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Variability of foot growth in width in relation to length among 3-year-old girls and boys

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Purpose: The aim of the study was to analyze the length and width of the feet and the mutual rate of growth of these features in 3-year-old girls and boys classified into age categories taking into account the semi-annual division. *Methods*: The study covered 800 children (400 girls and 400 boys) aged 3. The CQ-ST podoscope was applied as the research tool. The data were analyzed based on Student's *t*-test for independent samples, Mann–Whitney *U*-test, Wilcoxon test and simple regression. *Results*: There were statistically significant differences in the width of the right and left feet, for both girls (1st group: $p < 0.001$; 2nd group: $p = 0.006$) and boys (1st group: $p < 0.001$; 2nd group: $p < 0.001$), in the absence of differences in length. In the regression models created for the results of girls and boys classified into age categories, the coefficients of determination ranged from $R^2 = 0.24$ to $R^2 = 0.48$. *Conclusions*: The right and left feet of the examined girls and boys are characterized by symmetry in terms of length, while in terms of width, the left feet are larger than the right ones. In girls, the width of the foot increases proportionally by about 67–69% of the length, while in boys, the increase in foot width is 49–61% of the growth in length. In boys classified to the 2nd group, the growth of the foot in width in relation to its lenght in length is smaller than in the 1st group.

Key words: *foot, developmental changes, children, age ranges*

1. Introduction

The foot is one of the links in the proprioceptive kinetic chain and its structure is specific to humans. The vertical posture of the human body and the constant change of static and dynamic loads exerted on this part of the musculoskeletal system create specific construction requirements. The structure of the components that build the foot, their arrangement in relation to each other, functional connections, together create an intricate structure, capable of supporting and carrying even significant loads [1], [4], [5], [13], [29], [20]. The first attempts at verticalization in the initial stage of ontogenesis pose a particularly great challenge because the relatively large upper part of the child's body (torso and head) must be over on a small base of support of the feet [27]. The ability to maintain balance while learning to walk increases due to dynamic changes in the length and shape of the foot [15], [17], [23], [24]. According to Vrdoljak et al. [28], the foot grows the fastest between 2 and 3 years of age. The average annual increase in length is 1.8 cm in girls and 1.6 cm in boys. From 3 to 6 years of age, the growth in length is equal to 1 cm per year, while between 6 and 7 years of age, on average, only 5 mm. The length of a child's foot reaches its final dimensions in a more proportional way than other parts of the body. The foot in girls in the first year of life, and in boys aged 18 months, in terms of length is close to 50% of the length obtained in the final period of growth.

The development of the lower limbs is a complex process and proceeds differently at different stages of ontogenesis [1], [6], [7], [8], [11], [14], [19], [21], [26]. This knowledge is essential from the point of view of

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diagnosis and prevention of foot deformities. Therefore, the starting point for the considerations in this paper was the assumption that developmental changes at the beginning of ontogenesis are so dynamic that analyzing foot structure characteristics in children born in the same year, but without taking into account the half-year intervals, is insufficient. The aim of the study was to analyze the length and width of the feet and the mutual rate of growth of these features in 3-year-old girls and boys classified into age categories taking into account the semi-annual division.

2. Materials and methods

2.1. Participants

The study covered 800 children (400 girls and 400 boys) aged 3 from the Podkarpackie Province (South-Eastern Poland). The sample size representative for the site was estimated in due consideration of 95% confidence level and a 3% level of admissible error of fraction estimation. Children in the calendar age range of 3.00–3.99 years, right-handed and right-footed, whose parents/legal guardians gave written consent for them to participate in the study, were qualified. The exclusion criteria were deformities of the lower limbs, neurological diseases, diseases and/or injuries of the musculoskeletal system, including lower limbs. Premies were also excluded. The refusal or unwillingness of the child to cooperate during the research procedures was also the basis for exclusion from the study.

When qualifying children for the study, the calendar age expressed in the decimal system was taken into account. This age was the difference between the date of examination and the date of birth [10]. The 3-year-olds included children whose age ranged from 3.00 to 3.99 years, where the middle of the class was 3.50 years.

The examined girls and boys were divided into 2 groups, taking into account the half-year division.

– 1st group consisted of 400 children in the age range 3.00–3.49;
– 2nd group consisted of 400 children in the age range 3.50–3.99.

Both in the 1st and in the 2nd group there were 200 girls and 200 boys.

Comparision of the body mass, body height and BMI showed no statistically significant sex-related differences in any of the studied age groups (Table 1).

