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REVIEW PAPER

Applications of Pedobarographic Analysis in Children - A Systematic Review

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Abstract

Healthy plantar pressure distribution beneath the feet plays a crucial role in children's development from the very beginning, with any deviations potentially leading to various pathologic conditions. This review aims to examine recent applications of pedobarographic analysis in pediatrics applications, providing a clearer picture of current research practices and the topics being addressed. The authors conducted a comprehensive search across several scientific databases, including PubMed, Web of Science, Scopus, and Google Scholar, ultimately selecting 17 studies after applying specific criteria for inclusion. The findings demonstrate that pedobarographic analysis can effectively differentiate between age and sex differences in plantar pressure and detect the influence of various risk factors in healthy children. It was found that a child's foot health is closely linked to their physical activity level, with body fat percentage playing a significant role in pressure distribution. Furthermore, external factors like school bags and internal factors such as obesity were identified as major contributors to abnormal plantar pressure, and pedobarography proved successful in detecting these effects. The analysis also showed that pedobarography is an effective tool for assessing foot health, tracking changes, and monitoring long-term recovery or trends in children. However, the review also highlights a limitation in the scarcity of research, particularly in the areas of gait and plantar pressure in children. Only a few studies have focused on young healthy athletes, suggesting that future research could delve deeper into this population.

Keywords: *pedobarography; gait analysis; children; gait; plantar pressure*

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Introduction

Walking is a fundamental skill for humans, which helps them move efficiently in space. Most people learn to walk before their first birthday. However, in some cases, walking can be challenging, hindering the development of more advanced motor skills. Growth and maturation are critical biological processes in human development. The growth of the skeleton, muscle mass, body weight, and height affect the balance of children and adolescents, which is maintained by the feet. Children's feet are still developing and immature, making them vulnerable to acute and chronic foot diseases (de Bongoa Vallejo & Iglesias, 2014; Riddiford-Harland, Steele and Storlien, 2000). Delayed skeletal growth compared to rapid body weight increase can lead to foot deformities and higher rates of diagnosis. This is also observed in overweight and obese children.

An excellent distribution of plantar pressure can lead to better sport-specific movements, dynamic postural control, and overall body balance. Foot health is an essential aspect of overall health and plays a vital role in body functionality and postural health. Detecting and preventing foot deformities at an early stage can save many children's sporting careers.

In this context, dynamic pedobarography seems to be a relatively simple and noninvasive technology that measures the change in plantar pressure distribution throughout the stance phase of gait (Hafer et al., 2013). It is an easy method to use in a clinical setting; can provide plenty of information about foot–soil interaction; and, alongside other gait analysis methods, can help assess the impact of a medical intervention, a rehabilitation program, or the effects of an orthotic device (Raposto, Ricardo, Teles, Veloso and João, 2022). However, certain authors debated its clinical utility/value (Choi et al., 2014). Indeed, there are various studies conducted with pedobarographic devices concerning children, but topically dispersed.

Therefore, this study aims to systematically sort the studies regarding recent applications of pedobarographic analysis concerning children in the last 20 years.

Materials and Methods

This systematic review was conducted following recent guidelines for performing systematic reviews in sports science (Rico-González et al., 2022). Application of these guidelines included the standardization of search procedures through the Boolean operators and download process, and implementation of PICO, PRISMA, and STROBE tools to ensure the quality and transparency of conducted systematic process.

Eligibility criteria

Three scientific databases were used for initial research, PubMed, Web of Science, Scopus, and one search engine: Google Scholar. Databases were selected by their compatibility with the selected topic.

The first step of eligibility evaluation includes specific preconditions for the extraction of scientific papers following the PICO framework (Eriksen & Frandsen, 2018). Inclusion criteria were defined according to Richardson et al. (Richardson, Wilson, Nishikawa and Heyward, 1995): 1) Population: children (>12 years old); 2) Intervention: pedobarographic analysis; 3) Comparison: a) longitudinal monitoring of various children subentities to evaluate certain trends, and b) transversal comparisons between individuals and between subentities for determination of possible positive and/or negative trends in certain subentities; 4) Outcome: usefulness of pedobarographic analysis on children population. Onwards, the exclusion criteria were the following: studies in other languages besides English, studies with a deficiency of crucial information about the measuring process, studies without a clearly described process of consent gathering & ethical approval, and studies published before 2004.

The second step involves a selection of specific terms, and combinations of terms used in searching through selected databases. Selected specific terms were searched in combinations with Boolean operators (Frants, Shapiro, Taksa and Voiskunskii, 1999): children, pedobarography, plantar pressure, pedobarographic, gait, children AND pedobarography, children AND pedobarographic analysis, children AND plantar pressure, pedobarography AND plantar pressure AND children, pedobarography OR plantar pressure AND children, children AND pedobarographic, children AND pedobarographic AND gait, children AND pedobarographic OR gait, children, AND gait.

Extraction protocol

The authors assessed studies within the extraction protocol from 21/11/2023 to 10/12/2023. The authors initially screened n= 393 scientific studies. After removing the duplicates, further screening included a detailed evaluation of retrieved studies within folders. After selected filtrations, authors assessed eligibility evaluation and extracted n=17 studies for inclusion in this systematic review. The procedure of study selection is shown in Figure 1, by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Page et al., 2021).

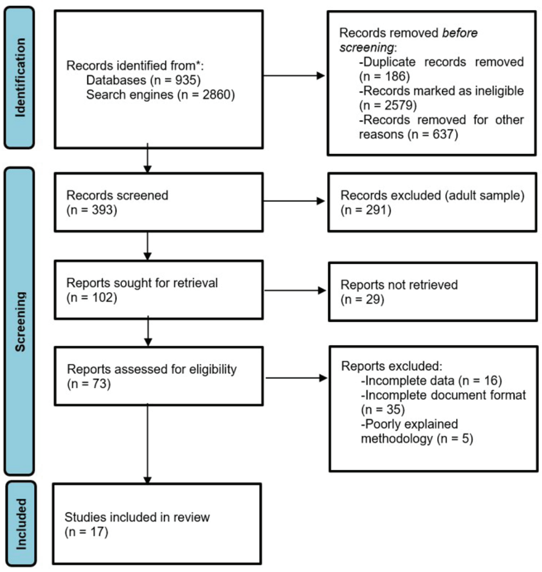

FIGURE 1. Flow diagram for screening and selection of studies according to Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA).

