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Evaluation of the rule-of-thumb: calculation of the toe allowance for developing feet

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The amount of toe allowance (TA, the space in front of the toes) in children's shoes is physiologically important and often estimated by the rule-of-the-parent's-thumb. Besides this, other rules-of-thumb exist mainly based on experiences or footprint analysis. The aim of this study is to scientifically evaluate these rules-of-thumb. TA was calculated as a function of growth rate, foot extension, and walking advance based on three-dimensional (3D) foot scans of 2554 children (6–16 years) during standing and walking. Foot extension was determined as the difference in foot length between static and dynamic weight-bearing, walking advance as movement of the most anterior point of toes, and growth rate as semi-annual foot growth. TA was smaller than all rules-of-thumb and was influenced by gender and foot length. These findings primarily present TA based on 3D foot scans which is important for shoe construction. It is recommended to use 90th percentiles instead of mean values for the construction of TA.

Keywords: children's footwear; 3D deformation; 3D scanning; foot measures; foot morphology; foot movement (in shoe); toe allowance

Introduction

The 'rule-of-the-parents'-thumb', commonly used for buying children's shoes, describes a method to fit children's shoes in length using a parent's thumb width to determine whether there is adequate space in front of the toes. This space is called toe allowance (TA) and determines, in addition to the actual foot length (FL), the required inner length of a shoe. From a physiological point of view, TA is important during every rollover process, even more for developing feet in order not to disturb natural foot development. Most parents are aware of this and want to support their children with correct shoe size. However, several factors affect the easy calculation of FL plus TA. First, only few studies have scientifically evaluated TA. Thus, TA is experience-based and not validated. Second, various shoe sizing systems exist. Consequently, the inner length differs because of varying increments from one size to the other. Furthermore, sizing systems are not standardized and attempts to define an international standard have not yet been successful (Hlavacek & Cheng, 2009). Third, it is accepted that feedback about TA cannot be obtained from the child.

Several studies address the relationship between ill-fitting footwear and foot problems. The shortcomings of footwear are highlighted in English adults with an alarming 63% with foot problems and 10% with disabling foot pain (Garrow, Silman, & Macfarlane, 2004). Tehraninasr

et al. (2008) refer to a dramatic increase of hallux valgus after the Second World War reasoned by more fashionable footwear. In children, a relationship has already been found between shoes that are too short in length and an increased hallux valgus angle (Klein, Groll-Knapp, Kindi, & Kinz, 2009). Furthermore, shoes provoke other foot deformities and also impair the statics of the whole body (Menz & Morris, 2005; Rajchel-Chyla, Skrzyńska, Janocha, & Gajewski, 2012).

Even if the importance of correct shoe length has reached the general population, in reality every shoe manufacturer individually defines shoe length, often based on fashion trends (Hlavacek & Chlachula, 2013). It could be argued that this is not a problem as long as developing feet have enough space in front of the toes. However, TA is also important for construction and thus functionality of shoes, e.g. for defining the flex line which is essential for a natural roll-over process.

In the 1960s and 1970s, main activities to improve children's shoes were done by a German consortium of manufacturers and researches (Arbeitskreis Kinderschuh). Their guideline AKA64-WMS includes a rule-of-thumb based on footprint analysis in which at least 12 mm for TA is required (Maier & Killmann, 2003). Stracker (1966) has found that TA for a foot between 170 and 180 mm long comprises 6–8 mm. Furthermore, he stated that TA is influenced by FL, ligamentous apparatus, and muscular

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tone. Considering that the feet of infants and young children grow faster, Schmidt (1989) has concluded that TA should be extended for this group of children.

Apart from the ‘rule-of-the-parent’s-thumb’ other rules-of-thumb exist either based on practical experiences or empirical findings from footprint analysis. First, TA can be calculated from the respective shoe size according to EU standard divided by two (e.g. for shoe size 30 a TA of 15 mm is recommended) (Maier, 1966, 1990). Second, TA comprises 5% of FL (Stracker, 1966). Other recommendations provide more detailed considerations by dividing TA into three parts: space of growth, forward movement of the foot within the shoe, and amount of the loss of the shoe’s original dimension by vamp creasing or shrinking (Rossi & Tennant, 2011).

