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Development of healthy children's feet—Nine-year results of a longitudinal investigation of plantar loading patterns

Kerstin Bosch [a,*], Joachim Gerß [b], Dieter Rosenbaum [a]

[a] Funktionsbereich Bewegungsanalytik, Klinik und Poliklinik für Allgemeine Orthopädie und Tumororthopädie, Universitätsklinikum Münster, Germany
[b] Institut für Medizinische Informatik und Biomathematik, Universitätsklinikum Münster, Germany

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ABSTRACT

The purpose of the present study was to provide normative data for foot loading patterns and foot form parameters in order to support decisions about the normal or abnormal development of the growing foot during childhood. In a longitudinal design, 36 healthy German children were followed over the course of nine years. The children had a mean age of 14.6 ± 1.8 months at the first appointment and 122.8 ± 2.0 months at the last appointment. The children participated in 17 measurement appointments every 3, 6 or 12 months. Dynamic foot loading was evaluated with plantar pressure measurements during walking and static footprints were taken to determine changes in foot form. During the investigation period an increase of peak pressures of the total foot by 190%, of the relative maximum force of the total foot by 20% and the foot length by 90% was observed. A decrease for the relative maximum force under the midfoot (63%) and for the arch index (49%) could also be demonstrated. Furthermore, body height showed a significant influence on foot length and midfoot width. Body weight had a significant influence on the static parameter midfoot width. Between genders, boys showed a significant wider midfoot and a smaller forefoot contact area as compared to girls. The established database can be used as comparative values for clinical decisions about the normal foot development.

1. Introduction

In childhood, the human musculoskeletal system is subject to astonishing developmental processes of bony and muscular structures. Initial coordinated movements cause compressive and tensile stresses that are important for appropriately changing the shape of bones and muscles for future loading requirements [1]. Without these developmental processes the increased demands for an upright posture and gait would not be achieved.

The foot is the connecting link between body and ground and therefore has an important task for the overall development of the musculoskeletal system. In order to fulfill the requirements for locomotion, the growing foot is subject to fundamental structural changes. This phase of functional alignment is essential for a physiological development of the foot.

However, the development of the infant's foot may reveal wide differences [2–4] so that the distinction between physiologic and pathologic development is difficult. Information exists about physiologic foot structures [5–9] and plantar loading [2–4,10–14]. While most previous reports are based on cross-sectional investigations, a longitudinal evaluation of pediatric developments over a longer observation period is lacking. However, this kind of background data might be helpful for comparisons in order to appraise individual clinical cases.

Therefore, the objective of this project was to provide information about the growth-related changes of foot shape and foot loading parameters in a longitudinal evaluation of healthy children from their first steps of independent walking to an age of 10 years.

2. Materials and methods

In 1999 we began to recruit healthy German children that had recently started to walk freely. In spring, 2005 we reached the proposed number of 100 children and closed the recruitment. Previously, we observed 90 healthy children within the first four-year period for preliminary normative values for foot loading development [2]. Now, after a longer observation period, we were able to analyze 43 children over nine years in a longitudinal approach. The remaining children are still under observation. Seven of these 43 children were excluded: three due to missing an appointment, four because of pathologic foot developments. Therefore, complete data sets of 36 children (20 girls; 16 boys) were available for final analysis.

The local Ethics Committee approved the investigation and the parents signed an informed consent form. Beginning at the age of six years, children were also asked to agree to participate. Exclusion criteria were orthopaedic, neurologic, systemic diseases or pre-term births.

In the course of the study, 17 measurement appointments were required: five measurements during the first year (M1–M5; every three months) followed by eight semi-yearly appointments (M6–M13) until reaching the age for attending school. The final four yearly appointments (M14–M17) followed the children

* Corresponding author at: Gait Lab – SPZ, St. Vincenz Hospital, Suedring 41, 48653 Coesfeld, Germany. Tel.: +49 0 2541 893007.
E-mail address: boschk@uni-muenster.de (K. Bosch).

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Table 1
Demographic and developmental data of the children at each appointment (M1–M17) (mean ± standard deviation, SD).

Appointment		Months	*n*	Age (months)		Height (cm)		Body Mass (kg)		BMI	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD
M1	0	0	36	**14.6**	±1.8	**78.0**	±3.3	**10.5**	±1.2	**17.3**	±1.5
M2	+3	+3	36	**17.5**	±1.9	**81.0**	±3.3	**11.5**	±1.5	**17.5**	±1.8
M3	+6	+3	36	**20.7**	±1.9	**84.8**	±3.2	**12.2**	±1.4	**16.9**	±1.6
M4	+9	+3	35	**23.6**	±1.8	**87.5**	±3.5	**12.9**	±1.5	**16.9**	±1.6
M5	+12	+3	36	**26.8**	±1.8	**90.1**	±3.7	**13.4**	±1.3	**16.5**	±1.3
M6	+18	+6	36	**32.8**	±1.9	**95.2**	±3.7	**14.6**	±1.6	**16.2**	±1.5
M7	+24	+6	35	**38.8**	±2.1	**99.1**	±4.1	**15.7**	±1.7	**16.0**	±1.3
M8	+30	+6	36	**44.9**	±1.9	**103.1**	±4.2	**16.8**	±1.9	**15.8**	±1.3
M9	+36	+6	36	**50.9**	±1.9	**106.7**	±4.2	**18.1**	±2.0	**15.9**	±1.3
M10	+42	+6	35	**56.8**	±2.0	**109.9**	±4.5	**18.9**	±2.1	**15.6**	±1.3
M11	+48	+6	35	**62.7**	±1.9	**113.3**	±5.1	**20.4**	±2.5	**15.9**	±1.4
M12	+54	+6	36	**68.5**	±1.9	**117.0**	±4.6	**21.8**	±2.5	**16.0**	±1.4
M13	+60	+6	36	**74.5**	±1.8	**120.6**	±5.1	**23.8**	±2.9	**16.4**	±1.5
M14	+72	+12	35	**86.6**	±1.8	**127.3**	±5.5	**26.6**	±3.3	**16.4**	±1.5
M15	+84	+12	36	**98.0**	±4.7	**133.3**	±5.6	**29.7**	±4.1	**16.7**	±1.8
M16	+96	+12	35	**110.5**	±1.7	**138.8**	±5.9	**32.9**	±4.3	**17.1**	±1.8
M17	+108	+12	36	**122.8**	±2.0	**145.5**	±6.3	**37.1**	±5.5	**17.5**	±2.1
Gestation week at birth			36	**39.5**	±1.6						
Age at the beginning of sitting (months)			36	**8.3**	±2.1						
Age at the beginning of crawling (months)			36	**8.9**	±1.7						
Age at the beginning of standing (months)			36	**10.4**	±1.9						
Age at the beginning of free walking (months)			36	**13.4**	±1.9						

