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ANALYSIS OF FOOT 3D SCANS OF BOYS FROM POLISH POPULATION

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Abstract:

In Poland, the currently used lasts are based on data obtained in the 1970s. These data may be largely out of date, which is due to changes resulting from secular trends, migration changes, and, above all, the fact that there are now tools that enable measurements to be made with significantly higher precision. Such tools are 3D scanners. In this article, we present the results of children's foot measurements taken using a 3D scanner. We collected data on the feet dimensions obtained with the 3D scanner for boys in the age range of 4–13. We have obtained data on dimensions, proportions, and the rate of changes in consecutive years. The obtained data confirmed the increase in dimensions of the children's feet as well as changes in proportions. These data will be used for development of new standard for lasts. The aim of the study was to collect anthropometrical data on boys' feet dimensions.

Keywords:

Children, anthropometry, feet measurements, shoe lasts

1. Introduction

Footwear has been used by us for many thousands of years. The oldest known footwear found in Armenia is estimated to be approximately 5,500 years old [1]. The examples of footwear used first were probably used much earlier. For millennia, footwear was essentially made to measure. Attempts were made to make mass-produced footwear, especially for the army and the most famous case of which are the shoes of the Napoleonic army. In this case, uniformity went so far that universal shoes were applied for the left and right foot, which can be considered regression in attempts to provide the wearer with comfort. It was only at the end of the nineteenth century that we could talk about the emergence of the footwear industry producing shoes on a mass scale for "anonymous" customers.

The shape of the shoe is determined by the shoe last. Wearing comfort largely depends on its parameters. In the case of children's shoes, it should also be taken into account that ill-fitting shoes or shoes with the non-anatomical shape may cause deformations of children's feet. There is controversy about how proper footwear for children should be constructed, but the fact that footwear can influence them is widely accepted and confirmed by a number of publications in which populations using footwear vs walking barefoot were compared [3–6].

The basis for developing lasts is the knowledge of the foot dimensions of a given population. In Poland, the first anthropometric measurements of feet carried out on a mass scale took place in 1955–1959. The research was conducted by the Anthropometry Commission of the Polish Academy of Sciences in Wrocław. Further research conducted by IPS Łódź took place in 1968 and 1973 (the results of the latter were the basis for the construction of official standards for lasts' design [PN-O-91050:1971 – Kopyta do przemysłowej produkcji obuwia – Kopyta zasadnicze]). Subsequent research was carried out in 1985 (the last nationwide anthropometric measurements) and 1996 – a test at the Central Laboratory of Footwear Industry in Kraków as part of the project: "Development of a system of preventive measures aimed at protecting the health of children's feet." The most up-to-date database of anthropometric measurements of children's feet is the population of 11,500 children aged 0–15 examined as part of the BARTEK Healthy Foot Academy 2007–2013. The research conducted by IPS Kraków consisted of taking a static image of the foot, anthropometric measurements using hand-held measuring devices, and an orthopedic assessment of the health condition of the feet [2].

The awareness of the phenomenon of the secular trend in the foot dimensions leads to a hypothesis that contemporary footwear designed on the basis of data from the 1970s to 1980s is not adapted to the foot dimensions of today's population – especially in children [13].

The phenomenon of the secular trend in the children's feet is confirmed by the research of the Łukasiewicz-ŁIT (former: Institute of Leather Industry in Kraków) [13]. Taking an advantage of implementation of modern anthropometric tools, 3D scanners, we are the pioneers in Poland in measuring the children's feet with 3D scanning technology.

The literature shows that there are data confirming that nearly 66% of the adult population wear footwear that is not adjusted to the foot size, mainly in width parameter [14]. It is due to the fact that it is possible to buy longer or shorter shoes to adjust to your feet but majority of shoes is available in one width only, consecutively, it is necessary to investigate if it is necessary to modify existing standards for lasts.

Obtaining the dimensions of the feet is not sufficient to prepare the shoe lasts. The last is not a perfect "copy" of the foot and merely averaging the results is not enough. It is necessary to translate the obtained foot dimensions into last parameters.

The shape of the last must be designed in such a way that the footwear is comfortable on the one hand and aesthetic on the other. The best example of this is the need to secure additional space in footwear, especially in the forefoot.

This applies, e.g., to the functional allowance (the space between the toes and the upper part where the toes move cyclically while walking) and the fashion allowance (additional space for the toes providing them with adequate space, which is especially important in shoes with a narrow toe). The functional allowance is particularly important because in extreme cases, the foot can move forward by 13 mm (two numbers in the French size system) [7].

In the case of children's shoes, narrow toes are not usually used, so there is no need to modify significantly the longitudinal profile of the last due to the height of the heel; however, the fact that children's feet grow constantly, which may amount to 10 mm per year, should be taken into account [7].

There are a number of methods for designing lasts based on the results of manual measurements, such as construction of the bottom of the last by Heinrich Meier, Franciszek Schneider, H. Macy [8], or the method used in Poland described in the industry standard BN-73/7781-04.

3D scanning has a number of advantages over manual measurements. First of all, it has higher accuracy and lower risk of measurement error [9]. In terms of technology development, there has been an exponential growth in 3D scanning technologies with various applications in recent years [11,12] that claim accuracy within 1 mm.

However, the introduction of 3D scanning has one major drawback. So far, no new methods have been developed to transfer the results from 3D scanning to the last. Classical methods used to design lasts based on manual measurements are inappropriate for scanner results because the results are incomparable [9,19]. An additional difficulty is the fact that regarding the differences between scanner measurement and manual methods, the results obtained by one method cannot be converted into the results from the other method (there are no consistent rules) [10].

The aim of the study was to collect anthropometrical data on boys' feet dimensions with a new, more precise tool – 3D scanner. In the long-term aim, these data will be used to update standards for design of footwear lasts used in industry.

2. Experimental method

Experimental research was undertaken on a sample of children from Poland. It included foremost populations from the region of Małopolska, Łódź Voivodeship, and Warszawa. Most of the children represented urbanized areas (85%), which reflects the general population in Poland. Exclusion criteria included severe foot deformations and amputations. Measurements were made for boys in the age between 1 and 17 years of age; however, in age categories 1–2 and 14–17, the number of children was insignificant, therefore in this work, data are given for boys between 4 and 13 years of age. Demographic data of children are presented in Table 1.

Table 1. Demographic data of boys involved in the study

Age	Boys
4	39
5	29
6	41
7	121
8	130
9	132
10	77
11	79
12	69
13	68
Total	**785**

Age was defined as the number of completed years. It means that a child aged 4 years, 1 day was assigned to age group 4. Foot measurements of children aged 4 ÷ 13 years were carried out using a 3D Laser FULL Foot Scanner, which allows obtaining a scan of the child's entire foot along with specific foot dimensions.The scanner allows us to determine length, width, height, and circumference measurements. They constitute the basic categories of anthropometric measurements used for population monitoring as well as footwear design.

The software automatically calculated measurements according to the built-in algorithm taking into account anatomical point on the foot. However, it was possible to correct the measurement if after visual inspection it was found that the measurements were made incorrectly. Data were collected for both feet.

Data collection was made as follows: Before every measurement the scanner was disinfected. This procedure was to avoid transmission of infection and measurement errors due to particles adhered to the foot surface. During measurements, participants stood on a glass plate and positioned their right and left feet in the scanner using a stable standing posture, avoiding any foot movement. Both legs of the participants were on the same level thanks to the attached to the scanner adjusting supports (Figure 1). After a successful scan, the foot was removed from the scanner and replaced by the other. The process of scanning of one foot lasts about 13 s. In case of some children, it was difficult to keep them motionless for that period and measurements were to be repeated. In some cases, the measurement was unsuccessful; therefore, their results have not been recorded. Another problem was the fact that in our scanner, the side walls were 8.5 cm thick, and consecutively, particularly small children had to stay in moderate stride.

The operator checked all foot scanning images and manually removed the artifacts when necessary after each scan. Since the measurements were made at schools and kindergarten,

Figure 1. The appearance of the 3D scanning station.

more detailed analysis and removal of artifacts and correction of measurements were made later.

