Sport Sciences for Health (2026) 22:55
https://doi.org/10.1007/s11332-025-01621-5

RESEARCH

Postural control in children with obesity: a cross-sectional comparison with normal-weight peers

Vittoria Carnevale Pellino[1] · Valeria Calcaterra[2,3] · Alessandro Gatti[1,4] · Caterina Cavallo[1,5] · Simone Balconi[1] · Luca Marin[1] · Nicola Lovecchio[6] · Daniela Lucini[7,8] · Gianvincenzo Zuccotti[2,9] · Alessandro Marco De Nunzio[5,10] · Matteo Vandoni[1]

Received: 20 May 2025 / Revised: 05 November 2025 / Accepted: 5 December 2025 / Published online: 19 January 2026

Abstract

Background Childhood obesity is a global public health concern since an excess in body weight causes postural control problems and consequently leads to reduced motor control and impaired movement patterns with an increased risk of falls and injuries interfering with children's daily life activities. The use of posturographic analysis together with adiposity level investigation could improve the assessment of postural impairments leading to tailored and more effective therapeutic approaches. Therefore, the aim of the present study is to evaluate and compare the different strategies used to maintain postural control between normal-weight children and children with obesity.

Methods A total of 33 Caucasian children (14 with obesity) were recruited. Anthropometric indexes were computed from the anthropometric measurements. Participants stood in an upright standing position, barefoot on the stabilometric platform, and performed two 30 s trials (eyes open – EO, and eyes closed – EC).

Results Results revealed a difference in postural control only in the minimum sway parameter under both EO and EC conditions. The BMI z-score and TMI indexes were positively associated with the sway length, delta X, and minimum sway parameters in EO conditions, while fewer and weaker associations were found in the EC condition.

Conclusion Our study did not highlight postural control impairments in prepubertal children with obesity when compared to their normal-weight peers. Despite some significant positive associations with postural control parameters, both the BMI z-score and the TMI indexes do not clearly predict postural control impairments in prepubertal children.

Keywords Balance · Postural Control · Children with Obesity · Stabilometric Platform · Anthropometric Measures

✉ Caterina Cavallo
caterina.cavallo01@universitadipavia.it

[1] Laboratory of Adapted Motor Activity (LAMA), Department of Public Health, Experimental Medicine and Forensic Science, University of Pavia, 27100 Pavia, Italy

[2] Pediatric Department, Buzzi Children's Hospital, 20154 Milan, Italy

[3] Department of Internal Medicine, University of Pavia, 27100 Pavia, Italy

[4] National PhD Program in One Health approaches to infectious diseases and life science research, Department of Public Health, Experimental Medicine and Forensic Science, University of Pavia, 27100 Pavia, Italy

[5] Research and Development Department, LUNEX SA, ISNI0000 0004 7673 0018, 50, Avenue du Parc des Sports,, 4671 Differdange, Luxembourg

[6] Department of Human and Social Sciences, University of Bergamo, 24127 Bergamo, Italy

[7] BIOMETRA Department, University of Milan, 20129 Milan, Italy

[8] Exercise Medicine Unit, Istituto Auxologico Italiano, IRCCS, 20135 Milan, Italy

[9] Department of Biomedical and Clinical Science, University of Milan, 20157 Milan, Italy

[10] Luxembourg Health & Sport Sciences Research Institute a.s.b.l., 50, Avenue du Parc des Sports, 4671 Differdange, Luxembourg

Introduction

Childhood obesity is a global public health concern, especially in developing countries, counting more than 350 million children worldwide. The recent estimates report that more than 29% and 31% of school-age girls and boys in Italy live with obesity, respectively [1]. Children with obesity have a higher risk of developing cardiovascular and metabolic diseases, with increased co-morbidity and mortality rates during their adulthood lives [2–5]. Body mass index (BMI) is a widely used parameter for defining overweight and obesity [6]. However, BMI cannot be directly applied to children due to continuous changes in height and weight during growth. To account for these variations, BMI is adjusted for age and sex, resulting in the BMI z-score. This parameter, which is computed based on sex-adjusted growth curves, is used to define the cutoffs describing overweight and obesity status in children. Similarly to adult populations, higher values of the BMI z-score are associated with increased fat percentages, and they are considered risk factors for both cardiometabolic and neurological diseases [7–9].

Given the limitations of BMI in distinguishing between fat and lean mass, alternative indices have been proposed to assess body composition. For example, the tri-ponderal mass index (TMI) can be a valuable tool to assess body composition in children, and prior studies explored its potential use as a predictor of metabolic syndrome in pediatrics [10]. Furthermore, because BMI z-score does not differentiate between lean and fat mass, Hudda et al. [11] developed a non-linear equation incorporating weight, height, ethnicity, and age, which more accurately estimates body fat mass.

Beyond metabolic and cardiovascular risks, obesity also affects motor functions, including postural control. Impaired postural control is a well-documented issue in adults with obesity and is associated with an increased risk of fall-related injuries. Excess weight creates a larger moment of forces, especially at the ankle joint level, making postural control more challenging [12, 13]. Postural control refers to the ability to achieve, maintain, or restore a state of stability during any activity, such as walking, running, or only standing. To evaluate postural control, one of the gold standard procedures is the use of force platforms, especially under static conditions [14–16]. These technological devices measure postural oscillations and analyze the movement of the center of foot pressure (CoP), that is influenced by both the movements of the CoM and the mechanisms of neuromuscular control of the body [17, 18]. In adults with obesity, excess abdominal weight alters the position of the CoP, which results in a shift towards the anterior edge, consequently leading to the anterior displacement of the CoM. The forward shift of both the CoM and the CoP leads to the generation of larger torques that require appropriate counteracting muscle actions. Consequently, the variability and the speed of CoP increase in response to the greater amplitudes of the motor commands [19].

Although the link between obesity and postural control is well established in adults, the extent to which obesity affects postural control in children remains unclear. While some studies found that higher BMI z-score is associated with worse postural control [20], other studies did not find any relation between adiposity and postural control [21]. However, understanding this association is crucial since postural control is an indicator of musculoskeletal health and a higher active lifestyle in children [22]. Additionally, postural control is related to the development of fundamental motor and movement skills [23].

Since body mass estimations provide a more precise assessment of obesity in children, integrating posturographic analysis with adiposity assessments may improve the evaluation of postural dysfunctions associated with varying adiposity levels.

For these reasons, the first aim of this study was to evaluate the differences in postural control between normal-weight and children with obesity. The second aim was to evaluate the relationships between adiposity indexes and fat mass on postural control in children with obesity.