through grammar school (Table 1). The average age at the onset of walking was 13.4 ± 1.9 months and the first measurements were carried out at an age of 14.6 ± 1.8 months in order to ensure free walking without support for several meters (Table 1).

Height and body mass were recorded at every appointment (Table 1). Furthermore, the following static foot shape parameters were recorded from a Harris mat footprint in bilateral stance: foot length [FLmax] and midfoot width [MFW].

The primary outcome measures were the dynamic foot loading parameters. The children were asked to walk barefoot at freely chosen walking speed across the pressure distribution platform that was embedded in the floor (Emed ST, Emed X with 4 sensors/cm^2; Novel GmbH Munich). In very young children inducements, e.g. enticed with toys, were made to guide them over the platform. Only occasionally, children were held by hand. Preliminary experiments with children between 15 months and 10 years had indicated that children would alter their natural walking style when they are forced to walk at a certain speed. A speed that is more than 10% slower than the spontaneously self-selected speed also increases gait asymmetry [15]. Therefore, since our main focus was to record the children's most natural gait pattern we did not prescribe walking speed. We only excluded trials with running or hopping patterns. The goal was to record five trials for the left and the right foot in order to ensure sufficient reliability [16].

Data analysis was performed with the database software ('Medical Professional') provided by Novel GmbH Munich. Feet were subdivided into five regions: hindfoot, midfoot, forefoot, hallux, toes. For the total foot as well as the selected foot regions the following parameters were determined: peak pressure (PP in kPa), maximum force (MF in % bodyweight), contact area (CA in % of the whole foot), arch index (AI).

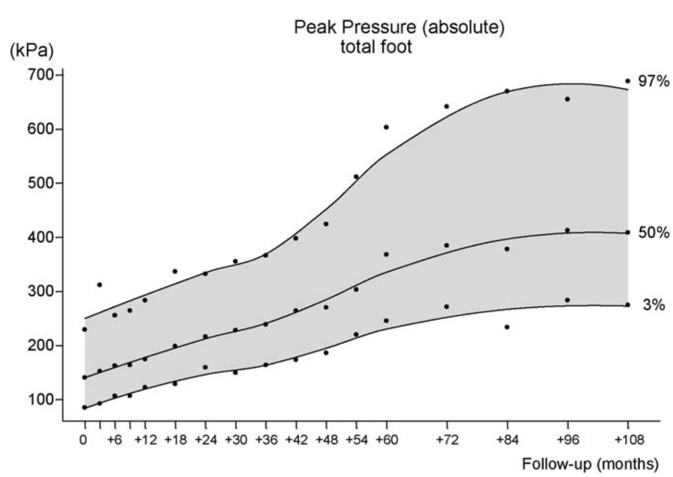

Fig. 1. Third, 50th and 97th percentiles of the peak pressure (kPa) of the total foot over the course of nine years.

Maximum force was determined in relation to the actual body weight of the subject. In order to account for the developmental changes the regional contact areas were expressed as a percentage of total foot contact. The arch index is a parameter for the development of the longitudinal arch and is defined as the ratio between midfoot contact area and total contact area [17].

2.1. Statistics

For descriptive statistics of the normative values the 3rd, 50th and 97th percentiles of all parameters were graphically depicted for every appointment. Mean temporal changes were displayed with a trend line (estimated by a LOESS approach [18]), which was fitted to the particular sequence. For inferential statistics linear regression models were applied using logarithmic data. A first model was established to evaluate potential differences between left and right feet. In a second model, the mean value of the left and right feet of every subject was used as response variable and the parameters gender, height, body mass and age at walking onset as covariates. In order to account for stochastic dependency between repeated measurements of an individual subject, in all models, parameter estimation was performed by means of generalized estimating equations (GEE). Systematic differences between both feet and effects of covariates were evaluated with Wald significance tests. *p*-Values were interpreted as explorative metrics. A value of $p < 0.01$ was considered as statistically significant in order to account for multiple testing. SAS version 9.1 (SAS Institute Inc., Cary, NC, USA) and S+ version 8.1 (TIBCO Software Inc., Palo Alto, CA, USA) were used.

3. Results

Due to the fact that no significant differences were found between the data of left and right feet, the mean values of both feet were used for further analyses.

3.1. Time-course of foot loading parameters

The results were presented as the median values of the parameters and their 3rd and 97th percentiles over the whole observation period.

