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Prediction of Anthropometric Foot Characteristics in Children

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Background: The establishment of growth reference values is needed in pediatric practice where pathologic conditions can have a detrimental effect on the growth and development of the pediatric foot. This study aims to use multiple regression to evaluate the effects of multiple predictor variables (height, age, body mass, and gender) on anthropometric characteristics of the peripubescent foot.

Methods: Two hundred children aged 9 to 12 years were recruited, and three anthropometric measurements of the pediatric foot were recorded (foot length, forefoot width, and navicular height).

Results: Multiple regression analysis was conducted, and coefficients for gender, height, and body mass all had significant relationships for the prediction of forefoot width and foot length ($P \leq .05$, $r \geq 0.7$). The coefficients for gender and body mass were not significant for the prediction of navicular height ($P \geq .05$), whereas height was ($P \leq .05$).

Conclusions: Normative growth reference values and prognostic regression equations are presented for the peripubescent foot. (J Am Podiatr Med Assoc 99(6): 497-502, 2009)

The anatomical, physiologic, and functional development of the lower limb and foot in utero and postpartum is well documented.[1-3] The growth and development of the foot in the child is genetically determined but can be affected by a variety of factors, for example, faulty intrauterine morphogenesis may be responsible for foot deformity and disability.[3] In addition, it is known that genetic predisposition, environmental conditions, and time affect the growth and development of the foot.[4] For clinicians involved in the management of the child's foot, it is of utmost importance to monitor the growth and development of the foot and to be aware that the growth of the foot is "synchronized" with the body and not with the leg.[5]

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It is recognized that 50% of the final length of the foot has been achieved by 12 to 18 months of age[6]; this milestone has been recorded by 12 months in girls and by 18 months in boys.[7] The growth rate of the pediatric foot is evidently high during infancy (≤1 year old) and drops rapidly until approximately 5 years of age; after this, the average increase in foot length is 0.9 cm per year for girls aged 5 to 12 years and for boys aged 5 to 14 years.[8] In contrast, it has been reported that a child's foot will grow in spurts and that these spurts do not occur at the same age for all children.[9] Although this is rather spurious, it is clear that the length and width of the pediatric foot increase linearly from the age of 3 years until 12 years in girls and from 3 years to 15 years in boys.[10] Normative growth reference figures based on current trends for the developing child have recently emerged[11]; however, there are no such values for the peripubescent child. Those that are published are rather dated and, therefore, do not consider the effect of modern disease or environmental factors on the growth and development of the foot; figures were published in 1956 for foot length[7] and in 1974 for forefoot width.[12] Owing to the age of these data, they are of questionable validity because changes in disease and modern health care will have a varying impact on musculoskeletal development. Revised reference values are required to reflect any changes in the health of the child's feet and the impact of modern health concerns on this. For example, anthropometric variances in foot structure between obese and nonobese children have been observed,[13] and these variances have serious implications for footwear fitting and for the biomechanics of foot function.

This study presents a database of growth reference values for anthropometric characteristics of the peripubescent foot. It also aims to use multiple regression to formulate regression equations that can be used by clinicians to quantify the anthropometric characteristics of the foot. The clinical application of these equations are further discussed.

Materials and Methods

A research protocol was initially submitted to the Glasgow City Council and an ethics application to Glasgow Caledonian University, School of Health and Social Care Ethics Committee. The Glasgow City Council granted approval for the researcher to contact primary schools in the Glasgow postal area, and Glasgow Caledonian University granted ethical approval for the research. Further permission was gained from head teachers willing to participate in the study.

SPSS version 11.5 (SPSS Inc, Chicago, Illinois) was used to randomly select 40 of the 197 schools listed in the Glasgow postal area. Invitation letters and consent forms were sent to the 40 randomly selected schools; eight agreed to participate. Information sheets and consent forms were distributed to all children aged 9 to 12 years. All children who returned a signed consent form were invited to participate. This study was cross-sectional and descriptive in design.

All equipment used was calibrated before use, and the measurement of navicular height has previously been shown to be reliable.[14] The lead researcher (S.C.M.) was responsible for taking and recording all of the values.

Height Measurement

A portable stadiometer (Leicester Height Measure; Seca Ltd, Birmingham, United Kingdom) was used to measure height, and the measurement was conducted in accordance with the method suggested by the National Center for Chronic Disease Prevention and Health Promotion.[15] Each child was asked to stand erect with his or her feet together and shoulders level. The four contact points (head, back, buttocks, and heels) were maintained during measurement. The head was positioned in the Frankfurt plane by the researcher, and the sliding bar was then lowered onto the crown of the head. Height was measured to the nearest millimeter, and the researcher noted the reading.