To the best of our knowledge, no public studies exist that have scientifically evaluated these rules-of-thumb. This study aims to systematically determine TA using a new algorithm based on considerations by Rossi and Tennant (2011). To achieve this, 2554 children were examined using a new scanner system, called DynaScan4D, which allows three-dimensional (3D) capturing of feet during walking (Barisch-Fritz, Schmeltzpfenning, Plank, Hein, & Grau, 2013; Schmeltzpfenning, Plank, Krauss, Aswendt, & Grau, 2009). The objectives of this study are as follows: (1) calculating required TA as a function of growth rate, foot extension, and barefoot walking advance. (2) Evaluating influences of gender, body mass, and FL on TA. (3) Determining the applicable amount of TA for footwear construction and manufacturing.

Participants and methods

Participants

The study was approved by the Ethics Committee of the university clinic. With the cooperation of 15 schools in the southern part of Germany, 2554 participants, aged between 6 and 16 years, were included in the study.

Children and their parents were informed by teachers and received written information about aims and contents prior to the study. Written consent of one legal guardian and voluntary participation of the child were preconditions. The exclusion criteria included problems influencing normal gait, in particular injuries and diseases of the lower extremities, serious foot deformities or diagnosed neurological deficits concerning balance.

Static and dynamic foot morphology was captured using DynaScan4D. One foot of each child was randomly defined and primarily measured during standing (half weight-bearing = HWB). To ensure equal load distribution, participants were instructed to flex and subsequently extend their knees. Furthermore, they were asked to look ahead and to stand still with their arms hanging loosely. To capture dynamic trials, children had to step centrally onto the glass plate. Furthermore, they were instructed to walk with predefined walking speed adjusted to body height (Barisch-Fritz, Schmeltzpfenning, Plank, & Grau, 2014). After several training trials, three valid trials were captured.

Secondary measures, age, and gender were documented; body weight was measured with an electronic bathroom scale in lightweight clothing and body height with a stadiometer. Body mass index (BMI, weight (kg)/height (m²)) was calculated and BMI-percentiles were defined by normalizing according to gender and age-based reference data of German children (Kromeyer-Hauschild et al., 2001).

Table 1 presents the final sample size. Only participants with all information were considered for analysing TA. The reasons for excluding participants were diverse. Main reasons were low quality of scans, i.e. holes in the surface texture. This insufficient quality of scan data was caused by problems due to the challenging alignment of shutter time. Further reasons for dropouts were malfunction of trigger and saving processes, high sensitivity of the scanner system to ambient light and deficits adjusting to skin type.

Table 1. Included participants and final sample size.

Component of toe allowance (TA)	Included participants: <i>n</i> = 2554		
	Growth rate	Foot extension	Walking advance
Definition	Calculated on the base of foot length (FL) and age	Calculated on the base of the difference between static and dynamic medial ball length (MBL)	Calculated on the base of most anterior point of toes
Number of participants based on	Age: <i>n</i> = 2551	Dynamic trials of MBL: <i>n</i> = 2546	Most anterior point: <i>n</i> = 2455
Number of processed foot scans	FL in half weight-bearing: <i>n</i> = 2313 Complete data to calculate required TA: <i>n</i> = 1966	Three valid trials of MBL: <i>n</i> = 2159	Three valid trails of most anterior point: <i>n</i> = 2330

Measurement system

DynaScan4D was used for recording static and dynamic foot morphology. This system, based on the principle of full-field triangulation by structured light projection, was developed at the University of Tuebingen. Five synchronized scanner units (z-Snapper, ViALUX GmbH, Chemnitz, Germany) were attached to a 4.6 m long and 0.8 m high walkway; two scanner systems on the right, two on the left side, and one below the 0.6×0.4 m glass plate (Schmeltzpfenning, Plank, Krauss, Aswendt, & Grau, 2010). Each scanner unit consists of one projector and one high-speed camera (Pike F-032 B/W, Allied Vision, Stadtroda, Germany). The recording rate of each camera is 205 frames per second with a resolution of 640×480 . The projector is based on digital light processor technology including a Digital Micromirror Device (DMD™, Texas Instruments Inc., Dallas, TX, USA). The maximum DMD™ speed and a precise synchronization of camera and projector are realized by a special accessory light modulator package developed by ViALUX for this purpose (Hoeftling & Ahl, 2004). The calculation of the elevation information is realized according to the equations by Frankowski, Chen, and Huth (2000). A strain gauge was used to monitor the scanning of the walking sequence and light detectors to detect the walking speed.