Peak pressure values gradually increased in the total foot and in the selected foot regions by 190% (total foot) from the first (M1 = 140.5 kPa) to the last (M17 = 408.5 kPa) measurement (Fig. 1; Table 2). The range of values between the 3rd and the 97th percentiles also increased but showed a distinct step after M11. Continuous increases of the regional peak pressure values were also seen (Fig. 1; Table 2). During the initial three months, the highest peak pressures were seen under the hallux but with increasing age the hindfoot took over as the region with the highest

Table 2
Third, 50th and 97th percentiles of the peak pressure (PP in kPa), contact area (CArel in %) and the maximum force (MFrel in %) of the total foot (total), the hindfoot (hf), the midfoot (mf), the forefoot (ff), the hallux (hx) and toes 2–5 (t). Third, 50th and 97th percentiles of the midfoot width (MFW in cm) for males and females, foot length (FLmax in cm) and the arch index (AI) over the course of nine years (*n* = number of feet).

	0 M1 *n* = 72	+3 M2 *n* = 72	+6 M3 *n* = 72	+9 M4 *n* = 70	+12 M5 *n* = 72	+18 M6 *n* = 72	+24 M7 *n* = 70	+30 M8 *n* = 72	+36 M9 *n* = 72	+42 M10 *n* = 70	+48 M11 *n* = 70	+54 M12 *n* = 72	+60 M13 *n* = 72	+72 M14 *n* = 70	+84 M15 *n* = 72	+96 M16 *n* = 70	+108 M17 *n* = 72
PP (kPa)																	
Total																	
97%	229.1	311.8	255.5	264.1	283.1	336.4	331.9	355.1	365.9	397.9	424.1	511.6	603.1	641.4	669.9	654.8	688.3
50%	140.5	152.1	162.4	163.8	174.5	198.5	216.0	228.0	238.5	263.9	270.0	303.0	368.0	384.5	378.0	412.5	408.5
3%	84.7	92.2	106.3	106.8	122.1	128.5	159.1	149.1	163.6	173.3	186.1	220.0	245.1	271.3	233.5	283.4	274.3
PPhf																	
97%	182.7	284.9	233.8	251.1	262.8	293.6	306.9	323.2	352.8	387.3	424.1	511.6	603.0	631.7	669.9	635.9	649.3
50%	96.5	115.0	130.0	131.5	136.5	169.0	187.5	200.5	212.5	243.0	246.0	285.5	359.0	369.5	335.5	379.5	348.0
3%	63.2	65.5	77.6	75.4	93.4	95.5	116.4	118.3	132.5	159.0	168.0	216.3	216.0	264.1	223.3	244.2	251.4
PPmf																	
97%	107.2	111.5	130.8	104.8	107.8	133.3	99.8	90.0	106.8	104.4	109.7	133.6	146.7	150.5	147.1	131.0	138.7
50%	71.1	75.0	73.9	70.0	71.6	66.1	72.0	66.0	66.5	65.0	63.5	65.0	73.5	73.5	70.5	73.5	73.0
3%	51.2	53.9	55.2	48.8	51.0	44.5	46.1	46.5	39.4	41.1	44.0	40.0	43.4	38.6	34.4	33.1	33.0
PPff																	
97%	117.9	161.5	158.8	150.9	174.4	170.4	204.0	211.9	245.4	264.1	286.6	309.4	390.6	421.2	410.1	540.7	522.1
50%	78.2	100.5	105.6	108.1	112.8	125.0	137.8	143.5	154.0	164.5	183.5	197.5	230.5	247.0	251.5	263.5	291.0
3%	45.9	65.6	72.8	78.4	86.5	78.5	104.1	106.7	112.3	103.2	130.4	139.1	150.4	148.7	154.0	170.1	191.6
PPhx																	
97%	222.6	228.7	252.6	220.5	219.8	261.4	268.3	312.2	303.6	307.2	348.5	377.4	381.5	446.2	428.8	502.6	538.4
50%	125.5	125.0	117.1	123.4	128.9	138.5	154.4	144.5	164.0	180.0	190.5	203.0	250.5	282.0	245.0	253.0	267.5
3%	63.8	57.7	50.3	51.2	66.2	75.3	68.3	54.7	79.1	80.5	95.2	102.6	126.4	145.8	99.3	132.9	123.3
PPt																	
97%	93.7	123.5	87.8	104.3	107.0	96.1	116.5	151.1	146.8	183.8	201.7	237.2	271.4	266.8	249.2	275.6	261.4
50%	47.8	53.2	49.0	56.0	50.5	53.5	65.5	67.0	80.5	86.3	96.0	109.0	128.5	153.0	125.0	131.0	149.5
3%	24.1	18.2	23.0	25.0	25.3	24.8	25.1	25.1	38.0	31.0	44.2	51.3	58.9	58.1	49.4	63.1	62.8
CArel (%)																	
Total																	
97%	100.3	100.3	100.3	100.7	96.7	100.3	100.3	100.7	100.5	100.6	100.6	100.8	100.5	100.1	100.0	100.1	100.0
50%	100.0	100.0	100.0	100.0	93.3	100.0	100.0	100.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3%	99.7	99.6	99.8	99.8	89.7	99.7	99.9	99.9	99.9	99.9	99.9	99.8	99.9	99.9	99.9	99.9	100.0
CAhf																	
97%	25.6	25.8	26.9	28.0	26.8	28.9	29.6	29.4	30.2	29.3	30.1	31.9	33.1	33.7	33.7	33.7	33.2
50%	22.0	22.0	22.7	22.5	22.8	23.1	23.3	24.1	24.3	24.6	24.9	25.6	26.8	27.8	28.0	28.2	28.2
3%	19.6	19.8	20.3	20.2	20.4	20.6	21.0	20.7	21.6	21.6	22.0	22.9	23.7	23.9	23.0	24.1	24.2
CAmf																	
97%	33.0	32.3	31.8	32.1	31.5	30.9	30.3	28.4	26.9	26.1	25.9	24.3	24.3	23.5	25.2	23.6	24.4
50%	29.6	28.5	27.9	26.9	26.2	24.5	22.9	21.8	21.0	20.0	19.8	18.1	17.1	16.8	16.8	15.7	17.5
3%	26.0	23.2	20.2	18.5	17.7	13.4	13.3	10.2	7.3	8.6	6.8	3.9	2.8	2.9	2.5	3.1	2.4
CAff																	
97%	36.8	39.5	40.9	43.0	42.6	42.0	41.1	42.9	42.5	44.8	44.5	45.1	45.9	45.3	46.0	46.2	47.2
50%	32.3	35.0	35.3	36.0	36.0	37.2	37.5	37.5	37.9	38.6	38.3	40.3	40.2	40.2	40.6	40.7	41.0
3%	28.5	28.9	31.5	30.8	32.6	33.7	33.4	34.0	35.4	34.7	34.6	36.0	36.1	35.4	34.2	35.9	36.6
CAhx																	
97%	10.3	10.0	10.0	10.1	10.2	9.8	10.0	10.7	11.2	10.6	11.4	11.6	11.9	12.3	11.9	10.8	11.9
50%	8.3	8.0	7.6	8.1	8.0	8.2	8.5	8.3	8.5	8.5	8.8	8.7	9.1	9.4	9.0	9.0	8.5
3%	5.8	5.6	5.7	6.1	6.3	6.4	6.7	6.1	6.9	6.9	6.5	6.4	6.9	7.2	7.0	6.9	6.6
CAt																	
97%	11.8	11.0	10.1	10.5	10.1	9.6	10.4	11.1	11.4	12.3	11.9	11.8	11.4	11.7	11.7	11.3	11.5
50%	7.5	7.1	6.3	6.5	6.7	7.1	7.3	7.9	8.2	9.1	9.1	8.1	7.7	7.4	7.2	6.6	6.6
3%	3.5	3.0	3.2	3.3	3.3	3.5	3.1	3.3	4.5	3.8	4.3	3.7	3.5	3.2	2.9	3.7	3.0
MFrel (%)																	

