Foot arch development in Japanese preschool children: a cross-sectional study using three footprint-derived indices

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Research Article

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Abstract

Background:

Foot arch assessment in early childhood is challenging because of thick plantar fat pads and ongoing skeletal maturation. Conventional subjective methods have limited reliability, and existing quantitative methods are often impractical for young children. Reliable and accessible quantitative assessment tools are needed for pediatric rehabilitation.

Purpose:

To evaluate foot arch development using three footprint-derived indices—Clarke's angle (CA), Chippaux-Smirak Index (CSI), and Arch Index (AI)—and to clarify their age-related changes and distinct characteristics.

Methods:

This cross-sectional study included 37 children aged 2–6 years (74 feet) from a barefoot daycare center. Footprint images were captured using Foot Look and analyzed using ImageJ. After measurement reliability was established in 15 participants, Generalized Estimating Equations (GEE) were used to analyze relationships between age in months and each index while accounting for left-right foot correlation. Kruskal-Wallis tests were used to compare children younger than 48 months with those aged 48 months or older.

Results:

All three indices demonstrated excellent intra- and inter-rater reliability (ICC ≥ 0.93). GEE analysis revealed that CA significantly increased with age (Estimate = 0.348, $p < 0.001$), while CSI (Estimate = -0.622, $p < 0.001$) and AI (Estimate = -0.201, $p < 0.001$) significantly decreased with age. Functional indices changed 1.8 times faster than the morphological index. Significant differences were also found between the younger and older age groups for all three indices (all $p < 0.001$).

Conclusions:

Morphological (CA) and functional (CSI, AI) indices capture distinct aspects of foot arch development and reflect both structural and functional changes during early childhood. This multifaceted assessment method demonstrated excellent reliability and provides accessible quantitative tools, including regression equations for age-specific reference values, that may support longitudinal monitoring and intervention evaluation in pediatric rehabilitation.

Level of Evidence: Level III, cross-sectional study.

Introduction

Foot arch development progresses throughout childhood, with the prevalence of flatfoot decreasing during this time. Although the most pronounced development of the medial longitudinal arch occurs between approximately 3 and 6 years of age, maturation continues gradually through later childhood and early adolescence [1–5]. Foot structure and function also evolve during this period. In comparison to adults, children exhibit greater relative midfoot loading, reflecting the immature longitudinal arch and developing foot structure. With increasing age and walking experience, children's plantar pressure patterns gradually become more similar to those observed in adults [1,6]. Foot stability depends not only on passive structures but also on the intrinsic foot muscles and the "foot core" system, which develop over time and contribute to arch support and dynamic control [7]. Obesity is an important factor associated with pediatric flatfoot. Across preschool and school-aged populations, the prevalence of flatfoot is consistently higher among overweight and obese children than among those with normal body weight [4,8,9].

Establishing clinically useful foot assessment methods is important for evaluating children with developmental disabilities, as gait and balance impairments are common among children with cerebral palsy, and foot abnormalities are frequently observed among those with Down syndrome [10,11]. The Foot Posture Index (FPI) provides a practical tool for classifying standing foot alignment in clinical settings [12]. Other assessment methods, such as the Navicular Drop Test and three-dimensional gait analysis, can offer additional structural or functional information; however, they are generally more technical and are often used as complementary tools rather than routine screening measures [13,14]. In particular, three-dimensional gait analysis demonstrates the altered kinematics and kinetics of planovalgus feet during walking, suggesting the need for reliable clinical tools alongside detailed biomechanical assessments [14].

Footprint-based indices offer a simple, noninvasive means to quantify foot arch characteristics in children. Various indices derived from footprint images have been proposed for foot arch assessment. However, Uden et al. emphasized the importance of multifaceted evaluation, highlighting the limitations of single-index approaches for typically developing children [15]. Clarke's angle (CA), a morphological index that reflects the prominence of the medial longitudinal arch, and the Chippaux-Smirak Index (CSI), a functional index based on the narrowest width of the midfoot relative to the forefoot, have both been widely used in pediatric footprint analysis [16]. The Arch Index (AI), proposed by Cavanagh and Rodgers, is a functional footprint-based measure derived from the relative contact area of the midfoot [17]. In addition, the CSI and AI reflect plantar contact characteristics under weight-bearing conditions and may be influenced by plantar fat pad thickness and body mass in young children [18,19]. Considering that structural and functional changes occur simultaneously during early childhood, combining morphological and functional indices may offer a more comprehensive understanding of individual developmental patterns.