The frequency for dynamic scanning was 46 Hz, which was obtained by a reduced spatial resolution (4×4 binning mode). The captured scenery had a volume of approximately $55 \times 35 \times 25$ cm. The accuracy of the system was tested by recording a bowling ball in static situation with full resolution and dynamic situation with 4×4 binning mode and a velocity of 0.8 m/s. The measurement error (root mean square error, RMSE) was 0.23 mm for the static and 0.89 mm for the dynamic situation.

Analysis of scan data and statistics

Recording and storage of 3D foot scans and further processing were executed using the DynaScan4D software. It aligned foot scans to the x -axis, which is the connecting line between the most medial points of the heel and the first metatarsophalangeal joint (metatarsal head 1 = MTH1).

Medial ball length (MBL) was calculated as distance between the most posterior point of the heel and the most medial point of the MTH1. The medial point was manually detected for each frame. The reliability of this procedure was determined for static (intra-class correlation

coefficient, ICC = 0.978, RMSE = 2.3 mm) and dynamic situations (ICC = 0.992, RMSE = 2.3 mm) (Barisch-Fritz et al., 2014). Mean values of three dynamic trials were used for calculating foot extension and walking advance. Foot extension was found for MBL but was not visible regarding the entire FL. The reason was that FL can only be observed during a short phase as several participants flatten their toes very lately. Regarding the roll-over process, most of body weight is already shifted to the forefoot when the toes touch the ground. Thus, it can be assumed that no additional extension takes place and MBL is representative for foot extension (Barisch-Fritz et al., 2014).

A multiple linear regression analysis was calculated to identify the influences of gender, FL (most posterior point of the heel and most anterior point of the longest toe in static condition), and BMI-percentile on TA (normalized to FL). The statistical analysis was performed using the software JMP (v 10.0.2, SAS, Cary, NC, USA).

Calculation of TA

The individual-required TA is presented as the sum of three components: foot extension, walking advance, and growth rate. Foot extension was defined as the difference in MBL between maximum during walking ($\text{Dyn}_{\max}$) and static HWB of MBL. $\text{Dyn}_{\max}$ was determined during the stance phase when body weight was shifted over the standing foot and thus most extension was expected. This phase was manually defined, with the start when MTH1 strikes and the end when heel takes off the ground (see Figure 1) (Blanc, Balmer, Landis, & Vingerhoets, 1999). MTH1 strike was standardized as full contact of MTH1 and heel take-off as second frame of rising when the heel was no longer completely loaded. Within this phase, $\text{Dyn}_{\max}$ was extracted and the difference to static HWB was taken as the relevant extension for TA.

Walking advance was defined as movement of the most anterior point of the toes in walking direction. This was determined within a certain phase: starting with heel take-off and ending when MTH1 lifts off the ground (see Figure 1). The starting position of the most anterior point of the toes was set to zero and the maximum positive movement was extracted.

Growth rate was calculated by cross-sectional analysis of the present sample. The difference of FL in HWB from one age to the other was calculated for each gender. The semi-annual growth rate is presented by half of this value (see Table 3). The assignment of the respective growth rate was done according to the age of each participant.

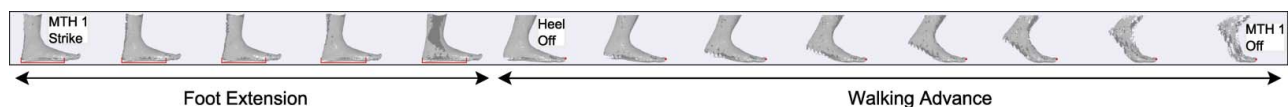


Figure 1. Example of a rollover process.

Table 2. Characteristics of the sample. Mean and standard deviation (SD) of anthropometric variables for different age groups and the whole sample.