Total																	
97%	133.2	162.2	163.9	159.5	157.9	211.2	137.3	126.9	133.7	123.2	141.7	137.5	133.8	159.4	126.9	129.2	130.8
50%	99.8	106.8	111.2	109.0	110.2	109.3	105.8	105.4	106.8	110.1	108.0	111.5	119.7	129.5	110.9	113.7	120.1
3%	83.1	86.0	86.7	86.2	86.7	86.9	88.8	89.3	92.9	94.9	99.0	100.3	105.7	111.1	98.8	102.1	107.5
MFhf																	
97%	69.9	92.9	85.8	90.3	98.5	126.5	90.8	87.1	100.8	94.4	101.5	104.6	108.2	117.1	99.1	98.4	101.5
50%	48.2	55.0	63.4	61.5	63.0	63.9	68.2	72.4	75.6	78.0	76.5	82.9	88.1	96.9	81.7	83.2	82.5
3%	32.5	34.4	40.9	34.3	44.9	43.6	54.1	55.0	56.2	59.0	61.6	63.9	70.4	76.2	64.6	70.1	67.7
MFmf																	
97%	62.3	74.6	68.4	59.9	55.7	50.3	57.8	39.2	40.2	35.3	31.9	30.1	31.0	35.3	31.9	29.7	35.0
50%	43.0	41.9	40.6	38.9	33.4	28.1	24.9	21.5	19.8	17.3	17.5	14.4	13.9	13.1	11.8	10.6	15.8
3%	27.4	26.8	17.8	14.6	14.3	9.0	9.0	5.1	4.8	5.1	4.0	2.5	2.3	2.2	1.6	1.2	1.4
MFff																	
97%	67.1	76.2	75.6	85.4	99.5	95.3	97.0	84.7	87.4	90.1	90.2	96.9	102.3	110.4	98.6	98.1	103.9
50%	49.8	61.4	63.6	65.1	69.0	71.1	74.4	74.2	76.6	78.4	77.1	83.0	89.0	93.8	81.8	88.1	93.0
3%	27.9	41.1	49.3	54.8	52.5	51.4	59.5	57.1	63.0	59.9	67.2	71.7	60.8	73.8	63.2	69.1	77.8
MFhx																	
97%	27.9	29.9	30.2	29.2	29.9	33.1	31.4	33.4	34.9	34.5	36.5	41.6	39.5	43.6	38.1	34.5	36.7
50%	15.9	15.2	15.5	16.4	16.3	18.3	18.5	18.5	20.6	20.7	21.0	23.1	25.9	31.2	24.8	23.5	22.1
3%	7.4	7.4	7.0	6.8	7.8	9.9	8.4	7.6	10.2	9.8	10.5	10.4	15.5	16.2	8.1	12.5	8.3
MFt																	
97%	16.2	14.9	13.7	16.6	15.9	12.8	14.8	16.6	19.4	19.5	21.3	18.5	22.6	26.5	20.9	17.4	19.2
50%	6.6	7.2	5.6	6.0	6.3	6.3	7.2	8.1	9.5	10.5	10.8	10.1	10.7	11.0	8.2	7.7	7.6
3%	2.4	1.6	1.7	2.0	1.8	2.5	2.0	1.9	2.7	2.0	3.3	3.5	3.8	3.1	2.0	2.3	2.4
	0	+3	+6	+9	+12	+18	+24	+30	+36	+42	+48	+54	+60	+72	+84	+96	+108
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17
	n = 60	*n* = 68	*n* = 68	*n* = 65	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 69	*n* = 72
MFW (cm)																	
97%	3.9	4.0	4.2	4.6	4.1	4.3	4.1	4.0	4.3	4.6	4.2	4.2	4.0	4.1	3.7	4.1	4.7
50%	3.2	3.2	3.1	3.5	3.2	3.0	2.7	2.8	2.7	2.9	2.7	2.7	2.7	2.8	2.6	2.7	2.9
3%	2.2	2.3	1.9	1.4	1.3	1.4	1.4	0.3	0.8	1.3	1.3	−1.2	−0.9	−1.1	−1.2	−0.6	−0.6
	0	+3	+6	+9	+12	+18	+24	+30	+36	+42	+48	+54	+60	+72	+84	+96	+108
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17
	n = 24	*n* = 30	*n* = 30	*n* = 29	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 32	*n* = 29	*n* = 32
Male																	
97%	4.0	4.2	4.2	4.6	4.6	4.5	4.2	4.0	4.4	4.6	4.2	4.2	4.0	4.2	4.3	4.2	4.2
50%	3.4	3.7	3.6	3.7	3.6	3.5	3.2	3.2	3.0	3.4	3.2	3.2	3.0	2.8	2.8	3.1	3.1
3%	3.0	2.9	2.8	2.4	2.0	2.3	1.5	1.6	2.0	1.5	1.4	1.8	2.0	−0.9	−0.6	1.8	−0.4
	0	+3	+6	+9	+12	+18	+24	+30	+36	+42	+48	+54	+60	+72	+84	+96	+108
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17
	n = 36	*n* = 38	*n* = 38	*n* = 36	*n* = 40	*n* = 40	*n* = 38	*n* = 40	*n* = 40	*n* = 38	*n* = 38	*n* = 40	*n* = 40	*n* = 38	*n* = 40	*n* = 40	*n* = 40
Female																	
97%	3.8	3.6	3.6	3.7	3.7	4.0	3.8	3.6	3.9	3.9	4.1	3.5	3.9	3.7	3.5	3.5	4.7
50%	3.0	3.0	2.9	2.8	2.9	2.7	2.4	2.4	2.2	2.6	2.6	2.5	2.3	2.4	2.5	2.6	2.8
3%	2.2	2.3	1.5	1.3	1.0	1.1	1.3	0.2	0.6	−1.1	1.2	−2.0	−1.8	−1.1	−1.2	−4.9	−1.5
	0	+3	+6	+9	+12	+18	+24	+30	+36	+42	+48	+54	+60	+72	+84	+96	+108
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17
	n = 62	*n* = 67	*n* = 68	*n* = 64	*n* = 71	*n* = 72	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 69	*n* = 72
FLmax (cm)																	
97%	12.7	13.5	13.9	14.4	14.5	15.4	16.0	16.4	17.3	17.5	18.2	18.7	19.5	20.8	21.8	22.3	23.2
50%	11.4	12.0	12.5	13.0	13.5	14.2	14.5	15.2	15.6	16.1	16.6	17.2	17.5	18.6	19.6	20.6	21.4
3%	10.0	10.8	11.1	11.8	12.0	12.7	13.2	13.7	14.1	14.7	15.2	15.7	16.4	16.9	17.9	18.6	19.0
	0	+3	+6	+9	+12	+18	+24	+30	+36	+42	+48	+54	+60	+72	+84	+96	+108
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17
	n = 72	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 70	*n* = 72