Environmental factors, particularly footwear habits, also affect foot development. In comparison with regularly shod peers, habitually barefoot children tend to have higher arches and more favorable foot morphology; moreover, inappropriate footwear may adversely affect foot structure [20–22]. The present study targeted children attending a barefoot daycare center to evaluate the natural course of foot development while minimizing the confounding influence of footwear habits.

Specifically, this study aimed to comprehensively evaluate characteristics of foot arch development in early childhood using three indices—one morphological index (CA) and two functional indices (CSI and AI)—and to elucidate their age-related changes and distinct characteristics.

Methods

Study Design and Participants

This cross-sectional study examined children aged 2–6 years attending a barefoot daycare center. Exclusion criteria were conditions that could affect foot morphology (e.g., cerebral palsy, Down syndrome, and musculoskeletal disorders), relevant medical histories, and incomplete data. The final sample comprised 37 children (19 boys, 18 girls; 74 feet), with age distribution as follows: 9 aged 2 years, 7 aged 3 years, 7 aged 4 years, 4 aged 5 years, and 10 aged 6 years.

Participant characteristics are presented in Table 1. The median age, height, and weight were 52 months (interquartile range [IQR]: 36–72 months), 99.8 cm (IQR: 92.8–115.2 cm), and 15 kg (IQR: 13.5–20.5 kg), respectively.

Footprint Image Acquisition

Footprint images were captured using Foot Look (Foot Look Co., Ltd., Fukuoka, Japan), a digital footprint imaging system. In comparison with traditional ink methods and pedography, Foot Look offers superior reproducibility, easier data storage and sharing, and enhanced infection control. Participants stood in a comfortable upright position on the Foot Look device, facing forward, while bilateral footprint images were captured simultaneously. A single examiner performed all imaging, ensuring that participants maintained a stable standing posture. When necessary, parents or daycare staff assisted in maintaining participant attention and posture.

Image Analysis and Index Calculation

Footprint images were analyzed using ImageJ software (National Institutes of Health, Bethesda, MD, USA) to calculate three indices: CA (Figure 1A), CSI (Figure 1B), and AI (Figure 1C).

CA

CA was measured as the angle formed by a line connecting the medial edge of the footprint (medial heel to first metatarsal head) and a line from the first metatarsal head to the apex of the medial longitudinal arch concavity [16]. CA is a morphological footprint-based index used to evaluate the medial longitudinal arch.

CSI

The CSI was calculated as the ratio of the minimum midfoot width (line CD) to the maximum forefoot width (line AB) multiplied by 100 [16]:

CSI = (midfoot width)/(forefoot width) × 100

The CSI is a functional footprint-based index reflecting plantar contact characteristics under weight-bearing conditions. As it is based on midfoot contact width, it may be influenced by plantar fat pad thickness and body mass in young children [18,19].

AI

The plantar surface, excluding the toes, was divided into three equal regions—forefoot (A), midfoot (B), and rearfoot (C)—using lines perpendicular to a line connecting the center of the second toe and the center of the heel. After measuring the area of each region, the AI was calculated using the following formula [17]:

AI = (midfoot area (B))/(total plantar area (A+B+C)) × 100

AI is a functional footprint-based index derived from the relative contact area of the midfoot and provides a quantitative measure of arch-related plantar contact characteristics [17].

Reliability Assessment

A total of 15 participants (30 feet) were selected to determine measurement reliability. For intra-rater reliability assessment, the same examiner performed measurements twice with a 1-week interval. For inter-rater reliability assessment, two independent examiners (physical therapists, each with > 5 years of pediatric rehabilitation experience) performed measurements using the same images.