Age (years)	N	Gender	Body height (m)	Body weight (kg)	BMI-percentile	Foot length (mm)
6	72	f: 35; m: 37	1.20 (0.05)	22.8 (3.6)	50.8 (28.2)	192.3 (10.5)
7	177	f: 88; m: 89	1.25 (0.06)	25.3 (5.0)	53.2 (27.8)	197.7 (12.4)
8	212	f: 111; m: 101	1.30 (0.06)	28.6 (5.7)	56.2 (27.0)	207.7 (12.0)
9	250	f: 117; m: 133	1.36 (0.06)	31.7 (6.1)	52.3 (28.4)	216.6 (11.1)
10	276	f: 144; m: 132	1.41 (0.07)	34.8 (8.0)	49.9 (29.7)	223.2 (12.6)
11	281	f: 156; m: 125	1.48 (0.07)	39.5 (8.9)	49.7 (29.7)	232.7 (13.8)
12	232	f: 105; m: 127	1.54 (0.08)	45.7 (10.9)	54.3 (30.0)	240.7 (13.5)
13	211	f: 116; m: 95	1.60 (0.08)	50.5 (13.2)	51.6 (30.8)	248.1 (14.9)
14	151	f: 81; m: 70	1.64 (0.08)	55.1 (12.5)	52.7 (29.8)	250.4 (15.5)
15	65	f: 33; m: 32	1.68 (0.10)	59.0 (11.8)	53.4 (27.4)	254.1 (17.6)
16	39	f: 22; m: 17	1.67 (0.09)	61.0 (13.8)	55.7 (30.0)	253.2 (17.7)
6–16	1966	f: 1008; m: 958	1.45 (15.3)	39.0 (13.8)	52.3 (29.1)	227.1 (22.6)

Note: N = number of participants; f = female participants; m = male participants; standard deviation is presented in brackets.

TA was normalized to FL for the examination of the influences on TA. This normalized value is called relative TA (i.e. relative TA = TA/FL).

Table 3. Annual and semi-annual growth rate calculated for male and female participants (cross-sectional analysis).

Age (years)	<i>N</i>	FL		Mean growth rate	
		Mean (mm)	(SD) (mm)	Annual (mm/year)	Semi-annual (mm/6 months)
Female participants (<i>n</i> = 1173)					
6	35	190.1	(10.7)	5.8	2.9
7	102	195.9	(12.4)	9.9	5.0
8	124	205.8	(11.9)	8.3	4.2
9	140	214.2	(11.6)	6.9	3.4
10	165	221.0	(13.0)	8.3	4.2
11	185	229.4	(12.8)	6.3	3.1
12	133	235.7	(11.9)	6.6	3.3
13	128	242.3	(11.5)	−0.3	−0.1
14	93	242.0	(11.4)	2.8	1.4
15	44	244.8	(9.8)	−1.6	−0.8
16	24	243.2	(13.4)		
Male participants (<i>n</i> = 1140)					
6	41	194.3	(9.7)	4.9	2.5
7	115	199.2	(12.7)	11.2	5.6
8	119	210.4	(12.1)	7.4	3.7
9	149	217.8	(11.0)	6.9	3.5
10	150	224.7	(11.9)	11.2	5.6
11	160	235.9	(13.4)	8.0	4.0
12	143	243.9	(13.3)	10.2	5.1
13	120	254.1	(15.8)	5.3	2.6
14	82	259.4	(13.4)	7.3	3.6
15	40	266.6	(17.5)	−2.5	−1.3
16	21	264.1	(15.8)		

Note: N = number of participants; FL = foot length; SD = standard deviation.

Results

The individually required TA was calculated for 1966 participants, aged between 6 and 16 years. Table 2 presents the characteristics of the sample.

Results of growth rate, foot extension, and walking advance

Table 3 presents the annual and semi-annual growth rate for male and female participants. FL of boys did not increase after the age of 15 years, of girls after the age of 13 years. FL of boys aged 6–14 years increased semi-annually from 2.5 to 5.6 mm. FL of girls aged 6–12 years increased semi-annually from 2.9 to 5.0 mm. Highest growth rate of boys and girls was found between 7 and 8 years and also of boys between 10 and 12 years.

Mean values of foot extension varied between −2.5 and 1.6 mm for female participants and −0.8 and 2.2 mm for male participants. Standard deviation (SD) of foot extension was high for all groups and both genders ranging from 1.7 to 7.5. Mean values of walking advance ranged from 1.4 to 2.0 mm for female and 0.6 to 1.9 mm for male participants. SD was lower for walking advance compared to foot extension, ranging from 0.3 to 1.7 (Table 4).