Table 2 (*Continued*)

	0	+3	+6	+9	+12	+18	+24	+30	+36	+42	+48	+54	+60	+72	+84	+96	+108
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17
	n = 72	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 70	*n* = 72	*n* = 72	*n* = 70	*n* = 72	*n* = 70	*n* = 72
AI																	
97%	0.40	0.38	0.36	0.36	0.36	0.36	0.35	0.34	0.31	0.30	0.30	0.28	0.27	0.27	0.27	0.26	0.27
50%	0.36	0.34	0.33	0.32	0.31	0.29	0.27	0.26	0.25	0.24	0.24	0.21	0.21	0.20	0.20	0.18	0.20
3%	0.30	0.27	0.24	0.21	0.22	0.16	0.16	0.13	0.10	0.11	0.08	0.05	0.03	0.04	0.03	0.04	0.03

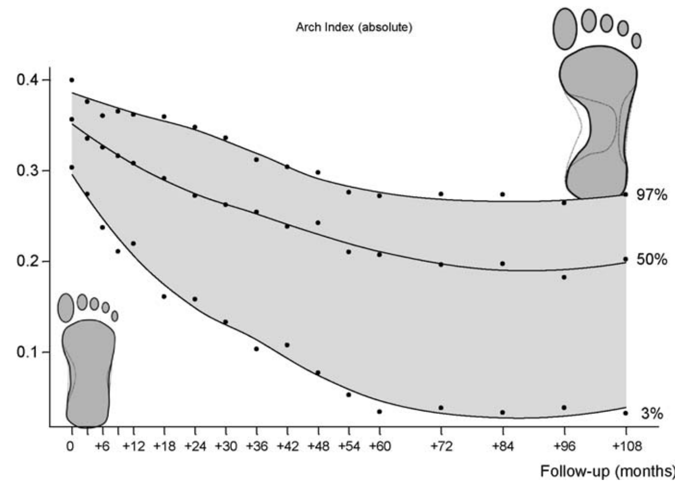

Fig. 2. Third, 50th and 97th percentiles of the arch index over the course of nine years.

loading. Towards the last measurements (M15–M17) the forefoot also experienced loads that exceeded the hallux values (Table 2).

When comparing the *relative contact area* the midfoot showed a decrease from 30% to 18% whereas the contact area of the hindfoot, forefoot and hallux increased in the observation period (Table 2).

The *maximum force* under the total foot increased from 100% to 120% of body weight. This effect was also seen in the hindfoot (+71%), forefoot (+87%), hallux (+39%) and lateral toes (+15%). Only the midfoot region was loaded less (−63%; Fig. 2). At M14 the highest values were seen in the total foot (130%), hindfoot (97%), hallux (31%) and toes (11%) (Table 2).