Materials and methods

Study design and participants

A cross-sectional study was conducted to determine the relationships between anthropometric characteristics and postural control (obtained from a bipedal posturographic assessment) performed under eyes open (EO) and eyes closed (EC) conditions. For each condition, time and frequency domain variables were obtained with a baropodometric platform from the motion of the CoP. A total of 14 Caucasian children with obesity (OB) of both sexes (6 females) were recruited using the non-probabilistic convenience sampling method from the endocrinology unit of the Buzzi children's hospital in Milan, Italy. Nineteen normal-weight (NW) children of both sexes (10 females) were recruited as the age-matched control group. Inclusion criteria were children of both sexes with BMI z-score below 1.0 standard deviation (SD) for the NW group and a BMI z-score above 2.0 SD for the OB group according to the BMI z-score cutoff provided by the World Health Organization (WHO) [24] and the ability to understand Italian. Exclusion criteria were cardiovascular and respiratory diseases, co-morbidities to OB, orthopedic injuries in the previous six months, and any condition that did not allow upright standing. The evaluators explained all the procedures to parents and children before the enrolment, and all participants were informed of the possibility of withdrawing from the study at any time without any repercussions. Parents, or legal guardians, and the adolescents gave their verbal and written informed consent. The sample size for the present investigation was determined in our previous study [25]. All procedures were in accordance with the Declaration of Helsinki [26] and were approved in advance by the ethics committee of Milano Area 1 (n. 2020/ST/298).

Anthropometric measurements

Anthropometric measurements were taken following the guidelines of the International Society for the Advancement of Kinanthropometry (ISAK) [27]. Weight was measured barefoot and in light clothing, standing in the middle of the scale platform (Seca, Hamburg, Germany) with hands along the trunk. Standing height was measured using a Harpenden stadiometer (Holtain Ltd., Cross-Well, UK) with a fixed vertical table and an adjustable head. The measurement was carried out with the subjects in an upright standing position, without shoes, and with their head in the horizontal plane of Frankfort. Two measurements were taken for each parameter, and a third was obtained if a discrepancy of 500 g and 0.5 cm was noted between the initial measurements. Anthropometric characteristics were then based on the average of the two closest measurements. BMI was calculated as body weight (kilograms, kg) divided by height squared (meters squared, m^2) and was transformed into BMI z-scores using WHO references [28]. Adiposity indexes including triponderal mass index (TMI) and fat mass were also calculated as follows:

i. TMI = weight (kg)/ height $(m)^3$ [29]; and
ii. Fat Mass = weight (kg) − exp[0.3073 × height2 − 10.0155 × weight − 1 + 0.004571 × weight − 0.9180 × ln(age) + 0.6488 × age0.5 + 0.04723 × male + 2.8055] [11]

(exp = exponential function, ln = natural logarithmic transformation, male = 1, female = 0).

Procedure and instrumentation

To avoid any interference with school commitments, all measurements were carried out in the afternoon from 4 to 6 pm. The assessments were carried out in the gait laboratory of the Buzzi hospital with a constant room temperature of 21 degrees Celsius. Participants stood barefoot on the stabilometric platform (FreeMed®, Sensormedica, Rome, Italy − 120 × 50 cm – sampling at 400 Hz) that was placed on a stable surface on the floor to avoid any distortion and signal disturbances.

The subjects were instructed to stand upright while maintaining their arms along the sides of their bodies. The evaluators asked participants to stand as still as possible. A visual target (5 cm in diameter) was placed at eye level and at a 2-m distance in front of the participant.

Two tests were performed for each subject: 30 s bipodal standing positions with eyes open (EO) and 30 s bipodal standing positions with eyes closed (EC). Participants stood with their feet positioned at a 30° angle between the longitudinal axes. A plastic positioning tool was used to standardize and speed up foot placement, then removed prior to measurement to prevent interference with COP recordings. Although 60 s trials are usually recommended to increase the reliability of postural control assessments, children up to the age of 12 years are unable to concentrate on such tasks for a long time. Also, a previous study showed good to excellent reliability indexes in typically developing children who performed three 10 s trials [30]. Therefore, 30 s trials were used to validly assess postural control in children of this age.

The stabilometric platform software extracted the sway area (SA; measured in mm^2, the area swept by the CoP motion) and the mediolateral and anteroposterior peak-to-peak oscillations of the CoP, defined as Delta *X* for the mediolateral axis and Delta *Y* for the anteroposterior axis.

Additional parameters were extracted by analyzing the orientation and shape of the confidence ellipse. The confidence ellipse is an ellipse covering 95% of the SA.

The ellipse eccentricity (EE) is defined as the ratio between the two axes of the confidence ellipse. The EE ranges from 0 to 1 and gives information about the shape of the confidence ellipse: when the EE is closer to 0, it indicates that the *X* axis and the *Y* axis have a similar length; hence, the ellipse is almost a circle. Conversely, an EE closer to 1 would indicate that the ellipse is flattened along one of the two axes. By its definition, this variable describes whether there is a preferred swaying direction, and it is correlated to the shape of the CoP displacement.

The ellipse inclination, which is expressed in degrees, is defined as the orientation in degrees of the main axis (or mediolateral axis) of the ellipse compared to the *Y* axis (or antero-posterior axis). The inclination of the ellipse gives information about postural symmetry [31].

Lastly, the ratio between the length of the sway path described by the movement of the CoP and the area of the ellipse containing the same sway path (L/S) was used as an indicator of postural energy expenditure [32]. A L/S ratio close to 1 indicates a healthy postural control, while a value lower than 1 can indicate (i) a reduced L, meaning that the subject uses little energy to keep a stable posture or (ii) an increased S when poor postural control leads to a wider CoP oscillation area [32].

Statistical analysis

To identify and correct transcription errors, all data were entered into a spreadsheet were carefully reviewed by a third researcher. Values are presented as means (95% confidence intervals, CI) for all variables. Children were excluded from the analysis if they had missing data. To evaluate the association between the adiposity indexes (BMI z-score, TMI, and fat mass) and the different outcomes of postural stability, we first conducted a bivariate correlation analysis, Pearson or Spearman, based on the data distribution and reported in the graphical representation. Then, we computed a linear regression analysis to analyze the relationship between postural stability and the adiposity indexes, adjusting for sex (Model 1), and further adjusting for age and sex (Model 2) as a sensitivity analysis. To further evaluate the differences between children with obesity and children with normal weight, groups using parametric or non-parametric analysis of covariance, as appropriate, adjusting for age and sex. A *p* value lower than 0.05 was considered statistically significant for all the analyses. Both non-standardized and standardized beta coefficients were reported for the regression models. Statistical analyses were performed using R software (version 4.4, R Foundation for Statistical Computing). The "ggplot2" package was used to create linear regression plots and the "Durga" for visualizing group comparisons Table 1.

