

# Predictive character of the foot's structural variables aids assessing postural stability in school-aged children: a cross-sectional study

**Beata Szczepanowska-Wolowicz**

Jan Kochanowski University

**Paulina Sztandera**

Jan Kochanowski University

**Ireneusz Kotela**

Jan Kochanowski University

**Marek Zak** (✉ [mzak1@onet.eu](mailto:mzak1@onet.eu))

Jan Kochanowski University

---

## Article

### Keywords:

**Posted Date:** April 19th, 2022

**DOI:** <https://doi.org/10.21203/rs.3.rs-1515772/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

---

# Abstract

The WHO Health Behaviour in School-aged Children study (2018) on the health status of adolescents in Europe highlights an escalation of factors instrumental in the development of postural defects, which may consequently deteriorate into serious postural complaints in adulthood. The study aimed to investigate the correlations between morphological structure of the foot and postural stability in children and adolescents. The study sample comprised 627 children (aged 10-15 years), who had the plantar part of their feet assessed in static conditions with a 2D podoscan. Individual foot loading paradigm variables were assessed with a baropodometric platform. Postural assessment was completed with a 2D Videography, facilitating morphological measurements of body asymmetry. Valgus of the knees, Clarke's angle, and Wejsflog index values also doubled as strong predictors of COP length. A negative correlation was established between the COP length and obesity, hallux valgus of the left foot, flat-footedness, and the lowered longitudinal foot arches. Higher COP surface area values were observed in the children affected by valgus of the knees, higher angle of the hallux valgus in the left foot, and those boasting longer feet. Clarke's L-foot angle, Wejsflog index, and valgus of the knees proved strong predictors affecting key postural stability variables.

## Introduction

A WHO Health Behaviour in School-aged Children collaborative cross-national study (2017/2018), comprising data on the health of adolescents in Europe, highlights an escalation of factors instrumental in the development of postural defects among children and adolescents [1]. In Europe, a large number of children have been diagnosed with postural defects, located mostly in the spine, knees, and feet [1].

Overall support, locomotion, and cushioning make up the foot's key functions. The cushioning is facilitated by the "springs", i.e. the foot's longitudinal arches. Provided those arches are adequately developed structurally, they can effectively offset all the loads which naturally occur when walking and running [2, 3, 4, 5].

Changes in the anatomical structure of the foot may prove detrimental to the entire bio-kinetic chain of the lower limbs, both in the static and dynamic conditions [6]. Any structural irregularities appearing within the foot may adversely affect the actual mechanics of the joint, overall postural stability, and appreciably modify an individual foot-loading paradigm, whilst also affecting balance [7].

Numerous studies prove beyond a reasonable doubt that specific type of footwear may appreciably affect the actual development of the child's foot and its overall mechanics [8, 9, 10]. Vulnerable structure of a child's foot is quite susceptible to numerous environmental factors, which naturally enforces the need for footwear as an adequate everyday protection. Yet another factor identified as appreciably affecting both structural and functional changes in the child's foot is posed by excessive body weight. Numerous studies also highlight the correlation between congenital sensory deficits and individual postural paradigm [11].

Assessment of overall postural stability is based on the interpretation of graphic records of the COP (centre of foot's pressure) sways. In static conditions, the COP record takes into account the inclination of the centre of gravity (COG), as well as the foot's pressure on the ground. A computerized, posturo-graphic platform may be used for this purpose in view of its objectivity.[7] The device commonly used in clinical practice, quite inexpensive, simple-to-apply, which may also prove rather handy for the screening purposes, is a podoscan. Whilst making routine use of it, we aimed to detect any foot abnormalities, as well as establish whether they actually affected the subjects' postural stability in any way.

General scarcity of research reports on the impact of foot structure on overall postural stability among children and adolescents, in conjunction with an acknowledged need to gain an insight into those correlations, as well evidenced in the Authors' own preliminary research, actually prompted them to have this deficit addressed at some depth, predominantly through assessing and comparing the morphological features within the structure of the foot, with a view to establishing any potential correlations with individual postural stability.

## Results

A Box-Cox transformation ( $\lambda = 0.421$ ) was applied with a view to having the distribution of the explained variable transformed into a more Gaussian-like form. The following table presents the results of the modelling - t value and p-value statistics.

Longer COP path is associated with the valgus of the knees, and higher Wejsflog index. Also, for the Clarke's left foot angle, indicating a foot with a raised arch, a longer COP path is encountered. A negative correlation was established between the length of COP and obesity, hallux valgus of the left foot, flat-footedness and the lowered arches (Table 1, Fig. 1,2).

Table 1

Correlations between the COP length, the foot's morphological variables, and the valgus of the knees.

Dependent variable	Predictor	t-value	p-value
COP length	Valgus of the knees	2.94	<b>0.003</b>
	Obesity (BMI)	-3.00	<b>0.003</b>
	Hallux valgus angle $\alpha$ L	-2.48	<b>0.013</b>
	Clarke's angle L (flat foot and foot with a reduced arch)	-3.11	<b>0.002</b>
	Clarke's angle L (foot with a raised arch)	1.86	0.063
	Wejsflog index	4.14	<b>&lt;0.001</b>
	Foot width	-3.77	<b>&lt;0.001</b>

The model comprised the age variable (t val = 1.75, p-val = 0.08).

Model parameters: Adjusted  $R^2 = 62.3\%$

Statistics F Snedecor-Fisher = 74.62 with number of degrees of freedom  $df_1 = 14$  and  $df_2 = 609$

$p\text{-val} < 0.001$

VIF (Variance Inflation Factor) does not indicate any collinearity issues for all VIF predictors  $< 2$ .