2.2. Design

The CQ-ST podoscope (Electronic System, Ltd., EU) was applied as the research tool. In the course of the study, the feet were examined while standing freely with the upper extremities loosely along the body. The examination entailed investigating both feet in every case. Both width and angle of the foot were unforced. The scan obtained during the examination allowed the researcher to determine specific points, based on which, the computer calculated foot indices. All foot scans were subjected to elaboration by the same researcher. The analysis includes the results of the foot length and width measurements.

The length of the foot was marked by a line connecting the most distal point of the forefoot (on the pad of the longest toe) with the farthest point within the hindfoot, in cm [3], [21].

Table 1. Comparison of somatic characteristics in 3-year-old girls and boys separated into half-yearly age range

Group	Girls				Boys				*t*/*Z*	*p*
	mean ± SD	Q_{25}	Me	Q_{75}	mean ± SD	Q_{25}	Me	Q_{75}		
Body mass [kg]										
1st	15.58 ± 2.13	14.00	15.00	17.00	16.26 ± 2.37	15.00	16.00	18.00	–0.03	0.973
2nd	16.73 ± 2.25	15.00	16.25	18.50	17.07 ± 2.13	15.50	17.00	18.00	–1.60	0.110
Body height [cm]										
1st	96.71 ± 4.15	94.00	96.50	99.50	98.21 ± 4.28	95.50	98.50	101.00	3.55	0.696
2nd	100.87 ± 4.05	98.00	100.50	103.50	101.09 ± 3.97	99.00	101.00	103.00	–0.70	0.484
BMI										
1st	16.59 ± 1.73	15.44	16.45	17.69	16.82 ± 1.88	15.61	16.65	17.74	–0.99	0.324
2nd	16.39 ± 1.55	15.31	16.32	17.44	16.68 ± 1.61	15.51	16.57	17.60	–1.68	0.092

Mean – arithmetic mean value, SD – standard deviation, Q_{25} – lower quartile, Me – median, Q_{75} – upper quartile, t – value of the Student's t-test statistics, Z – value of the Mann–Whitney U-test statistic, p – probability value.

The width of the foot was marked by a line connecting the most medially located point on the head of the 1st metatarsal bone (metatarsale tibiale, mtt) with the point lying most laterally on the head of the fifth metatarsal bone (metatarsale fibulare, mtf), in cm [3], [21].

In addition, body weight and height were measured. The body mass was measured with OMRON BF 500635 medical scale (Omron, Ltd., Japan), determined to the nearest 0.1 kg. The body height was measured to the nearest 0.1 cm using a GPM anthropometer (Vitako, Ltd., Switzerland). The obtained data were used to calculate the Body Mass Index (BMI).

The tests were performed in kindergartens at the gym or motor games room. So as to guarantee coherence of the research process, all measurements were taken in morning hours, with the same measurement devices operated by the researcher. During the examination, children were in their underwear, barefoot. The study was performed in line with the guidelines of the Declaration of Helsinki and approved by the Bioethics Review Committee of the University of Rzeszow, Poland (Approval number: 2/2/2017). Parents or carers were informed about the actual aim and assumptions of the study, including their right to withdraw from the study protocol at any point.

2.3. Statistical analysis

Normality of the distribution regarding characteristics was verified via the Shapiro–Wilk test. The Student's *t*-test for independent samples or Mann–Whitney *U*-test was used for inter-sex comparisons of somatic characteristics. The scores for the right and left foot were compared with the Wilcoxon pair order test. The variability of the rate of the foot's increase in width in relation to its increase in length was estimated on the basis of simple regression. The prediction of the dependent variable (foot width) was made on the basis of the value of the coefficient b of the slope of the regression line. The level of statistical significance was $p < 0.05$. The Statistica application, version 13.1 PL (StatSoft Inc., Tulsa, OK, USA; StatSoft, Krakow, Poland) was used to process the test results.

3. Results

The data collected in Table 2 indicate no statistically significant differences in the length of the right and left foot in the examined girls and boys.

The data collected in Table 3 show statistically significant differences in the width of the right and left feet for both girls (1st group: $p < 0.001$; 2nd group: $p = 0.006$) and boys (1st group: $p < 0.001$; 2nd group: $p < 0.001$). Left feet were wider than right feet.