Results

Table 1 shows the anthropometric and descriptive characteristics of the sample divided by groups. Postural control differences between children with normal weight and obesity are detailed in Table 2. As shown in Fig. 1, only the minimum sway is significantly different between groups (Cohen's $d = 1.222$; $p = 0.001$). The same was found in the eyes-closed condition (Fig. 2) with a Cohen's $d = 0.802$ ($p = 0.008$). To better understand these differences, they are also graphically illustrated in Figs. 1, 2, corresponding to the eyes-open and eyes-closed conditions, respectively. Table 3 shows the associations of static postural control parameters during the eyes-opened condition with the adiposity indexes. As shown in Table 3, sway length, delta *X*, and minimum sway exhibited positive associations with the BMI z-score in both models. Specifically, in model 2, the corresponding beta coefficients were $\beta = 0.371$ ($p = 0.035$), $\beta = 0.367$ ($p = 0.028$), and $\beta = 0.514$ ($p = 0.002$), respectively. Similarly, sway length, delta *X*, and minimum sway showed positive associations with the TMI index in both models. Specifically, in model 2, the corresponding beta coefficients were $\beta = 0.377$ ($p = 0.033$), $\beta = 0.352$ ($p = 0.036$), and $\beta = 0.473$ ($p = 0.005$), respectively. As far as the fat mass index is concerned, only the minimum sway parameter shows a positive association resulting in a beta of 0.363 ($p = 0.043$). While Table 4 shows the associations of static postural control parameters during the eyes-closed condition with the adiposity indexes. As shown in Table 4, minor axis sway and minimum sway showed positive associations with the BMI z-score in both models. Specifically, in model 2, the corresponding beta coefficients were $\beta = 0.340$ ($p = 0.029$) and $\beta = 0.345$ ($p = 0.049$), respectively. Only the minor axis sway showed a positive significant association with the TMI index in both models. Specifically, in model 2, the beta coefficient was $\beta = 0.348$ ($p = 0.026$). No statistically significant associations were found for the fat mass index.

Table 1 Anthropometric and descriptive characteristics of the sample

	NW ($N = 19$)	OB ($N = 14$)	Overall ($N = 33$)
Sex			
F	10 (52.6%)	6 (42.9%)	16 (48.5%)
M	9 (47.4%)	8 (57.1%)	17 (51.5%)
Age (y)	9.63 (8.56, 10.70)	10.14 (9.60, 10.68)	9.85 (9.19, 10.50)
Weight (kg)	34.00 (30.34, 37.66)	63.39 (55.63, 71.15)	46.47 (40.14, 52.80)
Height (m)	1.39 (1.32, 1.46)	1.49 (1.43, 1.56)	1.43 (1.38, 1.49)
BMI z-score	0.34 (−0.02, 0.70)	3.16 (2.93, 3.39)	1.54 (1.01, 2.07)
TMI	12.64 (11.86, 13.42)	18.81 (17.96, 19.66)	15.26 (14.06, 16.46)
Fat mass (kg)	8.14 (7.02, 9.26)	26.40 (22.63, 30.16)	15.88 (12.33, 19.44)

Values are presented as total number (%) for categorical variables; while continuous variables are presented as mean (95% CI)

NW group of normal weight children, *OB* group of children with obesity, *F* female, *M*, male, *BMI* body mass index, *TMI* tri-ponderal mass index

Table 2 Postural control differences between children with normal weight and obesity

EO				EC			
Variable	Mean (CI)	*p* value	Effect size	Variable	Mean Difference (CI)	*p* value	Effect Size
Sway length (EO)	73.426 (– 16.901, 163.753)	0.206	0.593	Sway length (EC)	58.782 (– 35.382, 152.946)	0.172	0.441
Sway area (mm^2)	346.89 (– 168.513, 862.293)	0.703	0.494	Ellipse area (mm^2)	87.339 (– 650.505, 825.183)	0.088	0.530
Ellipse inclination (°)	– 12.944 (– 46.777, 20.89)	0.431	0.268	Ellipse inclination (°)	– 32.128 (– 63.135, – 1.121)	0.057	0.718
Ellipse eccentricity	– 0.074 (– 0.238, 0.09)	0.417	0.300	Ellipse eccentricity	– 0.072 (– 0.253, 0.108)	0.407	0.274
L/S ratio	– 0.063 (– 0.79, 0.664)	0.895	0.059	L/S ratio	– 0.449 (– 1.02, 0.123)	0.281	0.394
Delta *X* (mm)	7.657 (– 2.368, 17.682)	0.221	0.553	Delta *X* (mm)	6.232 (– 4.682, 17.146)	0.139	0.401
Delta *Y* (mm)	4.783 (– 11.008, 20.575)	0.547	0.219	Delta *Y* (mm)	0.253 (– 17.565, 18.07)	0.108	0.659
Major axis (mm)	4.139 (– 6.772, 15.05)	1.000	0.271	Major axis (mm)	– 15.186 (– 59.559, 29.186)	0.081	0.450
Minor axis (mm)	6.373 (– 2.985, 15.731)	0.316	0.493	Minor axis (mm)	7.981 (– 1.688, 17.651)	0.066	0.590
Maximum sway (mm)	3.297 (– 2.651, 9.245)	0.529	0.402	Maximum sway (mm)	4.822 (– 12.033, 21.677)	0.222	0.198
Minimum sway (mm)	0.073 (0.029, 0.117)	0.001	1.222	Minimum sway (mm)	0.064 (0.006, 0.121)	0.008	0.802

Values are presented as mean (95% CI). The effect size = Cohen's d

EO eyes-opened condition, *EC* eyes-closed condition, *L/S* length and surface ratio

Discussion

The primary aim of the present study was to investigate the postural control in children with obesity and compare it with that of their normal-weight peers. Our findings revealed no significant differences in postural control between the two groups, except for the minimum sway parameter. Specifically, the OB group displayed greater minimum sway under both EO and EC tasks. The human body continuously reorganizes posture to counteract external perturbations (e.g., visual conditions like EC or EO tasks, or surface irregularities). Therefore, the complexity of sway patterns is considered an indicator of efficiency and adaptability of balance control mechanisms [33]. Wiesinger et al. [34] reported that children with obesity tend to exhibit reduced complexity in postural control. In this context, larger CoP sways might imply slower postural adaptations to change [33], and a reduced efficiency in maintaining balance [34]. Previous studies reported concerning evidence linking obesity to impairments in the proprioceptive system [35–37]. Previous findings suggest that the hyperstimulation of plantar mechanoreceptors, resulting from a higher body weight, can cause a progressive decline in receptor sensitivity that further deteriorates with age [37]. Indeed, Yang et al. [38] (2020) found impaired postural control in a group of adolescents over 15 years of age. Supporting this hypothesis, another study showed that the percentage of children and adolescents showing an incorrect postural control is strongly dependent on the age. Accordingly, the authors observed that the older adolescents' group showed a significantly higher prevalence of impaired balance compared to the 11-year-old group. A plausible explanation for our findings might rely on the different developmental growth patterns observed in children with obesity [39]. Existing literature has demonstrated that the onset of puberty tends to occur earlier in this population, potentially highlighting an association between postural control mechanisms and age. The rapid physiological and hormonal changes triggered by puberty may act to mitigate potential impairments in balance control, which could otherwise become more pronounced in the later stages of adolescence [40, 41]. Therefore, an accurate evaluation of postural control prior to the onset of obesity-related impairments may enable targeted interventions designed to reduce future declines in postural control. The secondary aim of this study was to evaluate the associations of the main adiposity indexes and fat mass with balance parameters. Our findings demonstrated that both the BMI z-score and the TMI were positively associated with increased sway length, delta *X*, and minimum sway parameters under EO condition. Fewer and weaker associations were observed under EC condition. Specifically, the BMI z-score was associated with the minor axis sway and minimum sway parameters, whereas the TMI was associated only with the minimum sway parameter. These findings indicate poorer mediolateral balance control as body weight increases. The human body possesses several mechanisms to counteract postural perturbations along the anteroposterior axis (e.g., muscular adjustments involving the ankle, knee, and hip joints); however, mediolateral stability relies primarily on hip-level