Body Mass

Manual Seca scales were used to measure body mass in kilograms. The participants were measured while wearing their school uniform, which tended to consist of trousers or skirt and t-shirt or blouse.

Foot Length Weightbearing

While barefoot, each participant was guided onto a footboard. They were instructed to place each heel at the back of the board, and foot length was measured during weightbearing in millimeters and was later converted to centimeters.

Forefoot Width Weightbearing

Forefoot width during weightbearing was measured with the participant standing in the resting calcaneal stance position. Forefoot width was defined as the distance between the most medial prominence of the first metatarsophalangeal head and the most lateral prominence of the fifth metatarsophalangeal joint. A pair of calipers was used to measure the distance between these reference points.

Navicular Height

Navicular height was measured with each participant in the resting calcaneal stance position. The most prominent medial aspect of the tuberosity was palpated and was marked with a pen. The distance between the most prominent medial aspect of the navicular tuberosity and the ground was measured with a ruler. Navicular height was noted as the distance between the navicular tuberosity and the ground measured in centimeters.

Results

Two hundred children aged 9 to 12 years (mean ± SD, 10.2 ± 0.8 years) were recruited. Of the 200 children recruited, 110 were girls, with a mean ± SD height of 142.9 ± 9.1 cm and body mass of 39.8 ± 10.4 kg. Ninety participants were boys, with a mean ± SD height of 142.8 ± 8.3 cm and body mass of 40.1 ± 10.1 kg.

Table 1 provides normative data for the sample regarding foot length for boys and girls. Foot length seems to be similar between both genders at 9 years of

Table 1. Foot Length by Age and Gender

		Foot Length (cm)											
		Girls						Boys					
Age (y)	Foot	No.	Mean	SD	Max	Min	Range	No.	Mean	SD	Max	Min	Range
9	L	27	21.4	1.4	23.8	18.9	4.9	14	21.4	1.2	23.6	19.4	4.2
	R	27	21.4	1.3	23.4	18.8	4.6	14	21.3	1.2	23.6	19.4	4.2
10	L	45	21.9	1.3	24.8	18.6	6.2	33	22.1	1.3	25.5	20.0	5.5
	R	45	21.9	1.3	24.0	18.0	6.0	33	22.0	1.3	25.5	19.8	5.7
11	L	31	22.8	1.1	25.0	20.8	4.2	32	23.1	1.2	25.4	20.2	5.2
	R	31	22.8	1.2	25.2	20.8	4.4	32	23.1	1.2	25.2	20.6	4.6
12	L	7	23.0	1.1	24.8	21.8	3.0	11	23.4	1.1	25.5	22.0	3.5
	R	7	23.2	1.3	25.0	21.8	3.2	11	23.4	1.2	25.5	21.8	3.7

Abbreviations: L, left; Max, maximum; Min, minimum; R, right.

age. A gender dimorphism is evident at approximately 11 years of age, with boys having marginally larger feet.

Table 2 provides normative reference values for forefoot width. At 9 years of age, girls have a marginally greater forefoot width (8.1 cm) compared with their male counterparts (7.9 cm). Yet, from the ages of 10 to 12 years, boys have a greater forefoot width (8.5 to 9.0 cm versus 8.2 to 8.9 cm), which is increasingly evident at 12 years of age. Reference information for navicular height is presented in Table 3. Navicular height can be seen to increase with age in girls (3.6 to 4.2 cm). Again, a gender dimorphism is evident whereby this increases throughout the years for girls but decreases at 12 years of age for boys.