In Table 4, the results of the simple regression analysis are contained, in which the dependent (explained) variable was the width of the foot and the independent (explanatory) variable was the length of the foot. These data indicate that in the regression models created for the results of girls and boys classified into age categories, the independent variables explained the variance of the dependent variables in the range of 24–48%. The coefficients of determination ranged from $R^2 = 0.24$ to $R^2 = 0.48$. The rate of foot width in relation to foot length increase in girls and boys was predicted on the basis of the slope of the regression line. These values indicated how much the width of the foot would increase if its length increased by one unit. For example, in the case of girls from the first group, the coefficient was $b = 0.69$. This means that an increase in foot length by one unit predicts that the width of the foot will increase by 0.69 cm, so the width of the foot increases proportionally, on average, by about 69% of the length.

Table 2. Comparison of foot length in 3-year-old girls and boys separated into half-yearly age ranges

Group	Right foot length [cm]					Left foot length [cm]					*Z*	*p*
	mean ± SD	max–min	Q_{25}	Me	Q_{75}	mean ± SD	max–min	Q_{25}	Me	Q_{75}		
Girls												
1st	14.67 ± 0.77	17.20–12.90	14.20	14.60	15.10	14.69 ± 0.77	17.20–12.90	14.20	14.65	15.10	–2.67	0.230
2nd	15.12 ± 0.76	17.00–13.40	14.50	15.10	15.70	15.13 ± 0.76	17.10–13.50	14.50	15.10	15.70	–0.21	0.834
Boys												
1st	15.04 ± 0.77	16.90–13.20	14.50	15.00	15.60	15.05 ± 0.77	17.00–13.20	14.50	15.00	15.67	–1.50	0.132
2nd	15.43 ± 0.78	17.70–13.30	14.90	15.40	15.90	15.45 ± 0.78	17.70–13.10	14.92	15.40	15.97	–1.95	0.051

Mean – arithmetic mean value, SD – standard deviation, max – maximum value, min – minimum value, Q_{25} – lower quartile, Me – median, Q_{75} – upper quartile, *Z* – value of the Wilcoxon test statistic, *p* – probability value.

Table 3. Comparison of foot width in 3-year-old girls and boys separated into half-yearly age ranges

Group	Right foot width [cm]					Left foot width [cm]					*Z*	*p*
	mean ± SD	max–min	Q_{25}	Me	Q_{75}	mean ± SD	max–min	Q_{25}	Me	Q_{75}		
Girls												
1st	5.60 ± 0.35	7.00–4.80	5.40	5.60	5.80	5.67 ± 0.38	7.00–4.80	5.40	5.70	5.90	–5.20	<0.001*
2nd	5.73 ± 0.31	6.40–4.70	5.50	5.80	6.00	5.78 ± 0.35	6.70–5.00	5.50	5.80	6.00	–2.76	0.006*
Boys												
1st	5.82 ± 0.36	7.10–4.90	5.60	5.80	6.00	5.91 ± 0.38	7.00–5.00	5.70	5.90	6.20	–5.40	<0.001*
2nd	5.92 ± 0.34	6.80–5.00	5.70	5.90	6.17	5.98 ± 0.36	7.10–5.00	5.70	6.00	6.20	–3.81	<0.001*

Mean – arithmetic mean value, SD – standard deviation, max – maximum value, min – minimum value, Q_{25} – lower quartile, Me – median, Q_{75} – upper quartile, *Z* – value of the Wilcoxon test statistic; *p* – probability value.

* $p < 0.05$.

Table 4. Variability of the foot lenght growth rate in relation to the foot width growth rate in 3-year-old girls and boys separated into half-yearly age ranges

Dependent variable	Independent variable	Group	*R*	R^2	*b*	*F*	*p*
Girls							
Right foot width	Right foot length	1st	0.69	0.48	0.69	181.17	<0.001*
		2nd	0.67	0.46	0.67	166.45	<0.001*
Left foot width	Left foot length	1st	0.68	0.46	0.68	168.55	<0.001*
		2nd	0.69	0.48	0.69	183.02	<0.001*
Boys							
Right foot width	Right foot length	1st	0.61	0.38	0.61	120.37	<0.001*
		2nd	0.57	0.32	0.57	92.87	<0.001*
Left foot width	Left foot length	1st	0.60	0.36	0.60	111.44	<0.001*
		2nd	0.49	0.24	0.49	63.39	<0.001*

R – coefficient of multiple correlation, R^2 – coefficient of determination, *b* – coefficient of slope of the regression line, *F* – value of the Fisher–Snedecor test statistic, *p* – probability value.

* $p < 0.05$.

