; Goulding et al., 2003). The desensitization protocol required the participants to immerse the plantar surface of their feet in ice water for 5 min. This technique effectively resulted in a significant reduction of plantar cutaneous sensation, but did not lead to substantial changes in postural sway. Although this protocol used a considerably shorter duration of ice immersion than previously reported techniques used in adult populations, the age of our participants precluded any extended period of desensitization (Hong et al., 2007; McKeon and Hertel, 2007; Stal et al., 2003). Moreover, because of the length of time necessary to complete SWMF assessment, no specific measures were taken to ensure the desensitization of the foot soles persisted throughout the duration of each trial in both $EO_{reduced}$ and $EC_{reduced}$ conditions. The limitations to our protocol could result in the lack of changes seen in postural sway. It has also been postulated that the use of traditional averaged sway parameters could fail to reveal subtle changes in COP dynamics and describe more complex aspects of postural control (McClenaghan et al., 1995; McKeon and Hertel, 2007). Therefore, future research should incorporate non-traditional methods of data analysis to provide greater insight in the behaviour of the COP in normal-weight versus overweight children.

5. Conclusions

The present study is a first step in gaining greater insight into the relative contribution of multisensory information to postural balance control in overweight versus normal-weight children. Despite the baseline differences in body mass and plantar cuteaneous sensation, overweight participants demonstrated no significantly increased amounts of sway during quiet bilateral stance under normal and experimentally altered sensory conditions. Therefore, this study did not establish any clear underlying sensory organization impairments that may affect standing balance in overweight children compared to normal-weight peers. It could then be suggested that another underlying mechanism accounts for overweight and obese children's functional balance deficiencies, as demonstrated in clinical balance tests. However, it is clear that the extent to which excess body mass affects sensory-motor function in children needs further investigation. Future research is also warranted to elucidate the exact nature of overweight children's postural control strategy and to identify its contribution to balance performance and motor skill competence in general.

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