Table 2. Forefoot Width by Age and Gender

		Forefoot Width (cm)											
		Girls						Boys					
Age (y)	Foot	No.	Mean	SD	Max	Min	Range	No.	Mean	SD	Max	Min	Range
9	L	27	8.0	0.5	9.0	7.1	1.9	14	7.8	0.5	9.0	7.2	1.8
	R	27	8.1	0.5	9.3	7.3	2.0	14	7.9	0.5	8.7	6.8	1.9
10	L	45	8.2	0.5	9.4	7.1	2.3	33	8.5	0.5	9.8	7.6	2.2
	R	45	8.3	0.5	9.4	7.3	2.1	33	8.5	0.5	9.9	7.4	2.5
11	L	31	8.5	0.5	9.6	7.5	2.1	32	8.6	0.5	9.9	7.6	2.3
	R	31	8.5	0.5	9.6	7.6	2.0	32	8.7	0.5	9.6	7.4	2.2
12	L	7	8.7	0.3	9.2	8.3	0.9	11	8.8	0.6	10.0	8.2	1.8
	R	7	8.9	0.3	9.4	8.6	0.8	11	9.0	0.6	10.0	8.1	1.9

Abbreviations: L, left; Max, maximum; Min, minimum; R, right.

Table 3. Navicular Height by Age and Gender

		Navicular Height (cm)											
		Girls						Boys					
Age (y)	Foot	No.	Mean	SD	Max	Min	Range	No.	Mean	SD	Max	Min	Range
9	L	27	3.6	0.5	4.4	2.4	2.0	14	3.9	0.6	5.3	2.8	2.5
	R	27	3.6	0.5	4.9	2.6	2.3	14	4.0	0.5	5.3	3.2	2.1
10	L	45	3.9	0.6	5.4	2.8	2.6	33	3.9	0.5	5.1	2.9	2.2
	R	45	3.9	0.6	5.2	2.9	2.3	33	4.0	0.5	5.1	3.0	2.1
11	L	31	4.0	0.6	5.6	3.0	2.6	32	4.1	0.5	5.4	3.2	2.2
	R	31	4.0	0.6	5.4	3.0	2.4	32	4.1	0.5	5.7	3.2	2.5
12	L	7	4.3	0.4	4.9	3.5	1.4	11	3.9	0.4	4.7	3.4	1.3
	R	7	4.2	0.5	4.8	3.5	1.3	11	3.8	0.57	4.7	2.8	1.9

Abbreviations: L, left; Max, maximum; Min, minimum; R, right.

After descriptive analysis of the data, multiple regression analysis was conducted. Multiple regression analysis is often used as a prognostic form of analysis that, in this case, allows for the prediction of anthropometric foot characteristics based on a set of identified variables (ie, height, body mass, and gender).[16, 17] The initial stages of this analysis involved regression analysis. This was conducted to determine whether there was any significance in the relationship between independent variables (height, weight, gender, and age) and the dependent variables (foot length, forefoot width, and navicular height). After this, it was determined that the coefficients for gender, height, and body mass all had significant ($P \leq .05$) relationships ($r \geq 0.7$) for the prediction of forefoot width and foot length. The coefficients for gender and body mass were not significant for the prediction of navicular height ($P \geq .05$); as expected, height was ($P \leq .05$).

The calculation of multiple regression formulae requires the use of a statistics package (SPSS version 15.0). In addition, all of the data were entered, stored, and analyzed using SPSS version 15.0. Multiple regression analysis is an extension of linear regression.[15] Linear regression looks at the relationship between two related variables (independent and dependent), and the analysis of these is based on the following equation[16]:

(1) $\hat{Y} = a + bX$

Using multiple regression analysis, the effects of multiple predictor variables are being analyzed; this is opposed to the one predictor variable in linear regression. The multiple regression equation is thus[16]:

(2) $\hat{Y} = a + b_1X_1 + b_2X_2 + b_3X_3$

where $\hat{Y}$ indicates the dependent variable; a, the regression constant; and $b_{1, 2, 3}$, the regression coefficient for the independent variable.

Discussion

This study was conducted to establish growth reference values for the peripubescent foot and considered foot length, forefoot width, and navicular height. The results for the complete sample indicate that from the ages of 10 to 12 years, boys tend to have a greater foot length than girls (Tables 1–3). It can also be observed that the growth in foot length increases between the ages of 9 and 12 years and continues to increase throughout this age span, which concurs with an earlier reported work.[9] This work also concurs with that of Blais et al,[7] who reported that at 12 years of age, the average length of the foot is similar for girls versus boys (23.2 versus 23.5 cm). In this study, the average foot length at 12 years of age is 23.1 cm for girls and 23.4 cm for boys.

Gould et al[9] indicated that boys have, on average, a wider forefoot width than girls. This work shows that girls have a wider forefoot at 9 years of age but that boys tend to have a greater width between the ages of 10 and 12 years. At 9 years of age, girls have a marginally greater forefoot width (8.1 cm) compared with their male counterparts (7.9 cm). Yet, from the ages of 10 to 12 years, males have a greater forefoot width (8.5 to 9 cm versus 8.2 to 8.9 cm), which is increasingly evident at 12 years of age.

