Original Article

Would foot arch development in children characterize a body maturation process?
A prospective longitudinal study

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A B S T R A C T

Background: Flatfoot (Pes Planus), often regarded as a physiological deviation in children, is of concern to parents because there is no test to predict the development of foot arch. This study aimed to use a new diagnostic flatfoot criterion to determine 1) how the footprint index changes during the development of foot arches, 2) what factors can predict a foot arch development, and 3) whether foot arch development could be a process of body growth.

Methods: 572 children were enrolled in a prospective longitudinal study of anthropometrical parameters and physical fitness twice at age of 6.7 and 8.2 years. The bimodal frequency distribution of the Chippaux-Smirak index (CSI) of the footprint was used to define flatfoot as CSI < 0.58 and non-flatfoot as CSI > 0.61. Body measurements and physical fitness tests were compared between children with flatfeet who developed foot arches and children who did not.

Results: Of 263 children with flatfeet, the CSI significantly changed from 0.72 to 0.46 in 70 children who developed foot arches over 1.5 years and the others had minimal change in the index. Children with foot arch development had a lower initial CSI, improved boys’ performance in one-leg balance, and less increase in girls’ body height than children who remained flatfooted, whereas sex and weight were similar in both groups.

Conclusion: This longitudinal study with the bimodal distribution of the CSI investigated how the development of foot arch advances in children around age 7. A significant and unique pattern in change of the CSI suggests involvement of a maturational stage in foot arch development. Along with the improved performance in one-leg balance, the unidirectional transition from flatfoot to non-flatfoot is associated with improvement in motor control of the ankle.

Trial registration: Chinese Clinical Trial Registry (ChiCTR-OCS-14004300).

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At a glance commentary

Scientific background on the subject

Flatfoot is often regarded as a physiological deviation in children. The foot arch is expected to develop naturally following skeletal growth. However, longitudinal study is limited in the literature to reveal how and when a flat-footed child develops stable foot arches.

What this study adds to the field

This longitudinal survey revealed a significant transitional stage of foot arch development when the Chippaux-Smirak index decreased to 0.72, while the index changed minimally before and after the transitional stage. Sex and weight, the factors associated with flatfoot in children, were not found to predict the transitional stage.

Introduction

Flatfoot is a depression of the medial longitudinal foot arch during weight-bearing [1]. Flatfoot in adults is often associated with increased stress on the tibialis posterior tendon and risk of injury in the lower leg [2–4]. However, flatfoot in children is considered an asymptomatic physiological deviation. Children were thought to naturally develop foot arches as they grow [5–7]; however, some children persistently have flatfeet until skeletal maturity. Therefore, flatfoot is often of concern to the parents because there is no test that can predict the possibility of foot arch development or the risk of persistent flatfoot in a child. Moreover, the process of development of foot arches has been seldom investigated in detail previously. The common recommendations for childhood flatfoot, such as observation, exercise, and orthosis, were based on insufficient knowledge of the natural process of foot arch development. The recommendations are still controversial and lack supportive scientific evidence. Some factors are associated with greater risks of persistent flatfoot among children. Younger children have flatter feet, and the incidence of flatfoot gradually decreases with age [6–9]. Theoretically, every child has an individual timing of foot arch development, which is unknown. In addition, sex and obesity are common factors that influence the timing of foot arch development. Female children demonstrate faster body growth and development (including foot arch development) than male children. Flatfoot is associated with childhood obesity [10–15]; however, whether obesity affects foot arch development, or children with flatfeet simply gain more weight remains unclear [16,17]. These risk factors of flatfoot were concluded from previous cross-sectional studies [5–8,10–16]; however, the predictive power has not been tested by longitudinal studies.

Several assessments of flatfoot have been reported with good to excellent inter-rater reliability [1,18], including visual inspection [19,20], physical navicular height [9,16,17,21], foot pressure distribution [5,6,8–12,22–24], 3-dimensional motion analysis [3], and radiographic bony structure [25]. Among the assessments, weight-bearing footprint is a simple method to record foot pressure distribution that is correlated to flatness of the foot. The Chippaux-Smirak index (CSI) is a popular measurement on footprint by the ratio of midfoot width to the metatarsal width [22–24,25]. We reported an interesting phenomenon of distribution of the CSI in school age children [22]. The data of CSI was clearly in a remarkable bimodal distribution where the mode with greater CSI was shown by those flatter feet, and the other mode by those non-flat feet. The classification was defined scientifically from an evidence of a natural bimodality in body measurement, which was traditionally made otherwise by an artificial cut point of continuous data.