The *arch index* – an indication for the changes of the longitudinal arch – gradually decreased by 44%. The range of values between the 3rd and the 97th percentiles grew larger and reflected pronounced inter-individual differences (Fig. 2; Table 2).

The statically determined *midfoot width* decreased by 9% from M1 to M17. Furthermore, increased variation of the 3rd percentile led to a wider range of values. The *foot length* showed a steady increase by 90% (Fig. 4; Table 2).

3.2. Covariates of foot loading parameters

The following illustrates the results of the multivariate statistical model for the parameters gender, height, body weight and age at walking onset. This approach tests for the influence of one covariate when the other factors are kept constant. The *p*-value then determines whether a significant effect can be attributes to this covariate (Table 3).

The **age at walking onset** did not show any effect on the development of the evaluated parameters.

3.3. Effect of height

Body height had a significant influence on foot length and midfoot width. A 5 cm difference in height (but identical weight, age at walking onset and gender) would be related to a longer foot (+0.4 cm) but a lesser foot width (−0.3 cm). A height increase of 5 cm would also influence the maximum force under the hindfoot (+8%), forefoot (+5%) and hallux (+9%). Contact area would increase by 2% in the hindfoot and 3% in the hallux. Peak pressures increased under the total foot (+10%), hindfoot (+14%), forefoot (+7%) and hallux (+8%). The midfoot showed a significant decrease of peak pressure (−6%), maximum force (−12%) and contact area (−8%).

Table 3
p-Values (Wald-statistics) and beta estimate of the multivariate model for peak pressure (PP), relative contact area (CArel), relative maximum force (MFrel), arch index (AI), midfoot width (MFW) and foot length (FLmax) with respect to the covariants gender, age at the onset of walking, height, weight. MFW and FLmax are based on absolute values. Significant differences are bold ($p \leq 0.01$).

	Gender		Appointment		Age onset of walking		Body height		Body weight	
	p	Beta	*p*	Beta	*p*	Beta	*p*	Beta	*p*	Beta
PP										
Total	0.8104	0.9902	0.2736	1.0271	0.1424	1.0176	<**0.0001**	**1.1009**	**0.0056**	**0.9843**
Hindfoot	0.3015	0.9506	0.3397	1.0308	0.0255	1.0293	<**0.0001**	**1.1348**	**0.0009**	**0.9731**
Midfoot	0.2374	1.0648	0.6252	0.9825	0.2885	0.9860	**0.0003**	**0.9448**	<**0.0001**	**1.0348**
Forefoot	0.8060	0.9902	0.3178	1.0259	0.9219	0.9991	**0.0003**	**1.0709**	0.3984	1.0033
Hallux	0.7699	1.0198	0.5212	0.9806	0.9705	1.0005	**0.0017**	**1.0838**	0.8812	0.9988
Toes 2–5	0.3482	1.0794	0.0125	1.0905	0.4263	0.9839	0.0111	1.0171	**0.0051**	**0.9704**
CArel										
Total	0.6331	1.0003	0.0162	1.0015	0.1842	1.0001	0.3672	1.0003	0.0347	0.9998
Hindfoot	0.0413	0.9631	0.5146	1.0058	0.7405	1.0016	<**0.0001**	**1.0217**	**0.0031**	**0.9960**
Midfoot	0.1916	1.1422	0.2610	0.9446	0.2052	0.9745	**0.0088**	**0.9203**	**0.0016**	**1.0303**
Forefoot	**0.0064**	**0.9648**	0.4350	1.0066	0.2804	1.0040	<**0.0001**	**1.0219**	<**0.0001**	**0.9943**
Hallux	0.6374	1.0157	0.6740	0.9917	0.3491	1.0054	0.0193	1.0306	0.0170	0.9914
Toes 2–5	0.8991	1.0096	0.5953	1.0153	0.4231	1.0146	0.1390	1.0338	**0.0022**	**0.9753**
MFrel										
Total	0.2096	0.9830	**0.0036**	**1.0247**	0.7359	0.9990	0.5891	0.9968	0.1051	0.9967
Hindfoot	0.2148	0.9703	0.8803	1.0023	0.6985	1.0023	<**0.0001**	**1.0761**	<**0.0001**	**0.9796**
Midfoot	0.1471	1.2298	0.4560	0.9423	0.1102	0.9471	**0.0083**	**0.8793**	**0.0051**	**1.0358**
Forefoot	0.2253	0.9712	0.5157	1.0107	0.3407	0.9933	<**0.0001**	**1.0542**	**0.0012**	**0.9877**
Hallux	0.2237	1.0814	0.6679	1.0141	0.3930	0.9911	**0.0001**	**1.0936**	<**0.0001**	**0.9660**
Toes 2–5	0.3782	1.1138	0.0112	1.1142	0.7972		0.0880		<**0.0001**	**0.9397**
AI	0.1326	1.1555	0.2556	0.9438	0.2283	0.9772	**0.0047**	**0.9167**	**0.0036**	**1.0315**
MFW	**0.0022**	**0.5884**	0.4526	0.0945	0.1240	−0.0734	**0.0023**	−**0.2688**	**0.0047**	**0.0760**
FLmax	0.2253	0.1882	**0.0030**	**0.3167**	0.5752	−0.0158	<**0.0001**	**0.4449**	0.0118	0.0266

Therefore, the arch index was reduced by 8% for 5 cm of height increase (Table 3).

3.4. Effect of body weight

Body weight had a significant influence on the static parameter midfoot width. A difference in 1 kg body weight was related to a wider foot (+0.08 cm). An increase of 1 kg body weight also influenced the maximum force under the hindfoot (−2%), forefoot (−1%), hallux (−3%) and toes (−6%). Peak pressures decreased under the total foot (−2%), hindfoot (−3%) and toes (−3%). On the contrary, the midfoot showed a significant increase of peak pressure (+3%), maximum force (+4%), contact area (+3%) and the arch index (+3%) (Table 3).