Reliability was evaluated using intraclass correlation coefficients (ICCs). ICC (3,1) and ICC (2,1) were calculated for intra-rater and inter-rater reliability, respectively. ICC values were interpreted according to the following criteria [23]: ≥ 0.90 = excellent, 0.75–0.89 = good, 0.50–0.74 = moderate, < 0.50 = poor.

Statistical Analysis

Preliminary Analysis: Left-Right Foot Correlation

Spearman's rank correlation coefficients were calculated to examine correlations between left and right foot data, and strong correlations were noted.

Main Analysis: Relationship Between Age and Each Index

Given the strong correlations observed between left and right feet, the generalized estimating equations (GEE) technique was used to analyze the data, accounting for this correlation structure [24]. This technique is appropriate for analyzing repeated measures or correlated clustered data, providing a robust estimation that properly accounts for within-subject correlation.

In the GEE model, age in months (continuous variable) was the independent variable, and the three indices (CA, CSI, and AI) were the dependent variables. An exchangeable correlation structure was specified for within-subject correlation, assuming equal correlation between left and right feet, which is appropriate for the data structure of this study.

Secondary Analysis: Comparison Between Age Groups

Based on prior research and preliminary data indicating notable developmental changes around 48 months (age 4), participants were divided into two groups: < 48 months and ≥ 48 months. Between-group differences for each index were then evaluated using Kruskal-Wallis tests. Normality was assessed using Shapiro-Wilk tests; nonparametric tests were applied due to non-normal distributions.

All statistical analyses were performed using R Studio (version 2025.09.2+418) and R (version 4.2.3), with the geepack package employed for GEE analysis. The significance level was set at 5% (two-tailed).

Ethical Considerations

This study was approved by the Ethics Committee of Japan Healthcare University (approval No. 25-2) and the Ethics Committee of Sapporo Medical University (approval No. 5-1-58). The study was conducted in accordance with the Declaration of Helsinki and relevant ethical guidelines. Prior to study implementation, the study purpose, methods, anticipated risks and benefits, and measures to protect personal information were fully explained to participants and their parents/guardians. Written informed consent to participate was obtained from the parents or legal guardians of all participating children.

Results

Measurement Reliability

All three footprint-derived indices demonstrated excellent measurement reliability (Table 2). Intra-rater reliability ICC values were 0.98 (95% confidence interval [CI]: 0.96–0.99) for CA, 0.97 (95% CI: 0.93–0.98) for the CSI, and 0.96 (95% CI: 0.92–0.98) for the AI. Inter-rater reliability was similarly high, with ICC values of 0.98 (95% CI: 0.95–0.99) for CA, 0.94 (95% CI: 0.88–0.97) for the CSI, and 0.93 (95% CI: 0.85–0.96) for the AI.

Left-Right Foot Correlation

Spearman's rank correlation analysis revealed strong positive correlations between left and right feet for all indices: CA (ρ = 0.86, $p < 0.01$), CSI (ρ = 0.84, $p < 0.01$), and AI (ρ = 0.83, $p < 0.01$). These results indicated that left and right foot data are not independent, supporting the validity of GEE analysis.

Relationship Between Age and Each Index

GEE analysis revealed significant associations between age and all three indices (Figure 2, Table 2).

CA

CA significantly increased with age (estimate = 0.348, standard error = 0.082, $p < 0.001$). The regression equation was $Y = 0.348 \times \text{age (months)} + 20.827$, with an estimated correlation coefficient α = 0.605 (37 clusters, minimum cluster size = 2) (Figure 2A). This indicated an increase of approximately 0.35° per month, corresponding to an estimated increase of 17° between 24 months (age 2) and 72 months (age 6) .

CSI

The CSI significantly decreased with age (estimate = -0.622, standard error = 0.106, $p < 0.001$). The regression equation was $Y = -0.622 \times \text{age (months)} + 77.061$, with an estimated correlation coefficient α = 0.819 (37 clusters, minimum cluster size =

2) (Figure 2B). This indicated a decrease of approximately 0.62 % per month, corresponding to an estimated decrease of 30% between ages 2 and 6.