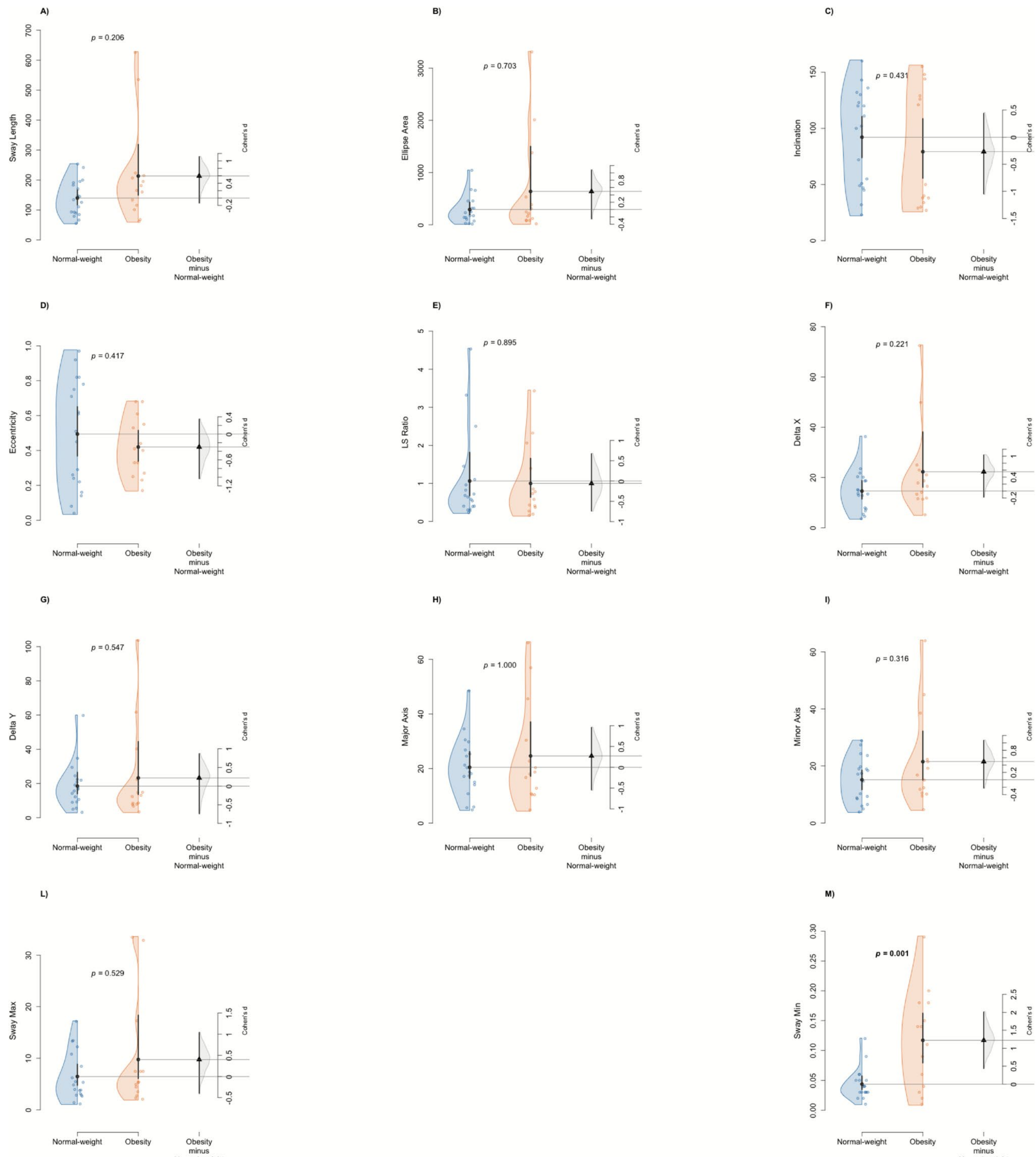

Fig. 1 Differences in static balance with eyes opened are displayed by Gardner–Altman plots, which show a representation of observed values by the two-group comparison (normal weight vs. with obesity), a bootstrap effect size (Cohen's d) estimation, mean and 95% confidence interval. Two-sided *p* values from analysis of covariance evaluating the differences between groups adjusting for sex and age

control. Thus, these findings suggest that early declines in postural control may first manifest in parameters related to mediolateral stability.

Furthermore, the additional body mass in children with obesity does not actively assist movement and further challenges postural stability [16, 33]. In line with the findings