The following data were collected (the given measurement is highlighted by red line in Figures 2–8):

- Foot length (distance from the most rearmost point of the foot along the axis of the foot determined in forefoot by a point in the middle between 1 and 5 metatarsal points [Figure 2]). Usually, the most forward point was placed on the second toe. These points correspond to *Pternion point* [15] in the rearfoot and *Pododaktylion* II [16].
- Forefoot width (distance between the most lateral and most medial point in the forefoot. Usually it was first and fifth metatarsal joint (Fig. 3). These points correspond to points *metatarsale tibiale* (mtt) and *metatarsale fibulare* (mtf) [15].
- Ball girth (circumferential dimension taken between the most lateral and most medial point in the forefoot (Fig. 4). Usually it was first and fifth metatarsal joint. These points correspond to points *metatarsale tibiale* (mtt) and *metatarsale fibulare* (mtf) [15].
- Instep girth (circumferential dimension taken along point placed on dorsal part of the foot in the place corresponding to *os cuneiform intermedium* [Figure 5]).
- Long heel girth (circumferential dimension through the middle of the heel and the point placed on dorsal part of the foot in the place corresponding to *os cuneiform intermedium* [Figures 6]).

The most significant difference between manual and 3D scanning measurements concerns foot length measurements. Although the measurement point on the heel is located where measurements are taken manually (Pternion), the front point is different. In manual measurements, the front point is the Acropodion. Usually Acropodion is on the first toe, sometimes on the second, whereas in 3D scanning the forward point is in point Pododaktylion II [16]. Therefore, theoretically dimensions reported with 3D scanner should be shorter.

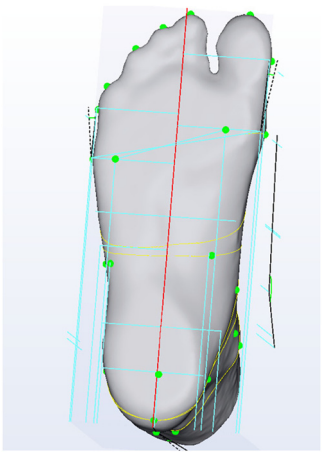

Figure 2. Foot length.

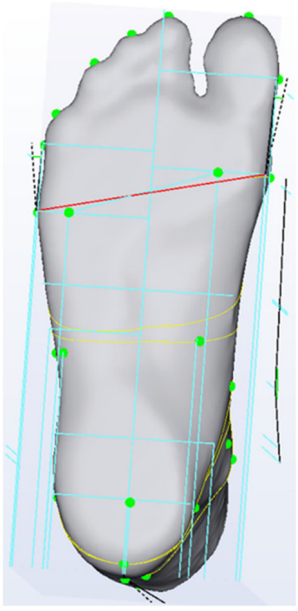

Figure 3. Forefoot width measurement.

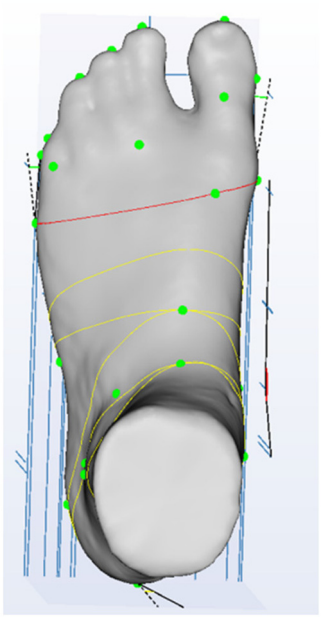

Figure 4. Ball girth.

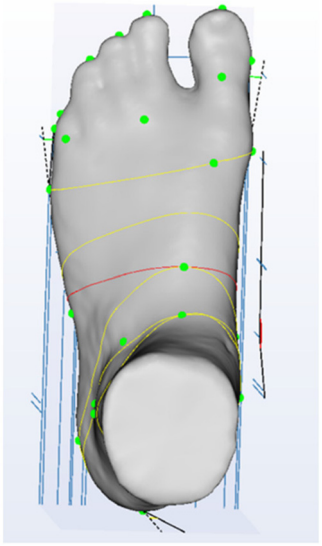

Figure 5. Instep girth.

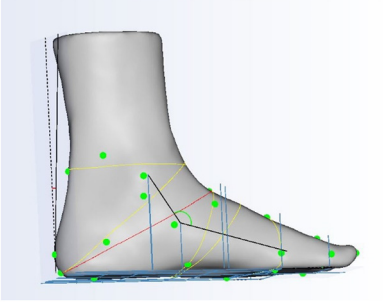

Figure 6. Long heel girth.

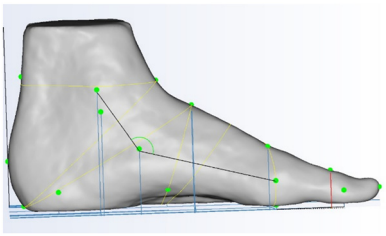

Figure 7. First toe metatarsal joint height.

3. Results and discussion

Tables 2–9 summarize the obtained results for every parameter. Data are presented for left and right feet separately and together. However, one should state that, according to the results of Student's *t*-test, at 0.05 significance level difference between left and right foot in relation to every parameter was insignificant. Data are presented in graphic format in Figures 9–16. Data "L + R" given in the tables were calculated as an average of all left and right feet together.

In all the measured parameters, an increase in the values was observed. However, the magnitude of changes varied depending on age. In Figures 17–23, data on change in values between various ages are presented. Dynamics of changes mean the difference between results in consecutive years.

Based on the results, we may conclude that dynamics of changes varied notably between various ages. In case of foot length, the most intense increase was between 3 and 4 years, and 5 and 6 years, after which, there was a gradual decrease, which later, in the age range of 10–11 reaches a third peak. In case of forefoot width, an intense increase is observed between age range 4 and 5, which reaches the lowest value between age range 5 and 6, and again gradually increases up to the age 12/13. In case of the ball girth, a similar situation is observed, but the intense increase is continued till the age 12/13. In case of the instep girth, it is difficult to point out any consistent trend; however, the most intense increase is observed in older age (from 11 and up). This observation is in line with known phases of ontogenetic changes identified by various authors, Weissenberg, Stratz, Huth [15]. Regarding changes in the heel girth, the most intensive increase was observed in earlier years of age, while in older age, it was less steady, lower level. Due to the fact that various dynamics of changes were observed in different foot parameters, the proportions of the feet changed. Data of changes in proportion of the foot length and other dimensions are presented in

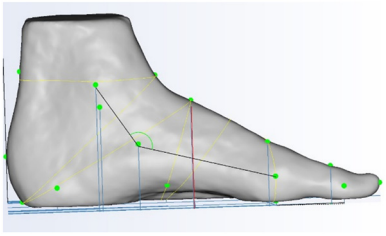

Figure 8. Instep height.

Table 2. Summary of statistical parameters analyzed for foot length

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	166.9	166.8	166.8	179.7	179.7	179.7	187.2	186.9	187.0
SD	10.4	10.9	10.6	10.3	10.7	10.4	12.0	11.5	11.7
Min.	143.9	145.5	143.9	165.0	164.3	164.3	155.1	158.6	155.1
Max.	191.7	193.5	193.5	198.5	202.9	202.9	218.1	219.7	219.7
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	200.5	200.5	200.5	209.1	209.2	209.1	216.9	217.0	217.0
SD	12.3	12.0	12.2	11.3	10.9	11.1	12.6	12.8	12.7
Min.	169.5	170.2	169.5	184.7	186.2	184.7	191.6	187.6	187.0
Max.	233.9	234.3	234.3	235.9	233.1	235.9	248.6	250.2	250.2

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	224.1	224.2	224.1	233.2	234.2	233.7	244.6	244.6	244.6	252.8	252.4	252.6
SD	12.9	13.2	13.0	11.1	11.0	18.7	15.1	14.9	15.0	13.8	13.3	13.5
Min.	192.0	195.1	192.0	206.5	206.2	206.2	211.0	209.0	209.0	219.0	220.6	219.0
Max.	259.4	259.8	259.8	262.3	261.8	262.3	275.1	275.1	275.1	278.1	279.0	279.0

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Table 3. Summary of statistical parameters analyzed for the forefoot width

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	67.9	70.9	69.4	72.0	72.5	72.2	74.1	74.7	74.4
SD	2.5	16.2	11.5	3.4	3.6	3.5	3.5	4.1	3.8
Min.	64.1	62.7	62.7	65.7	65.9	65.7	67.3	66.7	66.7
Max.	76.0	166.5	166.5	80.1	80.8	80.8	80.6	82.8	82.8
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	77.6	78.1	77.8	80.7	81.1	80.9	84.4	84.7	84.5
SD	3.7	3.8	3.7	3.5	3.7	3.6	4.0	4.1	4.0
Min.	68.1	69.2	68.1	70.0	71.1	70.0	76.2	75.8	75.8
Max.	88.5	89.3	89.3	91.1	90.3	91.1	94.6	95.6	95.6