AI

The AI also significantly decreased with age (estimate = -0.201, standard error = 0.036, $p < 0.001$). The regression equation was Y = -0.201 × age (months) + 37.491, with an estimated correlation coefficient α = 0.702 (37 clusters, minimum cluster size = 2) (Figure 2C). This indicated a decrease of approximately 0.20 per month, corresponding to an estimated decrease of 10 between ages 2 and 6.

Comparison Between Age Groups

When participants were divided into the < 48 months group (n = 16, 32 feet) and ≥ 48 months group (n = 21, 42 feet), significant differences were observed across all indices (all $p < 0.001$) (Figure 3).

CA was significantly higher in the ≥ 48 months group, with a median of 40.7° (IQR: 36.5–45.2°) compared with 28.5° (IQR: 24.2–32.8°) in the < 48 months group (Figure 3A). The CSI was significantly higher in the < 48 months group, with a median of 61.3% (IQR: 56.8–67.5%) compared with 42.6% (IQR: 37.8–48.2%) in the ≥ 48 months group (Figure 3B). The AI was also significantly higher in the < 48 months group, with a median of 26.8 (IQR: 24.2–29.5) compared with 17.5 (IQR: 15.2–20.1) in the ≥ 48 months group (Figure 3C).

Age-Specific Reference Values

Preliminary age-specific reference values for clinical application are presented in Table 3. Given the limited sample size, these values should be interpreted with caution. For more precise estimations, the GEE-derived regression equations (CA = 0.348 × age (months) + 20.83; CSI = -0.622 × age (months) + 77.06; AI = -0.201 × age (months) + 37.49) are recommended. These equations could allow calculation of expected values for any given age in months.

Discussion

This study evaluated foot arch development in children aged 2–6 years using three footprint-derived indices. The main findings were as follows: (1) all indices demonstrated excellent reliability (ICC ≥ 0.93); (2) the morphological index, CA, increased with age, whereas the functional indices, CSI and AI, decreased with age; (3) the magnitude of age-related changes was greater for the functional indices than for the morphological index. These findings suggest that foot arch development in early childhood involves both structural and functional changes, which do not necessarily occur at the same rate.

All three indices demonstrated excellent reliability, which may be partly attributed to the standardized image acquisition protocol and objective measurements performed with ImageJ. Previous studies have reported the methodological strengths and clinical utility of individual footprint-based indices, including AI, CSI, and CA; however, few studies have focused on their simultaneous application [16–19]. The present study extends prior work and supports the feasibility of multifaceted footprint assessment by demonstrating the reproducible measurements of all three indices in early childhood within a single analytical framework.

The significant increase in CA with age likely reflects progressive structural maturation of the foot. Flexible flatfoot is common among young children, and the medial longitudinal arch generally develops spontaneously during the first decade of life [25]. Given that CA is determined by the contour of the medial border of the footprint, it may reflect morphological changes in the arch profile with growth. In the present study, CA increased gradually from 2 to 6 years of age, consistent with the view that morphological development of the foot continues throughout childhood [25].

The observed decreases in the CSI and AI with age also align with developmental changes in plantar contact characteristics. These indices are determined by the relative extent of midfoot contact under weight-bearing conditions and may be influenced by plantar fat pad thickness and body composition, particularly in children and individuals with greater body mass

[18,19,27,28]. Therefore, CSI and AI reductions with age may reflect not only skeletal arch development but also age-related changes in plantar soft tissue characteristics and foot loading patterns. In this sense, functional indices may provide a more sensitive measure of early developmental changes in the pediatric foot.

Biomechanical maturation may also contribute to the observed age-related changes. The plantar aponeurosis is a key passive structure supporting the medial longitudinal arch, and the windlass mechanism described by Hicks explains its role in arch stabilization under load [29]. In addition, intrinsic foot muscles contribute to the dynamic support of the medial longitudinal arch [26,30,31]. The progressive contribution of these passive and active systems to arch maintenance may explain the age-related decline observed in functional indices.