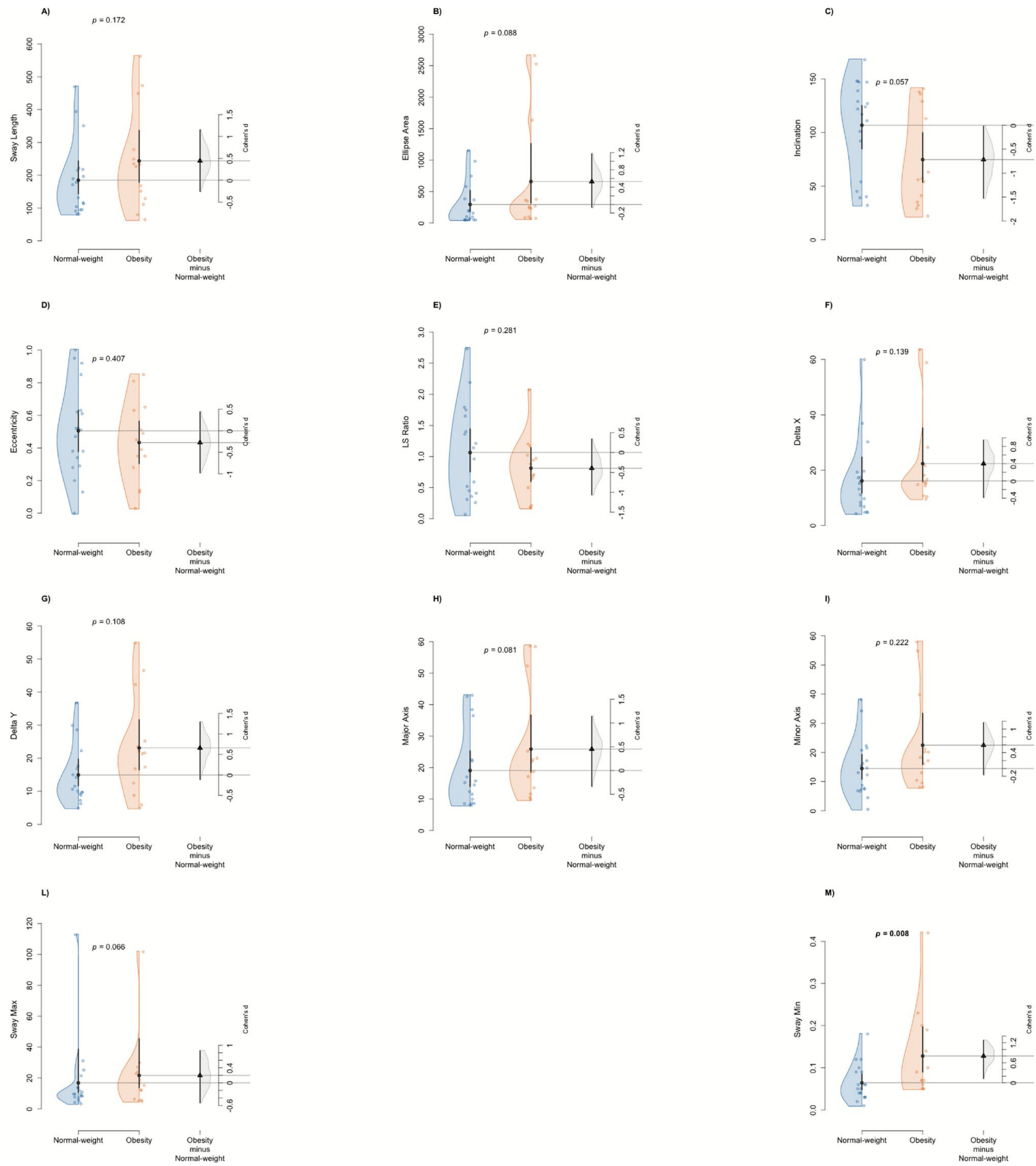

Fig. 2 Differences in static balance with eyes closed are displayed by Gardner-Altman plots, which show a representation of observed values by the two-group comparison (normal-weight vs. obesity), a bootstrap effect size (Cohen's d) estimation, mean and 95% confidence interval. Two-sided *p* values from analysis of covariance evaluating the differences between groups adjusting for sex and age

Table 3 Linear regressions showing associations of static balance with eyes opened with adiposity indexes in children

		Model 1			Model 2		
		b (95% CI)	*β*	*p*	*b* (95% CI)	*β*	*p*
BMI z-score	Sway length	29.436 (3.108, 55.764)	0.384	0.030	28.434 (2.101, 54.767)	0.371	0.035
	Sway area	144.818 (−4.398, 294.033)	0.340	0.057	136.912 (−9.346, 283.170)	0.322	0.065
	Ellipse inclination	−0.836 (−11.721, 10.050)	−0.028	0.876	−1.027 (−12.094, 10.041)	−0.034	0.851
	Ellipse eccentricity	−0.017 (−0.077, 0.043)	−0.102	0.572	−0.014 (−0.074, 0.046)	−0.087	0.628
	L/S ratio	−0.024 (−0.278, 0.230)	−0.035	0.848	−0.013 (−0.266, 0.240)	−0.020	0.915
	Delta *X* (mm)	3.360 (0.423, 6.297)	0.391	0.026	3.154 (0.368, 5.940)	0.367	0.028
	Delta *Y* (mm)	2.268 (−2.546, 7.082)	0.173	0.344	2.131 (−2.729, 6.990)	0.163	0.377
	Major axis sway	2.095 (−1.287, 5.476)	0.225	0.216	1.937 (−1.409, 5.284)	0.208	0.246
	Minor axis sway	2.692 (−0.109, 5.493)	0.337	0.059	2.481 (−0.143, 5.105)	0.311	0.063
	Maximal sway	1.462 (−0.299, 3.224)	0.293	0.100	1.377 (−0.361, 3.114)	0.276	0.116
	Minimum sway	0.022 (0.009, 0.034)	0.512	0.002	0.022 (0.009, 0.035)	0.514	0.002
TMI	Sway length	13.375 (1.658, 25.092)	0.392	0.027	12.838 (1.086, 24.590)	0.377	0.033
	Sway area	59.644 (−7.617, 126.904)	0.315	0.080	55.298 (−10.840, 121.437)	0.292	0.098
	Ellipse inclination	−2.117 (−6.914, 2.681)	−0.158	0.375	−2.237 (−7.114, 2.640)	−0.167	0.356
	Ellipse eccentricity	−0.008 (−0.035, 0.019)	−0.107	0.555	−0.006 (−0.033, 0.020)	−0.089	0.624
	L/S ratio	0.007 (−0.107, 0.120)	0.023	0.902	0.013 (−0.100, 0.126)	0.043	0.816
	Delta *X* (mm)	1.460 (0.143, 2.777)	0.382	0.031	1.348 (0.092, 2.603)	0.352	0.036
	Delta *Y* (mm)	0.676 (−1.492, 2.843)	0.116	0.529	0.598 (−1.593, 2.788)	0.103	0.581
	Major axis sway	0.742 (−0.783, 2.266)	0.179	0.328	0.654 (−0.858, 2.166)	0.158	0.383
	Minor axis sway	1.080 (−0.185, 2.346)	0.304	0.092	0.964 (−0.227, 2.155)	0.271	0.109
	Maximal sway	0.579 (−0.215, 1.373)	0.261	0.147	0.532 (−0.254, 1.318)	0.240	0.177
	Minimum sway	0.009 (0.003, 0.015)	0.470	0.004	0.009 (0.003, 0.015)	0.473	0.005
Fat mass (kg)	Sway length	2.267 (−1.930, 6.464)	0.197	0.279	3.176 (−1.088, 7.440)	0.276	0.139
	Sway area	10.636 (−12.849, 34.121)	0.167	0.362	16.940 (−6.357, 40.236)	0.265	0.148
	Ellipse inclination	−0.400 (−2.028, 1.228)	−0.088	0.619	−0.315 (−2.035, 1.405)	−0.070	0.711
	Ellipse eccentricity	−0.001 (−0.010, 0.008)	−0.033	0.855	−0.002 (−0.012, 0.007)	−0.101	0.590
	L/S ratio	−0.010 (−0.048, 0.028)	−0.096	0.603	−0.017 (−0.056, 0.021)	−0.170	0.367
	Delta *X* (mm)	0.260 (−0.209, 0.730)	0.202	0.266	0.422 (−0.022, 0.866)	0.327	0.062
	Delta *Y* (mm)	0.130 (−0.602, 0.862)	0.066	0.719	0.234 (−0.528, 0.996)	0.119	0.534
	Major axis sway	0.170 (−0.347, 0.687)	0.121	0.508	0.289 (−0.233, 0.811)	0.207	0.267
	Minor axis sway	0.219 (−0.220, 0.658)	0.183	0.315	0.379 (−0.031, 0.788)	0.316	0.069
	Maximal sway	0.070 (−0.206, 0.345)	0.093	0.609	0.134 (−0.144, 0.412)	0.179	0.332
	Minimum sway	0.002 (−0.000, 0.004)	0.333	0.051	0.002 (0.000, 0.005)	0.363	0.043