With regard to the regression model, where the explained variable was the COP area, it also proved expedient to have the Box-Cox transformation ( $\lambda = -0.099$ ) applied. It is worth noting that the model no longer boasts as much explaining force as the COP length. The COP area was not as strongly determined by the available variables, as taken under consideration in the model (Adjusted  $R^2 = 13.9\%$ ).

Additionally, the variables such as age ( $t \text{ val} = -4.109$ ,  $p\text{-val} < 0.001$ ) and gender, were incorporated into the model, where the reference category was gender = female ( $t \text{ val} = 3.161$ ,  $p\text{-val} = 0.002$ ).

When assessing the COP area, a significant correlation was noted between the subjects' age and gender. Their age ranged 10–15 years, the COP area was larger in the younger children, and smaller in the older ones. The differences in the COP area between girls and boys were also observed, i.e. in boys this area was notably larger.

With regard to postural and foot characteristics, higher COP surface area values were observed in the children affected by the valgus of the knees, with a higher angle of the hallux valgus in the left foot, boasting longer feet, whereas a smaller COP surface area was encountered in the individuals with a larger angle of the 5th toe of the left foot (Table 2).

Table 2  
Correlations between the COP surface area of the foot's morphological variables and the valgus of the knees.

Dependent variable	Predictor	t-value	p-value
COP surface area	Valgus of the knees	1.391	0.165
	Hallux valgus angle $\alpha$ L	1.535	0.125
	The fifth toe angle $\beta$ L	-1.762	0.079
	Foot length	1.719	0.086

In the model for the average X, the Yeo-Johnson transformation was applied ( $\lambda = 1.037$ ). The model for the average X, making use of the available variables, was characterised by a very low model adjustment value (Adjusted  $R^2 = 6.98\%$ ).

Larger values of mean X were observed for the individuals with the valgus of the knees, a foot with a raised arch (based on Clarke's angle), whereas the smaller values of mean X are associated with the overweight subjects (Table 3).

Apart from the variables presented in the model further below, there was also gender to be considered ( $p = 0.052$ )

For the average Y value, the quality of model adjustment was higher (Adjusted  $R^2 = 13.68\%$ ). In this case it also proved necessary to have the Yeo-Johnson transformation applied ( $\lambda = 0.870$ )

As may be inferred from Table 3, higher average Y values appeared in the children with a lowered arch in the left foot (based on Clarke's angle). The lower mean Y values were associated with the left foot with a higher arch and a narrower hindfoot.

Table 3  
Correlations between the stability indicators comprised within the foot's morphological variables and the valgus of the knees.

Dependent variable	Predictor	t-value	p-value
COP mean X	Valgus of the knees	2.251	<b>0.025</b>
	Hallux valgus angle $\alpha$ L	-1.294	0.196
	Clarke's angle P (foot with a raised arch)	2.047	<b>0.041</b>
	Overweight (BMI)	-2.622	<b>0.009</b>
	Obesity (BMI)	1.870	0.062
COP mean Y	Hallux valgus angle $\alpha$ L	1.620	0.106
	Clarke's angle L (foot with a reduced arch)	3.240	<b>0.001</b>
	Clarke's angle L (foot with a raised arch)	-3.570	<b>0.000</b>
	Hindfoot width	-2.411	<b>0.016</b>

The value of the X-axis following the Yeo-Johnson transformation was modelled ( $\lambda=-0.254$ ); model adjustment expressed with the aid of the Adjusted  $R^2 = 12.58\%$

The model demonstrated a statistically significant positive correlation between the X-axis and the valgus of the knees, and Wejsflog index (Table 4). The model also comprised such variables as age (t-val = -3.638, p-val < 0.001) and male gender (t-val = 3.616, p-val < 0.001).

In the case of the model for the Y axis, the Box-Cox transformation ( $\lambda=-0.228$ ), Adjusted  $R^2 = 14.88\%$  was applied.

Additionally, the model also comprised age (t val = - 4.714, p-val < 0.001), and male gender (t-val = 2.91, p-val = 0.004). This means that older children had lower Y-axis values, whereas the boys had higher Y-axis values (Table 4).

Table 4  
Correlations between the stability indicators comprised within the foot's morphological variables and the valgus of the knees.

Dependent variable	Predictor	t-value	p-value
COP X	Valgus of the knees	2.248	<b>0.025</b>
	Hallux valgus angle $\alpha$ L	2.497	<b>0.013</b>
	Wejsflog index	2.345	<b>0.019</b>
COP Y	Hallux valgus angle $\alpha$ L	2.069	<b>0.039</b>
	The fifth toe angle $\beta$ L	-1.644	0.101
	Foot length	2.043	<b>0.042</b>

## Discussion

Approx. 90% of children are born with healthy feet, whereas with age they become affected by various factors which account for a diversity of subsequent complaints, notably those of structural character. European studies indicate that only 3% of individuals over the age of sixty have structurally sound feet [12].

The fact that so few adults boast functionally efficient feet nowadays not only is attributable to various ailments and physical injuries sustained throughout one's lifetime, but also caused by wearing the ill-fitting footwear. Children are especially prone to be affected by many environmental factors in their adolescence, most of them of lifestyle origin [12, 13, 14].

Our own research outcomes indicate that dysfunctions in any part of the lower limb also affect overall postural stability, especially the standing posture. This consequently places an extra burden on the neuromuscular system, whose basic function consists in stabilising the foot, and maintaining overall balance control [15, 16, 17].

The position of respective toes, especially the hallux and the 5th toe, requires to be considered in terms of the COP trajectory. Any deviation in the position of the hallux and the small toe are reflected in the postural stability variables. The angle  $\alpha$  of the left hallux valgus correlates with the length of COP, COP area, average COPX, average COPY, COP X, COP Y. The angle of the small toe  $\beta$  correlates with the COP and COPY surface area. Any alteration in the positioning of those two is then bound to affect overall postural stability, apart from being statistically significant, as evidenced throughout the body of Authors' own research.