Notably, the CSI changed more rapidly than the AI or CA with age, suggesting that functional indices may be more sensitive than morphological ones to early developmental changes. This distinction is clinically important, as it indicates that individual indices may capture different aspects of foot development. Uden et al. emphasized that no single measure can sufficiently characterize the typically developing pediatric foot, highlighting the need for multifaceted evaluation [15]. The present findings support this perspective, demonstrating that the three indices each follow distinct developmental trajectories.

The similarity of the values observed at 5 and 6 years of age suggests a reduced rate of change in the later preschool period. This trend aligns with prior reports indicating rapid arch development in early childhood before becoming more gradual; however, the precise timing of maturation may vary according to measurement methods [35]. Taken together, the present data may imply relative stabilization, rather than complete maturation, by the later preschool years.

Previous studies, particularly those by Stavlas et al. and Chen et al., evaluated pediatric foot development primarily using single footprint-based indices [33,34]. In contrast, the present study simultaneously examined one morphological index (CA) and two functional indices (CSI and AI). This multifaceted method provides a more comprehensive description of foot arch development and addresses the methodological concern raised by Uden et al. regarding reliance on single-index assessment [15]. By capturing both structural and functional characteristics, the present study offers a broader perspective on developmental changes in the pediatric foot.

Several methodological strengths support the validity of the findings. First, all indices demonstrated excellent reliability, supporting reproducible measurement. Second, the analysis accounted for the correlation between left and right feet using GEE, which is appropriate for bilateral data (both feet from the same child) [24]. Third, the inclusion of children as young as 2 years allowed the characterization of an earlier stage of arch development than that examined in many previous studies.

At the same time, several limitations should be acknowledged. First, as the study was cross-sectional, developmental changes were inferred from age-group differences rather than directly observed longitudinally, warranting further longitudinal studies. Second, the modest sample size ($n = 37$) was sufficient for creating developmental curves but restricted the establishment of diagnostic cutoffs; thus, larger validation studies ($n > 500$) are needed. Third, recruitment from a barefoot daycare center may limit generalizability, necessitating comparative studies with shod children. Fourth, the single-center Japanese sample may not represent populations with different racial or ethnic backgrounds, which are known to influence foot morphology. Finally, footprint-based indices are influenced by both soft tissue and skeletal structure, particularly in young children. Therefore, the indices used in this study should be interpreted as complementary rather than interchangeable measures of foot arch development.

In conclusion, foot arch development in early childhood involves both morphological (CA: arch profile) and functional (CSI and AI: plantar contact characteristics) changes. The established assessment method demonstrated high reliability (ICC $\geq$ 0.93) and could provide accessible quantitative tools, including regression equations for age-specific reference values. Future large-scale longitudinal studies are needed to establish definitive normative data and further clarify the clinical significance of multifaceted arch assessment in pediatric rehabilitation.

Abbreviations

AI
Arch Index
CA
Clarke's angle
CSI
Chippaux-Smirak Index
GEE
Generalized Estimating Equations
ICC
Intraclass correlation coefficient
IQR
Interquartile range.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Japan Healthcare University (approval No. 25-2) and the Ethics Committee of Sapporo Medical University (approval No. 5-1-58). The study was conducted in accordance with the Declaration of Helsinki and relevant ethical guidelines. Written informed consent to participate was obtained from the parents or legal guardians of all participating children prior to participation.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

SM: Conceptualization, Methodology, Data collection, Formal analysis, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. YS: Data collection, Writing - review & editing. HM: Methodology, Supervision, Writing - review & editing. MT: Supervision, Writing - review & editing. TS: Data collection, Supervision, Writing - review & editing. TT: Supervision, Writing - review & editing. NK: Supervision, Writing - review & editing. All authors read and approved the final manuscript.