In this longitudinal survey, how foot arch develops in children was explored using the new classification of flatfoot [22]. The purposes of this study were to answer the following questions: 1) what are characteristics of the change in footprint index during development of the foot arches, 2) could sex, obesity, and physical fitness predict foot arch development, and 3) could foot arch development be a process of body maturation or body growth?

Materials and Methods

Study design

A prospective longitudinal study of anthropometrical parameters, foot arch development, and physical fitness in children was designed, in which participants underwent the same evaluation twice in a 1.5-year interval. This longitudinal survey was approved by the Institutional Review Board of the authors’ hospital and was registered as a clinical observational survey (ChiCTR-OCS-14004300).

Participants

Children in first grade at two elementary schools participated in the first survey in 2013 with written consent from parents, and the same group of children participated in the second survey 1.5 years later. Children with major neurologic, cardiovascular, renal, or rheumatologic diseases and those with musculoskeletal disorders such as hip dysplasia, congenital anomaly, leg length discrepancy, and recent injuries in the lower extremities were excluded.

Measures

In addition to taking weight-bearing footprint, anthropometrical parameters such as body height, body weight, and body mass index (BMI) were measured for the investigation of body growth and changes in footprint index. Physical fitness was evaluated by conducting three tests as follows: 20-m dash, standing long jump, and one-leg balance that were related to lower extremity fitness [27–30]. The 20-m dash is a measure of muscle strength and speed. In this test, each child ran over 20 m from a standing position, with the time recorded.
to the tenth of a second. The standing long jump is a measure of the explosive strength of the leg muscles. In this test, each child stood behind a marked line keeping both feet apart at shoulder width. Children jumped forward using both feet simultaneously. The distance from the starting line to the nearer landing foot was recorded in millimeters. The one-leg balance is a measure of combined visual, vestibular, and musculoskeletal control. In this test, each child (with eyes open) stood barefoot on one foot on a 30-cm-long wood block (3 × 3 × 30 cm). The longitudinal axis of the foot was in line with the block length and arm movements were allowed for balance. The time from lifting the opposite foot off the ground until it re-touched the ground was recorded to the tenth of a second. Children were instructed on how to perform the physical fitness tests by school teachers, and they practiced and observed other participants before a formal measurement was executed by a one-off measure.

Definition of flatfoot and non-flatfoot

Footprint was recorded during a sit-to-stand movement. Each participant was instructed to put both feet on two Harris and Beath footprint mats while sitting on a chair. The participant then stood with even weight on both feet and returned to the sitting position to complete the footprint recording. Children who had trunk tilting or foot movement during sit-to-stand were asked to do the footprint recording again. The investigators inspected the footprints on the spot, and each subject had only one set of footprints.

The ratio of the midfoot width to the forefoot width (known as the CSI) was calculated for each right footprint. A standardized measurement of footprint for better reliability was described in a previous study (inter-rater intraclass and test-retest intraclass correlation coefficients of 0.98 and 0.97, respectively) [22] (Fig. 1). A bimodal distribution of the footprint CSI was reported among school-age children whose footprints were recorded by sit-to-stand movement. The right mode was flatfooted with a wider midfoot width, whereas the left mode was non-flatfooted. The unique distribution was observed in different ages and both sexes. A stationary trough area of frequency distribution was observed at a CSI range of 0.58–0.61, thereby providing a natural boundary between flatfoot and non-flatfoot [22]. The classification was more reasonable than artificial separation of the footprint CSI data [10–12,26].