Table 1. STROBE checklist evaluation results of selected papers (n=17).

Authors	*1	*2	*3	*4	*5	*6	*7	*8	*9	*10	*11	*12	*13	*14	*15	*16	*17	*18	*19	*20	*21	*22	t
Alvarez et al., 2008	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	20
Jameson et al., 2008	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0	19
Taisa Filippin et al., 2008	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1	1	1	1	0	18
Becerro de Bengoa Vallejo et al., 2014	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	21
Erickson et al., 2015	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	20
Riddiford-Harland et al., 2015	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	20
Niiler et al., 2016	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0	20
Lampe et al., 2016	1	1	1	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	1	0	17
Kasović et al., 2018	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	1	1	1	1	1	1	0	18
Limpaphayom, Tooptakong & Osateerakun, 2019	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	21
Hagen et al., 2019	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	20
Mudge et al., 2020	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	20
Hösl et al., 2020	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	0	19
Štefan, Kasović & Zvonar, 2020	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	0	1	1	1	19
Kasović, Štefan & Zvonar, 2020	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	20
Dulai et al., 2021	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	21
Raposo et al., 2022	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	21

Legend: "0" = item with absence or lack of information; "1" = item with complete and explicit information; In title and abstract, *1 (title and abstract) = informative and balanced summary of what was done and what was found is provided. In introduction, *2 (background) = scientific background and rationale for the investigation being reported is explained; *3 (objectives) = state specific objectives and/or any pre-specified hypothesis. In Methods, *4 (study design) = key elements of study design are presented early in the paper, *5 (setting) = setting, locations, and relevant dates for data collection are described. This must include information on study period (specific dates), sport context (competition level, and competition category) and competition year(s) for all data collected; *6 (participants) = the eligibility criteria, and the sources and methods of case ascertainment and control selection were giver, as well as the rationale for the choice of cases and controls; *7 (variables) = all outcomes, exposures, predictors, potential confounders, and effect modifiers were clearly defined, also diagnostic criteria, if applicable; *8 (data source) = procedure for measurement is described; *9 (bias) = any efforts to address potential sources of bias were described, *10 (statistical methods) = statistical methods, including specific analytical methods used to examine subgroups and interactions, are described; = a measure of effect size is provided, *11 (quantitative variables) = Clarification of how quantitative variables were handled in the analyses. If applicable, description which groupings were chosen and why should be provided, *12 (statistical methods) = all statistical methods are correctly described, including those used to control. In Results, *13 (participants) = numbers of individuals at each stage of study were reported—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed, *14 (descriptive results) = characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders were properly reported, *15 (outcome data) = numbers in each exposure category were revealed, or summary measures of exposure, *16 (main results) =.statistical estimate and precision (i.e., 95% CI) for each sample or subgroup group examined is provided, *17 (other analyses) = other conducted analyses were reported—eg analyses of subgroups and interactions, and sensitivity analyses, In Discussion, *18 (key results) = a summary of key results with reference to study objectives is provided; *19 (limitations) = limitations of the study, taking into account sources of potential bias or imprecision are discussed, *20 (Interpretation) = Paper provides a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence, *21 (Generalisability) = the generalisability (external validity) of the study results is properly disscused. In Funding, *22 (funding) = the funding source of the study is cited or the absence of funding, if applicable; t = total score.

Included studies

The sample for this review comprises n=17 scientific studies published in English. All studies within a sample analyzed foot pressure parameters in children and adolescents in a certain context.

Quality assessment

Further, a quality assessment evaluation was performed through STROBE- "Strengthening the Reporting of Observational Studies in Epidemiology" checklist (Von Elm et al., 2007) to determine the quality of selected studies. All authors were present in the assembling of the concept. Screening and articles selection was conducted by authors Sporiš, Babić and Žigman. After the chosen 17 articles that have been selected for inclusion, all authors had to check and give their opinion. Point out any mistakes or why a certain article should be excluded. All authors unanimously agreed upon the selected articles.

The quality of selected studies was determined through the STROBE score ranking- results revealed the following stratification: n= 16 studies were estimated as "very high-quality" (18-22 points), only n=1 as "high-quality" (14-17 points), and there were no studies classified as "medium quality" (10-13 points), "low quality" (6–9 points) or "very low quality" (0–5 points). The greatest scores according to sections were recorded in *1-*6 (Title and abstract, Background, Objectives, Study Design, Setting, Participants). However, the lowest scores were obtained within sections of *16 (Main results) and *22 (Funding), due to the absence of CCI/95% CI and funding information- unfortunately the majority of studies. The overall mean score of all analyzed studies is 19.65 points, which is characterized as "high-quality".

Statistical Methods

Evaluation of impact within the extracted studies was assessed through the effect size (ES) calculation for each significant result report, within every selected study. Values were shown as reported in studies, usually calculated through Pearson's correlation coefficient (r), and Cohen's d Further analyses were conducted through descriptive statistics in the PC program Statistica 14. Additionally, this study represents Level I of evidence according to the medical guidelines (Ackley, Swan, Ladwig and Tucker, 2008) due to its systematic nature.

Table 2. Estimated ES values of extracted papers separately by study.