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	88.0	88.2	88.1	91.8	92.0	91.9	96.6	97.0	96.8	100.7	101.0	100.9
SD	3.9	4.1	4.0	5.4	5.5	5.5	5.7	5.4	5.5	6.0	6.2	6.1
Min.	79.3	79.9	79.3	82.0	81.6	81.6	84.2	85.0	84.2	88.7	87.4	87.4
Max.	97.9	96.6	97.9	107.1	109.1	109.1	112.3	111.5	112.3	115.0	116.2	116.2

Table 4. Summary of statistical parameters analyzed for the ball girth

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	167.1	168.0	167.5	176.3	177.7	177.0	175.7	178.1	182.9
SD	7.1	7.5	7.2	8.3	8.3	8.2	193.9	196.4	8.4
Min.	156.1	153.2	153.2	159.9	162.5	159.9	182.1	183.7	166.4
Max.	186.7	184.2	186.7	196.5	195.6	196.5	8.0	8.8	203.3
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	190.4	191.7	191.0	198.5	199.3	198.9	206.7	207.7	207.2
SD	8.9	8.7	8.8	8.4	8.4	8.4	9.7	9.7	9.7
Min.	166.8	171.0	166.8	174.1	176.3	174.1	186.0	187.2	186.0
Max.	212.0	213.6	213.6	221.9	223.1	223.1	232.5	234.1	234.1

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	214.4	215.9	215.1	224.5	225.5	225.0	234.6	232.6	233.6	244.8	245.6	245.2
SD	9.3	9.4	9.3	12.3	12.9	12.6	13.1	28.6	22.2	13.2	13.4	13.3
Min.	196.0	199.4	196.0	201.0	201.8	201.0	208.8	208.7	201.0	219.0	216.4	216.4
Max.	238.1	239.6	239.6	257.5	262.7	262.7	269.9	267.9	269.9	278.1	280.2	280.2

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Table 5. Summary of statistical parameters analyzed for the instep girth

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	173.4	172.9	173.1	180.6	179.1	179.8	187.7	187.9	187.8
SD	15.1	13.3	14.1	10.5	10.1	10.3	12.4	12.7	12.5
Min.	157.3	154.1	154.1	160.1	159.3	159.3	173.0	170.7	170.7
Max.	255.5	231.5	255.5	210.7	205.6	210.7	228.2	230.7	230.7
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	194.4	193.0	193.7	204.7	204.0	204.3	210.0	208.0	209.0
SD	12.2	10.5	11.4	11.8	11.4	11.6	10.2	19.4	15.4
Min.	169.3	169.6	169.3	180.5	180.5	180.5	186.4	23.3	23.3
Max.	260.9	245.3	260.9	261.1	251.3	261.1	250.0	260.9	260.9

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	218.4	218.9	218.6	227.5	227.3	227.4	237.1	235.8	236.5	249.6	247.7	248.6
SD	12.8	12.4	12.5	12.0	12.3	12.1	12.8	11.3	12.1	14.4	12.9	13.7
Min.	198.1	197.9	197.9	202.4	203.6	202.4	210.1	206.3	202.4	220.5	222.3	220.5
Max.	280.0	266.8	280.0	263.0	263.0	263.0	285.0	266.2	285.0	298.5	292.3	298.5

Table 6. Summary of statistical parameters analyzed for the long heel girth

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	219.2	219.4	219.3	237.6	236.0	236.8	253.9	253.8	253.9
SD	27.5	25.2	26.2	23.1	23.4	23.0	13.5	13.7	13.5
Min.	159.2	160.8	159.2	173.9	171.8	171.8	178.7	179.8	178.7
Max.	249.8	246.1	249.8	259.2	261.0	261.0	269.1	273.7	273.7
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	267.5	267.4	267.4	283.5	284.7	284.1	297.5	296.1	296.8
SD	14.6	15.2	14.8	11.4	8.8	10.2	10.1	10.6	10.3
Min.	185.4	187.3	185.4	183.8	264.0	183.8	228.1	213.9	213.9
Max.	301.9	289.3	301.9	302.0	313.0	313.0	321.1	316.8	321.1

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	308.5	308.4	308.5	321.0	319.1	320.1	333.8	332.9	333.3	347.8	344.4	346.1
SD	7.6	8.5	8.0	13.8	13.7	13.7	10.1	10.1	10.1	23.6	26.8	25.2
Min.	290.5	287.8	287.8	231.1	230.5	230.5	313.4	312.1	230.5	244.2	242.8	242.8
Max.	331.1	329.0	331.1	357.2	347.6	357.2	385.0	356.6	385.0	375.3	375.7	375.7

Table 7. Summary of statistical parameters analyzed for the toe hip height

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	13.4	13.4	13.4	14.5	14.9	14.7	14.9	15.0	15.0
SD	0.9	1.2	1.1	1.3	1.2	1.2	1.5	1.8	1.7
Min.	11.9	11.1	11.1	12.9	12.6	12.6	11.7	12.4	11.7
Max.	15.3	16.4	16.4	18.4	17.4	18.4	21.3	20.8	21.3
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	15.6	15.9	15.8	16.0	16.4	16.2	16.7	17.3	17.0
SD	2.0	2.1	2.0	1.5	1.6	1.6	1.6	1.7	1.6
Min.	12.2	11.8	11.8	11.7	12.9	11.7	12.7	13.5	12.7
Max.	31.5	31.8	31.8	20.7	20.6	20.7	21.1	20.8	21.1

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	17.3	17.4	17.4	18.0	18.4	18.2	18.6	19.0	18.8	19.9	20.6	20.2
SD	1.4	1.6	1.5	1.7	1.8	1.7	1.7	1.9	1.8	1.6	1.6	1.7
Min.	13.9	13.5	13.5	13.0	13.4	13.0	14.0	14.4	13.0	17.1	17.6	17.1
Max.	20.3	21.0	21.0	22.0	21.8	22.0	23.0	23.8	23.8	24.8	25.5	25.5

Table 8. Summary of statistical parameters analyzed for the first metatarsal joint height

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	25.9	25.5	25.7	26.7	26.8	26.8	27.6	27.2	27.4
SD	1.7	2.2	2.0	1.9	1.8	1.9	3.1	3.1	3.1
Min.	22.7	21.3	21.3	20.6	21.4	20.6	17.8	15.9	15.9
Max.	28.6	29.4	29.4	30.0	30.6	30.6	32.0	31.7	32.0
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	28.3	27.8	28.0	28.6	28.3	28.5	30.1	29.8	29.9
SD	3.6	3.3	3.4	4.7	4.6	4.6	4.3	4.0	4.2
Min.	18.4	19.0	18.4	19.1	18.8	18.8	18.1	18.5	18.1
Max.	35.6	32.9	35.6	53.1	51.1	53.1	36.9	37.6	37.6

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	30.9	30.7	30.8	33.3	32.8	33.1	33.6	33.1	33.4	34.9	34.0	34.4
SD	4.0	4.2	4.1	3.9	3.6	3.7	4.3	4.1	4.2	4.4	4.2	4.3
Min.	21.4	22.1	21.4	23.4	21.7	21.7	25.1	24.1	21.7	24.1	24.0	24.0
Max.	36.6	37.6	37.6	40.6	39.2	40.6	41.6	40.6	41.6	42.6	41.3	42.6

Table 9. Summary of statistical parameters analyzed for the instep height

	4			5			6		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	43.4	43.8	43.6	45.3	46.1	45.7	47.4	47.0	47.2
SD	2.8	3.0	2.9	4.6	4.4	4.4	5.8	5.2	5.5
Min.	37.6	38.5	37.6	31.2	31.1	31.1	29.4	29.8	29.4
Max.	49.5	50.7	50.7	51.7	53.5	53.5	55.6	53.4	55.6
	7			**8**			**9**		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	48.1	47.9	48.0	48.2	48.3	48.2	51.5	51.6	51.6
SD	7.9	7.3	7.6	9.6	9.7	9.6	9.2	9.2	9.2
Min.	29.8	29.8	29.8	30.7	31.1	30.7	30.8	31.3	30.8
Max.	63.4	58.9	63.4	63.5	65.9	65.9	66.0	65.4	66.0

	10			11			12			13		
	Left	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**	**Left**	**Right**	**L + R**
Average	52.6	52.5	52.6	57.5	57.5	57.5	57.2	56.9	57.0	58.1	58.3	58.2
SD	9.5	10.0	9.7	8.8	9.0	8.9	11.2	11.0	11.1	11.3	11.5	11.4
Min.	33.7	32.7	32.7	32.4	32.3	32.3	35.2	35.0	32.3	35.6	38.8	35.6
Max.	66.6	67.1	67.1	67.8	72.7	72.7	78.2	78.3	78.3	77.6	79.6	79.6

Figures 24–29, which show a polynomial trend line with the equation.