The frequency distribution of CSI was not unimodal unlike those of body height and body weight. A bimodal distribution was noted in the CSI data collected at age 6.7 years and 8.2 years (Fig. 2). The bimodal distribution of CSI provided a natural classification of foot arch status. The intersectional value

Fig. 1 Footprints of a flatfoot (1) and non-flatfoot (2) show a standardized measurement of the Chippaux-Smirak index: the ratio of midfoot width (D) divided by metatarsal width (C). The longitudinal axis (A) of the foot defined the midpoint (cross mark) for measuring the midfoot width (D). The medial tangential line and lateral tangential line (B) defined the metatarsal width (C). Line d was parallel to line c.

Fig. 2 Frequency distributions of the Chippaux-Smirak index measured in the same cohort of children at a mean age of 6.7 and 8.2 years. This shows a distinct bimodal distribution with a stationary trough area that is unaffected by age.
between the two modes was 0.59 (95% confidence interval, 0.58–0.61). Therefore, a flatfoot state was defined as a CSI \( \geq 0.61 \), whereas a CSI \( \leq 0.58 \) defined a non-flatfoot state. Notably, the few children with a CSI in the range of 0.58 and 0.61 were classified as undeterminate.

**Data analysis**

The two sets of data (at age 6.7 years and 8.2 years) were plotted to project patterns of change in CSI, body height, and body weight during the development of the foot arches. To test the association between factors and foot arch development, the children who transitioned from a flatfoot state to being non-flatfooted were compared with children who remained flatfooted during the two surveys. Since sex was a significant factor in foot arch development in children, the comparison was stratified to boys and girls. The initial data could be predictors of future foot arch development, and the changes in these factors were considered to simultaneously occur with foot arch development. For further analysis of the effects of sex and weight on subsequent foot arch development, the association was tested using the Chi-square test. According to the sex-specific BMI-for-age growth chart, children were stratified according to their BMI into four groups: underweight, normal, overweight, and obese [31]. Children in the first two groups were classified as having normal weight, whereas those in the last two groups were classified as being overweight.

The normality of the distributions of age, body measurements, and physical fitness test results was examined using the Kolmogorov–Smirnov test. The t-test was used for comparison when the normality assumption was satisfied; otherwise, the Mann–Whitney U test was employed. The chi-square test was used for nominal variables and all \( \alpha \) levels were set at 0.05.

**Results**

In total, 616 children in the first grade of elementary schools participated in the first survey from October to December 2013, and 572 participated in the second survey from April to June 2015. The rate of follow-up was 93%. Forty-four children missed the second survey; 29 children due to transfer to other schools and 15 children due to absence on the day of the survey (owing to illness or other reasons). The mean ages of the participants in the first and the second surveys were 6.7 ± 0.3 years and 8.2 ± 0.3 years. In the two surveys, the frequency of CSI distributions was clearly bimodal, and the trough area remained approximately 0.59. During the 1.5-year period, the number of children without flatfeet increased, whereas the number of children with flatfeet decreased (Fig. 2).

The 572 children who completed both surveys were classified into flatfoot and non-flatfoot groups according to the right foot CSI; there were 263 flatfooted children, 288 non-flatfooted children, and 21 children whose CSIs were in the undeterminate range. The body weight, BMI, and CSI were significantly different between flatfooted children and non-flatfooted children, either in boys or girls (Table 1A and 1B).

Of 263 flatfooted children, 70 (27%) were developing foot arch; their mean CSI significantly changed from 0.72 to 0.46 (−2.6). On the contrary, the mean CSI remained unchanged at 0.75 in the residual 189 children who remained flatfooted; this suggests a stationary status before foot arch development. In the initial non-flatfooted group, a change was observed in the mean CSI from 0.43 to 0.41 (−0.02) in 275 children who remained non-flatfooted. In 9 children who developed flatfoot, the mean CSI increased from 0.48 to 0.67 (+0.19) (Fig. 3).

In addition, the data from this longitudinal study were analyzed to provide insight into the distribution of changes in the two groups as mentioned earlier, demonstrating a marked difference in the changes. The initial unimodal distribution in the flatfooted group was bimodal in the second survey. Seventy children with a developed foot arch were combined with non-flatfooted children to establish a new non-flatfoot mode. However, the number of flatfooted children decreased, weakening the initial flatfoot mode. On the contrary, the unimodal distribution in the non-flatfooted group remained unimodal and slightly shifted to a smaller CSI during the study (Fig. 4).