Authors	Relation	Pearson's r
Alvarez et al., 2008	-	-
Jameson et al., 2008	Intraobserver reliability	0.975
	Interobserver reliability	0.969
Taisa Filippin et al., 2008	Static-dynamic contact areas of midfoot (non-obese)	0.7
	Static contact area-maximum mean pressure (non-obese)	-0.7
	Arch index-peak pressure (obese)	0.5
	Arch index-contact area (non-obese)	0.8
	Arch index- maximum mean pressure (non-obese)	-0.5
	Body mass-contact area (non-obese)	0.5
	Body mass-dynamic contact area (both groups)	0.5
Becerro de Bengoa Vallejo et al., 2014	-	-
Erickson et al., 2015	Decrease in Meary's angle-increase in MMF contact area	0.41
Riddiford-Harland et al., 2015	Moderate-intensity PA- middle forefoot pressure	0.321
	Vigorous-intensity PA- middle forefoot pressure	0.326
	Moderate- to vigorous-intensity PA- middle forefoot pressure	0.342
	Moderate-intensity PA- lateral forefoot pressure	-0.248
	Vigorous-intensity PA- lateral forefoot pressure	-0.264
	Moderate- to vigorous-intensity PA- lateral forefoot pressure	-0.267
	Vigorous-intensity PA- lateral midfoot pressure	-0.244
	Vigorous-intensity PA- second toe pressure	0.227
Niiler et al., 2016	Intra-rater reliability MFF	0.99
	Inter-rater reliability MFF	0.98
	Intra-rater reliability LFF	0.98
	Inter-rater reliability LFF	0.92
	Intra-rater reliability MMF	0.96
	Inter-rater reliability MMF	0.93
	Intra-rater reliability LMF	0.99
	Inter-rater reliability LMF	0.96
	Intra-rater reliability heel	1.00
	Inter-rater reliability heel	1.00
	Intra-rater reliability CPPI	0.99
	Inter-rater reliability CPPI	0.96
Lampe et al., 2016	M. tibialis posterior volume-supination angular impulse (clubfoot)	-0.707
	M. soleus volume-supination angular impulse (clubfoot)	-0.535
	M. soleus volume-plantar flexion angular impulse (clubfoot)	-0.534
	m. surae volume-plantar flexion angular impulse (clubfoot)	-0.535
Kasović et al., 2018	-	-

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Table 2. Estimated ES values of extracted papers separately by study.

Authors	Relation	Pearson's r
Limpaphayom, Tooptakong & Osateerakun, 2019	-	-
Hagen et al., 2019	-	-
Mudge et al., 2020	-	-
Hösl et al., 2020	Peak pressure in hindfoot-FFI-D	-0.35
	Peak pressure in medial-FFI-D	0.33
	Peak pressure in lateral-FFI-D	0.35
	Peak pressure in total midfoot-FFI-D	0.35
	Weight-normalized smaller hindfoot pressure-more disability	-0.46
	Larger ratio of medio-lateral hindfoot peak pressure-lower (better) FFI-D	-0.34
	Lower ratio in midfoot-lower FFI-D	0.28
	Larger peak force in hindfoot-better function (force-normalized)	-0.37
	Larger peak force underneath hallux-better function (force-normalized)	-0.42
	Larger medio-lateral ratio in heel-smaller FFI-D	-0.32
	Smaller force underneath hallux-larger pain scores	0.29
Štefan, Kasović & Zvonar, 2020	-	-
Kasović, Štefan & Zvonar, 2020	Chronological age-force-time integral & pressure-time integral	0.50-0.80
	Chronological age-contact area and contact time	0.37-0.74
	Chronological age-peak pressure and average pressure	0.32-0.63
Dulai et al., 2021	-	-
Raposo et al., 2022	Intra-rater reliability:	
	Force-time integral (overall)	0.79
	Pressure-time integral (overall)	0.89
	Maximum force (overall)	0.79
	Peak pressure (overall)	0.81
	Contact area (overall)	0.83
	Contact time (overall)	0.37
	Force-time integral (hindfoot)	0.83
	Pressure-time integral (hindfoot)	0.97
	Maximum force (hindfoot)	0.92
	Peak pressure (hindfoot)	0.88
	Contact area (hindfoot)	0.91
	Contact time (hindfoot)	0.86
	Force-time integral (midfoot)	0.91
	Pressure-time integral (midfoot)	0.97
	Maximum force (midfoot)	0.91
	Peak pressure (midfoot)	0.97
	Contact area (midfoot)	0.98
	Contact time (midfoot)	0.73
	Force-time integral (forefoot)	0.73
	Pressure-time integral (forefoot)	0.97
	Maximum force (forefoot)	0.73
	Peak pressure (forefoot)	0.44
	Contact area (forefoot)	0.68
	Contact time (forefoot)	0.55

Legend: PA- physical activity, MFF- medial forefoot, LFF- lateral forefoot, MMF- medial midfoot, LMF- lateral midfoot, CPPI- coronal plane pressure index, FFI-D- Foot Function Index domain.

Correlation analysis perhaps suits better to this type of study than Cohen's d/Hedge's d, due to the relation-oriented study designs rather than differences between groups. However, several authors did not use the ES measures although they had applicable analyses. These articles were included in the study but the absence of effect size meant that they could only be qualitatively assessed.

Results

According to Table 3 there are seven disease-related studies, seven studies were conducted on healthy children, while three of them were designed as recovery follow-ups after operations and/or treatments. Further, studies focused on pathologic conditions included diseases like obesity (Taisa Filipin, De Almeida Bacari and da Costa, 2005; Riddiford-Harland et al., 2015), Sever's disease (de Bengoa Vallejo et al. 2014), idiopathic clubfoot (Lampe et al., 2017), cerebral palsy (Raposo et al., 2022; Mudge et al., 2020), and them were focused on reliability, validity (Jameson et al., 2008), and minimal detectable change (Niiler et al., 2016) of pedobarographic devices, while two studies served as the age & sex-standardized norms of functional and regional impulse measures in

Table 3. List of studies included in this systematic review (n= 17).