In case of dynamics of increase in forefoot width there was observed gradual decrease of this parameter till age 7, 8 years and then there is observed growth, but till 13th year it does not reach the value from the 4 years of age. Similar situation is observed in case of ball girth, which is not surprising taking into account that these parameters relate to the same "area" of the foot. In case of the instep girth, a decrease in value is observed between 4 and 7 years. Later proportions seem to be stable with slight increase in 13 years. This increase, however, is not observed in case of instep height.

These results are consistent with the data presented by Varga et al. [17] who indicated that for children aged between 2 and 7, with the increase in age, the foot becomes thinner. Since they did not measure children over 7, we cannot confirm if there was the opposite trend in older age, such as it was observed in our research. In this case, one should also take into account the

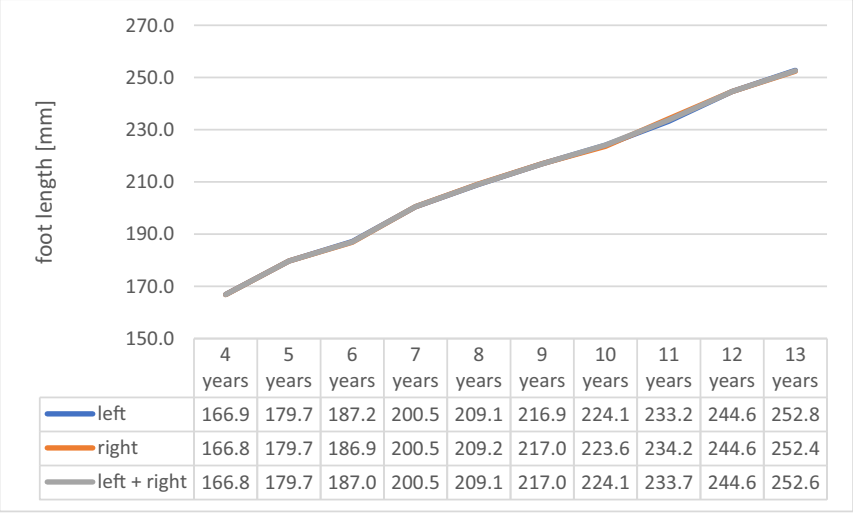
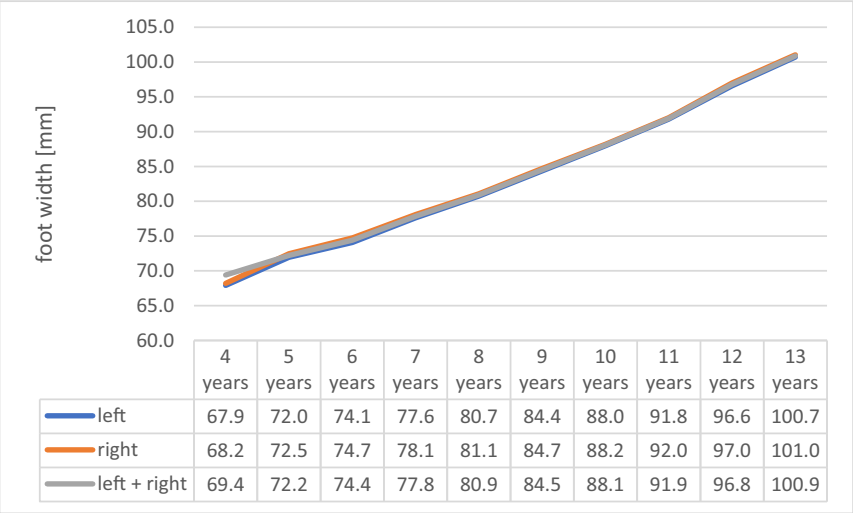
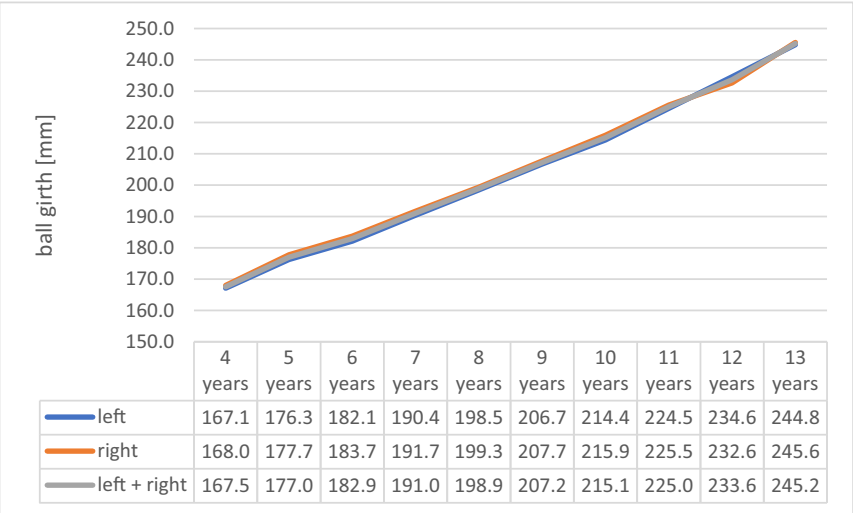


Figure 9. Changes in the foot length.



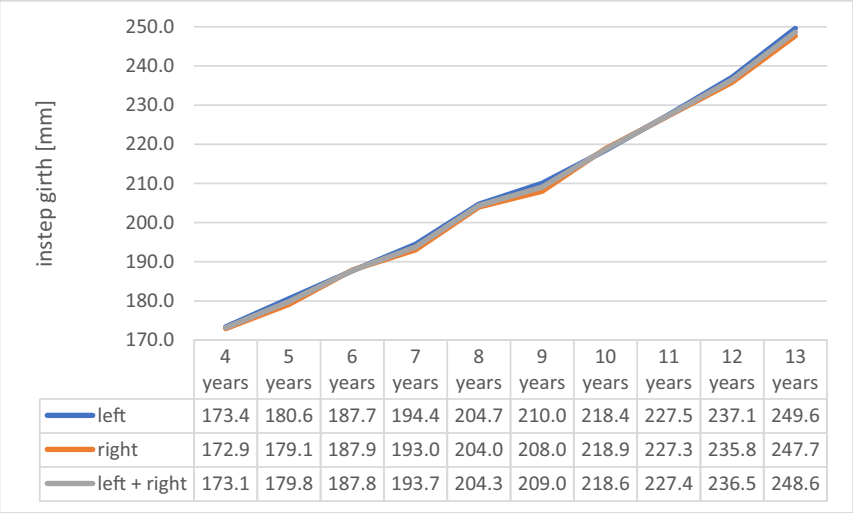
	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	67.9	72.0	74.1	77.6	80.7	84.4	88.0	91.8	96.6	100.7
right	68.2	72.5	74.7	78.1	81.1	84.7	88.2	92.0	97.0	101.0
left + right	69.4	72.2	74.4	77.8	80.9	84.5	88.1	91.9	96.8	100.9

Figure 10. Changes in the foot width.