Calculation of TA

Table 4 presents the amount of required TA for several fields of FL. The fields of FL were based on the increment of 6.67 mm of the EU sizing system. Mean values and SD as well as 90th percentiles of foot extension, walking advance, growth rate, and TA were calculated for each gender. Mean values and SD of TA were 5.0 (3.7) mm for female and 6.9 (3.8) mm for male participants. The 90th

Table 4. Calculation of toe allowance (TA) for each field of foot length (FL).

FL (mm)	N	Foot extension		Walking advance		Growth rate		Toe allowance (TA)		
		Mean (SD)	90th percentile	Mean (SD)	90th percentile	Mean (SD)	90th percentile	Mean (SD)	90th percentile	
(mm)		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
Female participants										
171.0–177.6	6	−2.5 (7.5)	2.9	1.6 (0.3)	1.8	4.0 (1.5)	5.0	3.1 (9.3)	9.7	
177.6–184.2	20	0.1 (2.6)	4.4	1.6 (0.9)	2.6	4.3 (1.0)	5.0	5.9 (2.8)	9.8	
184.2–190.9	38	0.5 (3.1)	4.8	1.7 (1.1)	3.3	4.0 (0.9)	5.0	6.2 (3.6)	11.4	
190.9–197.5	50	0.2 (2.9)	4.2	1.5 (1.0)	3.0	4.3 (0.8)	5.0	6.0 (3.1)	9.7	
197.5–204.2	67	0.4 (3.4)	4.0	1.6 (1.1)	3.1	4.1 (0.7)	5.0	6.1 (3.7)	10.0	
204.2–210.9	75	0.3 (2.8)	3.8	1.4 (0.9)	2.4	4.0 (0.6)	5.0	5.7 (3.0)	9.4	
210.9–217.5	106	0.9 (2.9)	5.1	1.5 (1.2)	3.2	3.8 (0.7)	4.2	6.2 (3.3)	11.0	
217.5–224.2	134	0.7 (3.2)	4.5	1.5 (1.2)	2.9	3.4 (1.2)	4.2	5.6 (3.8)	10.6	
224.2–230.9	105	0.7 (2.7)	4.1	1.4 (1.1)	2.6	2.7 (1.5)	4.2	4.8 (3.1)	8.9	
230.9–237.5	135	0.7 (3.5)	4.4	1.5 (1.3)	3.0	2.0 (1.7)	4.2	4.1 (4.1)	8.9	
237.5–244.2	100	1.1 (2.8)	4.8	1.5 (1.0)	2.8	1.7 (1.7)	3.4	4.3 (3.2)	9.0	
244.2–250.9	88	0.7 (3.1)	4.8	1.3 (1.0)	2.6	1.4 (1.7)	3.2	3.3 (3.8)	8.3	
250.9–257.5	54	1.6 (3.3)	6.0	2.0 (1.7)	4.0	1.1 (1.6)	3.2	4.7 (4.2)	11.5	
257.5–264.2	20	1.0 (2.2)	3.8	1.4 (0.9)	2.8	0.8 (1.4)	3.2	3.2 (2.2)	6.3	
264.2–270.9	10	1.6 (5.3)	8.5	1.6 (1.0)	2.6	0.4 (1.2)	3.1	3.6 (5.2)	11.1	
Male participants										
171.0–177.6	10	1.2 (3.1)	6.3	1.2 (0.7)	2.7	5.2 (1.2)	5.6	7.6 (3.3)	13.0	
177.6–184.2	6	1.6 (1.7)	3.5	1.6 (0.6)	2.3	4.3 (1.5)	5.6	7.4 (1.8)	10.0	
184.2–190.9	22	2.2 (4.3)	6.1	1.6 (1.1)	3.2	4.0 (1.7)	5.6	7.8 (4.5)	11.9	
190.9–197.5	41	0.9 (3.8)	4.8	1.6 (1.0)	2.7	4.6 (1.3)	5.6	7.0 (4.0)	11.0	
197.5–204.2	69	1.2 (3.1)	5.2	1.9 (1.3)	3.7	4.2 (1.2)	5.6	7.3 (3.4)	11.8	
204.2–210.9	79	1.3 (2.7)	5.3	1.7 (1.1)	3.1	4.3 (1.0)	5.6	7.3 (3.1)	12.1	
210.9–217.5	86	1.1 (3.2)	5.4	1.7 (1.0)	3.2	4.1 (0.9)	5.6	6.9 (3.7)	11.5	
217.5–224.2	92	1.5 (3.1)	5.2	1.8 (1.3)	3.6	4.4 (1.0)	5.6	7.7 (3.3)	12.2	
224.2–230.9	89	1.0 (3.2)	5.0	1.8 (1.2)	3.7	4.3 (0.9)	5.6	7.2 (3.5)	11.3	
230.9–237.5	97	0.9 (3.0)	4.6	1.6 (1.0)	2.6	4.5 (1.0)	5.6	7.0 (3.3)	10.9	
237.5–244.2	89	1.4 (3.4)	6.1	1.6 (1.5)	3.3	4.4 (1.0)	5.6	7.4 (4.1)	13.2	
244.2–250.9	64	1.0 (3.7)	5.4	1.7 (1.5)	3.1	3.8 (1.3)	5.1	6.5 (4.1)	10.8	
250.9–257.5	59	1.1 (3.2)	5.1	1.7 (1.5)	4.3	3.7 (1.5)	5.1	6.4 (4.2)	11.5	
257.5–264.2	46	1.1 (3.1)	5.3	1.8 (1.3)	3.2	3.3 (1.7)	5.1	6.1 (4.0)	11.7	
264.2–270.9	53	0.6 (3.7)	4.6	1.6 (1.1)	2.9	2.7 (1.7)	5.1	4.9 (4.3)	9.7	
270.9–277.5	36	2.2 (3.9)	7.1	1.6 (1.4)	3.3	2.3 (1.7)	4.1	6.1 (4.5)	11.3	
277.5–284.1	12	1.6 (4.5)	10.7	1.9 (1.2)	4.1	2.0 (2.0)	4.8	5.5 (4.8)	13.3	
284.1–290.7	8	−0.8 (3.7)	5.8	1.1 (1.0)	3.4	1.4 (1.6)	3.6	1.7 (4.6)	9.4	
All participants ($n = 1966$)										
Female	1008	0.7 (3.1)	4.4	1.5 (1.2)	2.9	2.8 (1.7)	4.2	5.0 (3.7)	9.8	
Male	958	1.2 (3.3)	5.1	1.7 (1.2)	3.2	4.0 (1.4)	5.6	6.9 (3.8)	11.5	