When taking due note of the above-referenced aspects, defective status of the lower limbs and its impact upon overall stability should also be considered. Brzeziński et al. [18], when examining 6992 children, aged 8–12 years, encountered the lower limb defects in 90.2% of the subjects; the boys having been more

frequently affected. Much like in our own research, age and male gender significantly affected postural stability variables. A significant predictive variable was the knee valgus, confirmed to affect the length of COP, COP surface area, mean COP X, and COP Y. Apart from the COP surface area, this dependence was also deemed appreciably significant.

There are numerous studies corroborating the correlation between the foot arching and postural stability. An ostensibly trivial, painless problem of the lower longitudinal arches may account for an adverse knock-on effect on the physiological gait pattern, whereas prospectively it may well cause pain in the peripheral joints and the spine. The Clarke's angle is a reliable and commonly applied diagnostic tool in assessing podiatric disorders [19]. The select variables under study indicate that the Clarke's angle is a prognostic variable for the COP path length, mean COP X and Y axis. The Wejsflog index as the indicator also proved a strong predictor for the COP length, and the range of COP movement in the X axis. Puszczalowska-Lizis, Ciosek [20], whilst examining the structure of the feet in conjunction with the somatic features in the pre-school children, highlighted a negative effect of body weight on the development of the foot's longitudinal arch among their subjects.

The present Authors noticed the effect of sexual dimorphism on the differences in modelling the preferential character of the manipulative and stabilising functions of the lower limbs. In the study of Puszczalowska-Lizis [20], the effect of gender and excessive body weight on the size of longitudinal and transverse arches was readily acknowledged. The correlation between the foot arches and overall postural stability in young adults and elderly persons was observed by Kim et al. [21], i.e. a greater difference in COP sways between the flatfooted individuals and those with the properly arched feet.

Also, Tahmasebi et al. [22] and Chao [23] reported deterioration in overall stability in the individuals presenting the lowered longitudinal arches. The effect of a reduced mobility of the foot arch on postural control and COP sways was also observed by Birinci and Demirbas [24], and Mun [4]. Based on the results of our own research, it was established that the knee valgus, Clarke's angle, and Wejsflog's index affected the variables of postural stability, being also the strong predictors of COP length ( $R^2 = 62.3\%$ ).

The effect of foot structure on overall postural balance among adults has been addressed by numerous investigators, although a manifest deficit of such investigative effort is reported with regard to children and adolescents. When assessing the morphological structure of the foot, due account must be taken of its correlation with overall postural stability. The results of our own research gave us sufficient ground to venture the following conclusion: abnormalities in the morphological structure of the foot affect the variables of overall postural stability among children and adolescents. The morphological variables of the feet, as distinguished following the linear regression analysis, effectively justify the actual selection of postural stability variables under study.

The final conclusion took into account the characteristics of anatomical structure of the feet for which the model variables turned out to be of the highest values. It is our assumption, therefore, that the strongest predictors affecting the length of COP are the valgus of the knees, L toe angle and L Clarke's

angle, and Wejsflog index ( $R^2=62.3\%$ ). It may then readily be inferred that the left limb, which boasts a stabilising function, affects overall stabilisation of the standing position, as opposed to the right one.

Whilst acknowledging the strong effect of abnormal morphological structure of the feet on overall postural stability, the consequences of which may be distant, yet well capable of adversely affecting the entire biokinetic chain, we have been looking for specific solutions which would facilitate reliable and accurate assessment of morphological variables of the foot among children and adolescents. To the best of our knowledge, ours is the first study to highlight overall significance of abnormalities in the morphological structure of feet, and their effect on overall postural stability among children.

A podoscan, an assessment instrument frequently used in routine clinical practice, may easily be applied in the screening tests. Any abnormalities actually detected at this point should then be subject to further, more accurate diagnostic procedures. Bearing in mind the likely subsequent costs of treating the resultant complaints located in the musculoskeletal system, it seems expedient to have specifically structured prevention measures put in place to facilitate their early detection.

Our quest was therefore focused predominantly on looking for simple, objective, non-invasive, cost-effective, yet reliable solutions which, when applied in clinical practice, would immediately draw due attention to any abnormalities encountered in the feet, and their crucial correlation with overall postural stability. Encouraging results clearly indicate that taking adequate interest in overall functionality of the feet, especially throughout adolescence, has nowadays become a generally acknowledged necessity.

Appreciable effect of consistently pursuing a target-oriented, physiotherapeutic management, specifically aimed at improving an individual sense of balance in various disorders, is already well addressed and documented in numerous studies [25, 26, 27].

## Conclusions

The Clarke's L-foot angle, Wejsflog index, and valgus of the knees were established as the strong predictors affecting postural stability variable, whereas the positioning of the hallux and the small toe proved a predictive variable affecting the postural stability variables. Assessment of the foot's key structural variables and postural stability in school-aged children highlighted overall significance of the issue itself, consequently prompting specific measures aimed at preventing adverse consequences directly resultant from the foot's functional disorders, likely to jeopardise postural stability in adulthood.

## Research Design And Methods

The study group consisted of 627 children, aged 10–15 years, including 299 (47.7%) girls and 328 (52.35%) boys (Table 5).

Table 5  
Basic characteristics of the study group.