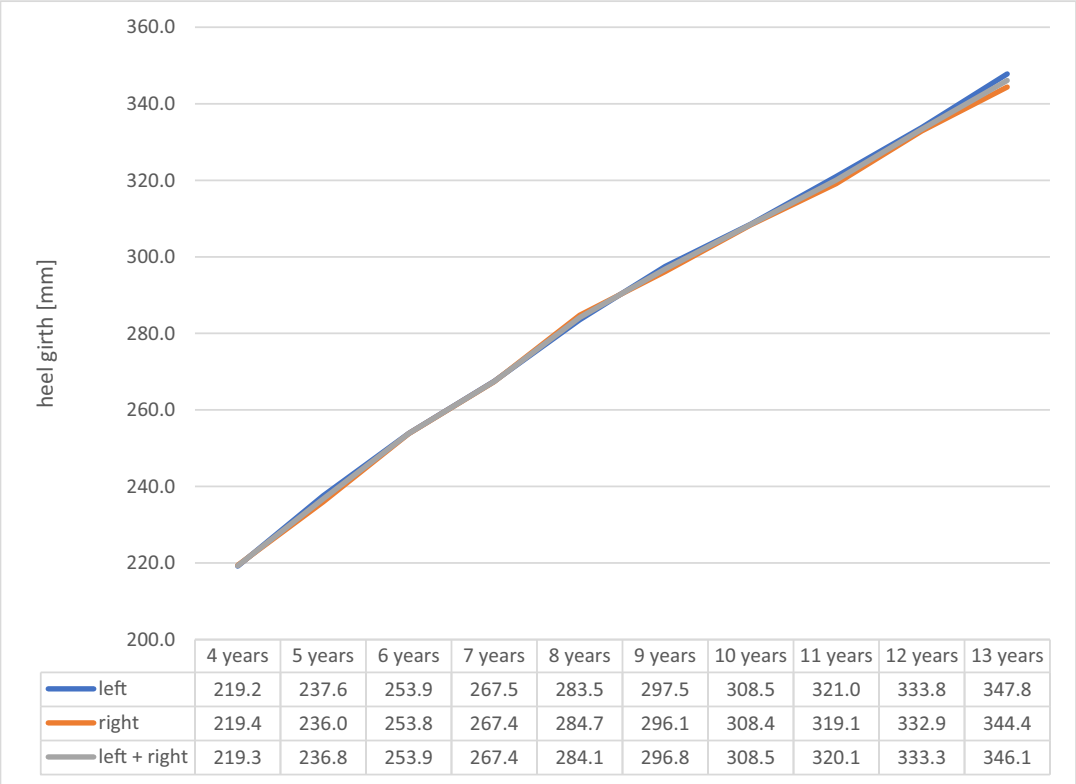
	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	167.1	176.3	182.1	190.4	198.5	206.7	214.4	224.5	234.6	244.8
right	168.0	177.7	183.7	191.7	199.3	207.7	215.9	225.5	232.6	245.6
left + right	167.5	177.0	182.9	191.0	198.9	207.2	215.1	225.0	233.6	245.2

Figure 11. Changes in the ball girth.



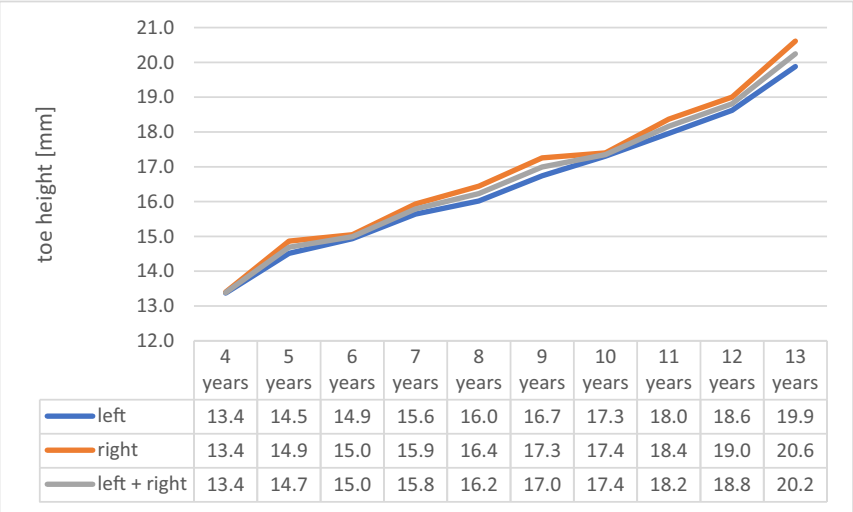
	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	173.4	180.6	187.7	194.4	204.7	210.0	218.4	227.5	237.1	249.6
right	172.9	179.1	187.9	193.0	204.0	208.0	218.9	227.3	235.8	247.7
left + right	173.1	179.8	187.8	193.7	204.3	209.0	218.6	227.4	236.5	248.6

Figure 12. Changes in the instep girth.



	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	219.2	237.6	253.9	267.5	283.5	297.5	308.5	321.0	333.8	347.8
right	219.4	236.0	253.8	267.4	284.7	296.1	308.4	319.1	332.9	344.4
left + right	219.3	236.8	253.9	267.4	284.1	296.8	308.5	320.1	333.3	346.1

Figure 13. Changes in the heel girth.

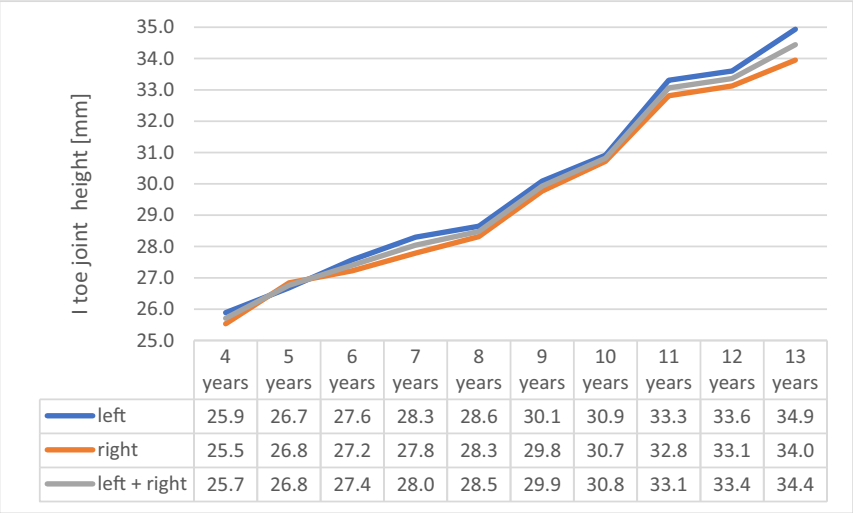


	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	13.4	14.5	14.9	15.6	16.0	16.7	17.3	18.0	18.6	19.9
right	13.4	14.9	15.0	15.9	16.4	17.3	17.4	18.4	19.0	20.6
left + right	13.4	14.7	15.0	15.8	16.2	17.0	17.4	18.2	18.8	20.2

Figure 14. Changes in the toe height.

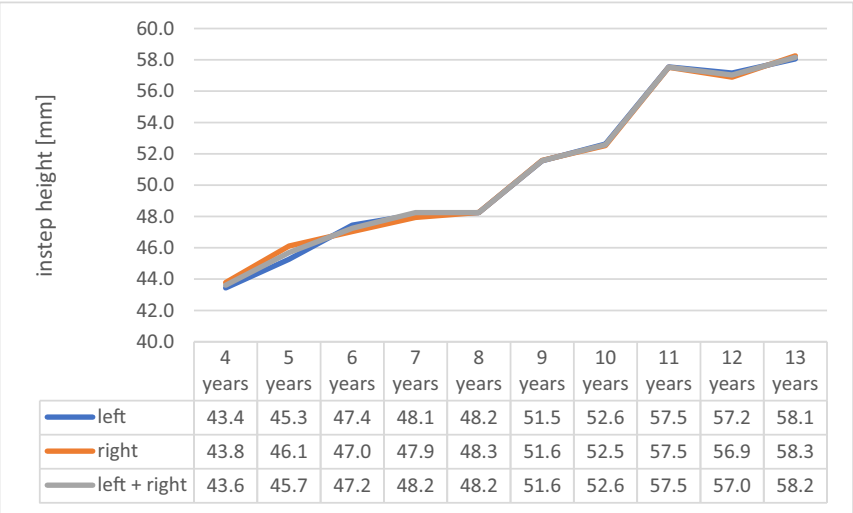
observations from measurements made in years 2008 and 2009 [18], when a high fraction of boys aged 11 years was observed, in whom a high incidence of foot deformities such as lowering of the arch and heel overpronation was still observed (26 and 32.3%, respectively). The fact that their feet still developed may be associated with a rapid increase in the height of the instep in age range of 11–13 years (as it was also observed according to the data related to the dynamics of changes in instep height). However, to evaluate it, it is necessary to obtain statistically significant population of boys of age over 13. In case of heel girth, a steady growth of this parameter is observed throughout the whole period. In case of first toe joint height, proportions are more or less the same.