The scatterplots of body height, body weight, and footprint index data of the two surveys demonstrated distinct characteristics for each variable. Body height data were distributed

| Table 1A Comparison of baseline conditions between flatfooted and non-flatfooted boys at the first survey. |
|---------------------------------------------------------------|
| Flatfooted boys (n = 163) | Non-flatfooted boys (n = 116) | \( p \) value |
| Age (y) | 6.7 ± 0.3 | 6.8 ± 0.3 | 0.124<sup>a</sup> |
| Height (cm) | 120.4 ± 5.0 | 121.4 ± 5.4 | 0.110<sup>a</sup> |
| Weight (kg) | 24.0 (21.0–27.0) | 23.0 (20.0–25.0) | 0.015<sup>a</sup> |
| BMI | 16.4 (15.0–18.1) | 15.3 (14.4–16.5) | <0.001<sup>a</sup> |
| Footprint index (CSI) | 0.739 ± 0.072 | 0.439 ± 0.065 | <0.001<sup>a</sup> |
| 20-m dash (sec) | 5.1 (4.7–5.5) | 5.0 (4.7–5.3) | 0.170<sup>a</sup> |
| Long jump (cm) | 110.0 (100.0–120.0) | 110.0 (100.0–123.8) | 0.131<sup>a</sup> |
| One leg balance (sec) | 4.0 (2.7–6.4) | 3.9 (2.7–9.0) | 0.661<sup>a</sup> |

Data in parenthesis are expressed in standard deviation or interquartile range.

BMI: body mass index, CSI: Chippaux-Smirak index.

<sup>a</sup> Mann–Whitney U test.

<sup>b</sup> Independent t-test.

<sup>c</sup> Statistically significant.
above the 45° line through the origin; this indicates an increase in the body height of each child by a similar amount in the 1.5 years (Fig. 5a). Body weight data showed a similar distribution, however, data were spread along a steeper line. This indicates children who were initially heavier gained more weight (Fig. 5b). On the contrary, the scatterplot of the CSI showed four distinct groups of children. Most data were distributed around the 45° line that passes through the origin; including flatfooted children who remain flatfooted were in the right upper quadrant and children with non-flatfeet, who retained their original foot state, were in the left lower quadrant. The mean CSI minimally changed in these two groups of children. The data in the right lower quadrant represent 70 children who were developing foot arches. Only scarce data points appeared in the left upper quadrant, representing the few children initially with non-flatfeet then became flatfooted (Fig. 5c).

To evaluate factors associated with foot arch development, 70 children whose foot arch status changed were compared with 189 children who remained flatfooted. The comparison was stratified to boys and girls first. Foot arch development in boys was associated with smaller initial CSI and greater improvement in one-leg balance. Foot arch development in girls was associated with smaller initial CSI and less increase of body height. The future foot arch development could not be predicted by sex, height, weight, and BMI, and the observed increase in height, weight, and BMI in the two surveys were not associated with foot arch development (Table 2A and 2B). Boys and girls, as well children with different status of weight, had a similar rate of transition from flatfoot to non-flatfoot during the 1.5-year follow up (Table 3).

**Discussion**

This longitudinal observational study found some unique characteristics of footprint CSI change in human foot arch development. First, the unique bimodal distribution of the foot arch index was distinctly different from the unimodal distribution of body height and weight (Fig. 2). Second, the transition from being flatfooted to not being flatfooted implies significant unidirectional change among children of the same age (Fig. 4). Third, the CSI scatterplot showed that most children remained in their original foot arch state, and only a few demonstrated the transition from a flatfooted to non-flatfooted state (Fig. 5c). These characteristics suggest that a process of body maturation might be responsible of foot arch development, rather than a result of body growth (Fig. 5a, b).

The significant change in CSI during the foot arch development could be explained by children who were developing a motor skill in controlling foot protonation. A flatfoot on footprint could result from the medial midfoot touching the Harris mat during sit-to-stand movement. On the contrary, a non-flatfoot on footprint results from a more controlled or stable foot arch during sit-to-stand. The timing of foot arch development depends on when a child develops the ability to control foot protonation. This study revealed that prior to the
first survey, 288 (50%) of 572 children (mean age, 6.7 years) had already developed the ability, and they were non-flatfooted in the sit-to-stand movement; during the subsequent 1.5 years, another 70 children developed this ability.