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Tables

Table 1. Participant Characteristics

Characteristic	Value
Total participants, n	37
Boys, n (%)	19 (51.4)
Girls, n (%)	18 (48.6)
Total feet analyzed	74
Age distribution, n	
2 years	9
3 years	7
4 years	7
5 years	4
6 years	10
Age (months) , median (IQR)	52 (36-72)
Height (cm), median (IQR)	99.8 (92.8-115.2)
Weight (kg), median (IQR)	15 (13.5-20.5)

IQR = interquartile range

Table 2. Generalized Estimating Equations Analysis Results

Index	Estimate	SE	95 % CI	p-value	α	Regression Equation
Clarke's Angle (°)	0.348	0.082	0.187 to 0.509	<0.001	0.605	Y = 0.348×age + 20.83
Chippaux-Smirak Index (%)	-0.622	0.106	-0.830 to -0.414	<0.001	0.819	Y = -0.622×age + 77.06
Arch Index	-0.201	0.036	-0.272 to -0.129	<0.001	0.702	Y = -0.201×age + 37.49

SE = standard error; CI = confidence interval; α = estimated correlation coefficient (within-subject correlation); age = age in months. All models used 37 clusters with minimum cluster size of 2 and exchangeable correlation structure.

Table 3. Age-Specific Reference Values and Regression Model Estimates

Age Groups (n, feet)	Clarke's Angle (°)		Chippaux-Smirak Index (%)		Arch Index	
	Observed	Estimated	Observed	Estimated	Observed	Estimated
2 years (n=9, 18 feet)	24.4 (21.2-27.8)	31.3	68.5 (64.2-73.5)	62.1	28.6 (26.1-31.2)	28.7
3 years (n=7, 14 feet)	34.2 (30.5-38.1)	36.3	55.8 (49.7-61.2)	54.6	25.3 (22.8-27.9)	25.4
4 years (n=7, 14 feet)	45.8 (41.2-50.3)	39.6	48.2 (42.5-54.1)	47.1	19.2 (16.8-22.5)	22.8
5 years (n=4, 8 feet)	47.1 (43.5-51.2)	44.1	32.9 (28.2-38.5)	39.6	21.9 (19.2-24.8)	19.3
6 years (n=10, 20 feet)	46.5 (42.8-50.1)	48	29.3 (24.1-34.2)	28.6	21.9 (18.5-25.2)	21.8

Observed values: Median(IQR). IQR = interquartile range.

Estimated values calculated from regression equations using median age of each group: CA = 0.348 × age(months) + 20.83; CSI = -0.622 × age(months) + 77.06; AI = -0.201 × age(months) + 37.49.