Model 1 was adjusted for sex. Model 2 was adjusted for sex and age

b beta unstandardized coefficients, *β* beta standardized coefficients, *CI* confidence interval, *BMI* body mass index, *TMI* tri-ponderal mass index

of Wiesinger et al. [34], no correlation was found between body weight and *x* axis sway under EC conditions. This lack of correlation may be attributable to the increased difficulty of the task rather than to deficiencies in the balance control system. Indeed, in the absence of visual inputs, the human body must rely entirely on the vestibular and proprioceptive systems to maintain balance [42].

Villarrasa-Sapiña et al. [33, 43] (2018) found that increased fat mass appears to be associated with poorer postural control and worsened balance parameters. Specifically, the authors reported that trunk and leg mass indexes were the best predictors for postural control in children. However, their study assessed body composition using the dual-energy X-ray absorptiometry (DXA) method. In contrast, the present study aimed to determine whether less invasive and more cost-effective indexes could similarly predict balance impairments. Hence, BMI z-scores and TMI indexes do not seem to clearly predict potential impairments in postural control.

Conversely to previous studies, our findings did not reveal differences in the L/S ratio parameter, which might otherwise have supported the hypothesis of compromised balance control in children with obesity. Although we observed some evidence of greater difficulty in maintaining and restoring

Table 4 Linear regressions showing associations of static balance with eyes closed with adiposity indexes in children

		Model 1			Model 2		
		b (95% CI)	*β*	*p*	b (95% CI)	*β*	*p*
BMI z-score	Sway length	18.337 (− 11.204, 47.878)	0.218	0.215	16.279 (− 11.762, 44.320)	0.194	0.245
	Sway area	36.192 (− 226.863, 299.247)	0.051	0.781	27.632 (− 236.963, 292.227)	0.039	0.832
	Ellipse inclination	− 7.386 (− 18.195, 3.423)	− 0.247	0.173	− 7.492 (− 18.515, 3.530)	− 0.250	0.175
	Ellipse eccentricity	− 0.036 (− 0.096, 0.025)	− 0.210	0.238	− 0.031 (− 0.087, 0.025)	− 0.183	0.270
	L/S ratio	− 0.165 (− 0.378, 0.048)	− 0.277	0.125	− 0.153 (− 0.360, 0.055)	− 0.256	0.143
	Delta *X* (mm)	2.073 (− 1.472, 5.619)	0.211	0.242	1.751 (− 1.423, 4.924)	0.178	0.268
	Delta *Y* (mm)	− 0.132 (− 6.88 − 4, 6.620)	− 0.007	0.968	− 0.253 (− 7.116, 6.611)	− 0.014	0.940
	Major axis sway	− 5.774 (− 23.046, 11.499)	− 0.123	0.500	− 5.865 (− 23.495, 11.764)	− 0.124	0.502
	Minor axis sway	3.175 (0.282, 6.069)	0.371	0.033	2.915 (0.316, 5.514)	0.340	0.029
	Maximal sway	0.340 (− 5.416, 6.095)	0.022	0.905	0.453 (− 5.391, 6.298)	0.029	0.875
	Minimum sway	0.018 (0.001, 0.036)	0.359	0.042	0.018 (0.000, 0.035)	0.345	0.049
TMI	Sway length	11.713 (− 1.100, 24.525)	0.314	0.072	10.605 (− 1.583, 22.793)	0.284	0.086
	Sway area	40.429 (− 76.191, 157.049)	0.129	0.484	35.871 (− 81.721, 153.462)	0.114	0.538
	Ellipse inclination	− 3.512 (− 8.316, 1.293)	− 0.264	0.146	− 3.577 (− 8.482, 1.327)	− 0.269	0.147
	Ellipse eccentricity	− 0.016 (− 0.043, 0.011)	− 0.213	0.234	− 0.014 (− 0.039, 0.012)	− 0.179	0.283
	L/S ratio	− 0.069 (− 0.165, 0.027)	− 0.260	0.152	− 0.062 (− 0.155, 0.031)	− 0.234	0.184
	Delta *X* (mm)	1.131 (− 0.433, 2.695)	0.259	0.150	0.955 (− 0.449, 2.358)	0.218	0.175
	Delta *Y* (mm)	0.515 (− 2.494, 3.523)	0.064	0.729	0.451 (− 2.612, 3.515)	0.056	0.765
	Major axis sway	− 0.770 (− 8.535, 6.995)	− 0.037	0.841	− 0.811 (− 8.749, 7.127)	− 0.039	0.836
	Minor axis sway	1.469 (0.185, 2.752)	0.385	0.026	1.326 (0.168, 2.484)	0.348	0.026
	Maximal sway	0.652 (− 1.906, 3.211)	0.095	0.606	0.720 (− 1.880, 3.319)	0.105	0.576
	Minimum sway	0.007 (− 0.001, 0.015)	0.323	0.070	0.007 (− 0.001, 0.015)	0.305	0.085
Fat mass (kg)	Sway length	0.678 (− 3.866, 5.222)	0.054	0.763	2.088 (− 2.311, 6.488)	0.166	0.340
	Sway area	− 6.546 (− 46.005, 32.913)	− 0.062	0.737	− 1.569 (− 42.794, 39.656)	− 0.015	0.938
	Ellipse inclination	− 1.237 (− 2.846, 0.373)	− 0.275	0.127	− 1.294 (− 2.997, 0.409)	− 0.288	0.131
	Ellipse eccentricity	− 0.002 (− 0.011, 0.007)	− 0.076	0.673	− 0.005 (− 0.014, 0.004)	− 0.201	0.242
	L/S ratio	− 0.016 (− 0.048, 0.017)	− 0.175	0.338	− 0.025 (− 0.057, 0.007)	− 0.282	0.119
	Delta *X* (mm)	0.064 (− 0.480, 0.609)	0.044	0.810	0.280 (− 0.214, 0.773)	0.190	0.256
	Delta *Y* (mm)	− 0.129 (− 1.141, 0.884)	− 0.047	0.797	− 0.063 (− 1.132, 1.005)	− 0.023	0.904
	Major axis sway	− 1.001 (− 3.587, 1.585)	− 0.141	0.435	− 1.043 (− 3.781, 1.696)	− 0.147	0.442
	Minor axis sway	0.205 (− 0.258, 0.668)	0.159	0.373	0.396 (− 0.018, 0.809)	0.308	0.060
	Maximal sway	− 0.077 (− 0.941, 0.786)	− 0.033	0.857	− 0.154 (− 1.062, 0.755)	− 0.066	0.732
	Minimum sway	0.002 (− 0.001, 0.004)	0.208	0.250	0.002 (− 0.001, 0.005)	0.293	0.111

Values are presented as mean (95% CI). Model 1 was adjusted for sex. Model 2 was adjusted for sex and age

b beta unstandardized coefficients, *β* beta standardized coefficients, *CI* confidence interval, *BMI* body mass index, *TMI* tri-ponderal mass index

balance in the OB group, the data do not provide sufficient evidence to conclude the presence of an impaired postural control system.

