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Kinematic differences between normal and low arched feet in children using the Heidelberg foot measurement method

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ABSTRACT

The purpose of this study was to investigate the kinematics of normal arched and low arched feet in children and use this data to quantify the differences between the two foot types during walking gait. Multi-segment foot motion was measured, using the Heidelberg foot measurement method (HFMM), for 25 normal arched feet and 27 low arched feet in 9–12-year-old children. The kinematic differences in the foot between the two groups during walking were relatively small, except for the medial arch and forefoot supination angles. The magnitude of the medial arch angle was approximately 108greater in the low arched group than the normal arched group throughout the gait cycle. There was a significant difference found in the forefoot supination angle ($p < 0.03$), relative to the midfoot, between the two groups at initial heel strike, and maximum and minimum values throughout the gait cycle. The values for the normal group were significantly higher in all these angles indicating that the forefoot of the low arched foot remains less pronated during the gait cycle. There was no significant difference in the motion of the rearfoot between the two foot types. The results of this study provide normative values for children's feet and highlight the mechanical differences in flexible flat feet in this age group. This data contributes to knowledge on foot kinematics in children and will be valuable for future research on the structure, function and potential treatment of the flexible flat foot.

1. Introduction

Three-dimensional (3D) gait and motion analysis have advanced rapidly in the last decade to the point where multi-segment analysis of the paediatric foot is possible and of interest to scientists and clinicians [1–7]. Children are an important target population for 3D motion analysis of the foot because of the specific primary effects of musculo-skeletal and neuromuscular pathologies on children's feet (e.g., equinovarus deformities in cerebral palsy or flat feet) the related functional impairment on gait and the need to develop evidence-based approaches to their clinical management. The majority of work in 3D foot analysis has been carried out on adult populations, with a few exceptions [1,5,8]. In their study of adolescent feet, MacWilliams et al. [8], demonstrated the capability of their model to analyse smaller, younger feet, and hence provided a normative database of kinematic and kinetic data for adolescent feet. Stebbins et al. [5] proposed a model for use with children that had already been validated for adult feet and found the kinematic patterns were consistent with results from adults. Both of these studies were carried out on healthy normal feet.

Until recent years, those analysing the low arched or flexible flat foot relied on simple foot measurement and two-dimensional analysis. Many theories regarding the structure and function of the low arched foot have been based on static footprints or the change in position of the navicular during dynamic movement [9–14]. The limitations of two-dimensional analyses and the extrapolation of these results to the younger foot have not been established. Therefore, in vivo three-dimensional measurement of foot motion in children that allows for the analysis of the movement of the unconstrained foot is necessary to understand factors contributing to flat feet, their effects on gait, classification of foot abnormalities, and planning of suitable interventions in symptomatic patients. Recent developments in foot biomechanic measurement [5,6,8] produce more information than previously about the motion of the midfoot, particularly its motion relative to the adjacent segments of the forefoot and rearfoot.

Studies of the adult flat foot [15] and pathological posterior tibial tendon dysfunction (PTTD) [16–19] have reported an increased hindfoot eversion in PTTD during the loading response

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[16,17], with differences attributable to variations in the reference position. Hunt and Smith [15] looked at the mechanics of the flat versus normal foot, but was limited to an adult population and the stance phase of gait. Their study failed to reveal the expected biomechanical differences between low and normal arched feet, and found a restraint in motion rather than excessive motion. Differences in motion of the rearfoot have often been associated with structural misalignments of the forefoot, particularly during the stance phase of gait [20]. However, this was recently challenged by Cornwall et al. [21] who reported no relationship between rearfoot motion and forefoot alignment during walking in a healthy adult population. There is currently no reported data on this relationship in the flat foot. Even though the range of motion of the hallux has not been specifically reported for flat feet, deformities such as hallux valgus have identified flat foot as an intrinsic factor [22,23]. Ledoux and Hillstrom [24] reported that flat feet had significantly more force under the hallux than normal arched feet and suggested that it would indicate mechanical changes in hallux motion.

The purpose of this study was to investigate the kinematics of the foot in normal and low arched feet in children, and quantify the differences in multi-segment foot motion between the two foot types. Firstly, it was hypothesized that similar to previous findings in the adult flat foot there would be restraint rather than excess of rearfoot frontal plane motion in children with low arched feet. It was further hypothesized that the motion of the forefoot relative to the midfoot would be different between the low and normal arched foot when measured in both the frontal and transverse planes by the HFMM. Finally, there were no expected differences in the motion of the hallux or in stride length and cadence. Additionally, the kinematic data presented in this paper can provide a reference for comparison to pathological feet in future work.