Variable	Girls (n = 299) Mean ± SD	Min-Max	Boys (n = 328) Mean ± SD	Min-Max	Z	p
Body mass [kg]	43.86 ± 11.48	21–77	45.28 ± 13.21	23–99	-0.764	0.445
Height [cm]	151 ± 10	128–173	152 ± 12	126–183	-0.250	0.803
BMI	18.84 ± 3.35	11.35–29.32	19.24 ± 3.72	12.37–36.51	-1.008	0.314
Mean-arithmetic mean, SD-standard deviation, Z- statistical values of the Mann-Whitney-Wilcoxon test for two independent samples, BMI- body mass index, p-significance level						

The assumptions of the study took into account the inclusion criteria, i.e. informed consent to attend the study protocol, complete documentation of the study, no defects in the locomotor system. The exclusion criteria comprised the lack of informed consent to attend the study protocol, incomplete documentation of the study, and any defects in the locomotor system, as established through an interview.

A series of pertinent measurements were taken, i.e. individual body height was measured with the aid of a German-made SECA meter (93/42/EEC, 2007/47/EC), body weight by a Japanese-made Tanita BC-418MA scales (93/42/EEC Annex II). Assessment of the plantar part of the foot in static conditions was made with a 2D podoscan. Plantar pressure of the foot exerted against the surface in static conditions was assessed with an Italian-made FreeMed platform, operated by with FreeStep Pro software (FreeMed, Sensor Medica Italy, no.10806). Postural assessment was completed with 2D Videography (Sensor Medica, Italy), a device facilitating morphological measurements of body asymmetry.

The 2D FootCAD podoscan is a computerized podoscope assessing the plantar part of the foot. The length, width, pertinent angles and axes of the foot are determined, as well as the load-bearing zones of the foot are also subjected to interpretation [3, 8, 9].

The following indicators were assessed: foot length - in mm, forefoot width - in mm, Clarke's angle – in °, Wejsflog (W) index, hallux valgus angle ( $\alpha$ ) – in °, the angle of the varus deformity of the fifth toe ( $\beta$ ) - in ° (Fig. 3) [3, 28, 29].

The Clarke angle values were the basis for the assessment of the longitudinal arch of the foot. And so: flat foot occurs in the range  $< 30^\circ$ , foot with a reduced arch  $31^\circ - 41^\circ$ , properly arched foot  $42^\circ - 54^\circ$ , foot with a raised arch  $> 55^\circ$  [3, 13, 28, 29].

The Wejsflog index (foot length/width, ratio 3:1) was used to assess the transverse arch. The transversely flat rate is indicated by the values closer to "2", the values of the correct rate are closer to "3". The correct

valgus angle ( $\alpha$ ) is up to  $9^\circ$  [3, 4].

A dynamometric platform (FreeMed, Sensor Medica, manufactured in Italy), operated by FreeStep Pro software, was used for all stabilometric tests [3, 30]. The subject adopted a free-standing position, with his feet parallel, upper limbs hanging loosely along the trunk, his eyes looking straight ahead. The duration of the measurement was 30 seconds.

The subject was in a free-standing position, with his feet parallel, upper limbs hanging loosely along the trunk, his eyes looking straight ahead.

The interpretation of the movement of the foot pressure center (COP) was made during the assessment of the following indicators: length of sway - determines the length of the COP trajectory in mm – COP length; surface - surface area of the COP sway in  $\text{mm}^2$  - COP field area; mean X - mean value in mm of the COP trajectory in the X axis - COP X mean; mean Y - mean value in mm of the COP trajectory in the Y axis - COP Y mean; X axis - the range of COP movement in the X axis in mm in the mid-lateral direction of ML - COP X; Y axis - the range of COP movement in the Y axis in mm in the antero-posterior direction AP - COP Y [3, 29].

Currently, the most common method of assessing individual balance is COP signal measurement. In stabilometry, the most frequently analysed variables attesting to a correlation with deteriorated balance are the length of the COP trajectory, the actual size of the COP deflection area, mean COP X and Y, and COP shifts in the X and Y axis [30].

A 2D Videography is yet another software package powering the FreeMed Posture (Sensor Medica, Italy) device applied in the study. It is a system dedicated to postural and gait assessment, fitted out with a camera and a tripod. A 2D Videography (Video Pack) makes it possible to take comprehensive morphological measurements of any possible body asymmetries. The readouts are subsequently processed by the FreeStepPro software (no 10806), which automatically measures and compares possible asymmetries and pertinent angles.

The subjects' knee valgus was successfully assessed with the aid of 2D Videography.

## **Statistical methods**

Statistical software R v.4.0.1 was used to process the data yielded throughout the study protocol. The arithmetic mean, standard deviation, Mann-Whitney-Wilcoxon test for two independent measurements, and the significance level were applied for the basic description.

Morphological variables of the feet, i.e. hallux valgus angle, Clarke's angle, Wejsflog index were taken into account, as well as the key somatic variables, i.e. age, sex, BMI.

With a view to checking the correlation between the stability indices and the above-referenced variables, linear regression models were applied. Dependent variables were subjected to a transformation. For the

variables with positive values Box-Cox transformation was used, whereas for the remaining variables - the Yeo-Johnson counterpart. All variables were selected using stepwise backward regression, based on the Snedecor's F statistics.

In view of the risk of strong collinearity in the case of several variables, the mean values were prepared instead of considering the right and the left foot separately. Correlation coefficient for both feet was established to have oscillated above 0.75, which makes it possible to have both feet taken under consideration conjointly, whilst making use of average values. The Wejsflog index, the forefoot, hindfoot, and foot length appeared in the model as an average for both feet.

## **Study Limitations**

It proved unfeasible to have a group of individuals actively involved in sports effectively identified within the study population. Otherwise, comparison of the respective results/variables under study conclusively highlighted the adverse effects of physical inactivity. Also, there was no possibility to have the study population stratified by specific age-ranges, so consequently the study outcomes may not fully reflect the key characteristics of respective age groups, owing to small sample sizes.