Studies	n of participants	Subgroups & age	Aim & problem	assessment tool	results	P
Alvarez et al., 2008	n=146 subjects, n=79 male; n=67 female	15 age groups- 6 months intervals (± 3 months) old between 18 months- 15 years	Determine possible age-related differences in foot pressure profiles in children	The Tekscan HR MatTM pressure measurement system and Research Foot Module (South Boston, MA)	Differences were found across 3 age groups: group 1: <2 years; group 2: 2–5 years; and group 3: >5 years	Stance at initiation at the medial midfoot (P= 0.01), maximum % force at the heel (P= 0.019), & maximum % force at the medial midfoot (P= 0.01)
Jameson et al., 2008	n=23 children, n=9 female; n=14 male	One cohort, 11.4 ± 3.3	1) Validity and reliability-determination technique for COPP; 2) establishing normative database for the COPP in children.	EMED ST2 pedobarograph (Novel, Munich, Germany)	Clinically acceptable validity and reliability for the pedobarograph COPP technique	Long axis of the foot (P= 0.001), mean difference between first and second determinations of the long axis (P= 0.001), mean difference between 4 analysts' determinations of the long axis (P= 0.001)
Taisa Filippin et al., 2008	n=20 children, n=10 obese; n=10 non-obese	Obese (OG) age 9.7 ±0.9, & non-obese (NOG), age 9.6 ±0.7	Can static footprints predict dynamic plantar pressures in obese children?	Digital planimeter (Placom - CST)	No significant correlation between BM and arch index; footprints and pedobarography should not be used at this time for clinical decisions regarding the feet of obese children	BM & static contact area for OG (P≤ 0.05); body mass & dynamic contact area for both groups (P≤ 0.05)
Becerro de Bengoa Vallejo et al., 2014	n=46 male soocer players, n=22 Sever's disease; & n=24 control	Boys with unilateral Sever's disease (SD) (10.45 ± 0.80), & healthy boys (H) (10.50 ± 0.78)	To compare static plantar pressures & distribution of body weight across lower limbs, & prevalence of gastrocnemius soleus equinus in children with/ without Sever's disease	Digital portable force plate (EPS-Platform; Loran Engineering, Castel Maggiore, Bologna, Italy)	Children with unilateral Sever's disease demonstrate higher static plantar pressures at the affected foot than the unaffected foot	SD- symptomatic feet peak pressure values higher than asymptomatic feet (P= 0.001), peak pressure of symptomatic feet (SD) versus corresponding feet in heel (P= 0.001)
Erickson et al., 2015	n= 19 patients, n= 10 male; n= 9 female	One cohort, 12.0 ± 3.9 years old	Dynamic pedobarographic evaluation of surgically treated cavovarus foot deformity in children with Charcot–Marie–Tooth disease	EMED pedobarograph system (Novel, Munich, Germany)	Pedobarographic measures showed statistical significance for increased contact area and decreased peak preassure force in most mask areas after surgical treatment.	Contact area: P= 0.001 in all regions except lateral forefoot; peak pressure force: P= 0.01 in lateral midfoot and forefoot; P= 0.001 for pressure time and peak pressure in hindfoot
Riddiford-Harland et al., 2015	73 overweight/obese children, n= 47 female; n= 26 male	One cohort, 8.3 ± 1.1 years old	To establish whether the peak plantar pressures generated by obese children during walking were associated with their physical activity	Novel-ortho automask software (version 13.3.16; Novelgmbh, Munich, Germany); Novel-win multimask software (version 13.3.16; Novelgmbh, Munich, Germany)	Children who generated higher pressures beneath their forefoot and midfoot during walking had lower levels of physical activity	Moderate-intensity (P= 0.007), vigorous-intensity (P= 0.006) & moderate- to vigorous-intensity (P= 0.004) physical activity significantly correlated with middle forefoot & lateral forefoot pressure (P= 0.040; P= 0.028; P= 0.027). Lateral midfoot (P= 0.044) and second toe (P= 0.021) pressure significantly correlated with vigorous-intensity activity

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Studies	n of participants	Subgroups & age	Aim & problem	assessment tool	results	P
Niiler et al., 2016	n=106 overall, n= 46 male; n= 62 female	Healthy children aged 2–17 years (10.6 ± 5.1); ages 2 (n = 10), 3 (n = 6), 4 (n = 4),5 (n = 7), 6–8 (n = 12), 9–11 (n = 19), & 12–17 years (n = 50)	Reliability and MDC in foot pressure measurements in typically developing children	TekScanresistive foot pressure mat (Boston, MA)	Inter- and intra-rater reliability was high for all measurements, variability was low, indicating small direct measurement error.	Not applicable
Lampe et al., 2016	Children with idiopathic clubfoot (n=12), n= 9 male; n= 3 female; n= 43 control	Children with idiopathic clubfoot group (2.5-16 years), & control group	Long-term 10-year study based on pedobarography, biomechanics, and MR measurements of muscle volumes	EMED-SF (Elektronisches Meßsystem zur Erfassung von Druckverteilungen; Novel Inc., Munich, Germany)	No tendency toward relapse during growth; a tendency toward normal partial load distributions was observed	Wilcoxon signed-rank test (P < 0.01) in partial lateral loads; reverse r between the volume of m. tibialis posterior & supination angular impulse (P= 0.002); m. soleus & supination angular impulse (P= 0.034), plantar flexion angular impulse (P= 0.034), also m. surae & plantar flexion angular impulse (P= 0.033)
Kasović et al., 2018	n= 127 schoolchildren, male (n = 62) & female (n = 65)	One cohort, aged 6.7 (±0.5) years	Authors wanted to determine the influence of schoolbag carriage on pattern changes in plantar pressure during walking among schoolchildren of first grade	EMED-XL pressure platform (Novelgmbh, Munich, Germany)	Schoolbag carriage significantly affected pressure distribution in feet among schoolchildren, which may cause or enhance feet deformities	Increased peak pressure for the forefoot (P= 0.000), midfoot (P= 0.000) and hindfoot (P= 0.004); average pressure for the midfoot (P= 0.005); contact surface at the forefoot (P= 0.000) & midfoot (P= 0.000)
Limpaphayom, Tooptakong & Osateerakun, 2019	n=22 patients (33 clubfeet) & n=22 healthy children (44 feet)	Patients: 11 unilateral and 11 bilateral clubfeet, & control group, at least 5 years old (12.8 ± 8.1)	To evaluate the results of the clubfoot treated with selective soft tissue release by comparing plantar force measurements and kinematics in clubfoot patients and controls.	Footscan® 7.92 software (RSScan International, Olen, Belgium)	Clubfoot patients demonstrated a longer contact time, larger contact area, lower peak pressure, and force relative to body weight in toe, midfoot, and heel areas	Plantar force significantly lower in patients than controls (P= 0.03)
Hagen et al., 2019	n=7 patients (13 feet)	One cohort, 2 girls & 5 boys, aged 12.43 ± 1.27 years (range 11–14 years)	Are the pedobarographic measurements can demonstrate functional changes in the month after surgery? SESA operation of juvenile flexible flatfoot	currex FOOTPLATE pro (currex GmbH, Hamburg, Germany)	The functional changes after SESA can be accurately assessed using pedobarography	Ground force increased in lateral foot areas (P< 0.001) and decreased in medial areas (P< 0.001); in the medial forefoot, force increased 14 days after surgery (P< 0.05)

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Table 3. List of studies included in this systematic review (n= 17).