Figures

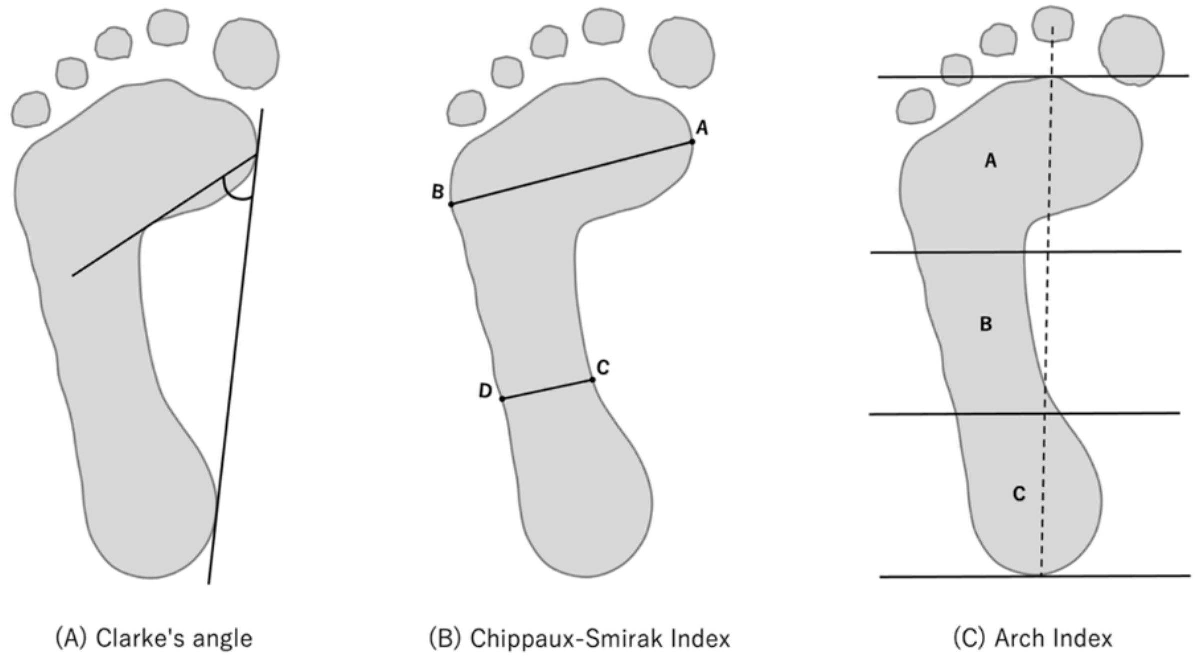

Figure 1. Measurement Methods for Footprint-Derived Indices

Figure 1

Measurement Methods for Footprint-Derived Indices

(A) Clarke's angle (CA): Angle formed between a line connecting the medial edge (heel to first metatarsal head) and a line from the first metatarsal head to the apex of the medial longitudinal arch concavity.

(B) Chippaux-Smirak Index (CSI): Ratio of minimum midfoot width (CD) to maximum forefoot width (AB), expressed as a percentage.

(C) Arch Index (AI): Ratio of midfoot area (B) to total plantar area (A+B+C), where the plantar surface is divided into three equal regions.

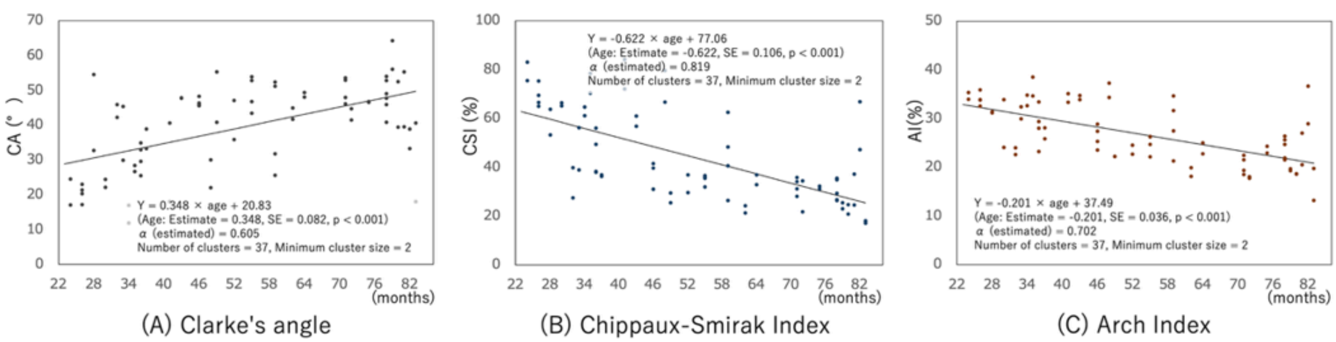

Figure 2. Relationship Between Age and Footprint-Derived Indices

Figure 2

Relationship Between Age and Footprint-Derived Indices

(A) Clarke's angle significantly increased with age (Estimate = 0.348, $p < 0.001$).

(B) Chippaux-Smirak Index significantly decreased with age (Estimate = -0.622, $p < 0.001$).

(C) Arch Index significantly decreased with age (Estimate = -0.201, $p < 0.001$).

Solid lines represent regression lines derived from Generalized Estimating Equations analysis; shaded areas represent 95% confidence intervals. Each point represents one foot (n = 74 feet from 37 children).

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Figure 3

Comparison of Indices Between Age Groups

Box plots comparing (A) Clarke's angle, (B) Chippaux-Smirak Index, and (C) Arch Index between children younger than 48 months (n = 16, 32 feet) and those 48 months or older (n = 21, 42 feet). Box plots show median (center line), interquartile range (box), and range (whiskers).

***$p < 0.001$ (Kruskal-Wallis test).