2. Methods

2.1. Participant information

Table 1
Summary of participants' characteristics. Means given with standard deviation in brackets.

Arch type	Normal arch	Low arch
Gender	10 males, 15 females	15 males, 12 females
Age (year)	11.1 (±1.2)	11.2 (±1.2)
Mass (kg)	45.3 (±10.1)	48.6 (±13.2)
Height (cm)	148.6 (±12.1)	151.0 (±11.4)

Participants were recruited from a group of ninety-four 9–12-year-old children who had been previously categorized into high, normal and low arched foot groups, using both static and dynamic two-dimensional measurements of the medial longitudinal arch (Supplementary A). The 94 children had been recruited to a larger study and were asymptomatic, pre-pubescent, and had the ability to perform the required tasks. To facilitate the investigation of the natural foot, a history of lower limb injury or podiatric treatment were an exclusion criterion. With a desired sample size of 50 children, 28 children were randomly selected from each of the normal and low arched groups and invited to participate in this study. Of the 56 children invited 52 agreed to participate, 25 boys and 27 girls, with 10 boys and 15 girls in the normal arched group and 15 boys and 12 girls in the low arched group. Table 1 presents a summary of the anthropometric and age characteristics of the two groups. Institutional ethics approval was granted for this project and written consent was obtained from the parent/guardian.

2.2. Equipment and Testing procedures

The Vicon Workstation 4.6 Motion Analysis System with eight digital cameras (M2Cam) was used to measure the coordinates of markers placed on the lower leg and foot. Video data were captured at 100 Hz. The absolute calibration residual values ranged from 1.2 to 1.4 mm throughout the data collection phase. The mean difference in the calibration residual over the various capturing days was small (<0.6 mm). Seventeen reflective markers of 10 mm diameter were attached to the lower limb at the following anatomical locations (Fig. 1): medial and lateral knee joint lines; tibial tuberosity; two on the tibial shaft; medial and lateral malleoli; medial, lateral, and central calcaneus; navicular tuberosity; proximal and distal first metatarsal; distal second metatarsal; proximal and distal fifth metatarsal; and hallux [6,25]. To reduce error all marker placements in this study were carried out by the same author (DT).

A single static trial was recorded in a normal stance position. Participants were then asked to walk at a self-selected pace along a 5 m track. Only one foot was recorded at a time due to difficulties with marker dropout, particularly during the swing phase. A minimum of five trials were collected for both right and left feet for each participant. No filters were used on the coordinate data. All trials were time normalised to the gait cycle. The Heidelberg foot measurement method [6] was used to calculate the multi-segment motion of the foot considering the tibia, talus, calcaneus, navicular, first and fifth metatarsals and the hallux (Supplementary B).

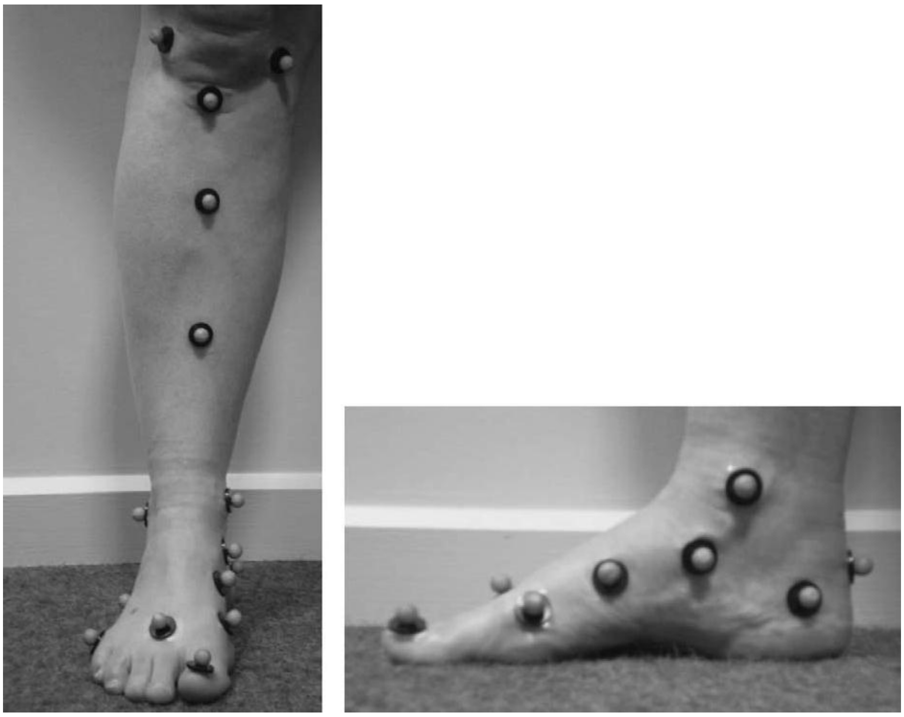

Fig. 1. (a) Coronal view of marker placement and (b) sagittal view of medial foot markers.