As mentioned before, these measurements are made with 3D scanner for the first time in Poland, therefore, it is difficult to find data to compare. However, in case of proportions, one should assume that even the numbers are different, the tendencies of changes in proportions should be independent of measurement tools used. In this case, the most convenient would be comparison with data obtained in the years 2008–2009 in measurements made with manual tools in the so-called “Akademia



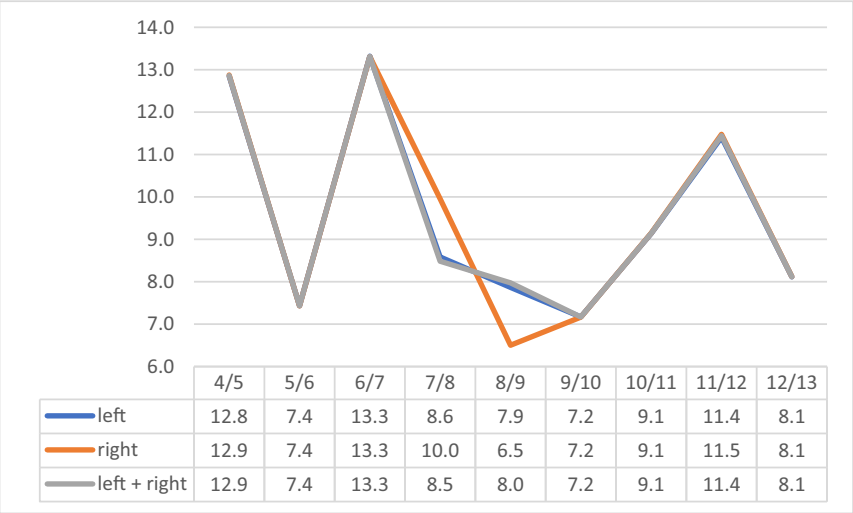
	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	25.9	26.7	27.6	28.3	28.6	30.1	30.9	33.3	33.6	34.9
right	25.5	26.8	27.2	27.8	28.3	29.8	30.7	32.8	33.1	34.0
left + right	25.7	26.8	27.4	28.0	28.5	29.9	30.8	33.1	33.4	34.4

Figure 15. Changes in the first toe joint height.



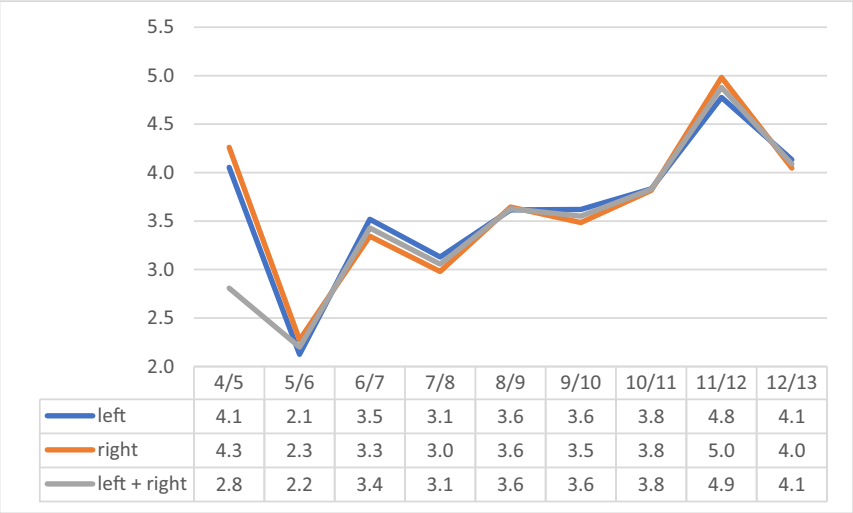
	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years
left	43.4	45.3	47.4	48.1	48.2	51.5	52.6	57.5	57.2	58.1
right	43.8	46.1	47.0	47.9	48.3	51.6	52.5	57.5	56.9	58.3
left + right	43.6	45.7	47.2	48.2	48.2	51.6	52.6	57.5	57.0	58.2

Figure 16. Changes in the instep height.



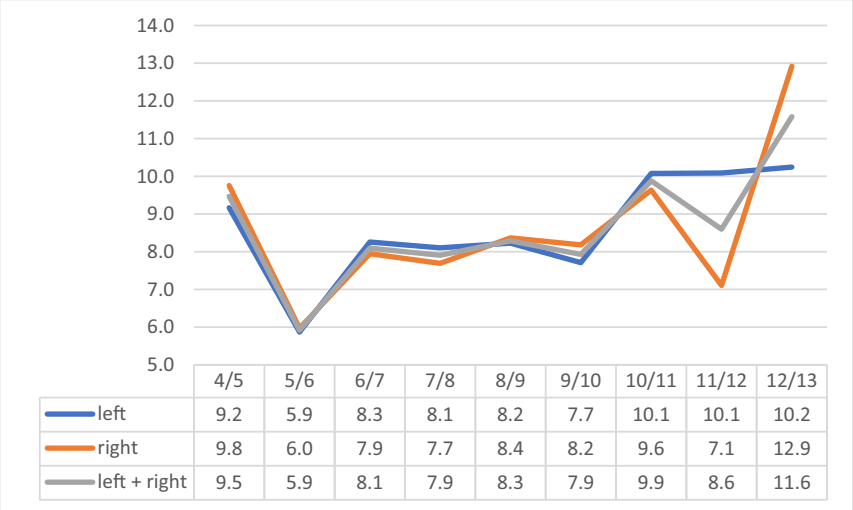
	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	12.8	7.4	13.3	8.6	7.9	7.2	9.1	11.4	8.1
right	12.9	7.4	13.3	10.0	6.5	7.2	9.1	11.5	8.1
left + right	12.9	7.4	13.3	8.5	8.0	7.2	9.1	11.4	8.1

Figure 17. Dynamics of changes in the foot length, in mm.



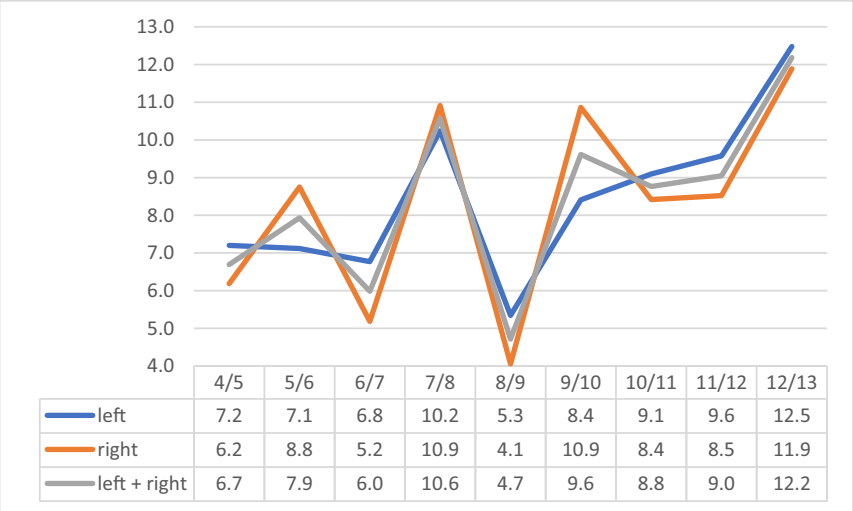
	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	4.1	2.1	3.5	3.1	3.6	3.6	3.8	4.8	4.1
right	4.3	2.3	3.3	3.0	3.6	3.5	3.8	5.0	4.0
left + right	2.8	2.2	3.4	3.1	3.6	3.6	3.8	4.9	4.1

Figure 18. Dynamics of changes in the forefoot width, in mm.



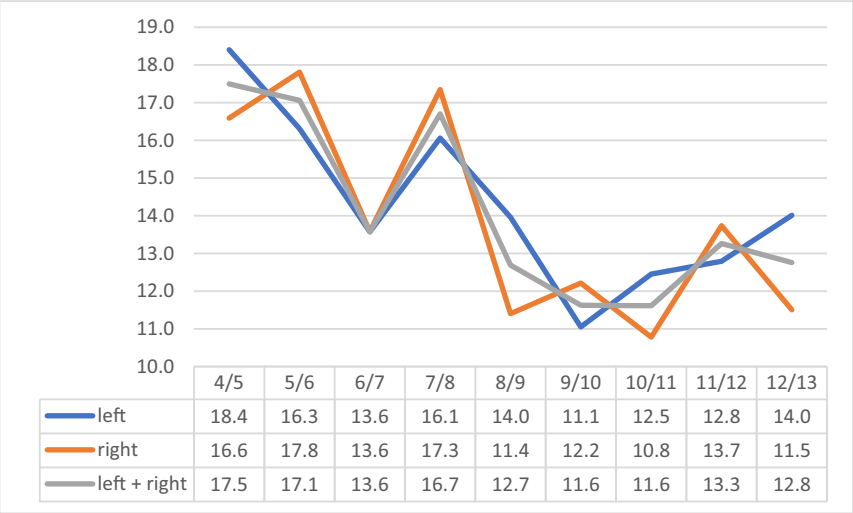
	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	9.2	5.9	8.3	8.1	8.2	7.7	10.1	10.1	10.2
right	9.8	6.0	7.9	7.7	8.4	8.2	9.6	7.1	12.9
left + right	9.5	5.9	8.1	7.9	8.3	7.9	9.9	8.6	11.6

Figure 19. Dynamics of changes in the ball girth, in mm.