This absence of differences may be related to certain limitations of our study, such as the task conditions or sample characteristics. Firstly, the size of our sample was limited, which may reduce the generalizability of the findings to larger or different populations. This limitation underlines the need for future studies with broader recruitment efforts to further explore postural control in adolescents. In addition, we did not assess the stage of pubertal development in our sample, which may have influenced our findings, as some participants might have already entered puberty, a process that typically begins earlier in children with obesity.

Another limitation lies in the restricted testing setup, as only two postural conditions were assessed, which varied solely in the visual input stimulus. To further explore this topic, future studies should evaluate balance under a wider range of conditions.

Despite these limitations, this study also presents some strengths. We evaluated the association of two different indexes (the BMI z-score and TMI) with balance control, trying to investigate their applicability in identifying the risk of balance impairments. Furthermore, by focusing on the relationship between obesity and postural control, our research highlights an important area of concern for public health.

Future studies should address these limitations by evaluating and comparing postural control in a larger, more diverse sample while incorporating participants across a broader age range. This approach would allow for a more comprehensive exploration of the onset and progression of potential balance control impairments related to obesity.

Conclusions

The present findings did not highlight balance impairments in prepubertal children with obesity. Secondarily, the use of adiposity indexes such as BMI z-score and tri-weight mass indexes does not seem to provide clear information about postural control abilities in children, neither to predict potential postural control impairments when determining the impact of excessive body weight on balance outcomes in this population.

Author contributions G.Z., M.V., and V.C. developed the theoretical framework. V.C., V.C.P., M.V., and D.L. designed the methodology. A.G. and S.B. carried out the experiments and collected the data. A.G. analyzed the results and prepared figures. V.C.P. and C.C. wrote the first draft of the manuscript. M.V., A.D.N., N.L., and L.M. supervised the project and contributed to manuscript revision. All authors read and approved the final manuscript.

Funding Open access funding provided by Università degli Studi di Pavia within the CRUI-CARE Agreement. This study did not receive any external funding.

Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval The study received ethical approval from the Ethics Committee of Milano Area 1 (No. 2020/ST/298).

Informed Consent Informed consent was obtained from the parents/legal guardians of all participants involved in the study, and assent was obtained from the participants. Written informed consent for publication of this paper was also obtained from the parents/legal guardians.

References

1. NCD Risk Factor Collaboration (NCD-RisC) (2024) Worldwide trends in underweight and obesity from 1990 to 2022: a pooled analysis of 3663 population-representative studies with 222 million children, adolescents, and adults. Lancet 403(10431):1027–1050. https://doi.org/10.1016/S0140-6736(23)02750-2
2. Almulla AA, Zoubeidi T (2021) Association of overweight, obesity and insufficient sleep duration and related lifestyle factors among school children and adolescents. Int J Adolesc Med Health 34(2):31–40. https://doi.org/10.1515/ijamh-2021-0041
3. Morales Camacho WJ, Molina Díaz JM, Plata Ortiz S, Plata Ortiz JE, Morales Camacho MA, Calderón BP (2019) Childhood obesity: aetiology, comorbidities, and treatment. Diabetes Metab Res Rev 35(8):e3203. https://doi.org/10.1002/dmrr.3203
4. Arpesella M et al (2008) Obesity nutritional aspects and life style from a survey on a sample of primary school pupils in the Pavia province (Northern Italy). Ital J Public Health 5:12–17. https://doi.org/10.2427/5849
5. Calcaterra V et al (2022) The effect of healthy lifestyle strategies on the management of insulin resistance in children and adolescents with obesity: a narrative review. Nutrients 14(21):4692. https://doi.org/10.3390/nu14214692
6. Deurenberg P, Weststrate JA, Seidell JC (1991) Body mass index as a measure of body fatness: age- and sex-specific prediction formulas. Br J Nutr 65(2):105–114. https://doi.org/10.1079/bjn19910073
7. Kaltenhauser S et al (2023) Association of body mass index and waist circumference with imaging metrics of brain integrity and functional connectivity in children aged 9 to 10 years in the US, 2016-2018. JAMA Netw Open 6(5):e2314193. https://doi.org/10.1001/jamanetworkopen.2023.14193
8. Kolsgaard MLP, Joner G, Brunborg C, Anderssen SA, Tonstad S, Andersen LF (2011) Reduction in BMI z-score and improvement in cardiometabolic risk factors in obese children and adolescents. The Oslo adiposity intervention study—a hospital/public health nurse combined treatment. BMC Pediatr 11:47. https://doi.org/10.1186/1471-2431-11-47
9. Kujala UM, Vaara JP, Kainulainen H, Vasankari T, Vaara E, Kyröläinen H (2019) Associations of aerobic fitness and maximal muscular strength with metabolites in young men. JAMA Netw Open 2(8):e198265. https://doi.org/10.1001/jamanetworkopen.2019.8265
10. Peterson CM et al (2017) Tri-ponderal mass index vs body mass index in estimating body fat during adolescence. JAMA Pediatr 171(7):629–636. https://doi.org/10.1001/jamapediatrics.2017.0460
11. Hudda MT et al (2019) Development and validation of a prediction model for fat mass in children and adolescents: meta-analysis using individual participant data. BMJ 366:l4293. https://doi.org/10.1136/bmj.l4293
12. Wills M (2004) Orthopedic complications of childhood obesity. Pediatr Phys Ther 16(4):230–235. https://doi.org/10.1097/01.PEP.0000145911.83738.C6