Studies	n of participants	Subgroups & age	Aim & problem	assessment tool	results	P
Mudge et al., 2020	n=25 children with unilateral (n=18) and bilateral (n=7) CP or acquired brain injury	a) 25 children with lower limb spasticity, aged 8–16 years (11 male); b) 120 healthy children in control group	Can pedobarography predict the occurrence of heel rocker in children with lower limb spasticity?	emed®-AT/2 capacitance pressure distribution platform (Novel GmbH, Munich, Germany)	PIC can assess heel rocker with high accuracy. Both point of initial contact and rollback provide sensitive information on foot strike pattern, enhancing the utility of pedobarography	Increasing PIC associated with absence of heel rocker (P< 0.005 - independent correlation structure; & P< 0.005 -exchangeable correlation structure)
Hösl et al., 2020	n=51 children and adolescents with idiopathic flexible flatfeet	One cohort, aged 7–17	What is the association between the FFI and pedobarographic assessments in flatfeet of children and adolescents?	Emed platform (Novel, Munich, Germany)	Reduced peak forces and pressures underneath the hindfoot and hallux, a lateral shift (smaller medio-lateral ratios) of hindfoot pressure and force and a medial shift (larger medio-lateral ratios) of midfoot pressure seem to be negatively associated with foot-related disability	Peak pressure in hindfoot, medial, lateral and total midfoot correlated to the FFI-D (P= 0.012–0.020), weight normalized-correlation of smaller hindfoot pressure to more disability (P= 0.001); Larger ratio of medio-lateral hindfoot peak pressure related to lower FFI-D scores (P= 0.015), lower ratio in midfoot related to lower FFI-D scores (P= 0.046); larger peak force in hindfoot & underneath hallux related to better function (P= 0.008; P= 0.003); Heel- larger medio-lateral ratio related to smaller FFI-D values (P= 0.022); smaller force underneath the hallux correlated to larger pain scores (P= 0.045)
Štefan, Kasović & Zvonar, 2020	n= 641 healthy children	One cohort	Determine whether lower levels of physical activity are associated with higher plantar pressure	EMED-XL pressure platform (Novelgmbh, Munich, Germany)	Lower levels of physical activity were associated with higher force- and pressure-time integrals, longer contact time and higher peak and mean plantar pressures in both feet.	Boys had higher force-time integral and mean plantar pressure values in the left, mean plantar pressure value in right foot, compared to girls (P< 0.05); differences in force-time integral (P< 0.001), contact area (P< 0.001), contact time (P= 0.007) & mean plantar pressure (P= 0.048); level of physical activity doing in spare time (P= 0.007) & during breaks between classes (P< 0.001) in favor to boys

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Table 3. List of studies included in this systematic review (n= 17).

Studies	n of participants	Subgroups & age	Aim & problem	assessment tool	results	P
Kasović, Štefan & Zvonar, 2020	n= 1 284 schoolchildren (n= 714 boys & n= 570 girls)	6–14 years olds (9.6 ± 2.3) separated into gender and age-stratified groups	Establishment of (gender & age specific) reference database for the foot characteristics of children during walking	EMED-XL pressure platform (Novelgmbh, Munich, Germany)	Boys had longer force-time integral, higher contact area and contact time values, and higher peak plantar pressure, while no significant differences in pressure-time integral and average plantar pressure between sexes was observed. Older boys and girls had higher values in all measured variables.	(P< 0.001); (P< 0.001); (P< 0.001); (P= 0.017); (P< 0.001)
Dulai et al., 2021	n= 102, n= 50 male & n=52 female	2-17 years old children divided into five age groups (2-3, 4–6, 7–10, 11-14, and 15-17)	To: 1) quantify and characterize the pattern and spectrum of foot impulses in walking-aged, typically developing children; & 2) compare these to impulses from nondisabled adults	Pedobarography platform (emed-x, Novel GmbH, Munich, Germany)	The age-standardized norms of functional and regional impulse measures in children reported in this study can be used as a comparative benchmark in the clinical assessment of children presenting with various foot deformities.	Midfoot impulse decreased with age (P= 0.001), forefoot balance shifted medially (medial forefoot: P= 0.004; medial-lateral forefoot balance: P= 0.019)
Raposo et al., 2022	n= 10 children with CP	One cohort	To investigate test–retest reliability and MDC of plantar pressure insoles in children with CP when walking in regular footwear	Foot insoles Pedar-X system® (Novel, Munich, Germany)	Plantar pressure insoles are reliable tool for measuring different gait-related variables in children with CP	Not applicable

Legend: COPP- center of pressure progression, BM- body mass, MDC- minimal detectable change, MR- magnetic resonance, SESA- subtalar extra-articular screw arthroereisis, PIC- Point of initial contact, FFI- Foot Function Index, CP- cerebral palsy.

children (Kasović, Štefan and Zvonar, 2020; Dulai et al., 2021). One evaluates school carriage in schoolchildren (Kasović, Zvonar, Gomaz, Bolčević and Anton, 2018) and associations between plantar pressure and physical activity (Kasović et al., 2020), while the other (Alvarez, De Vera, Chhina and Black, 2008) determines and discusses age differences in foot pressure among healthy children. Recovery follow-ups were performed after a surgically treated cavovarus foot deformity in children with Charcot–Marie–Tooth disease (Erickson, 2015), as well as the clubfoot treated with selective soft tissue release (Limpaphayom, Tooptakong and Osateerakun, 2020), and one after the SESA operation of juvenile flexible flatfoot (Hagen, Pape, Kostakev and Peterlein, 2020). Onwards, a total of n= 2779 children were included in all listed studies, while n= 219 of them were in control groups. However, one study (Kasović et al. 2020) has almost half of all participants counted in this review (1284 of 2779). Total sample of n= 2648 in this review of the participants were healthy children, while n= 131 of them had one of the listed diseases. Indeed, only one study covers young (soccer) athletes (de Bengoa Vallejo et al., 2014). Girls make up almost a third of the total sample (35.33%; n= 982), but unfortunately, there are no studies that include young female athletes or exclusively female samples. Five studies included a cohort sample, five studies had experimental and control groups, while three studies had their sample separated by age group.

