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ORIGINAL ARTICLE

Influence of Foot Morphology on Postural Sway During Childhood

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Abstract

Purpose Postural control matures during childhood alongside the musculoskeletal system, though development is often asynchronous and influenced by sex. In this process, foot morphology is especially relevant, as the plantar surface provides key somatosensory input to the central nervous system. However, the role of foot-ground interaction in balance regulation remains largely unexplored. In this study, we attempted to clarify the association between foot morphology—measured via footprint-based indices—and static balance through postural sway analysis.

Methods Using a pressure platform, we simultaneously collected data on center of pressure (COP) trajectories during quiet upright stance and plantar pressure distribution in a sample of 178 children aged 6–11. Raw data were processed to calculate sway area and COP path length, as well as the Arch Index, which was used to categorize foot morphology as cavus, normal, or flat.

Results Among girls aged 8–9 years, statistically significant differences in postural sway parameters were observed across foot morphology groups, with individuals presenting cavus feet exhibiting greater sway area and COP path length values. A comparable tendency was also identified in those aged 10–11. In contrast, boys aged 10–11 with flat feet displayed lower sway area values under the eyes-closed condition and reduced COP path length under the eyes-open condition compared with peers presenting normal or cavus foot morphology.

Conclusion Overall, these findings suggest that postural control during childhood is influenced by the mechanical and sensory characteristics of the foot–ground interface, and that sex represents a relevant moderating factor in this relationship.

Keywords Postural sway · Foot · Medial longitudinal arch · Sex

Introduction

One of the most important milestones in the motor development of human beings is represented by the ability to safely maintain the upright posture, preserving balance against gravity and other external perturbances while staying as far as possible from the risk of falling. This ability, which results from the sophisticated work of the central nervous system in receiving and integrating information from the visual, vestibular, and somatosensory systems, matures with age. In particular, several studies demonstrated that the postural control system reaches adult-like performance during adolescence, approximately at 13 years of age [1].

Considering the central role of upright balance in human motor function, the effectiveness of the postural control system is often assessed through the quantitative analysis of postural sway, that is, the subtle and largely imperceptible body oscillations reflecting the continuous neuromuscular adjustments required to maintain stability [2]. This evaluation is typically based on the analysis of time-series describing the position of the point of application of the resultant of the forces exchanged between the body and the ground through the plantar regions, known as the center of pressure (COP). By processing COP trajectories recorded during short trials—generally lasting between 30 and 60 s—on a force or pressure platform, several parameters can be derived, such as sway area, COP path length, and COP velocity. These metrics have been shown to provide reliable information for the characterization of postural sway [3, 4].

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Importantly, the position of the COP during quiet upright stance is influenced by the way forces are transmitted between the body and the external environment, which occurs through the distribution of pressure across the foot–ground contact interface. Since this pressure distribution is closely related to an individual's foot morphology, a relationship between COP position and the structural characteristics of the foot (particularly as regards its longitudinal medial arch which predominantly contribute to establish the foot-ground contact features) can reasonably be expected. Exploring such a relationship becomes relatively straightforward when plantar pressure data and COP trajectories are collected simultaneously. This can be achieved using pressure-sensitive platforms or mats, which provide point-by-point pressure measurements across the plantar surface. These devices allow the estimation of contact area and pressure distribution across the entire foot while also determining COP position through the integration of the pressure values recorded by each sensor. Consequently, the combined analysis of plantar surface parameters and COP metrics may offer a comprehensive perspective on how foot morphology influences postural stability, providing a useful framework for both research and practical applications.

However, it is noteworthy—and somewhat unexpected—that despite the seemingly intuitive link between foot morphology and postural control, relatively few studies have examined this relationship, and the available evidence remains inconsistent. Hertel, Gay, and Denegar [5] were among the first to investigate this topic, reporting that individuals with a high longitudinal foot arch (i.e., cavus feet) exhibited larger sway areas during single-leg stance, indicating reduced postural stability compared with individuals with normal foot structure. More recently, a systematic review by Sedaghati et al. [6], which included 25 studies conducted over the past two decades, suggested that both high-arched and flat-footed individuals tend to demonstrate poorer postural control than those with normal foot morphology. Nevertheless, these findings are influenced by substantial heterogeneity across studies, particularly with respect to the methods used to assess balance (e.g., static vs. dynamic tasks, instrumented measurements vs. clinical scales) and the approaches adopted to classify foot morphology, including footprint-based indices, foot scanners, the navicular drop test, etc.

Available data concerning children and adolescents are even more limited, probably also because, in this population, the relationship between postural control and foot morphology appears considerably less straightforward, as both systems are still developing and their interaction may also be influenced by sex [1, 7, 8]. An early study by Lin et al. [9] examined 64 children aged 4–10 years using a force platform to compute sway area, which was subsequently correlated with several footprint indices. The main findings revealed a significant moderate negative correlation between foot morphology and postural sway in the youngest participants (4–5 years) when tested under visual deprivation and on a compliant surface. This result suggests that reduced plantar support may compromise postural control, similarly to what was previously observed in adults [5]. More recently, Wako et al. [10] reported that in 8-year-old children the presence of flatfoot was associated with greater postural instability, expressed as increased sway area and COP path length, with differences observed between sexes. To the best of our knowledge, these two studies represent the only attempts to specifically investigate the role of foot morphology in the effectiveness of the postural control system in pediatric populations. Thus, although several studies have investigated the relationship between foot morphology and postural sway in pediatric populations through COP analysis, evidence remains limited regarding the combined effects of age, sex, and foot morphology on postural control during childhood, particularly under different sensory conditions.

Based on such considerations, the main aim of the present study is to expand the current knowledge regarding the existence of differences in postural sway parameters (i.e., sway area and COP path length) in children having different foot structure in terms of longitudinal medial arc height, the latter characterized by means of footprint indexes calculated on the basis of electronic pedobarography, The findings of such investigation could have practical implications for early screening of postural or musculoskeletal issues, informing clinical assessment and preventive interventions in pediatric populations. Additionally, the results may support the design of targeted rehabilitation strategies in children with postural control/foot disorders, footwear recommendations, or physical activity programs aimed at improving balance and reducing the risk of future lower-limb dysfunctions.