With navicular height (Table 3), a difference between the genders was detected. At 9 years of age, boys have a higher navicular height than girls by approximately 0.4 cm. There is no obvious difference at the age of 10 years; boys have a marginally higher navicular height at 11 years of age, and girls have a higher navicular height at 12 years of age. This gender dimorphism may be explained by patterns of growth and maturation and changes in foot posture. Foot growth is related to the growth of the body and not of the leg.[5] Thus, at approximately 12 years of age, girls have their peak growth spurt,[17] and, therefore, it is postulated that foot posture changes in response to physical development. Boys are not reported to have their peak growth spurt until approximately 14 years of age,[18] and it may be expected that at this time, navicular height would increase. However, because there were no boys older than 12 years recruited into the study, this theory cannot be further verified.

Multiple regression equations are given in Table 4, and these allow for the prediction of a child's foot length, forefoot width, and navicular height when other factors are known (ie, height, age, and weight). In the literature, to our knowledge, there are no formulated predictive equations available for foot length, forefoot width, or navicular height in children. Centile charts for foot length[7] and forefoot width[12] are available but are dated and may not reflect the impact of modern concerns in pediatric medicine; for example, evidence indicates that childhood obesity affects the anthropometric characteristics of the pediatric foot.[13] However, it is worth stating that predicted foot size and forefoot width derived from the equations are relatively similar to the data proposed by previous authors. Nevertheless, with developments in modern medical care, it is necessary to update these reference figures to accurately reflect the anthropometric structure of the pediatric foot.

The factors that affect the growth and development of the pediatric foot can be multifactorial and are not completely understood. Multiple regression offers the clinician and the researcher a statistical

Table 4. Multiple Regression Formulae for Anthropometric Foot Measures

Dependent Variable	Regression Formula
Foot length weightbearing (L foot)	6.14 + (0.39 × gender [f = 0, m = 1]) + (0.11 × height [cm]) + (0.03 × weight [kg])
Foot length weightbearing (R foot)	6 + (0.34 × gender [f = 0, m = 1]) + (0.11 × height [cm]) + (0.03 × weight [kg])
Forefoot width weightbearing (L foot)	4.11 + (0.190 × gender [f = 0, m = 1]) + (0.022 × height [cm]) + (0.026 × weight [kg])
Forefoot width weightbearing (R foot)	4.63 + (0.166 × gender [f = 0, m = 1]) + (0.014 × height [cm]) + (0.028 × weight [kg])
Navicular height (L foot)	−1.12 + (0.04 × height [cm])
Navicular height (R foot)	−0.52 + (0.04 × height [cm])

Abbreviations: f, female; L, left; m, male; R, right.

method in which clinical phenomena can be further understood. In this case, multiple regression equations have been developed to allow for the prediction of foot characteristics based on growth anthropometrics. These reference equations could be used in the clinical assessment of the child (see below) and could also be useful where surgical intervention is warranted, for example, if congenital foot abnormality is evident, resulting is unilateral anthropometric variance. Use of the predictive equations can also be applied in more routine practice.

Consider that you are involved in the multidisciplinary management of a 9-year-old boy diagnosed as having global developmental delay (height, 105 cm; body mass, 38 kg). During routine assessment, you become concerned that the child's foot is not within the expected limits for developmental age. How would you confirm this?

Following traditional methods, the first step would be to consult growth reference charts, which would provide an appropriate reference value for age. However, in pediatric practice, it is often necessary to consider the global development of the individual patient, and, following earlier regression analysis, one must consider all factors and their impact on foot development. Knowing the height, age, and body mass of the child, the proposed equations could be used to predict expected foot length (see the example below). The following equation would be used for foot length during weightbearing (Table 4):

(3) $6.14 + (0.39 \times \text{gender } [f = 0, m = 1]) + (0.11 \times \text{height [cm]}) + (0.03 \times \text{weight [kg]})$

The equation would translate as follows:

(4) $6.14 + (0.39 \times 1) + (0.11 \times 105) + (0.03 \times 38) = \text{Left foot length for age (cm)}$

(5) $6.14 + (0.39) + (11.55) + (1.14) = 19.2 \text{ cm}$

Consider that a patient was taking growth hormone and was concerned about the changes in foot size. If a physician was mapping growth hormone intake to changes in height and foot length, foot characteristics could be determined via substitution of the relevant values in the equation. This would provide a reference value based on the norms from the population to which the child could be compared.