Initially, we had assumed that all footwear worn by the study subjects was adequately selected and well-fitting. As we progressed through the study protocol, however, we had to concede we were actually confronted with an altogether different situation, as numerous subjects tended to wear either too tight, or far too loose-fitting footwear.

## **The Compliance Statement**

All research methods applied throughout the study protocol were pursued/implemented in full compliance with pertinent guidelines, regulations, and applicable legislation in place.

## **Declarations**

### **Acknowledgments**

The Authors feel particularly indebted to Dr Julie Stebbins, University of Oxford, whose insightful, critical input throughout proved instrumental in enhancing both the academic and hands-on appeal of their study.

The Authors also remain most grateful to all children and their parents/guardians for their committed involvement in the study protocol.

This research project was funded by the Ministry of Education and Science - "Regional Initiative of Excellence" - spanning the period 2019–2022; Grant Ref. No 024/RID/ 2018/19; amount of financing allocated: PLN 11 999 000.00.

## Authors' Contributions Statement

Conceptualization, B.S.W. and M.Z. Methodology, B.S.W., and M.Z. Software, B.S.W., P.S. Validation, B.S.W., I.K., and M.Z. Formal analysis, B.S.W., P.S. and M.Z. Resources, B.S.W., P.S. Data curation, B.S.W., P.S., I.K. Writing – original draft, B.S.W. and M.Z. Writing, review, and editing, M.Z. Visualization, B.S.W., P.S. Supervision, P.S., I.K. Project administration, B.S.W., I.K., Funding acquisition, B.S.W and M.Z. All Authors have read and endorsed the concluding version of the manuscript.

## Competing Interests Statement

The Authors report no conflicts of interest in the present study.

## Data Availability Statement

All the datasets analysed in the present study are available from the Corresponding Author upon reasonable request.

## The Ethics Approval Statement

The study design and protocol were granted approval and duly endorsed by the Bioethics Review Committee, established in pursuance of pertinent statutory constraints at the Faculty of Medicine and Health Sciences, Jan Kochanowski University of Kielce, Poland, following rigorous appraisal of the investigators' application for ethics approval, completed on June 20, 2016 (Ethics Approval Ref. No. 26/2016).

## The Informed Written Consent Statement

Written informed consent was obtained from the parents/guardians of the minor study subjects for their attendance in the study protocol. It was based on the detailed information on the actual aims and research methods to be applied, having prior been furnished to them by the Investigators.

## References

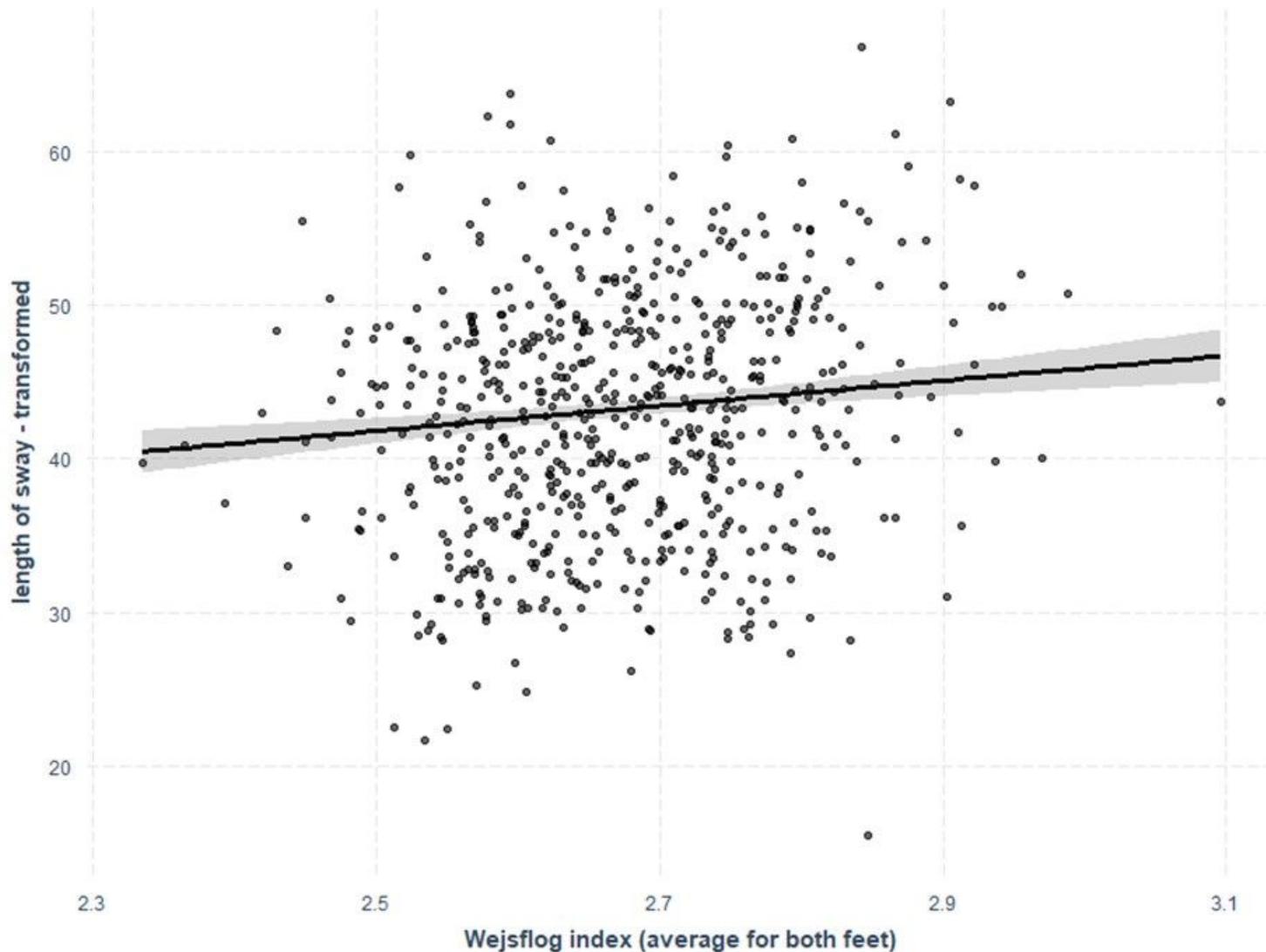
1. Inchley, J., Currie, D., Young, T., Samdal, O., Torsheim, T., Augustson, L. et al (red.). Growing up unequal: gender and socioeconomic differences in young people's health and well-being. HEALTH BEHAVIOUR IN SCHOOL-AGED CHILDREN (HBSC) Study: International report from the 2013/2014 survey. World Health Organization 2016.
2. Jastrzębski, P., Kaczor, T., Żłobiński, T., Stolecka-Warzecha, A., Błońska-Fajfrowska, B. Metatarsalgia as osteoarticular cause of foot dysfunction. *Ann. Acad. Med. Siles.* **73**,134–143 (2019).  
Doi:10.18794/aams/102683
3. Szczepanowska-Wołowicz, B., Sztandera, P., Kotela, I., Zak, M. Feet deformities and their close association with postural stability deficits in children aged 10–15 years. *BMC Musculoskeletal Disorders* **20**, 537(2019). Doi:10.1186/s12891-019-2923-3