3.5. Effect of gender

Between genders, a significant difference was seen for the midfoot that was on the average 6 mm wider in boys as compared to girls. Furthermore, the boys showed a 4% smaller forefoot contact area (Table 3).

4. Discussion

The results provide an impressive overview of foot development of the child during the first nine years of independent walking. Therefore, a unique database of normative values of the functional and morphometric development of the child's foot could be established in a longitudinal design. The percentile presentations are valuable for the assessment of physiologic or pathologic foot development in children from the onset of walking until the age of 10 years.

For the subsequent interpretation of the results it should be noted that gait speed was not measured as it was explained above. Furthermore, the analysis was confined to foot parameters so that a potential influence of hip, knee and upper extremity movements was not considered.

4.1. Time-course of foot loading parameter

In accordance with previous results of the first four years of walking [2,4,12] an ongoing development of foot loading and foot shape parameters could be demonstrated in this nine-year follow-up. The continuous increase of the foot length through nine years confirms previous findings of cross-sectional investigations in healthy children [19].

The gradual increase of peak pressure values is not finished in this higher age and indicates the continuing development of the growing foot [2]. In the initial months of walking, local peak pressures under the hallux were seen; this pattern of a pronounced hallux loading appears to be characteristic for this early phase of gait acquisition [2,12,20]. During the first year, the location of these peak pressures disappeared in the hallux and appeared more often in the hindfoot region [2]. This is in accordance with a previous report in children between 6 and 10 years [13]. The peak pressures under the forefoot appear to increase beyond the investigated age so that a further development towards an adult-like foot loading pattern can be expected [21–23]. The shift of peak pressure of the different foot areas as described above indicates changes of the plantar fat pad as well as a more dynamic roll over process during the first years of independent walking [12,24]

In comparison to a sample of 32-year-old adults, the investigated children reached between 53% and 99% of the regional pressures [21]. This is an indication for the advanced but still incomplete development of peak pressures at the age of 10.

The increase of the relative maximum force of the total foot also shows a development towards a dynamic roll over process as it is seen in healthy adults. The contact area and maximum force values reveal only minor differences after M12 (beyond 4.5 years) when compared to adult values [21].

While the dynamic foot loading parameters under the hindfoot, forefoot, hallux and toes increased, the midfoot revealed a continuous reduction of loading, except for peak pressure. Furthermore, all midfoot-related parameters indicate a significant development of the longitudinal arch from a flat-footed to a normal or even high-arched pattern. This indicates that the initial developments observed in the early months of walking [4] continue through the nine years of investigation. The wide range of values of the midfoot width and the arch index reflect the inter-individual differences of static and dynamic foot shapes with increasing age. However, after M10 the arch index of the children is only 5% higher than in adults [21]. The arch development may therefore be initiated early on so that at an age of 10 years the inter-individual differences vary as much as in adults.

4.2. Influence of the covariates of foot loading parameters

The age at walking onset did not reveal any influence on the foot development. As soon as the children had acquired an upright, bipedal walking pattern, neither an early nor a late walking onset had an impact on foot development.

The covariates body height and weight show contrary results. The influence of body height leads to an increase of the foot loading and shape values for most regions but a decrease in the midfoot. The body weight, however, leads to an increase of the midfoot values and a decrease for most of the other foot regions.

For the interpretation of the influence of body weight on peak pressures it should be pointed out that a higher weight showed this influence only for constant covariates in the hypothetical multivariate model. The significant influence of body weight – as reflected in reduced pressure values under the total foot, hindfoot and lateral toes but an increase under the midfoot – could be seen as a support for previous findings indicating that only extreme overweight or weight differences lead to an increase of peak pressures [21,25,26].

The multivariate model showed a similar development for the maximum force. In the hindfoot, forefoot, hallux and lateral toes the forces reduced, whereas the midfoot forces increased. This may be due to the higher body weight that leads to a flattening of the longitudinal arch and a larger contact area thus bearing a higher relative load. This assumption is supported by the increase of the midfoot contact area, the arch index and the midfoot width, which is also based on the influence of body weight.

The increase of body height leads to a decrease of midfoot contact area, midfoot width and arch index. That indicates a less flattening of the longitudinal arch, which results in an increase and shift of loading parameters under the other foot regions.

4.3. Gender-specific differences

Having been described earlier [27], foot length does not differ significantly between boys and girls between 1.2 and 10.0 years. Furthermore, the push-off is not more pronounced in boys as compared to girls [27]. However, the wider midfoot in boys was confirmed not only for the first years of walking [2,14] but also for the whole nine years. The same holds true for the flatter longitudinal arch in boys [28]. The significantly greater forefoot contact area corresponds to previous results [19] and contradicts other reports of narrower feet in girls [6,29]. However, these studies were performed in different age groups and the reports were usually based on different static foot evaluations and did not investigate the dynamic roll over process. Strength deficits or weaker tendinous and ligamentous structures of the female foot might explain these differences but should be verified in future studies.

These results provide a detailed documentation of the development of the healthy child's foot. The previous statements that were mostly based on cross-sectional studies could be confirmed and expanded by ranges of values for the investigated parameters and their growth-related developments.

The interpretation of foot parameters should consider the potential influence of the covariates of the multivariate model but leaves room for further discussions.

Due to the fact that the longitudinal growth of the foot, as well as body height and weight changes are not terminated at the age of 10 years, further developments can be expected beyond the present observation period. However, the most pronounced changes may have occurred until this age and the speed of development may slow down.