4. Discussion

Our own study did not show statistically significant differences in the length of the right and left feet in the examined girls and boys. Therefore, they can be considered inconsistent with the results obtained by Demczuk-Włodarczyk [3]. The author observed the dominance of the length of the left foot in girls and boys between 3 and 7 years of age. In turn, Vrdoljak et al. [28], similarly to our study, did not observe differences in the length of the right and left feet in girls and boys aged 2–7 years. Naimah et al. [16] also found symmetry in the length and width of the right and left feet in Malaysian children, although these feet were shorter in relation to the population of children living in Europe.

The analysis of the obtained material allowed us to conclude that both in girls and boys, regardless of the age category, the left feet were wider than the right ones. These results may suggest the influence of the gradually developing functional dominance of one of the lower limbs and the related functional asymmetry towards the dominance of the left lower limb in the support function. These observations are confirmed by the results of Matsuda et al. [12], who, based on the analysis of a study of 396 Japanese children aged 3–6 years, drew attention to the uneven distribution of the foot load and lower arching of the left foot, and explained the asymmetry with the lateralization of the support and pedipulation functions of the lower limbs. Önell [18] noted that the dominance of one side of the body may be important from the point of view of stabilizing the standing position and the distribution of loads on the lower limbs.

The length of the foot, often considered as the basis of the unit of measurement that allows the growth of the foot, can be related to other features that are important from the point of view of the shape of the feet. An interesting issue is the dynamics of foot width

development in relation to its length. Our study has demonstrated that the development of these features is harmonious. The intensive increase in length is accompanied by an intensive increase in foot width. In girls from the 1st group, the width of the foot increased proportionally by about 69% (right foot) and 68% (left foot) of the length, while in boys – by 61 and 60%, respectively. In turn, in girls from the 2nd group, foot width increased by about 67% (right foot) and 69% (left foot) of length, and in boys – by 57 and 49%, respectively. A comprehensive look at the values of the slope of the regression line shows a downward trend in boys, as these values in the 2nd group were lower than in the 1st group. This indicates that the relationship between the growth rate of width in relation to length in boys is gradually weakening. The lack of similar reports precludes the possibility of discussing the obtained results with the conclusions of other authors. Study by Vrdoljak et al. [28], who showed that the period between 2nd and 3rd year of age is characterized by the greatest variability of foot length, and from 3rd to 6th year of age the foot grows quite evenly, increasing in length by about 1 cm annually. Based on the study of 2745 preschool children from Zagreb and Split, the authors found that the dynamics of foot length growth is determined by an exponential curve, and the differences in foot shape in terms of age and sex are negligible. However, they pointed out to the presence of ambivalence depending on geographical location and ethnic differences. Preschool children from the Republic of Croatia had longer feet by about 1 cm compared to the feet of Mexican [22], Malaysian [2] and Chinese children [25]. González-Elena et al. [5] pointed out that up to 8 years of age the foot grows predominantly in length, and after this age the width/length ratio in children is similar to that observed in adults. Demczuk-Włodarczyk [3], on the other hand, observed an acceleration in the development of foot width in males between the ages of 4 and 20, and in females later, at the age of 7–8 years, and the increments were about 2–3 mm.

Our study is one of the few works in the area of issues concerning the variability of the rate of increase in width of the foot in relation to its increase in length. A pioneering concept is the detailed approach of including a semi-annual breakdown. Therefore, in terms of assumptions, the work can be considered innovative. Data obtained as a result of research on a representative, age-homogeneous sample suggest that the dynamic increase in the dimensions of children's feet requires constant monitoring of the condition of footwear. This procedure might allow for its frequent replacement, and thus reduce the deformation of the feet. González-Elena et al. [6] reported that current shoe designs do not reproduce the wide variability in forefoot morphology. The authors consider that when designing ergonomic footwear for children, should be taken into account the position of the forefoot inside the shoe. Accordingly, the results of our study and their analysis can also be a source of knowledge for shoe manufacturers, valuable especially at the shoe design stage, in the direction of taking into account the appropriate proportions of width to length.

5. Conclusions

The right and left feet of the examined girls and boys are characterized by symmetry in terms of length, while in terms of width, the left feet are larger than the right ones. In girls, the width of the foot increases proportionally by about 67–69% of the length, while in boys the increase in foot width is 49–61% of the growth in length. In boys classified to the 2nd group, the growth of the foot in width in relation to its lenght in length is smaller than in the 1st group. This knowledge is useful for control the size of the footwear in order to prevent deformities of the feet, especially in early childhood.

Competing interests

The authors declares that they have no competing interests.

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