Pedobarographic devices which were used in the studies listed are mainly from one manufacturer company (Novel Inc., Munich, Germany), with the devices like EMED pedobarograph system (six studies), including variations (EMED ST2, EMED-SF, emed®-AT/2, emed-x, EMED-XL), software like the Novel-ortho automask software & Novel-win multimask software, and the Foot insoles Pedar-X system® from the last study from Table 3. Other studies include pressure plates from various manufacturers from Europe and US: South Boston, MA; Placom – CST; EPS-Platform; Loran Engineering, Castel Maggiore, Bologna, Italy; Boston, MA; RSScan International, Olen, Belgium; currex GmbH, Hamburg, Germany. The most recent study (Raposo et al., 2022) is the only one to include portable devices for peak pressure assessment, load distribution & gait lines- Foot insoles, while the devices in the other studies were fixed.

16 of 17 studies were in conclusion satisfied with the data collected through pedobarographic analyses, and the desired conclusions were drawn. Nevertheless, one study (Taisa Filippin et al., 2008) warns about the use of footprints and pedobarography in clinical practice, a statement later disproved by Riddiford-Harland et al. (Riddiford-Harland et al., 2015).

Due to heterogeneity of population, methodological designs of included studies a absence of effect size measure in some of the studies meta-analysis was not performed.

Studies on Healthy Children

One of the earlier studies in this field, conducted by Alvarez et al. (2008), aimed to determine possible differences in foot pressure profiles in healthy children regarding their age. The authors used a protocol that included a dynamic test with self-selected speed and walking patterns and obtained relative force and time data across foot segments: heel, lateral midfoot, medial midfoot, lateral forefoot, and medial forefoot. The subjects were initially separated into 15 age groups, and all possible interrelations were checked. Significant differences were found across three age groups that differed in three of the four a priori pedobarographic variables: % of stance at initiation at the medial midfoot (P= 0.001), maximum (%) force at the heel (P= 0.019), and maximum (%) force at the medial midfoot (P= 0.001). Indeed, these age groups were: Group 1 (<2 years), Group 2 (2–5 years), & Group 3 (>5 years). Valuable data was presented, particularly in terms of the relationship between maturation and gait biomechanics. Group 1 spent the most time (77.6%) on the medial midfoot compared to Group 2 (37.6%) and Group 3 (11.9%), which means that maturation occurred from a medially loaded midfoot (flatfoot) to a laterally loaded midfoot. The time of stance phase to complete initiation of foot loading also decreased inversely, proportional with age in all groups (24% to 18.3%).

The second study (Jameson et al., 2008) was conducted to determine the validity and reliability of the determination technique for the center of pressure progression (COPP) & to establish a normative database for COPP in children. Validity was determined by comparing the pedobarographic and kinematic-based determinations of the orientation of the longitudinal (or long) axis of the foot, while the reliability was assessed by comparing repeated measures of the long axis of the foot from 4 analysts. Validity comparison difference revealed a significant (P= 0.001) difference between the featured protocols, although the actual differences of this magnitude have not affected clinical decision-making and were therefore determined not to be of clinical significance. Further, intra-observer reliability (first and second determination) was significantly high (P= 0.001; r= 0.975), as well as inter-observer reliability (P= 0.001; r= 0.969). The normative database for healthy children revealed that the normal COPP is located under the heel segment for 23.7% of stance, under the midfoot segment for 28.7% of stance, and under the forefoot segment for 47.5% of stance respectively. Such information is surely valuable in clinical practice, as it should facilitate the characterization of abnormal foot-loading patterns, clinical decision-making, and the assessment of outcomes after a variety of interventions. Niiler et al. (2016) aimed to determine the reliability and minimal detectable change (MDC) in foot pressure measurements in typically developing (healthy) children. The protocol included three pedobarographic measurements taken per foot (all subjects), with six subjects returning for a second visit for assessment of day-to-day variability. Using a five-region mask, segmental impulses were determined, while the inter-rater, intra-rater, and day-to-day data were analyzed using intraclass correlation coefficients (ICC) to quantify reliability. Variability of the obtained coronal plane pressure index (CPPI)) was analyzed to quantify the MDC. Reliability was proven to be excellent, with intra-rater ICCs (0.96–1.00), & inter-rater ICCs (0.92–1.00). MDC-s were, however, high with the largest contributing factor- day-to-day variability. High relative variability in the CPPI and the medial mid-foot impulse resulted in very high MDCs for these measures. However, this study provided a framework for the quantitative comparison of foot pressure data between visits for a single patient, and warned about the use of CPPI, as it should be considered relatively (per patient).

It appears that the scientists around Kasović & Zvonar have done the most research (Kasović et al., 2018; Štefan, Kasović and Zvonar, 2020; Kasović et al, 2020) regarding the pedobarographic assessment in healthy children. The first study discusses the influence of schoolbag carriage on the pattern changes in plantar pressure among schoolchildren. A sample of n= 127 children was measured through the pedobarography with and without carriage. Unfortunately, many values were proven to be significant (Table 3), while the authors suggest that the changes in the distribution of intra-foot pressure may be the source of potential foot problems in the future. The second study involved a sample of n= 641 children while the authors wanted to determine whether the lower levels of physical activity are associated with higher plantar pressure among children. According to the results of this study, lower levels of physical activity were associated with higher force- and pressure-time integrals, longer contact time, and higher peak and mean plantar pressures in both feet (Table 3). This is a valuable result for the further promotion of regular physical activity and healthy living among children, as the best way to prevent the majority of chronic diseases. The third study included the greatest sample (n= 1284) to establish a reference database for the foot characteristics of children during walking. Results were further compared between age and gender subgroups to obtain a clarified picture. As significant differences were expected, this study is the very first one to publish a reference database for pedobarographic data of healthy children.