Note: FL = foot length, presented in a field based on the EU increment 6.67 mm, defined as $\geq \text{value} \times 1$ to $< \text{value} \times 2$; SD = standard deviation

percentile of TA was 9.8 mm for female and 11.5 mm for male participants.

final model can explain 15% of ($R^2 = 0.15$) of the variance of relative TA.

The regression function was

$$Y = 8.31 + -0.45X_1 + -0.03X_2 + 0.002X_3$$

Influences on TA

The multiple linear regression analysis for the prediction of the relative TA (Y) was based on the explanatory variables gender (X_1), FL (X_2), and BMI-percentile (X_3). The

Results of the model are presented in Table 5. The variables gender and FL were statistically significant in this

Table 5. Influences on the relative TA (multiple regression analysis).

Variable	Coefficient (β)	Standard error	95% CI	F-ratio	P
Intercept	8.31	0.37	7.58–9.05	22.23	>0.001
Gender	−0.45	0.04	−0.52 to −0.38	−12.17	>0.001
FL	−0.03	0	−0.03 to −0.02	−15.19	>0.001
BMI-percentile	0	0	−0 to 0	1.82	0.069

Note: FL = foot length; CI = confidence interval; F-ratio = F-statistic for testing that the effect is zero.; P = P-value for the effect test (JMP 10.0.2, SAS, Cary, NC, USA).

model. Figure 2 presents relative TA plotted against FL, including fitted regression functions of male and female participants.