The flatfooted children with foot arch transition had significantly lower CSI than the other flatfooted children in the first survey. The difference between a CSI of 0.72 and 0.75 was insufficient to conduct a clinical guideline in predicting transition to the non-flatfooted state. However, it suggests that, in addition to the dramatic decrease in CSI during foot arch transition, the CSI gradually decreases with age. It was speculated that each child has a CSI (as a toddler), which slowly decreases at an individual speed during childhood. When body development have advanced to a state that CSI distributes around 0.72, the transition of the foot arch is likely to occur. In addition, another evidence from this study is that the CSI in non-flatfooted children decreased from 0.43 to 0.41 in 1.5 years. Further longitudinal studies (from toddlers to adolescents) are therefore required to verify this speculation.

In this study, it was observed that foot arch development in boys was associated with improvement in one-leg balance. This indicates a bidirectional relationship between structure...
Fig. 5 Scatterplots of (A) body height, (B) body weight, and (C) Chippaux-Smirak index data in the two surveys showing a contrast between the universal increase in height and weight and a unique pattern in the CSI.

| Table 2A Comparison between flatfooted boys with and without subsequent foot arch development. |
|-------------------------------------------------------------|
| **Remained flatfooted (n = 114)** | **Changed to non-flatfooted (n = 45)** | **p value** |
| Age (y) | 6.7 ± 0.3 | 6.8 ± 0.3 | 0.59a |
| Height (cm) | 120.3 ± 5.1 | 120.6 ± 4.6 | 0.66b |
| Weight (kg) | 24.0 (21.0–27.0) | 24.0 (22.0–27.0) | 0.81c |
| BMI | 16.0 (14.9–18.0) | 16.1 (15.0–18.5) | 0.97a |
| Arch index (CSI)c | 0.749 (0.070) | 0.718 (0.073) | 0.01b |
| 20-m dash (sec) | 5.1 (4.7–5.5) | 5.0 (4.6–5.4) | 0.91a |
| Long jump (cm) | 105.0 (95.0–115.0) | 110.0 (100.0–115.0) | 0.76a |
| One leg balance (sec) | 4.2 (2.9–6.5) | 3.5 (2.4–5.0) | 0.06b |

Changes between the two surveys

| | Remained flatfooted | Changed to non-flatfooted | p value |
| Increase in height (cm) | 8.5 ± 2.0 | 8.8 ± 1.6 | 0.39a |
| Increase in weight (kg) | 5.0 (3.7–8.0) | 5.9 (3.7–7.9) | 0.64b |
| Increase in BMI | 1.0 (0.3–2.2) | 1.1 (0.4–2.2) | 0.64a |
| Change in CSIc | 0.003 ± 0.077 | −0.252 ± 0.037 | <0.01b |
| Change in 20 M Dash (sec) | −0.4 (−0.7–−0.2) | −0.5 (−0.8–−0.2) | 0.30a |
| Change in long jump (cm) | 14.0 (5.0–25.0) | 15.0 (2.5–26.5) | 0.98a |
| Change in balance (sec)c | 2.0 (−0.6–6.2) | 3.6 (1.1–9.3) | 0.03b |

Data are expressed as median (interquartile range) and mean ± standard deviation.

BMI, body mass index; CSI, Chippaux-Smirak index.

a Mann–Whitney U test.

b t-test.

c Statistically significant.
and function. In the first pathway, a stable structure in the foot would result in better performance in the one-leg balance test. This pathway is supported by the smaller initial CSI, indicating that a foot with higher arch is associated with later advancement in one-leg balance. In the reverse pathway, motor function related to the biomechanical control of the foot would result in less foot protonation movement during the sit-to-stand movement and therefore a narrower midfoot width on the footprint. Recent interventional studies supported the idea that muscle training improves one-leg balance [20,32]. Foot arch development in girls was associated with less increase in body height. Since body height and foot arch stability [20,32]. Foot arch development in girls and boys is not as associated with foot flatness [33]. Whereas subjects should stabilize foot and ankle structure on the coronal plane to maintain standing on the long narrow block. Therefore performance of one leg balance was related to foot arch development.