4. Mun, K.R., Chun, S., Hong, J., Kim, J. The Relationship Between Foot Feature Parameters and Postural Stability in Healthy Subjects. *Hum Factors* **61(7)**, 1077–1085 (2019).  
Doi.org/10.1177/0018720819828545
5. McKeon, P.O., Hertel, J., Bramble, D., Davis, I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. *Review Br J Sports Med.* **49(5)**, 290 (2015). Doi: 10.1136/bjsports-2013-092690
6. Viseux, F., Lemaire, A., Barbier, F., Charpentier, P., Leteneur, S., Villeneuve, P. How can the stimulation of plantar cutaneous receptors improve postural control? Review and clinical commentary. *Clinical Neurophysiology* **49**, 263–268 (2019). Doi.org/10.1016/j.neucli.2018.12.006
7. Cen, X., Xu, D., Baker, J. S., Gu, Y. Effect of additional body weight on arch index and dynamic plantar pressure distribution during walking and gait termination. *PeerJ* **21**, 8:e8998 (2020). Doi: 10.7717/peerj.8998
8. Hollander, K., de Villiers, J.E., Sehner, S., Wegscheider, K., Braumann, K.M., Venter, R., Zech, A. Growing-up (habitually) barefoot influences the development of foot and arch morphology in children and adolescents. *Sci Rep.* **14,7(1)**,8079(2017). Doi: 10.1038/s41598-017-07868-4.
9. Barisch-Fritz, B., Mauch, M. Foot development in childhood and adolescence. *Handbook of Footwear Design and Manufacture. Woodhead Publishing Series in Textiles* 49–71(2013). DOI: 10.1533/9780857098795.1.49
10. Qichang, Mei., Yaodong, Gu., Liangliang, Xiang., Peimin, Yu. Foot shape and plantar pressure relationships in shod and barefoot populations. *Biomech Model Mechanobiol.* **19(4)**,1211–1224(2020). DOI:10.1007/s10237-019-01255-w
11. De Araújo, P.P., De Moura Filho, O.F., Valenti, V.E., Gallo, S.M., Camargo, M.R., Say, K.G., Marcomini, R.S., de Oliveira, G., Monteiro, C.B., Wajnsztein, R., de Abreu, L.C. Stabilometric parameters analysis in children with visual disorder. *Int Arch Med.* **7 (1)**, 1(2014). Doi: 10.1186 / 1755-7682-7-1.
12. Petersen, E., Zech, A., Hamacher, D. Walking barefoot vs. with minimalist footwear - influence on gait in younger and older adults. *BMC Geriatr.***20(1)**, 88(2020). Doi: 10.1186/s12877-020-1486-3
13. Bookstein, F.L., Domjanic, J. The Principal Components of Adult Female Insole Shape Align Closely with Two of Its Classic Indicators. *PLoS One* e0133303 (2015).  
Doi.org/10.1371/journal.pone.0133303
14. McRitchie, M., Branthwaite, H., Chockalingam, N. Footwear choices for painful feet – an observational study exploring footwear and foot problems in women. *J Foot Ankle Res.* **11**, 23 (2018). Doi: 10.1186/s13047-018-0265-2
15. Woźniacka, R., Oleksy, Ł., Jankowicz-Szymańska, A., Mika, A., Kielnar, R., Stolarczyk, A. The Association Between High-Arched Feet, Plantar Pressure Distribution and Body Posture in Young Women. *Sci Rep.* **9(1)**, 17187(2019). Doi: 10.1038/s41598-019-53459-w
16. Kudo, S., Sakamoto, K., Shirakawa, T. Comparison of foot kinematics and the morphology of intrinsic musculature of the foot using a foot-type classification based on function. *J Phys Ther Sci.* **32(3)**, 238–242(2020). Doi.org/10.1589/jpts.32.238.