Materials and Methods

Participants

This retrospective study analyzes data collected between 2022 and 2025 by the Laboratory of Biomechanics and Industrial Ergonomics at the University of Cagliari (Italy), in collaboration with several primary schools located in the metropolitan area of Cagliari. The data were gathered during a series of projects aimed at investigating basic motor functions—namely postural control, gait, and functional mobility—in children with typical developmental trajectories [11–13]. The sample here analyzed consists of 178 participants (mean age = 8.7 years), stratified into three age groups: 56 children aged 6–7 years (33 girls), 86 aged 8–9 years (51 girls), and 36 aged 10–11 years (18 girls). The main anthropometric characteristics of the participants are reported in Table 1.

Participants were included in the analysis only if they were free from sensory or intellectual impairments that could affect the development or performance of postural control [14]. None of the participants reported a history of neurological or musculoskeletal disorders, and all had received negative screening results for specific learning disabilities. This screening was conducted in accordance with the provisions of the Italian Law No. 170/2010, which establishes educational and support measures for students diagnosed with dyslexia, dyscalculia, dysorthography, and related neurodevelopmental conditions such as Nonverbal Learning Disorder or Attention Deficit Hyperactivity Disorder. The original experimental protocol was reviewed and approved by the Ethics Committee of the University of Cagliari (protocol no. 0001470 of 01/11/2022) and conducted in accordance with the principles of the Declaration of Helsinki and its subsequent amendments. Authorization for data collection was obtained from the school headmasters, and written informed consent was provided by the participants' parents or legal guardians.

Equipment and Data Collection Procedure

COP time-series and plantar pressure distribution were simultaneously collected by means of a pressure platform (FDM-S, Zebris Medical GmbH, Germany), connected to a personal computer via USB. The device consists of 2560 capacitive sensors arranged into a 64×40 matrix (range = 1–120 N/cm^2; accuracy $\pm$ 5%) and operates at a sampling frequency in the range 50–120 Hz.

To guarantee a quiet and comfortable testing environment, children were called in pairs into a dedicated silent room and asked to stand barefoot on the platform. They were instructed to maintain a relaxed posture with their arms alongside the body (without touching it) and to fix their gaze on a visual target positioned 3 m in front of them at eye level. Moreover, to ensure a consistent reference position and reduce potential variability associated with differences in foot placement—which is known to influence postural sway measurements [15]—a paper mask with footprints oriented at 30° and an intermalleolar distance of approximately 8–10 cm was placed on the platform. This setup allowed the standardization of foot position in accordance with the recommendations of the International Society for Posture and Gait Research [16]. All children performed three 30-second trials under two conditions: with visual input (eyes open, EO) and without visual input (eyes closed, EC). The order of the conditions was randomized, and brief rest intervals were provided between trials to minimize fatigue and maintain attention.

Data Processing

Postural Sway

COP time-series was exported as ASCII file from the management software of the platform, filtered with a bidirectional 4th-order Butterworth filter (10 Hz cut-off) and processed using a custom Matlab® routine to obtain the following sway parameters:

- Sway area (mm^2): the area of the 95% confidence ellipse encompassing the COP trajectory. This ellipse represents the region that contains 95% of the COP data points recorded during the trial and provides a summary measure of the spatial dispersion of postural sway, with larger areas indicating greater instability [17];
- COP Path length (mm): the total distance traveled by the COP during the recording period. It is calculated as the cumulative sum of the point-to-point displacements of the COP trajectory over time [17] and reflects the amount of corrective postural adjustments produced by the neuromuscular control system to maintain upright stance [4].

These two metrics represent complementary indicators that, when analyzed together, provide a comprehensive description of an individual's postural stability [4].

The mean of the three trials per condition was used as the representative value for each variable. Figure 1 presents a graphical representation of the two parameters obtained under both EO and EC conditions for a representative participant.

Table 1 Anthropometric features of the participants

	Entire sample	6–7 years	8–9 years	10–11 years
Participant # (M,F)	178 (76M, 102F)	56 (23M, 33F)	86 (35M, 51F)	36 (18M, 18F)
Height (cm)	131.2 (9.8)	122.8 (7.0)	132.7 (7.4)	141.8 (7.0)
Body mass (kg)	30.2 (8.8)	25.3 (6.3)	31.1 (7.8)	36.4 (10.1)
Body mass index (kg m^{-2})	17.2 (3.4)	16.6 (3.2)	17.5 (3.2)	17.7 (4.2)

Values are expressed as mean (SD)