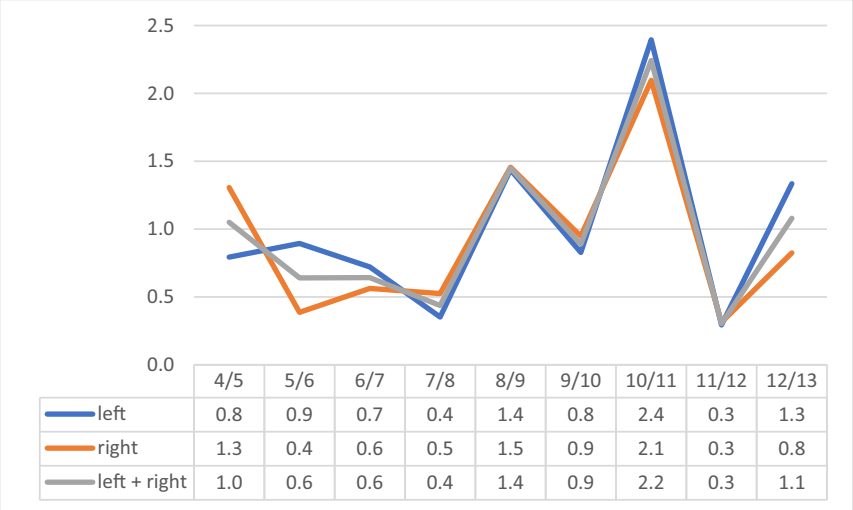
	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	7.2	7.1	6.8	10.2	5.3	8.4	9.1	9.6	12.5
right	6.2	8.8	5.2	10.9	4.1	10.9	8.4	8.5	11.9
left + right	6.7	7.9	6.0	10.6	4.7	9.6	8.8	9.0	12.2

Figure 20. Dynamics of changes in the instep girth, in mm.



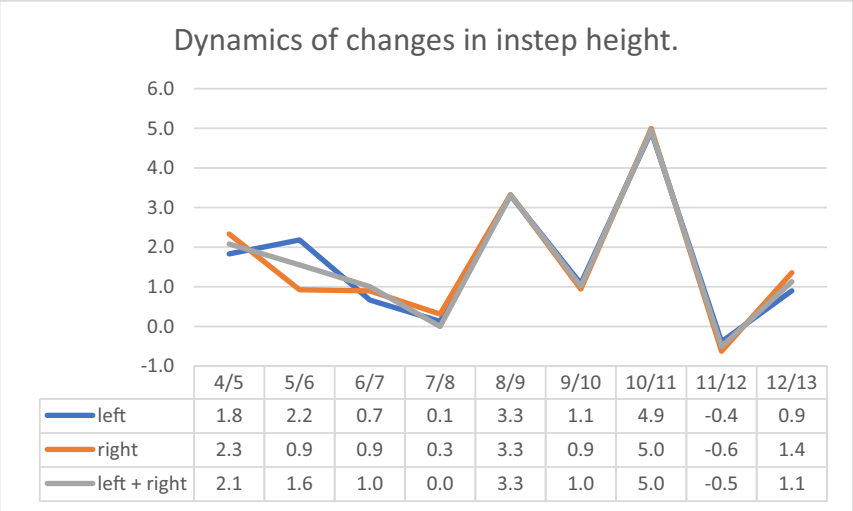
	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	18.4	16.3	13.6	16.1	14.0	11.1	12.5	12.8	14.0
right	16.6	17.8	13.6	17.3	11.4	12.2	10.8	13.7	11.5
left + right	17.5	17.1	13.6	16.7	12.7	11.6	11.6	13.3	12.8

Figure 21. Dynamics of changes in the heel girth, in mm.



	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	0.8	0.9	0.7	0.4	1.4	0.8	2.4	0.3	1.3
right	1.3	0.4	0.6	0.5	1.5	0.9	2.1	0.3	0.8
left + right	1.0	0.6	0.6	0.4	1.4	0.9	2.2	0.3	1.1

Figure 22. Dynamics of changes in the first toe joint, in mm.



	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13
left	1.8	2.2	0.7	0.1	3.3	1.1	4.9	-0.4	0.9
right	2.3	0.9	0.9	0.3	3.3	0.9	5.0	-0.6	1.4
left + right	2.1	1.6	1.0	0.0	3.3	1.0	5.0	-0.5	1.1

Figure 23. Dynamics of changes in instep height, in mm.

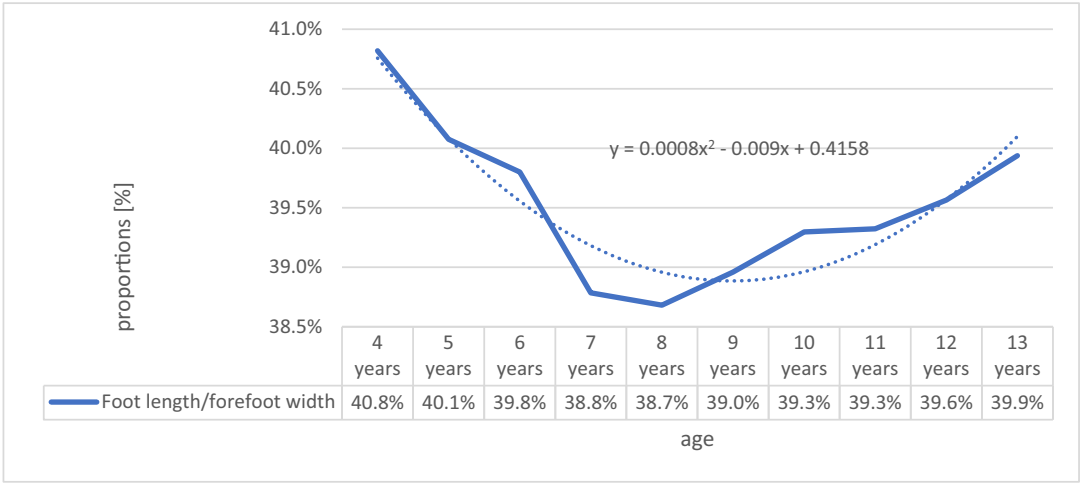


Figure 24. Proportion of the foot length to the forefoot width.

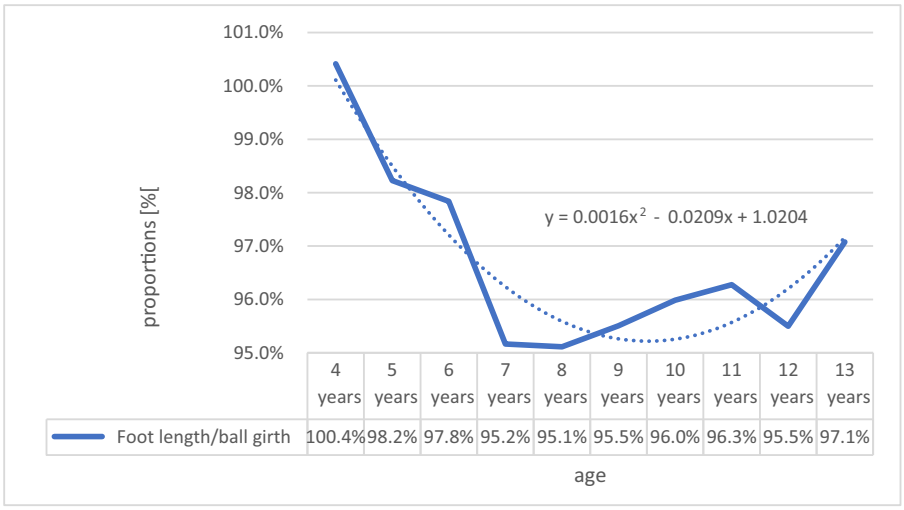


Figure 25. Proportion of the foot length to the ball girth.