17. Deleu, P.A., Chèze, L., Dumas, R., Besse, J. L., Leemrijse, T., Bevernage, B. D., Birch, I., Naaim, A. Intrinsic foot joints adapt a stabilized-resistive configuration during the stance phase. *J Foot Ankle Res.* **13(1)**,13(2020). Doi.org/10.1186/s13047-020-0381-7.
18. Brzeziński, M., Czubek, Z., Niedzielska, A., Jankowski, M., Kobus, T., Ossowski, Z. Relationship between lower-extremity defects and body mass among polish children: a cross-sectional study. *BMC Musculoskelet Disord.* **20**, 84(2019). Doi.org/10.1186/s12891-019-2460-0.
19. Pita-Fernández, S., González-Martín, C., Seoane-Pillado, T., López-Calviño, B., Pértega-Díaz, S., Gil-Guillén, V. Validity of Footprint Analysis to Determine Flatfoot Using Clinical Diagnosis as the Gold Standard in a Random Sample Aged 40 Years and Older. *J Epidemiol.* **25(2)**,148–154 (2015). Doi.org/10.2188/jea.JE20140082.
20. Puszczalowska-Lizis, E., Ciosek, J. Foot shape and its relationship with somatic characteristics in pre-school children. *Medical Studies* **33(3)**, 214–221(2017). Doi.org/10.5114/ms.2017.70348.
21. Kim, J. A., Lim, O. B., Yi, C. H. Difference in static and dynamic stability between flexible flatfeet and neutral feet. *Gait Posture.* **41(2)**, 546–550(2015). Doi.org/10.1016/j.gaitpost.2014.12.012.
22. Tahmasebi, R., Karimi, M.T., Satvati, B., Fatoye, F. Evaluation of Standing Stability in Individuals With Flatfeet. *Foot Ankle Spec.* **8(3)**, 168–174(2015). Doi.org/10.1177/1938640014557075.
23. Chao, T. C., Jiang, B. C. A Comparison of Postural Stability during Upright Standing between Normal and Flatfooted Individuals, Based on COP-Based Measures. *Entropy* **19**,76(2017). Doi.org/10.3390/e19020076.
24. Birinci, T., Demirbas, S.B. Relationship between the mobility of medial longitudinal arch and postural control. *Acta Orthop Traumatol Turc.* **51(3)**,233–237(2017). Doi.org/10.1016/j.aott.2016.11.004
25. Cattaneo, D., Coote, S., Rasova, K., Gervasoni, E., Groppo, E., Prokopiusova, T., Reznickova, J., Montesano, A., Jonsdottir, J. Factors influencing balance improvement in multiple sclerosis rehabilitation: A pragmatic multicentric trial. *Ann Phys Rehabil Med.* **63(2)**,93–98(2020). Doi: 10.1016/j.rehab.2019.05.007
26. Puszczalowska-Lizis, E., Dąbrowiecki, D., Jandziś, S., Żak, M. Foot Deformities in Women Are Associated with Wearing High-Heeled Shoes. *Med Sci Monit.* **25**,7746–7754(2019). Doi: 10.12659/MSM.917983
27. Zhong, D., Xiao, Q., Xiao, X., Li, Y., Ye, J., Xia, L., Zhang, Ch., Li, J., Zheng, H., Jin, R. Tai Chi for improving balance and reducing falls: An overview of 14 systematic reviews. *Ann Phys Rehabil Med.* **63(6)**, 505–517(2020). Doi: 10.1016/j.rehab.2019.12.008
28. Szczepanowska-Wołowicz, B., Sztandera, P., Kotela, I., Zak, M. Body weight-dependent foot loads, assessed in terms of BMI and adiposity, in school-aged children: a cross sectional study. *Sci Rep.* **10**,12360 (2020). Doi: 10.1038/s41598-020-69420-1.
29. Puszczalowska-Lizis, E., Bujas, P., Omorczyk, J., Jandzis, S., Zak, M. Feet deformities are correlated with impaired balance and postural stability in seniors over 75. *PLoS One* **12(9)**, e0183227(2017). Doi: 10.1371/journal.pone.0183227.