Discussion

Calculated TA compared to the rules-of-thumb

The objective of this study was to calculate TA based on three components. Mean values of TA were smaller than values of the rules-of-thumb. Consequently, 90th percentiles were recommended for the applicable amount of TA. The fact that mean values are not appropriate to determine the amount of TA has been discussed before in the field of fit improvement (Harrison & Robinette, 2005). Several alternative methods can be found, for example fit mapping (Harrison & Robinette, 2005) or a cluster analysis (Mauch, Grau, Krauss, Maiwald, & Horstmann, 2009). Insufficient inner shoe length can negatively affect developing feet (Klein et al., 2009). Thus, the use of 90th percentiles instead

of mean value implies that 90% of the present sample needs less space in front of the toes than this threshold.

The 90th percentile was 9.8 mm for female and 11.5 mm for male participants. Comparing calculated TA to the ‘rule-of-the-parent’s-thumb’, it can be concluded that required TA is smaller than previously assumed. Thus, an average thumb width must be considered. In several countries, adult’s thumb widths have always been used as a unit of measure and have been approximated as one inch (25.4 mm) (Kramers & van Haeringen, 1974). In times of touch screen displays, thumb width is once again important. The ideal width of a target on the touch screen (72 pixels) also agrees with 25.4 mm (Dandekar, Raju, & Srinivasan, 2003). Anthropometric studies have found that males’ thumb widths range from 11 to 27 mm and females’ from 10 to 24 mm (Georgia Tech, 2007). Thus, only the minimum values agree with the empirical findings of TA.

The conclusion of the second rule-of-thumb, based on footprint analysis, that at least 12 mm TA is needed (Maier, 1966, 1990), approaches the 90th percentile thresholds. However, the calculated 90th percentiles of TA cover the individual-needed TA of 90 percent of participants. These values are smaller than 12 mm as recommended by Maier. Thus, 12 mm might be a generous value of TA and not a minimum amount as stated (Maier, 1966, 1990).

The 90th percentiles of TA differ for each field of FL. This has also been assumed by the third rule-of-thumb, which is that 5% of FL is appropriate for TA (Stracker, 1966). The present findings do not confirm that longer feet need more space in front of the toes. The opposite is the case, showed by negative β -value of FL within multiple regression analysis. The reason that longer feet do not need more TA is that walking advance and foot extension were comparable within all fields of FL, but growth rate decreased. For the same reason, there is no agreement of the present findings with the forth rule-of-thumb. This rule-of-thumb is that TA should be half of the EU shoes size in mm (Maier, 1966, 1990), which also implies higher values of TA for longer feet.

Influences on TA

The aim to evaluate influences on relative TA showed that only 15% of variance was explained by gender and FL. The amount of TA was smaller for female participants.

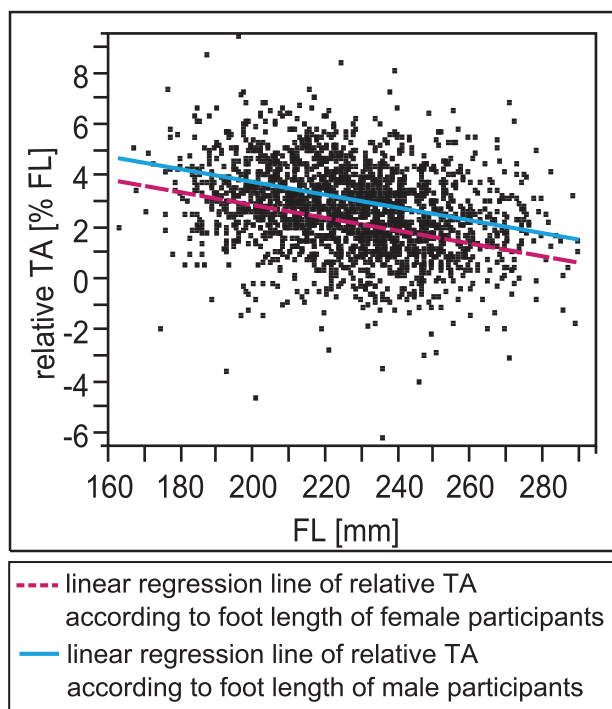


Figure 2. Relationship between gender, FL, and relative TA.

Furthermore, less TA is needed with increasing FL, due to the decrease of growth rate. This rejects the rules-of-thumb of Stracker (1966) and Maier (1966, 1990). Moreover, the significant influence of FL is not practically relevant (see Figure 2). The significance is probably caused by the large sample size n . It can be speculated that there are other variables that additionally explain variance within TA. Several dependencies have been mentioned, e.g. characteristics of ligaments, muscle tone, and foot type. These relationships should be examined in further studies to improve the prediction of TA.