The most recent study (Dulai et al., 2020), as well as the first one in Table 3 (Alvarez et al., 2008), analyzed several age groups of healthy children, to quantify and characterize the gait pattern and spectrum of foot impulses, and secondly to compare these to impulses from non-disabled adults. Data revealed that the impulse through the midfoot was highest in the youngest age group, with a corresponding lower impulse through the medial forefoot. Proportionally with the age advancement, the midfoot impulse decreased (P= 0.001), and the forefoot balance shifted slightly more medially (%Medial Forefoot: P= 0.004; Medial-Lateral Forefoot Balance: P= 0.019). When compared to adults, there were no significant differences between 15-17-year-old children and adults in any of the regional percent impulses and impulse ratios. This data was somehow predictable and in agreement with the previous studies.

Disease-related Pedobarographic Studies

The study of Filippin et al., 2008 tried to determine if static footprints can predict dynamic plantar pressures in obese children. The authors compared static and dynamic footprints in two groups- obese and healthy children, through analysis of differences (t-test) and possible correlations (Pearson's r). However, no significant correlation between BM and arch index was found. Further, the results showed that the correlation between static and dynamic measures revealed that the variance in dynamic midfoot contact area can be predicted by the footprints only in healthy children, but not in the obese ones. Such results may lead to the conclusion that pedobarography should not be used for clinical decision-making regarding the feet of obese children. Contrary to that, Riddiford-Harland et al. (2015) successfully explored if the peak pressures during walking were associated with objectively measured physical activity in obese children. Significant values are visible in Table 3 and obtained data revealed that children with higher pressures beneath their forefoot and midfoot during walking had lower levels of physical activity, and therefore were at higher risk of foot pain or discomfort occurrence.

The second one (de Bengoa Vallejo et al., 2014) compared static pedobarographic foot pressure parameters of athlete children with and without Sever's disease. Sever's disease is one of the most common causes of heel pain in athletic children and is often associated with gastrocnemius ankle equinus. Results indicate significantly higher ($P< 0.001$) maximum and average peak pressures & forefoot pressures in the affected heel of participants in the Sever's disease group, than in the control group. However, there was no difference between the groups in the surface contact area. Second, the %BW supported by the heel was significantly higher in participants in the Sever's disease group than in the control group for both feet ($P= 0.001$). Lastly, high heel plantar pressures may be associated with the symptoms that characterize Sever's disease, and this method could serve as a screening tool in clinical practice.

Onwards, the only long-term study within this review (Lampe et al., 2017) was a 10-year study based on pedobarography, biomechanics, and MR measurements of muscle volumes regarding children with idiopathic clubfoot disease. The Clubfeet of 12 children were examined repeatedly over up to 10 years using pedobarography and continuously compared to the controls. The results indicate significant values (Table 3) in Spearman's r (inverse) & Wilcoxon signed-rank test differences in partial lateral loads. Interestingly, the functional and anatomical differences between the two groups existed, but the general developmental changes during growth were similar. The combination of pedobarographic data and derived joint moments with MR-measured muscle volumes indicate that the higher ankle joint moments in clubfoot were associated with smaller muscle volume and were generated by higher joint rigidity.

The next study (Hösl et al., 2020) involved the examination of idiopathic flexible flatfeet in children. Precisely, the authors searched for an association between the Functional Feet Index (FFI) and pedobarographic assessments in flatfeet of children through analysis of bivariate partial correlations and contact times as co-variate. Reported results as visible in Table 3, indicate the practical utility of pedobarography regarding flatfeet evaluation. Authors emphasized the importance of focusing on the peak pressures/forces in the hind- or midfoot or beneath the hallux whilst performing such evaluations.

The last two studies in this group examined the possible usage of pedobarography in children with cerebral palsy (CP). Firstly, Mudge et al. (2020) tried to explore if pedobarography (specifically point of initial contact- PIC) can successfully predict the occurrence of heel rocker in children with lower limb spasticity (CP). The heel rocker is one of the three rockers proposed by Perry to describe the action of the ankle and foot as the body progresses forward over the stance limb (Perry, 1992). Ultimately, the PIC can successfully assess heel rocker with high accuracy, with a threshold of 14% of foot length identifying the correct heel rocker status in 94% of cases. Anyhow, Raposo et al. (Raposo et al., 2022) investigated test–retest reliability and MDC of plantar pressure insoles in children with CP when walking in regular footwear, which is probably the first implementation of portable pedobarographic devices in the context of children's health assessment. The whole footprint showed an excellent ICC (≥ 0.75), except for the contact time variable (ICC= 0.36; 95% CI 0 to 0.784). Speaking of segmented foot measures, a good to excellent

range of ICC values (≥ 0.60) was found, except for peak pressure (ICC= 0.439; 95% CI 0 to 0.807) and maximum force (ICC= 0.552; 95% CI 0 to 0.845) at the forefoot. Meanwhile, the SEM and MDC values were within an acceptable range for each of the variables, both whole and segmental footprints.

Recovery Follow-Ups

The first recovery follow-up (Erickson et al., 2015) concerns surgically treated cavovarus foot deformity in children with Charcot–Marie–Tooth disease. The recovery dynamic was assessed through the pedobarographic evaluation. Therefore, preoperative and postoperative dynamic pedobarographic measurements were made and analyzed using the five-mask technique. Pedobarographic measures showed a statistical significance for the increased contact area ($P= 0.001$-0.000) (except for the lateral forefoot) and decreased peak forces ($P= 0.01$-0.003) in most mask areas after the surgical treatment. Peak pressure and redistribution of varus pressure patterns trended toward improvement. However, the correlation between radiographic and pedobarographic data showed only a mild correlation between a decrease in Meary's angle and an increase in the medial forefoot contact area ($r=0.41$). Finally, the authors concluded that pedobarography may serve as a useful tool for recovery tracking, but should be used in addition to clinical and radiographic examination.