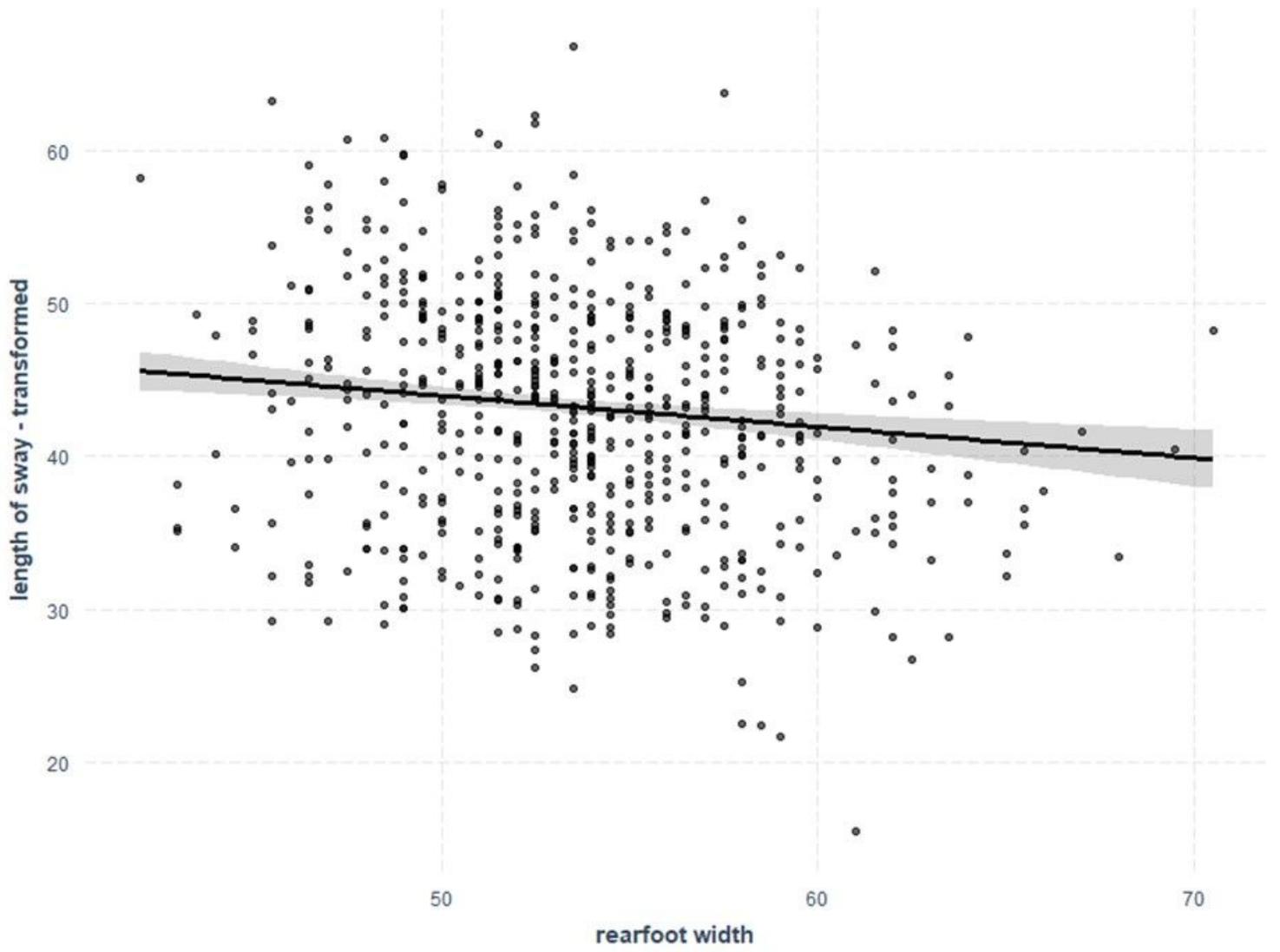
30. Feka, K., Brusa, J., Cannata, R., Giustino, V., Bianco, A., Gjaka, M. et al. Is bodyweight affecting plantar pressure distribution in children?: An observational study. *Medicine* **99(36)**, e21968 (2020). Doi: 10.1097/MD.00000000000021968.

## Figures



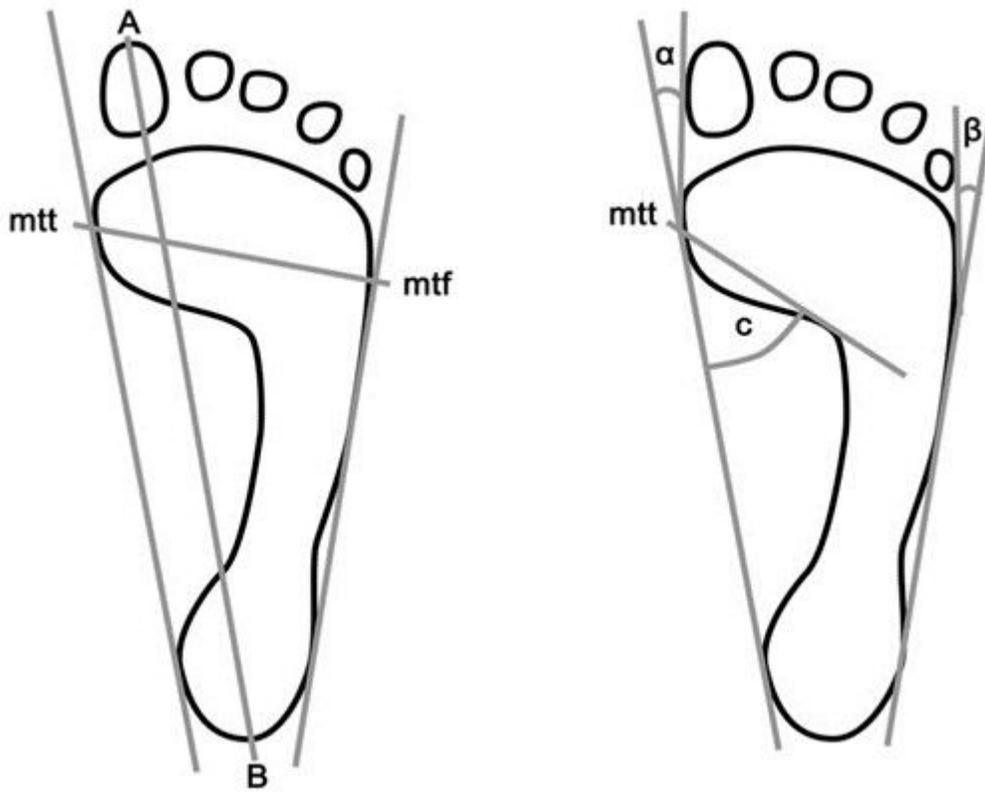
**Figure 1**

The correlation between COP length and the Wejsflog index.



**Figure 2**

The Correlation between COP length and the hindfoot width.



**Figure 3**

The method of determining the foot variables under study. A-B-foot length, mtt-mtf-foot width, C- Clarke's angle,  $\alpha$ - hallux valgus angle,  $\beta$ -varus deformity of the 5th toe

Source: Own research [3]. "Feet deformities and their close association with postural stability deficits in children aged 10–15 years," by B. Szczepanowska-Wolowiec, P. Sztandera, I. Kotela, and M. Zak, 2019, BMC Musculoskeletal Disorders, 20: 537, p.3 (<https://doi.org/10.1186/s12891-019-2923-3>). Copyright 2019 by the BMC