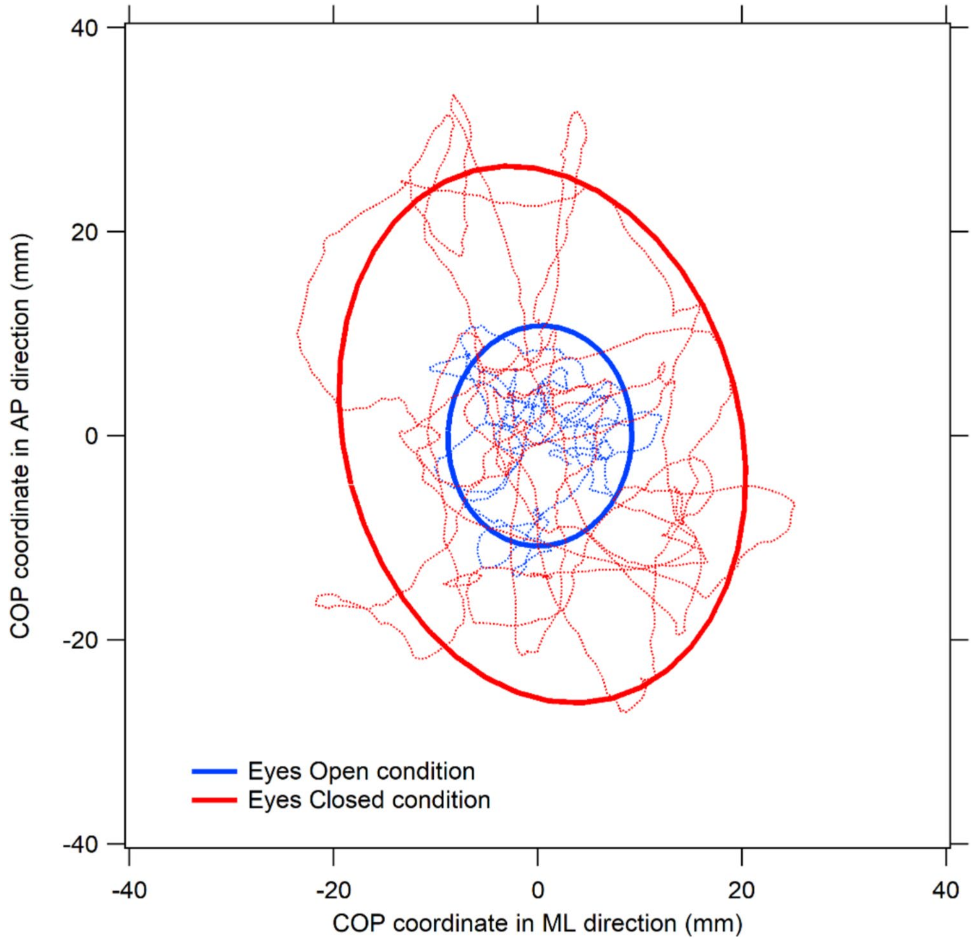

Fig. 1 Example of sway path (dotted line) and sway ellipse (solid line) as obtained from a 30 s bipedal test for a participant. Data acquired and computed under eyes-open and eyes-closed conditions are indicated, respectively, in blue and red color

Foot Morphology

Plantar pressure distribution data were exported from the platform management software as ASCII matrices (in which each a_{ij} element represents the pressure value recorded by the sensor located in the *i* row and j column), and processed using a custom-developed Matlab® routine to compute overall and sub-region (i.e., forefoot, midfoot and rearfoot) contact areas. Such variables also allowed the calculation of the Arch Index (AI) according to the procedure proposed by Cavanagh and Rodgers [18]. In particular, the AI was calculated as the ratio between the midfoot contact area and the overall foot contact area, excluding the toes. Based on AI values, each foot was classified according to the cut-off proposed by Chae, Kang, and Noh [19] as

- High arch (cavus foot): when $AI < 0.17$
- Normal arch: when $0.17 \leq AI \leq 0.28$
- Low arch (flat foot): when $AI > 0.28$

Statistical Analysis

A preliminary one-way multivariate analysis of variance (MANOVA) was employed to verify the possible presence of significant differences between right and left feet in terms of overall and sub-region contact areas. Then, four two-way MANOVAs were performed separately for each sex (males and females) and visual condition (eyes open and eyes closed), treating them as independent datasets. In all cases, foot morphology (i.e., cavus, normal, and flat) and age group (6–7, 8–9, and 10–11 years) were set as independent variables, while the postural sway parameters (i.e., sway area and COP path length) represented the dependent variables. The level of significance was set at $p = 0.05$, and eta-squared (η^2) values were reported as indicators of effect size. When a significant main effect of foot morphology or age group was observed, two-way ANOVAs were conducted as a follow-up analysis for each dependent variable. In this case, the significance level was adjusted using the Bonferroni correction to account for multiple comparisons ($p = 0.05/2$) and, when appropriate, Holm–Sidak post hoc tests were performed to explore pairwise differences between groups. Data were preliminarily checked for compliance with model assumptions. In particular, normality of residuals was verified using the Shapiro–Wilk test, and homogeneity of variances was assessed with Levene's test. These conditions were met for all variables, even in the presence of slightly unequal group sizes. All the statistical analyses were carried out using the software SPSS v.26 (IBM Corp., Armonk, NY).

Results

Preliminary analyses confirmed the absence of significant differences in the AI and in the overall and sub-regional foot–ground contact areas between the right and left limb [F(3, 352) = 0.463, $p = 0.708$, *Wilks' λ* = 0.996, $\eta^2 = 0.004$]; therefore, data from both sides (that is 356 feet) were treated as independent observations in all subsequent analyses. By considering the cut-off values for the AI previously mentioned, the final distribution of the participants according to their foot morphology included 184 high-arched feet (112 from female participants), 118 normal-arched feet (68 from females), and 54 low-arched feet (24 from females). Descriptive statistics for all postural sway parameters calculated under the two visual conditions (i.e., EO and EC) are reported in Tables 2 and 3, respectively. Mean values of sway area and COP path length across the different foot morphologies and age groups are also shown in Figs. 2 and 3.

Postural Sway Under Eyes Open Condition

Girls

The MANOVA analysis revealed a significant main effect of both age group and foot morphology on sway parameters [F(4, 388) = 4.42, $p = 0.002$, *Wilks' λ* = 0.915, $\eta^2 = 0.044$], [F(4, 388) = 3.93, $p = 0.004$, *Wilks' λ* = 0.924, $\eta^2 = 0.039$], respectively. In particular, the post hoc analysis revealed that girls aged 6–7 years exhibited significantly greater COP path length compared with those aged 8–9 years (mean difference = 47.1 mm, $p = 0.002$). As regards the effect of foot morphology, it was found that girls with high-arched feet were characterized by larger sway area values with respect to those with normal arches (mean difference = 52.7 mm^2, $p = 0.008$) and longer COP path length (mean difference = 33.1 mm, $p = 0.035$).

Boys

Even in this case, the MANOVA revealed a significant main effect of age group [F(4, 284) = 5.35, $p < 0.001$, *Wilks' λ* = 0.865, $\eta^2 = 0.070$] and foot morphology [F(4,