It is acknowledged that the recruitment of 200 children in the research is relatively inconsequential when establishing a reference database, and further work is warranted. Future researchers may wish to look longitudinally at a larger sample size and increase the sample age range to further establish a reference database for the pediatric foot. Future research must consider the socioeconomic background of participants and the effect that it has on the growth and development of the foot. In addition, the effect of ethnicity on the growth and development of the foot would also provide interesting findings that are not currently available. Further work is required to validate the multiple regression equations established from this research.

Conclusions

It is obvious that there is relative agreement between authors related to the rates of growth in the foot across time and the relation to terminal length and width. However, robust up-to-date figures are required along with longitudinal evidence that includes older age groups. Navicular height is an important measure considering its relationship with foot abnormalities, and baseline values are urgently required. All measurements also need consideration across ethnic and socioeconomic groups. It is obvious that if robust predictions can be made, this will have an impact on the care plans devised by clinicians. These predictions will also be of interest to the footwear industry to predict growth trends in children and proactively develop appropriate footwear compared with being reactive to changes in foot size and shape across age ranges.

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References

1. Tax HR: *Podopediatrics*, 2nd Ed, p 88, Williams & Wilkins, Baltimore, MD, 1985.
2. Thomson P: *Introduction to Podopaediatrics*, WB Saunders Co Ltd, London, 1993.
3. Watt GF, Goel K, Wilcox DE, et al: "Paediatric Podiatry and Genetics," in *Neale's Disorders of the Foot*, 7th Ed, ed by D Lorimer, G French, M O'Donnell, et al, p 81, Churchill Livingstone, London, 2006.
4. Unger H, Rosenbaum D: Gender-specific differences of the foot during the first year of walking. Foot Ankle Int **25:** 582, 2004.
5. Beeson P, Nesbitt P: "The Paediatric Patient," in *Assessment of the Lower Limb*, 2nd Ed, ed by LM Merriman, W Turner, p 341, Churchill Livingstone, Edinburgh, 2002.
6. Bertsch C, Unger U, Wikelmann W, et al: Evaluation of early walking patterns from plantar pressure distribution measurements: first year results of 42 children. Gait Posture **19:** 235, 2004.
7. Blais MB, Green WT, Anderson M: Lengths of the growing foot. J Bone Joint Surg Am **38:** 998, 1956.
8. Tachdjian MO: *Pediatric Orthopaedics*, Vol 1, 2nd Ed, WB Saunders, Philadelphia, 1990.
9. Gould N, Moreland M, Trevino S, et al: Foot growth in children age one to five years. Foot Ankle **10:** 211, 1990.
10. Cheng JC, Leung SS, Leung AK, et al: Change of foot size with weightbearing: a study of 2829 children 3 to 18 years of age. Clin Orthop Relat Res **342:** 123, 1997.
11. Bosch K, Gerss J, Rosenbaum D: Preliminary normative values for foot loading parameters of the developing child. Gait Posture **26:** 238, 2007.
12. Malina RM, Hamill PVV, Lemeshow S: *Manual of Physical Status and Performance in Childhood*, Vol 1B, ed by AF Roche, RM Malina, Plenum Press, New York, 1973.
13. Morrison SC, Durward BR, Watt GF, et al: Anthropometric foot structure of peripubescent children with excessive versus normal body mass: a cross-sectional study. JAPMA **97:** 366, 2007.
14. Morrison SC, Durward BR, Watt GF, et al: The intrarater reliability of select measures conducted on the paediatric foot. The Foot **15:** 180, 2005.
15. National Center for Chronic Disease Prevention and Health Promotion. How to measure height (2002). Available at: http://www.cdc.gov/healthyweight/assessing/bmi/childrens_bmi/measuring_children.html#height. Accessed July 16, 2003.
16. Portney LG, Watkins MP: "Regression" in *Foundations of Clinical Research Applications to Practice*, p 590, Prentice Hall International (UK) Ltd, London, 1993.
17. Wittink DR: *The Application of Regression Analysis*, Prentice Hall International (UK) Ltd, London, 1988.
18. Kumar P, Clark M: "Endocrine Disease" in *Clinical Medicine*, 6th Ed, p 1051, Elsevier Saunders, London, 2003.