Critical considerations

Generally, calculated TA must be critically considered as it should not be interpreted as a legitimization to further shorten the forefoot of shoes. This is often the case for female footwear due to fashion trends and visual reduction of shoe length. Furthermore, the three components of TA must be individually considered to understand the amount of TA.

First, foot extension is determined by differences between standing and the maximum during walking. Foot extension was small and for some instances negative which means that FL is smaller during walking than while standing. It can only be speculated that muscle contractions, which have been studied during walking (Gefen, Megido-Ravid, Itzhak, & Arcan, 2000; Scott & Winter, 1993), are responsible for this 'shortening.' The contractions can restrict the flattening of the medial longitudinal arch which might be linked to foot type. Furthermore, the amount of error (RMSE) due to visual definition of MBL affects the findings, even if ICC is very high.

Second, walking advance also influences the amount of TA. The definition of walking advance varies from others that describe the movement of the foot within the shoe (Rossi & Tennant, 2011). Values for motion within the shoes used in footwear industry range from 4.23 mm (EU) to 6 mm (Austro-Point) up to 9 mm Mehr-Weiten-System [more widths system for children's shoes in Germany], WMS) (Rossi & Tennant, 2011). In this study, walking advance was calculated while walking over a glass plate where adherence friction is high. The relative motion within the shoe might be higher. Values for the relative motion within the shoe have only been analysed with respect to intrinsic kinematics of the foot (Arndt et al., 2007; Nester et al., 2007). No general data is available for this relative motion as it depends on the overall shoe fit. Nevertheless, a shoe should be designed with the aim of minimal relative motion by improving the overall fit of the shoe and thus the hold of the foot. The reduction of the relative motion to values of walking advance, calculated within this study, can contribute to reduced friction and reduced long-time effects of shoes, like callosity of deformities (Grünewald, 2002; Rossi & Tennant, 2011).

Third, growth rate was cross-sectionally collected and calculated for half a year. This possibly does not reflect the individual growth rate. Even if the obtained results are similar to results of the study of Cheng et al. (1997), they must be regarded with caution. Furthermore, shoes are often worn longer than half a year. When addressing correct fit (e.g. flex line), it is very challenging to design a shoe for a longer period. As a consequence, the foot should be measured regularly to determine whether it still fits in the shoe.

Conclusion

This study primarily presents empirical data of TA, based on 3D scans and applicable thresholds, based on 90th percentiles. TA was smaller than all rules-of-thumb and no significant influence of FL and gender could be found. These findings are important for manufacturers to improve daily footwear for general developing feet. To implement the findings, it is imperative that the following points are considered:

- (1) TA does not significantly increase with increasing FL. Thus, TA is identical for all shoe sizes in developing feet. This finding results from the increased growth rate in smaller feet and a tendency of increasing foot extension in longer feet.
- (2) TA does not significantly differ between the genders. Thus, no individual grading for boys and girls is needed.
- (3) The finding of this study is that TA is smaller than previously assumed. This fact does not permit a simple shortening of the forefoot or toe box. Rather, the findings can help to improve the construction of lasting boards and shoe lasts to the effect of an improved positioning of the flex line within children shoes.
For this reason, MBL and in particular the ranges of MBL are very important to provide children's feet (also feet with longer toe length relative to their instep length) with a proper flex line and sufficient TA.
- (4) The findings can only be implemented if the overall fit of shoes will be reconsidered. Thus, a shorter TA is solely practicable for shoes with appropriate lacings to ensure that the foot within the shoe will not slide forward and permanently harm the foot.
- (5) A manually triggering of the toes can only be avoided by sufficient height of the space in front of the toes (TA). Thus, TA must be considered as an additional length with sufficient height to allow toe height.

Furthermore, the findings give parents when buying children's shoes the assurance that one thumb width is enough space in front of the toes. However, two concerns

must be considered: First, the amount of TA depends on the overall shoe fit. Second, parents' thumb widths vary and do not provide information about overall shoe fit. In general, this study provides suggestions for standardizing TA for developing feet.

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