Table 2 Postural sway parameters obtained in the presence of visual input

	Foot morphology		
	Normal arch	High arch	Low arch
Girls			
Sway area (mm^2)			
6–7 years	223.4 (86.6) [189.85–257.03]	241.8 (113.6) [199.41–284.26]	258.8 (144.9) [137.61–379.97]
8–9 years	150.7 (72.1) [123.79–177.63]	225.3 (118.5)[a] [196.14–254.4]	161.9 (69.3) [89.16–234.66]
10–11 years	157.4 (89.1) [93.65–221.14]	257.5 (144.9) [180.27–334.72]	145.8 (82.7) [86.69–204.95]
COP path length (mm)			
6–7 years	346.1 (85.3) [312.98–379.14]	345.7 (65.0) [321.46–369.96]	383.7 (33.9) [355.32–412.04]
8–9 years	269.2 (77.8) [240.15–298.3]	323.2 (88.8)[a] [302.86–343.54]	267.9 (26.7) [239.92–295.9]
10–11 years	284.9 (94.1) [217.66–352.33]	372.6 (110.0) [313.93–431.18]	288.3 (144.9) [184.62–391.93]
Boys			
Sway area (mm^2)			
6–7 years	228.7 (63.4) [197.22–260.23]	281.2 (118.8) [222.1–340.27]	307.0 (198.7) [164.88–449.17]
8–9 years	196.1 (77.6) [161.69–230.51]	180.9 (112.9) [144.87–217.11]	216.1 (64.7) [162.01–270.12]
10–11 years	168.9 (49.9) [133.23–204.69]	164.7 (75.4) [121.17–208.2]	196.8 (99.2) [133.78–259.88]
COP path length (mm)			
6–7 years	349.2 (55.7) [321.46–376.89]	385.6 (93.4) [339.09–432.02]	383.0 (92.7) [316.66–449.26]
8–9 years	346.7 (95.3) [304.4–388.91]	313.3 (81.4) [288.49–339.09]	283.7 (24.7) [263.01–304.37]
10–11 years	345.4 (62.4) [300.92–390.13]	323.5 (85.4) [274.15–372.78]	207.0 (148.4)[a,b] [112.75–301.34]

Values are expressed as mean (SD). Corresponding 95% confidence intervals are reported in brackets beneath each mean value

[a]Statistically significant difference vs. Normal Arch

[b]Statistically significant difference vs. High Arch ($p < 0.05$ in both cases)

Table 3 Postural sway parameters obtained in the absence of visual input

	Foot morphology		
	Normal arch	High arch	Low arch
Girls			
Sway area (mm^2)			
6–7 years	315.1 (196.3)	298.0 (180.6)	350.9 (205.9)
	[238.99–391.25]	[230.57–365.41]	[178.75–523.07]
8–9 years	186.9 (85.0)	235.4 (110.3)	219.8 (101.4)
	[162.51–228.48]	[208.29–262.54]	[113.37–326.14]
10–11 years	254.2 (193.9)	318.1 (114.3)	169.7 (93.7)[b]
	[115.5–392.99]	[257.21–379.01]	[102.68–236.69]
COP path length (mm)			
6–7 years	487.4 (181.4)	431.3 (98.3)	481.9 (59.0)
	[417.07–557.72]	[394.56–467.94]	[432.62–531.27]
8–9 years	348.4 (99.8)	404.7 (95.7)[a]	373.4 (61.3)
	[311.06–385.58]	[381.18–428.21]	[309.13–437.72]
10–11 years	428.9 (162.8)	491.1 (134.5)	332.7 (168.9)[b]
	[312.5–545.39]	[419.44–562.77]	[211.86–453.52]
Boys			
Sway area (mm^2)			
6–7 years	288.2 (89.0)	320.2 (137.8)	300.7 (196.0)
	[243.89–332.46]	[251.66–388.76]	[160.51–440.95]
8–9 years	316.1 (143.9)	284.9 (215.5)	353.4 (135.7)
	[252.3–379.86]	[216.06–353.87]	[239.96–466.84]
10–11 years	261.9 (95.9)	392.8 (238.0)	209.7 (105.7)[b]
	[193.27–330.51]	[255.33–530.21]	[142.5–276.8]
COP path length (mm)			
6–7 years	469.8 (103.3)	535.3 (147.7)	483.0 (133.5)
	[418.45–521.23]	[461.89–608.75]	[387.49–578.52]
8–9 years	453.9 (114.7)	435.7 (127.6)	345.4 (48.1)
	[403.07–504.76]	[394.9–476.54]	[305.23–385.6]
10–11 years	438.5 (95.1)	469.6 (126.3)	325.4 (233.3)
	[370.48–506.58]	[396.68–542.47]	[177.22–473.65]

Values are expressed as mean (SD). Corresponding 95% confidence intervals are reported in brackets beneath each mean value

[a]Statistically significant difference vs. Normal Arch

[b]Statistically significant difference vs. High Arch ($p < 0.05$ in both cases)

284) = 8.12, $p < 0.001$, *Wilks'* $\lambda = 0.805$, $\eta^2 = 0.103$] on sway parameters. A significant age × morphology interaction was also found [F(8, 284) = 2.55, $p = 0.011$, *Wilks'* $\lambda = 0.870$, $\eta^2 = 0.067$]. The post hoc analysis revealed that boys aged 6–7 years exhibited significantly greater sway area than those aged 8–9 and 10–11 years (mean differences = 76.5 and 89.7 mm^2; $p < 0.001$). Similarly, COP path length was significantly greater in the youngest group compared with both the 8–9 and 10–11 year groups (mean differences = 20.1 and 80.8 mm; $p = 0.011$ and $p < 0.001$, respectively).

Regarding foot morphology, children with flat feet exhibited significantly lower COP path length values than those with high-arched ($p = 0.040$) and normal arches ($p = 0.009$).

Postural Sway Under Eyes Closed Condition

Girls

The MANOVA revealed a significant main effect of age group (but not of foot morphology) on sway parameters [F(4, 388) = 3.83, $p = 0.005$, *Wilks'* $\lambda = 0.926$, $\eta^2 = 0.038$]. A significant age × morphology interaction was also observed [F(8, 388) = 1.98, $p = 0.048$, *Wilks'* $\lambda = 0.923$, $\eta^2 = 0.039$], indicating that the influence of foot morphology on postural stability varied across developmental stages. The post hoc analyses revealed that girls aged 6–7 years exhibited significantly greater sway area and COP path length compared with those aged 8–9 years (mean differences = 88.9 mm^2 and