13. Taylor ED et al (2006) Orthopedic complications of overweight in children and adolescents. Pediatrics 117(6):2167–2174. https://doi.org/10.1542/peds.2005-1832
14. Baratto L, Morasso PG, Re C, Spada G (2002) A new look at posturographic analysis in the clinical context: sway-density versus other parameterization techniques. Mot Control 6(3):246–270. https://doi.org/10.1123/mcj.6.3.246
15. Guzmán-Muñoz E et al (2023) Anthropometric profile and physical activity level as predictors of postural balance in overweight and obese children. Behav Sci 13(1):73. https://doi.org/10.3390/bs13010073
16. McGraw B, McClenaghan BA, Williams HG, Dickerson J, Ward DS (2000) Gait and postural stability in obese and nonobese prepubertal boys. Arch Phys Med Rehabil 81(4):484–489. https://doi.org/10.1053/mr.2000.3782
17. Correale L, Carnevale Pellino V, Marin L, Febbi M, Vandoni M (2020) Comparison of an inertial measurement unit system and baropodometric platform for measuring spatiotemporal parameters and walking speed in healthy adults. Mot Control 25(1):89–99. https://doi.org/10.1123/mc.2020-0060
18. Lovecchio N, Zago M, Perucca L, Sforza C (2017) Short-term repeatability of stabilometric assessments. J Mot Behav 49(2):123–128. https://doi.org/10.1080/00222895.2016.1152225
19. Simoneau M, Teasdale N (2015) Balance control impairment in obese individuals is caused by larger balance motor commands variability. Gait Posture 41(1):203–208. https://doi.org/10.1016/j.gaitpost.2014.10.008
20. Villarrasa-Sapiña I, Álvarez-Pitti J, Cabeza-Ruiz R, Redón P, Lurbe E, García-Massó X (2018) Relationship between body composition and postural control in prepubertal overweight/obese children: a cross-sectional study. Clin Biomech 52:1–6. https://doi.org/10.1016/j.clinbiomech.2017.12.010
21. Yang L, Lu X, Yan B, Huang Y (2020) Prevalence of incorrect posture among children and adolescents: finding from a large population-based study in China. iScience 23(5):101043. https://doi.org/10.1016/j.isci.2020.101043
22. Sarto F et al (2022) Physical active lifestyle promotes static and dynamic balance performance in young and older adults. Front Physiol 13:986881. https://doi.org/10.3389/fphys.2022.986881
23. Fisher PA, Ball TJ (2005) Balancing empiricism and local cultural knowledge in the design of prevention research. J Urban Health 82(2 Suppl 3):iii44-55. https://doi.org/10.1093/jurban/jti063
24. Mei Z, Grummer-Strawn LM (2007) Standard deviation of anthropometric Z-scores as a data quality assessment tool using the 2006 WHO growth standards: a cross country analysis. Bull World Health Organ 85(6):441–448. https://doi.org/10.2471/blt.06.034421
25. Vandoni M et al (2022) Effects of an online supervised exercise training in children with obesity during the COVID-19 pandemic. IJERPH 19(15):9421. https://doi.org/10.3390/ijerph19159421
26. World Medical Association (2013). World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. JAMA, 310(20): 2191–2194. https://doi.org/10.1001/jama.2013.281053
27. da Silva V, Vieira F (2020) International society for the advancement of kinanthropometry (ISAK) global: international accreditation scheme of the competent anthropometrist. Revista Brasileira de Cineantropometria & Desempenho Humano. https://doi.org/10.1590/1980-0037.2020v22e70517
28. World Health Organization (2011). Waist circumference and waist-hip ratio : report of a WHO expert consultation, Geneva, pp 8–11 December 2008. [Online]. Available. https://apps.who.int/iris/handle/10665/44583.Accessed 06 Dec 2022
29. Gul Siraz U, Hatipoglu N, Mazicioglu MM, Ozturk A, Cicek B, Kurtoglu S (2023) Triponderal mass index is as strong as body mass index in the determination of obesity and adiposity. Nutrition 105:111846. https://doi.org/10.1016/j.nut.2022.111846
30. Calcaterra V et al (2018) Smoke exposure and cardio-metabolic profile in youth with type 1 diabetes. Diabetol Metab Syndr 10(1):1–7
31. Gołąb A (2022) Describing center of pressure movement in stabilometry by ellipse area approximation. Physiol Rep 10(17):e15390. https://doi.org/10.14814/phy2.15390
32. Chiari L, Rocchi L, Cappello A (2002) Stabilometric parameters are affected by anthropometry and foot placement. Clin Biomech 17(9–10):666–677
33. Villarrasa-Sapiña I, García-Massó X, Serra-Añó P, Garcia-Lucerga C, Gonzalez L-M, Lurbe E (2016) Differences in intermittent postural control between normal-weight and obese children. Gait Posture 49:1–6. https://doi.org/10.1016/j.gaitpost.2016.06.012
34. Wiesinger H-P, Buchecker M, Müller E, Stöggl T, Birklbauer J (2022) Decreased postural complexity in overweight to obese children and adolescents: a cross-sectional study. Front Hum Neurosci 16:850548. https://doi.org/10.3389/fnhum.2022.850548
35. Bataweel EA, Ibrahim AI (2020) Balance and musculoskeletal flexibility in children with obesity: a cross-sectional study. Ann Saudi Med 40(2):120–125. https://doi.org/10.5144/0256-4947.2020.120
36. Cimolin V et al (2019) Do wearable sensors add meaningful information to the timed up and go test? A study on obese women. J Electromyogr Kinesiol 44:78–85. https://doi.org/10.1016/j.jelekin.2018.12.001
37. Maktouf W, Durand S, Boyas S, Pouliquen C, Beaune B (2018) Combined effects of aging and obesity on postural control, muscle activity and maximal voluntary force of muscles mobilizing ankle joint. J Biomech 79:198–206. https://doi.org/10.1016/j.jbiomech.2018.08.017
38. Kasović M, Štefan L, Piler P, Zvonar M (2022) Longitudinal associations between sport participation and fat mass with body posture in children: a 5-year follow-up from the Czech ELSPAC study. PLoS ONE 17(4):e0266903. https://doi.org/10.1371/journal.pone.0266903
39. Holmgren A, Martos-Moreno GÁ, Niklasson A, Martínez-Villanueva J, Argente J, Albertsson-Wikland K (2021) The pubertal growth spurt is diminished in children with severe obesity. Pediatr Res 90(1):184–190. https://doi.org/10.1038/s41390-020-01234-3
40. D'Hondt E, Deforche B, De Bourdeaudhuij I, Lenoir M (2009) Relationship between motor skill and body mass index in 5- to 10-year-old children. Adapt Phys Act Q 26(1):21–37. https://doi.org/10.1123/apaq.26.1.21
41. Webster EK, Sur I, Stevens A, Robinson LE (2021) Associations between body composition and fundamental motor skill competency in children. BMC Pediatr 21(1):444. https://doi.org/10.1186/s12887-021-02912-9
42. García-Liñeira J, Leirós-Rodríguez R, Chinchilla-Minguet JL, García-Soidán JL (2021) Influence of visual information and sex on postural control in children aged 6–12 years assessed with accelerometric technology. Diagnostics 11(4):637. https://doi.org/10.3390/diagnostics11040637
43. Birtane M, Tuna H (2004) The evaluation of plantar pressure distribution in obese and non-obese adults. Clin Biomech 19(10):1055–1059. https://doi.org/10.1016/j.clinbiomech.2004.07.008