5. Conclusion

The typical development of the healthy child's foot shape and foot loading was documented with percentile representation of the investigated parameters. The values may be used as reference values in clinical applications in pediatrics where 3rd, 50th and 97th percentiles are commonly used. Values that are outside this range should lead to a detailed clinical examination by a physician. The values should not be used to substitute a medical examination but could support clinical decision-making.

The normal development of a child's foot is characterized by relevant changes of foot shape and foot function. The development is subjected to pronounced inter- and intra-individual differences. A rapid development can be seen in the initial months after walking onset. Gender-specific differences can be demonstrated. In summary, the present project provides a unique database of normative values for the description of the child's foot loading and shape during the first nine years of independent walking. The information may be used to differentiate between physiologic and pathologic developments of children in this age group.

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Conflict of interest statement

There are no financial and personal relationships with other people or organisation which may lead to a conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2010.08.003.

References

[1] Tittel K. Beschreibende und funktionelle Anatomie des Menschen. Urban & Fischer; 1998.
[2] Bosch K, Gerss J, Rosenbaum D. Preliminary normative values for foot loading parameters of the developing child. Gait Posture 2007;26:238–47.
[3] Hallemans A, De Clercq D, Dongen SV, Aerts P. Changes in foot-function parameters during the first 5 months after the onset of independent walking: a longitudinal follow-up study. Gait Posture 2006;23:142–8.
[4] Bertsch C, Unger H, Winkelmann W, Rosenbaum D. Evaluation of early walking patterns from plantar pressure distribution measurements. First year results of 42 children. Gait Posture 2004;19:235–42.
[5] Forriol F, Pascual J. Footprint analysis between three and seventeen years of age. Foot Ankle 1990;11:101–4.
[6] Gould N, Moreland M, Trevino S, Alvarez R, Fenwick J, Bach N. Foot growth in children age one to five years. Foot Ankle 1990;10:211–3.

[7] Mauch M, Grau S, Krauss I, Maiwald C, Horstmann T. Foot morphology of normal, underweight and overweight children. Int J Obes (Lond) 2008; 32:1068–75.
[8] Staheli LT, Chew DE, Corbett M. The longitudinal arch. A survey of eight hundred and eighty-two feet in normal children and adults. J Bone Joint Surg Am 1987;69:426–8.
[9] Volpon JB. Footprint analysis during the growth period. J Pediatr Orthop 1994;14:83–5.
[10] Aharonson Z, Voloshin A, Steinbach TV, Brull MA, Farine I. Normal foot—ground pressure pattern in children. Clin Orthop Relat Res 1980;220–3.
[11] Alvarez C, De Vera M, Chhina H, Black A. Normative data for the dynamic pedobarographic profiles of children. Gait Posture 2008;28:309–15.
[12] Hallemans A, D'Aout K, De Clercq D, Aerts P. Pressure distribution patterns under the feet of new walkers: the first two months of independent walking. Foot Ankle 2003;24:444–53.
[13] Hennig EM, Staats A, Rosenbaum D. Plantar pressure distribution patterns of young school children in comparison to adults. Foot Ankle Int 1994;15:35–40.
[14] Unger H, Rosenbaum D. Gender-specific differences of the foot during the first year of walking. Foot Ankle Int 2004;25:582–7.
[15] Goble DJ, Marino GW, Potvin JR. The influence of horizontal velocity on interlimb symmetry in normal walking. Hum Mov Sci 2003;22:271–83.
[16] McPoil TG, Cornwall MW, Dupuis L, Cornwell M. Variability of plantar pressure data. A comparison of the two-step and midgait methods. J Am Podiatr Med Assoc 1999;89:495–501.
[17] Cavanagh PR, Rodgers MM. The arch index: a useful measure from footprints. J Biomech 1987;20:547–51.
[18] Cleveland WS, Devlin SJ. Locally-weighted regression: an approach to regression analysis by local fitting. J Am Stat Assoc 1988;83:596–610.
[19] Morrison SC, Durward BR, Watt GF, Donaldson MD. Prediction of anthropometric foot characteristics in children. J Am Podiatr Med Assoc 2009;99:497–502.
[20] Hennig EM, Rosenbaum D. Pressure distribution patterns under the feet of children in comparison with adults. Foot Ankle 1991;11:306–11.
[21] Bosch K, Nagel A, Weigend L, Rosenbaum D. From "first" to "last" steps in life—pressure patterns of three generations. Clin Biomech (Bristol Avon) 2009;24:676–81.
[22] Bryant AR, Tinley P, Singer KP. Normal values of plantar pressure measurements determined using the EMED-SF system. J Am Podiatr Med Assoc 2000;90:295–9.
[23] Menz HB, Morris ME. Clinical determinants of plantar forces and pressures during walking in older people. Gait Posture 2006;24:229–36.
[24] Brophy L, Ounpuu S, Westwell-O'Connor M, Bell K, DeLuca P. The analysis of ankle kinematic and foot contact patterns following the onset of walking in normal children. In: GCMAS Conference; 2001.
[25] Dowling AM, Steele JR, Baur LA. What are the effects of obesity in children on plantar pressure distributions? Int J Obes Relat Metab Disord 2004;28:1514–9.
[26] Mickle KJ, Steele JR, Munro BJ. The feet of overweight and obese young children: are they flat or fat? Obesity (Silver Spring) 2006;14:1949–53.
[27] Anderson M, Blais M, Green W. Growth of the normal foot during childhood and adolescence: length of foot and interrelations of foot, stature, and lower extremity as seen in serial records of children between 1–18 years of age. Am J Phys Anthropol 1956;14:287–308.
[28] Pfeiffer M, Kotz R, Ledl T, Hauser G, Sluga M. Prevalence of flat foot in preschool-aged children. Pediatrics 2006;118:634–9.
[29] Dowling A, Steele J, Baur L. How does obesity and gender affect foot shape and structure in children?In: ISB 29th Congress; 2005. p. 512.