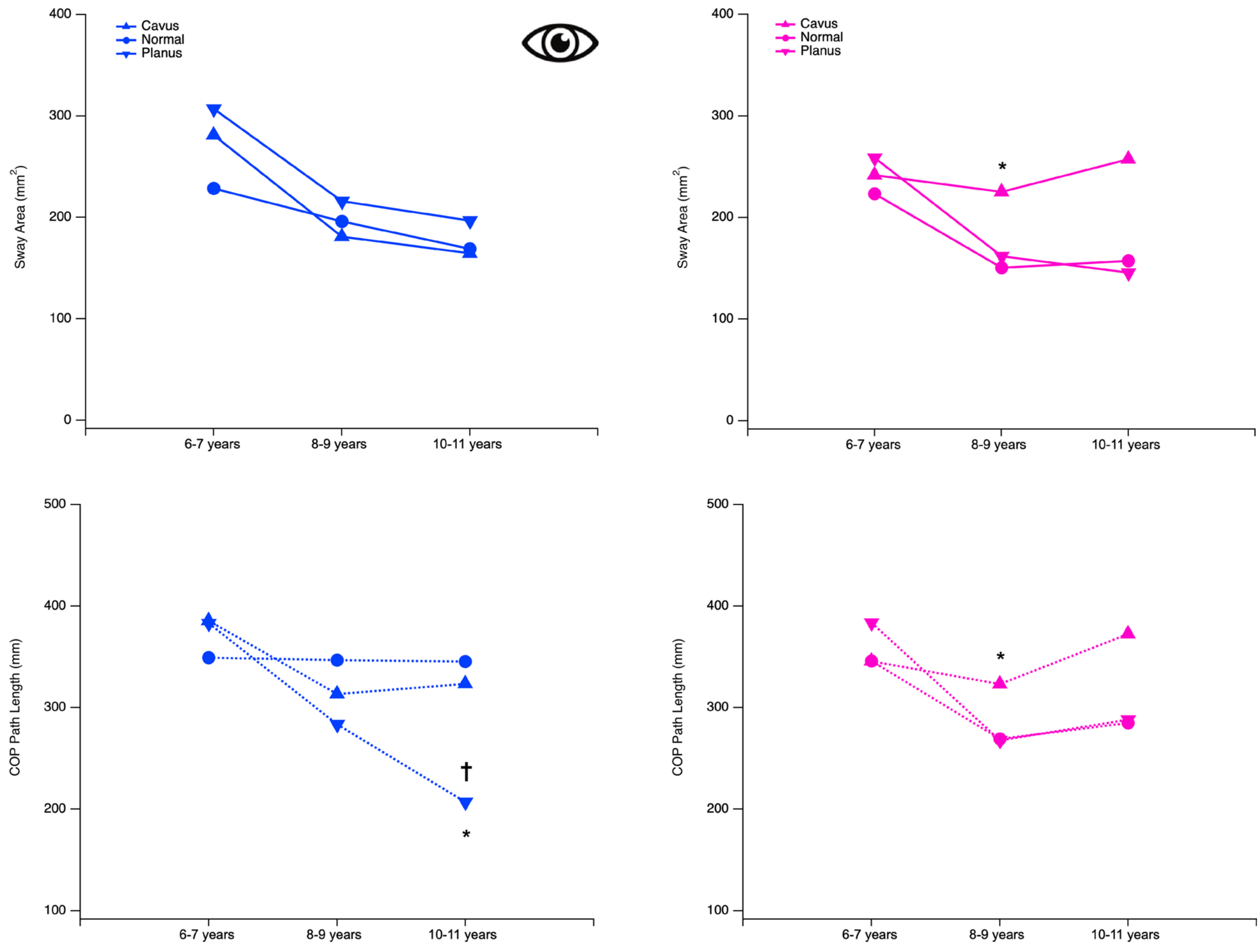

Fig. 2 Postural sway under eyes-open condition. Sway area (top row) and COP path length (bottom row) across different plantar morphologies and age groups, for boys (left) and girls (right). The symbol * indicates a statistically significant difference vs. Normal Arch. The symbol † indicates a statistically significant difference vs. High Arch ($p < 0.05$ in both cases)

75.0 mm, respectively; $p < 0.001$). Instead, no significant differences were observed between the 8–9 and 10–11 years groups.

Boys

Significant main effects of age group [$F(4, 284) = 4.52$, $p = 0.001$, *Wilks'* $\lambda = 0.884$, $\eta^2 = 0.060$] and foot morphology [$F(4, 284) = 3.11$, $p = 0.016$, *Wilks'* $\lambda = 0.918$, $\eta^2 = 0.042$] on sway parameters were detected. Post hoc analyses indicated that boys aged 6–7 years exhibited significantly longer COP path length than those aged 8–9 and 10–11 years (mean differences = 67.2 and 85.4 mm; $p = 0.026$ and $p = 0.013$, respectively). No significant differences were observed between the 8–9 and 10–11 years groups. Regarding foot morphology, boys with high-arched feet showed significantly greater COP path length compared with those with flat feet (mean difference = 83.9 mm, $p = 0.013$).

Discussion

The primary aim of this study was to quantitatively evaluate the effect of foot morphology on static balance, as measured by postural sway parameters, under both eyes-open and eyes-closed conditions in a cohort of typically developing children stratified by age and medial longitudinal arch type (the latter expressed through the AI parameter). This was achieved through the simultaneous acquisition of COP time-series data and plantar pressure measurements using a pressure plate.

First, it should be noted that, consistent with most previous studies on children in similar age ranges [1, 7, 20–22], younger participants (i.e., those in the 6–7 years age group) exhibited poorer performance of their postural control system compared with their older peers. Specifically, they were characterized by significantly larger COP path length (both sexes, all visual conditions) and sway area (boys under EO conditions and girls under EC