Of 288 children without flatfeet, nine (3%) became flatfooted at the second survey. A similar finding from another study reported that 10% of 3- to 5-year-old children transitioned from being non-flatfooted to being flatfooted in 1 year [26]. This phenomenon could indicate an unstable state in the initial stage of foot arch development. For a child who just developed a new motor function, the performance of this function could be unreliable, especially at a younger age. In addition, a sudden eversion of the ankle could occur upon taking the footprint, thereby resulting in a flatfoot CSI in the second survey.

The limitations of this study include the use of the CSI, a two-dimensional image of foot pressure distribution, to measure a three-dimensional structure of the foot arch; consequently, the validity of using the CSI to define a flatfoot requires further justification. Harris mat and footprint CSI were employed because of the cost-effectiveness, simplicity, reliability, and appropriateness for a field survey of school-age children.

### Table 2B Comparison between flatfooted girls with and without subsequent foot arch development.

| Age (y) | 6.7 ± 0.3 | 6.7 ± 0.3 | 0.37c |
| Height (cm) | 118.1 ± 5.1 | 118.4 ± 4.6 | 0.81b |
| Weight (kg) | 22.0 (20.0–25.0) | 22.0 (20.0–25.0) | 0.71a |
| BMI | 15.6 (14.7–17.3) | 15.9 (15.2–17.3) | 0.65a |
| Arch index (CSI)c | 0.762 ± 0.063 | 0.721 ± 0.072 | 0.01b |
| 20-m dash (sec) | 5.3 (4.9–5.7) | 5.1 (4.9–5.6) | 0.56a |
| Long jump (cm) | 100.0 (90.0–110.0) | 100.0 (90.0–112.5) | 0.72a |
| One leg balance (sec) | 3.6 (2.5–6.8) | 5.0 (2.8–7.2) | 0.55a |

*Data are expressed as median (interquartile range) and mean ± standard deviation.
BMI, body mass index; CSI, Chippaux-Smirak index.

### Table 3 Rate of subsequent foot arch development in 254 flatfooted children stratified with different sex and body weight states.

| | Boys with flatfeet in the first survey | Girls with flatfeet in the first survey | Normal weight in the first survey | Overweight in the first survey |
|---|---|---|---|---|
| Children transited from flatfoot to non-flatfoot | 45 (29.0%) | 25 (25.3%) | 54 (28.6%) | 16 (24.6%) |
| Children remained flatfooted | 110 (71.0%) | 74 (74.7%) | 135 (71.4%) | 49 (75.4%) |
| Total | 155 (100%) | 99 (100%) | 189 (100%) | 65 (100%) |
children. Second, there was an unavailability of normative data for physical fitness tests in Taiwanese children aged 6–7 years to determine their percentile ranking for analysis. The children significantly improved in terms of physical fitness in the 1.5 years, and the change in amount, rather than percentile ranking, was analyzed. Third, measurements were taken in the physical fitness tests by a one-off performance, rather than the number of trials for average. Participants were instructed on how to perform the physical fitness tests, and they practiced and observed other participants before a formal measurement. Fourth, ligamentous laxity was similarly associated with flatfoot [16]; however, no data of ligamentous laxity or Achilles tendon tightness were included in the analysis. Fifth, some flatfooted children might have worn insoles or orthoses to support foot arch during the 1.5 years. Data regarding who wore insoles, type of insoles, and how long they wore insoles were not obtained in this study. Last, the performance of one leg balance is possible. Besides, some subjects with one side flatfoot and one side non-flatfoot were not considered in this study.

Conclusions

This longitudinal survey revealed a unique developmental process of human foot arches, which consisted of a rapid and significant developmental stage at the same age as body maturation and a slow and minor change before and after the maturation stage, as for body growth. It was observed that sex and weight, the traditional factors associated with flatfoot in children, could not predict the significant developmental stage in this longitudinal study. The transition from flatfoot to non-flatfoot is associated with an improvement in one-leg balance. The close association between foot arch maturation and one-leg balance suggests the requirement of further studies (using balance training) to enhance foot arch development.

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Declaration of competing interest

The authors have no financial or ethical conflicts of interest to report.

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