The second study (Limpaphayom et al., 2020) was conducted to evaluate the results of the clubfoot treated with selective soft tissue release, by comparing plantar force measurements and kinematics in clubfoot patients and controls. The mentioned technique included initial nonoperative treatment by Kite's method- a manipulative maneuver and separately corrected forefoot adduction, heel inversion, and ankle equinus by a long leg cast (before surgery). As well as in the previous study, (clubfoot) patients demonstrated a longer contact time, larger contact area, lower peak pressure, and force relative to body weight in the toe, midfoot, and heel areas. Plantar force in the patients was indeed significantly lower than in the control group ($P= 0.03$). In conclusion, the authors emphasize the importance of limited soft tissue release during surgeries concerning idiopathic clubfoot.

Hagen et al. (2020) examined if the pedobarographic measurements were able to demonstrate functional changes in the month after subtalar extra-articular screw arthroereisis (SESA) surgery of juvenile flexible flatfoot. Pre- and post-operative measurements were conducted, and results were compared. The pedobarographic measurements showed a lateral shift after surgery, toward a healthier pressure arrangement within the feet. This lateralization of contact area and force can be seen in both foot types, valgus and planus. Also, the gait normalizes with the reduction of ground forces in the medial midfoot, which might indicate the formation of a (healthy) longitudinal arch.

Discussion

Pedobarographic devices are a relative novelty in science and clinical practice, and there are only several studies that involve pedobarography protocols, especially in children. However, devices manufactured by Novel Inc. based in Munich, Germany, appear to be the most used pedobarography devices in general. Although previous studies have reported satisfactory metric values, more research on validity and reliability is required to confirm its usefulness. The device can be used across all age groups, including children, both healthy and those affected by the disease. Healthy children often engage in physical activities that shape their entire body correctly and naturally before, during, and after puberty. These principles are reflected in the maturation of the feet. Therefore, physical activity should play an important role as a means of preventing foot deformities in children. As two studies have confirmed its validity and reliability (Jameson et al., 2008; Niiler et al., 2016), pedobarography could be widely used in sports centers, clinics, and laboratories to follow the development of as many children as possible. Particular attention should be paid to potential risk factors related to healthy posture and plantar pressure distribution, external load such as the school bag- which is often relatively heavy for children (Kasović et al., 2020), and internal load- obesity. Higher plantar pressure associated with constantly carrying excess weight on their developing feet may lead to foot pain and dysfunction in overweight and obese children (Riddiford-Harland et al., 2015). The higher plantar pressures during walking in obese adults and the associated foot pain have also been shown to affect the ability of individuals to participate in physical activity (Riddiford-Harland et al., 2015; Hills, Hennig, McDonald and Bar-Or, 2001). Such a causally consequential relationship may lead to the (negative) Matthew's effect (Perc, 2014), in this case, it is a vicious circle where lack of physical activity leads to deformities, which lead again to physical activity evasion. Unfortunately, the increasing number of obese children presents significant challenges for various sectors such as health, education, and sports. Pedobarography could serve as an additional tool to prevent foot deformities from an early age. The data provided by pedobarography represents the structural health of the feet and maybe the more convincing diagnosis for parents to change their children's diet and energy consumption while they can still influence it. Most disease-related studies have confirmed the usefulness of pedobarography in detecting plantar pressure disorders. One study (Lampe et al., 2017) also proved the usefulness of pedobarography in longitudinal studies, in this case over 10 years. Pedobarography successfully detected symptoms of Sever's disease, clubfeet, and flatfeet. Speaking of disorders, many children with disorders of the neuromuscular system, including children with spastic cerebral palsy, are unable to position the foot effectively at initial contact (Mudge et al., 2020). Furthermore, an intact heel rocker is dependent on appropriate pre-positioning of the foot in terminal swing, one of the prerequisites of normal gait (Mudge et al., 2020; Gage & Schwartz, 2009). However, the authors successfully employed pedobarography in two CP-related studies. In the first study, heel pain status was successfully predicted (94% of cases), while in the other study the use of a portable pedobarographic device - plantar pressure insoles - was tested and approved. This has implications for the use of pedobarography in the follow-up of patients recovering from surgery for cavovarus foot (Charcot–Marie–Tooth disease), clubfoot, and juvenile flexible flatfoot. To be cautious, there was only a mild correlation with radiographic data (Erickson et al., 2015), so pedobarography for determination purposes may be combined with one or more devices involving different technologies.

Conclusion

Pedobarographic analysis successfully determines age and sex differences and recognizes the effects of risk factors in healthy children. As the children grow, the time from the stance phase to the complete initiation of loading of the foot decreases inversely proportional to age, the midfoot impulse decreases in favor of lateral midfoot load, and the forefoot balance shifts slightly more medially. Foot health in children therefore depends to a certain extent on the individual's level of physical activity, often closely related to body fat percentage. The major risk factors appear to be external (e.g. school bag) and internal (e.g. obesity) load, and therefore their negative effects on the plantar pressures in children could be detected through the pedobarography. In the cases such as obesity, Sever's disease, clubfoot, flatfeet, and CP, pedobarography can successfully serve as a primary or adjunct tool to assess the condition, track changes, and as long-term protocols for the monitoring of certain trends. Finally, pedobarography has provided relative satisfaction to researchers in terms of recovery follow-up tracking, and many authors do approve of its usage. The limitation of this review, which can be explained as a literature gap, lies in the relative scarcity of explored topics concerning gait and plantar pressure in children, with no studies conducted on young healthy athletes, to look at the possible association with sports success, specific disciplines, and positions within a particular sport, as well as studies regarding talent identification purposes, which may be in the focus of the future research regarding this field.

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Conflicts of Interest

The authors declare no conflict of interest.

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