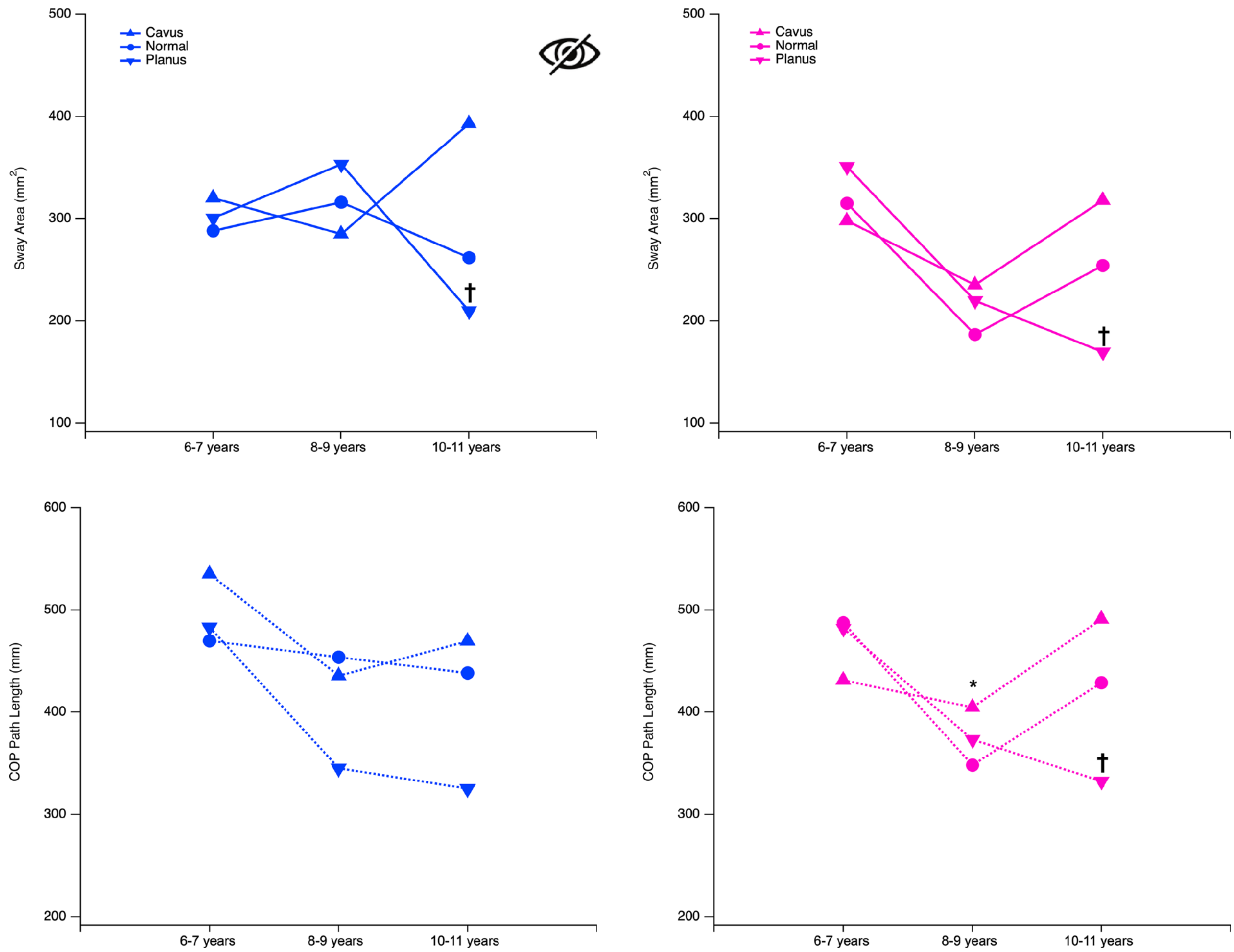

Fig. 3 Postural sway under eyes-closed condition. Sway area (top row) and COP path length (bottom row) across different plantar morphologies and age groups, for boys (left) and girls (right). The symbol * indicates a statistically significant difference vs. Normal Arch. The symbol † indicates a statistically significant difference vs. High Arch ($p < 0.05$ in both cases)

conditions). Such differences are usually attributed to the physiological maturation of the systems involved in postural control (i.e., visual, vestibular, and somatosensory), which occurs at different stages of childhood, as well as to the progressive ability of the central nervous system to efficiently integrate afferent information and generate the muscular contractions necessary to maintain upright posture.

However, because children also undergo parallel musculoskeletal development, it is reasonable to expect that the changes in foot morphology occurring during childhood may influence the performance of the postural control system. This expectation is further supported by the fact that humans predominantly rely on the somatosensory system to maintain balance when the environment is well illuminated, and the base of support is sufficiently rigid and stable [23, 24]. In principle, a reduced foot–ground contact area, as occurs in the case of a cavus foot, is accompanied by a proportional reduction in plantar cutaneous sensory input and may therefore impair the effectiveness of the postural control system, resulting in increased body sway [5].

This mechanism may partly explain the findings observed in the present study among girls aged 8–9 with cavus feet (but a similar trend was observed among those aged 10–11, although in this latter case statistical significance was not achieved, probably due to the limited size of this group). Indeed, these participants exhibited higher values of sway area (EO condition only) and COP path length (both EO and EC conditions) compared with those with normal feet. Conversely, the same trend was not observed in males of the same age. However, in the 10–11 age group, boys with cavus feet exhibited a trend toward greater sway compared with those with both normal and flat feet. These sex-related differences may be related to sex-specific trajectories in the development of the longitudinal arch, which tends to mature earlier in girls [25].

To achieve a more comprehensive interpretation of the distinctive sway patterns observed across the foot morphology groups, the different sensory demands associated with the two testing conditions should also be considered. Although visual information generally plays a relatively minor role in postural control in adults [26], it is considerably more important in children, as sensory integration mechanisms are not yet fully mature during development [27]. Accordingly, the removal of visual input is expected to induce a reweighting of somatosensory and vestibular information, potentially enhancing the contribution of plantar sensory feedback associated with foot morphology. However, the effects observed under eyes-open and eyes-closed conditions were not fully consistent across age and sex groups, preventing definitive conclusions regarding the specific role of visual input in the relationship between foot morphology and postural control. This finding may reflect the ongoing maturation of sensory integration processes during childhood, during which the relative contributions of visual, vestibular, and somatosensory information to balance regulation are still evolving. Future studies specifically designed to compare sensory conditions may help clarify how sensory reweighting processes interact with foot morphology throughout development.