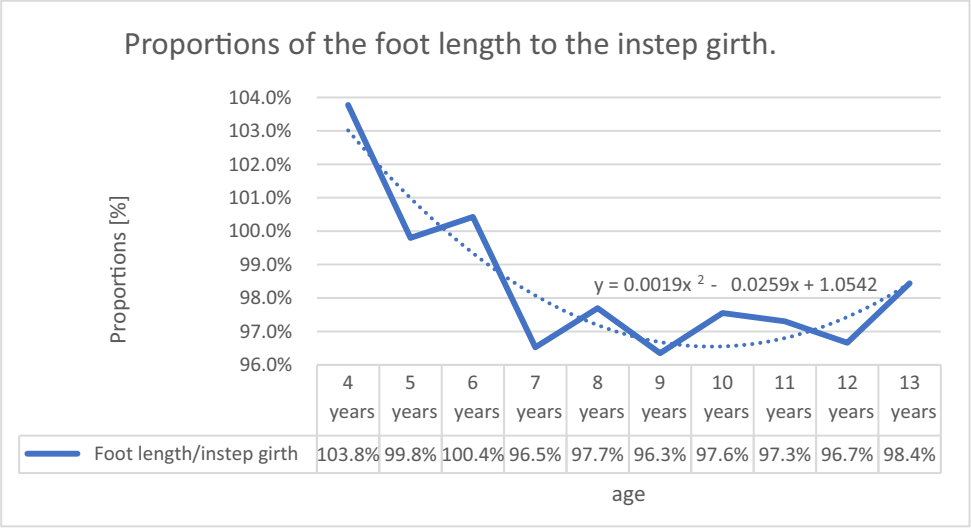


Figure 26. Proportion of the foot length to the instep girth.

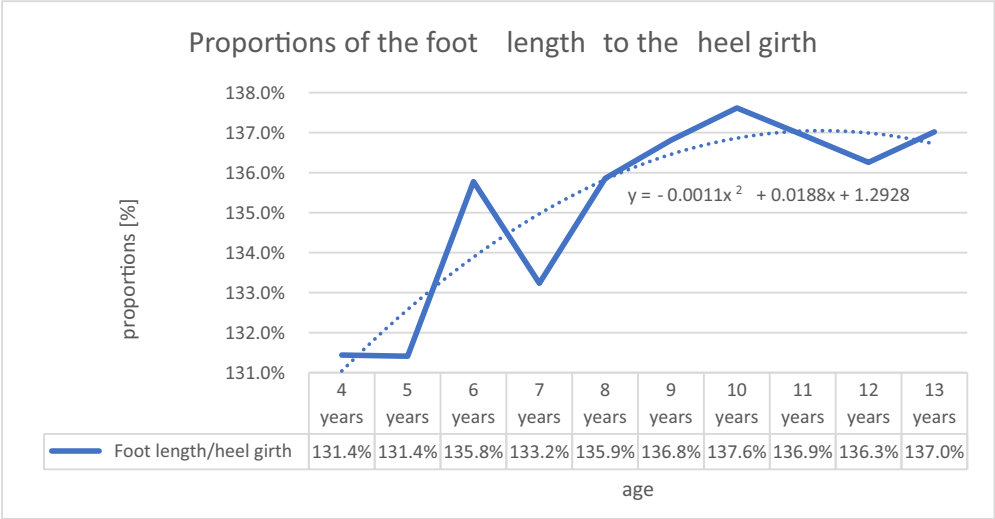


Figure 27. Proportion of the foot length to the heel girth.

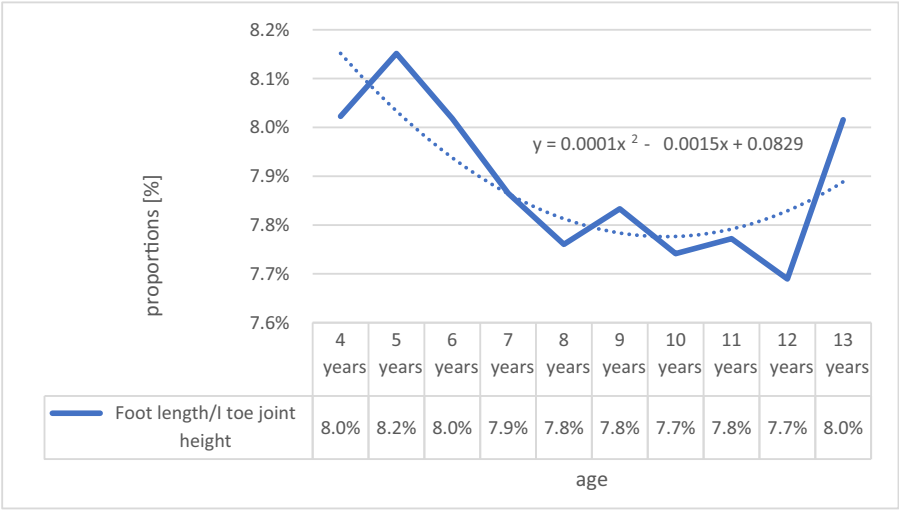


Figure 28. Proportion of the foot length to the first toe joint height.

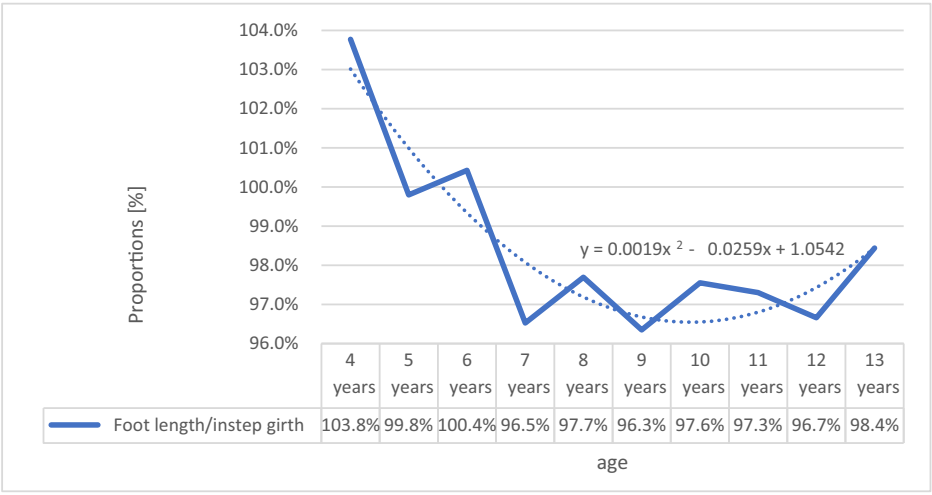


Figure 29. Proportion of the foot length to the instep girth.

Zdrowej Stopy" initiative [2]. In these measurements, data were collected on boys aged 4–11 years. In case of proportions of the foot length/forefoot width, the initial proportions in age 4 were nearly identical (40.8 vs 39.1 in AZS). Later the value of proportions decreased gradually up to the age of 11, when it reached 37.3. In case of our recent measurements, the value of proportions decreased to 38.7 at the age of 8, but later it started to increase. In AZS measurements, there were no data on children older than 11, so we cannot exclude the possibility that later it increased too, but differences in boys of age 8–11 is notable. Analogical situation is in case of proportions of the foot length to the ball girth. In case of AZS, it is 97.6 (in this research 100.4). In case of AZS, there is a constant decrease up to the age of 11, whereas in case of this research, analogically as in case of foot length/width, the proportion reaches its minimum at the age of 8 and later starts to increase. Difference between both population is just 14 or 15 years; therefore, it is difficult to point out secular trend as responsible for such differences. We will be investigating this problem more thoroughly in the future on bigger population.

Changes in proportions of the feet in children are an important aspect which should be taken into account during design of lasts. The actual standard for lasts used in Poland takes it into account and there are differences in proportions for every age group.

4. Conclusion

The 3D scanning method significantly speeds up the foot measurement process and allows us to obtain more accurate data. First of all, it is more comfortable for children. However, due to the algorithms used and the selection of places on the foot on which the measurements are performed, it is not possible to compare the obtained results with archive data – obtained in manual measurements. Therefore, it is not possible to objectively confirm the common opinions that children's feet are slimmer than those of their peers from decades ago, and therefore the secular trend cannot be confirmed. We assume that the obtained data, thanks to their accuracy, will allow us to develop lasts that are better adjusted to the requirements of the users.

The observed increase in all dimensions had different rates in relation to individual parts of the foot. The largest increase occurred in the length of the foot, so the foot became slimmer with age. However, after the age of 8, the trend reverses. The exception to this rule is the increase in the heel girth in relation to the length of the foot. From the point of view of footwear and last manufacturers, this observation is important because it means that when grading lasts, the change in proportions should be taken into account so that the lasts reflect this trend. For a given measurement, different growth rates occurred during different periods of growth. In the case of foot length, the highest was at a younger age. Forefoot width and circumference increased with the increase in age. These differences in growth rates can be considered consistent with cycles of ontogenetic development in children. However, reliable confirmation of this fact would require conducting studies on the same population of children year after year.

Obtained data will be used to modify the standards for footwear lasts used in Poland in particular. We expect to modify the standard for lasts – PN-O-91055: 1987 Kopyta Wielkości (last sizes). We also hope there will be an opportunity to compare our data with data in other countries.

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