Another interesting aspect that emerged from the analysis concerned children aged 10–11 years with flat feet. In this group, both boys and girls were characterized by a reduced COP path length (boys in EO and EC conditions, statistically significant in the latter; girls in EC only) and a reduced sway area (girls in EC only). Taken together, these findings would support the hypothesis that a larger foot–ground contact area may be beneficial for the effectiveness of the postural control system, for the same reason mentioned previously—namely, that a greater number of cutaneous receptors receive information from the external environment and transmit it to the central nervous system. However, existing findings in the literature are contradictory. For instance, while Lin et al. [9] reported the existence of a significant moderate negative correlation between AI and sway area (i.e., children aged 8–10 with flat foot are characterized by reduced sway), the results of Wako et al. [10] showed that, in children aged 8 years, girls with flat feet exhibited larger sway areas compared with those with normal or cavus feet. Such discrepancies may partly be explained by differences in the classification of the longitudinal arch, as Wako et al. [10] used the Chippaux–Smirak Index (CSI) for this purpose. Although AI and CSI are well correlated, they are sensitive to different aspects of foot morphology due to the way they are calculated (for example, a broad forefoot may lead to a reduced CSI without affecting the AI). As a result, the classification of foot types may differ substantially depending on the index used. The same authors acknowledged that heterogeneity in the classification of the arch type, originating from a lack of standardized assessment protocols, might explain the large differences observed in terms of the prevalence of flatfoot in previous studies. This apparent inconsistency suggests that the relationship between flatfoot morphology and postural control is likely influenced by developmental stage and sex. Indeed, the differences observed were not uniformly distributed across age groups, indicating that maturation-related factors may contribute to the heterogeneous results reported in the literature.

In summary, while the effect of cavus foot morphology on postural sway appears relatively straightforward to interpret (although the sex-related differences observed here warrant further investigation), clarifying the role of flatfoot is considerably more complex. This complexity likely reflects the multifactorial origin of flatfoot morphology, which arises from a combination of factors including muscle strength, bony structure, and soft-tissue characteristics.

Some limitations of the study should be acknowledged. At first, it should be recalled that footprint-based indexes provide only an indirect estimate of the arch structure and are influenced by factors such as soft-tissue thickness, body mass, and weight-bearing distribution, which may vary considerably during growth and may not accurately reflect the underlying bony arch. Secondly, since our analysis was focused on bipedal static weight-bearing conditions only, it was not possible to obtain information regarding the dynamic behavior of the medial longitudinal arch during gait or functional activities. Lastly, anthropometric factors such as height and body mass were not included in the analysis. Regarding height, previous studies have reported inconsistent findings: some observed a significant, albeit modest, association between postural sway parameters and stature [15], whereas others failed to detect such a relationship [28], thus the actual influence of this aspect remains to be fully clarified. In order to facilitate direct comparison with previous studies (most of which did not apply anthropometric normalization), we chose to analyze non-normalized data. With respect to body mass, we found that 24% of the participants were classified as overweight or obese. As mass excess is known to influence both postural control and plantar pressure distribution [29, 30], future studies should consider this aspect.

Taken together, the results of the present study suggest that foot morphology plays a relevant role in influencing postural control during childhood through both mechanical and sensory mechanisms associated with the characteristics of the foot–ground interface. In particular, altered plantar loading patterns and differences in somatosensory feedback may contribute to the adoption of distinct postural control strategies, whereas the observed sex-related differences are likely attributable to different maturation trajectories of the postural control system during childhood. If confirmed by further studies and replicated in broader populations, these findings may have important practical implications. For instance, children characterized by altered foot morphology and poorer postural control may benefit from periodic monitoring and, when clinically appropriate, referral to interventions aimed at improving proprioception, balance abilities, and foot function, such as adapted physical activity programs, balance-oriented training, and exercises targeting the intrinsic foot musculature. Furthermore, longitudinal studies are needed to clarify the long-term functional implications of these associations, as persistent alterations in postural control during development may influence movement efficiency, fatigue resistance, injury susceptibility, and participation in physical activity over time.

In conclusion, early identification of factors that may negatively influence the proper development of postural control in children is essential for designing and implementing targeted interventions, such as training programs and physical therapy. Particular attention should be given to the concurrent development of the musculoskeletal system—especially the foot—since the interaction between the foot and the ground plays a crucial role in providing sensory information necessary for maintaining balance. Our findings suggest, at least in part, that different types of medial arch may be associated with differences in postural control performance. Moreover, sex-related differences should be considered, as the maturation trajectories of the systems involved appear to differ markedly between boys and girls. Future research involving larger cohorts should ideally incorporate a broader range of measures to better characterize foot morphology—for example, including data on alignment as well as imaging techniques such as radiography and ultrasonography—and examine the influence of additional factors such as cutaneous sensitivity, excess body mass, and levels of physical activity, all of which may significantly affect the somatosensory and neuromuscular systems.

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Data Availability The result data of this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval The original experimental protocol was reviewed and approved by the Ethics Committee of the University of Cagliari (protocol no. 0001470 of 01/11/2022) and conducted in accordance with the principles of the Declaration of Helsinki and its subsequent amendments.

References

1. Verbecque, E., L. Vereeck, and A. Hallemans. Postural sway in children: a literature review. *Gait Posture*. 49:402–410, 2016. https://doi.org/10.1016/j.gaitpost.2016.08.003.
2. Era, P., and E. Heikkinen. Postural sway during standing and unexpected disturbance of balance in random samples of men of different ages. *J. Gerontol.* 40(3):287–295, 1985. https://doi.org/10.1093/geronj/40.3.287.
3. Piirtola, M., and P. Era. Force platform measurements as predictors of falls among older people: a review. *Gerontology*. 52(1):1–16, 2006. https://doi.org/10.1159/000089820.
4. Ruhe, A., R. Fejer, and B. Walker. The test–retest reliability of centre of pressure measures in bipedal static task conditions: a systematic review of the literature. *Gait Posture*. 32(4):436–445, 2010. https://doi.org/10.1016/j.gaitpost.2010.09.012.
5. Hertel, J., M. R. Gay, and C. R. Denegar. Differences in postural control during single-leg stance among healthy individuals with different foot types. *J. Athl. Train.* 37(2):129–132, 2002.
6. Sedaghati, P., F. K. Pakdel, and H. Zarei. Investigating the effects of high-arch and flat foot deformities on postural control: a systematic review and meta-analysis. *J. Mod. Rehabil.* 17(4):363–374, 2023. https://doi.org/10.18502/jmr.v17i4.13884.
7. Nolan, L., A. Grigorenko, and A. Thorstensson. Balance control: sex and age differences in 9- to 16-year-olds. *Dev. Med. Child Neurol.* 47(7):449–454, 2005. https://doi.org/10.1017/S0012162205000873.
8. Jiang, H., Q. Mei, Y. Wang, J. He, E. Shao, J. Fernandez, and Y. Gu. Understanding foot conditions, morphologies and functions in children: a current review. *Front. Bioeng. Biotechnol.* 11:1192524, 2023. https://doi.org/10.3389/fbioe.2023.1192524.
9. Lin, C.-H., H.-Y. Lee, J.-J.J. Chen, H.-M. Lee, and M.-D. Kuo. Development of a quantitative assessment system for correlation analysis of footprint parameters to postural control in children.

Physiol. Meas. 27(2):119–130, 2006. https://doi.org/10.1088/0967-3334/27/2/003.

10. Wako, M., T. Fujimaki, J. Ichikawa, R. Shinohara, S. Otawa, A. Kobayashi, M. Kushima, H. Yui, Z. Yamagata, H. Haro, Yamanashi Adjunct Study of the Japan Environment and Children's Study Group. Relationship of flatfoot to physical performance and postural stability in children: the Yamanashi adjunct study of the Japan environment and children's study. *Gait Posture*. 124:109992, 2026. https://doi.org/10.1016/j.gaitpost.2025.109992.
11. Fastame, M. C., E. Spada, D. Cimmino, B. Leban, M. Porta, F. Arippa, G. Casu, and M. Pau. Motor and cognitive skills implicated in the motor observation questionnaire for teachers (MOQ-T): a multidisciplinary approach. *Heliyon*.9(6):e16659, 2023. https://doi.org/10.1016/j.heliyon.2023.e16659.
12. Fastame, M. C., M. Porta, B. Leban, F. Arippa, G. Casu, and M. Pau. How do the motor efficiency and visuo-spatial skills of primary school children relate to their teachers' evaluation of visuo-spatial skills? *Hum. Mov. Sci.*101:103342, 2025. https://doi.org/10.1016/j.humov.2025.103342.
13. Porta, M., D. Cimmino, B. Leban, F. Arippa, G. Casu, M. C. Fastame, and M. Pau. Smoothness of gait in overweight (but not obese) children aged 6–10. *Bioengineering*. 10(3):286, 2023. https://doi.org/10.3390/bioengineering10030286.
14. Westcott, S. L., L. P. Lowes, and P. K. Richardson. Evaluation of postural stability in children: current theories and assessment tools. *Phys. Ther.* 77(6):629–645, 1997. https://doi.org/10.1093/ptj/77.6.629.
15. Chiari, L., L. Rocchi, and A. Cappello. Stabilometric parameters are affected by anthropometry and foot placement. *Clin. Biomech.* 17(9–10):666–677, 2002. https://doi.org/10.1016/S0268-0033(02)00107-9.
16. Kapteyn, T., W. Bles, C. Njiokiktjien, L. Kodde, C. Massen, and J. Mol. Standardisation in platform stabilometry being part of posturography. *Agressologie*. 24:321–326, 1983.
17. Prieto, T. E., J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans. Biomed. Eng.* 43(9):956–966, 1996. https://doi.org/10.1109/10.532130.
18. Cavanagh, P. R., and M. M. Rodgers. The arch index: a useful measure from footprints. *J. Biomech.* 20(5):547–551, 1987. https://doi.org/10.1016/0021-9290(87)90255-7.
19. Chae, J., Y.-J. Kang, and Y. Noh. A deep-learning approach for foot-type classification using heterogeneous pressure data. *Sensors*. 20(16):4481, 2020. https://doi.org/10.3390/s20164481.
20. Odenrick, P., and P. Sandstedt. Development of postural sway in the normal child. *Hum. Neurobiol.* 3:241–244, 1984.
21. Riach, C. L., and K. C. Hayes. Maturation of postural sway in young children. *Dev. Med. Child Neurol.* 29(5):650–658, 1987. https://doi.org/10.1111/j.1469-8749.1987.tb08507.x.
22. Pau, M., and M. Pau. Postural sway modifications induced by backpack carriage in primary school children: a case study in Italy. *Ergonomics*. 53(7):872–881, 2010. https://doi.org/10.1080/00140139.2010.489965.
23. Horak, F. B. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age Ageing*. 35(2):ii7–ii11, 2006. https://doi.org/10.1093/ageing/afl077.
24. McKeon, P. O., and J. Hertel. Diminished plantar cutaneous sensation and postural control. *Percept. Mot. Ski.* 104(1):56–66, 2007. https://doi.org/10.2466/pms.104.1.56-66.
25. Tong, J. W. K., and P. W. Kong. Medial longitudinal arch development of children aged 7 to 9 years: longitudinal investigation. *Phys. Ther.* 96(8):1216–1224, 2016. https://doi.org/10.2522/ptj.20150192.
26. Peterka, R. J. Sensorimotor integration in human postural control. *J. Neurophysiol.* 88(3):1097–1118, 2002. https://doi.org/10.1152/jn.00605.2001.
27. Peterson, M. L., E. Christou, and K. S. Rosengren. Children achieve adult-like sensory integration during stance at 12-years-old. *Gait Posture*. 23(4):455–463, 2006. https://doi.org/10.1016/j.gaitpost.2005.05.003.
28. Becker, S., A. Thomas, L. Ulrich, L. Becker, C. Dindorf, J. Berger, and M. Fröhlich. Reference values for static posturography of sportive and healthy adults aged 18–30 years. *BMC Sports Sci. Med. Rehabil.* 17:94, 2025. https://doi.org/10.1186/s13102-025-01128-z.
29. Hue, O., M. Simoneau, J. Marcotte, F. Berrigan, J. Doré, P. Marceau, S. Marceau, A. Tremblay, and N. Teasdale. Body weight is a strong predictor of postural stability. *Gait Posture*. 26(1):32–38, 2007. https://doi.org/10.1016/j.gaitpost.2006.07.005.
30. Dowling, A. M., J. R. Steele, and L. A. Baur. What are the effects of obesity in children on plantar pressure distributions? *Int. J. Obes.* 28(11):1514–1519, 2004. https://doi.org/10.1038/sj.ijo.0802729.