Table 2
Summary of the variables with a significant difference between the normal and low arched groups.

Variable	Mean difference between groups (low–normal)	Lower bound	Upper bound	Significant p-value
Initial right medial arch angle	10.7	7.15	14.32	<0.001
Initial left medial arch angle	10.6	7.39	13.89	<0.001
Right medial arch angle max	9.9	6.54	13.21	<0.001
Left medial arch angle max	10.5	7.13	13.80	<0.001
Right medial arch angle min	9.5	5.36	13.64	<0.001
Left medial arch angle min	9.2	5.20	13.18	<0.001
Initial right hallux flex angle	−5.5	−9.50	−1.47	0.008
Initial left hallux abd angle	2.5	0.44	4.67	0.019
Time left subtalar angle max stance	−5.8	−10.68	−0.95	0.021
Initial right forefoot sup angle	4.2	1.39	6.96	0.004
Initial left forefoot sup angle	6.2	3.58	8.88	<0.001
Right forefoot sup angle max	4.1	1.59	6.66	0.002
Left forefoot sup angle max	6.1	3.42	8.80	<0.00
Right forefoot sup angle min	3.1	0.33	5.85	0.029
Left forefoot sup angle min	5.1	2.41	7.84	<0.001
Initial left forefoot abd angle	−3.3	−6.32	−0.38	0.028
Left forefoot abd angle max	−4.0	−7.29	−0.77	0.016

Note: All mean differences are expressed as degrees except for the timing of the left subtalar rotation max angle which is expressed as a percentage of the gait cycle.

The validation procedures of the HFMM used in this study and a detailed explanation of segment definitions and marker placement has been previously described by Simon et al. [6].

2.3. Statistical analysis

Five walking trials on each foot, giving a total of ten trials per participant, were included in the analyses. From each trial one representative stride was selected. Time-histories for each included stride for the following nine measurement method variables were examined: medial arch angle, lateral arch angle, hallux flexion, tibial abduction, subtalar rotation, midfoot supination, forefoot supination (relative to the midfoot), forefoot abduction, and hallux abduction. From each of the nine time-histories five values: (1) heel strike, (2) the maximum, (3) the timing of the maximum, (4) the minimum and (5) the timing of the minimum were extracted. In addition, for subtalar rotation the maximum and minimum values were examined in both the stance and swing phase of the gait cycle. Thus, for each participant, a data set of 47 values was compiled from the output of the HFMM for each stride, resulting in a total of 470 (47 × 10 strides) data points per participant. Temporo-spatial values describing stride length, stride time, stride velocity, stride cadence, and timing of toe-off were also measured for each participant. Means and standard deviations were calculated for these values.

Hypotheses were assessed using two-way repeated measures Analysis of Variance (ANOVA) to identify significant differences both within each subject and between the normal and low arched group for the temporo-spatial and kinematic results, particularly for the rearfoot, forefoot and hallux. The specific data points for the ten trials for each variable were used as the dependent variables and the low and normal arched groups as the between-subject factor in this analyses. An alpha level of 0.05 was selected and a Bonferroni correction applied to account for multiple comparisons. T-tests were undertaken to investigate bilateral differences for all data points. To describe the consistency of the pattern of each variable's time history the positive root of the coefficient of multiple correlations (CMC) was calculated, as proposed by Kadaba et al. [26].

3. Results

3.1. Differences in range of motion

Significant differences were observed between the low and normal arch groups for the medial arch angle, forefoot supination and abduction angles and hallux flexion and abduction using repeated measure ANOVAs (Table 2). The pattern and range of motion of the rearfoot was similar for the normal and low arched foot. There were no significant differences ($p > 0.05$) between initial, maximum or minimum values of subtalar joint motion between the two foot types. However, a 5.8% difference in the timing of the maximum subtalar joint eversion on the left foot between the two groups proved significant. The initial, maximum and minimum forefoot supination angles were significantly different ($p < 0.03$) between the normal and low arched. The low arched foot remained less pronated (relative to the midfoot) with the mean difference ranging from 3.18 to 6.28 throughout the gait cycle. In the transverse plane, the movement of the low arched foot was also significantly more abducted and, unlike the normal arched group, failed to reach adduction on the left side only during the gait cycle. The low arched group showed significantly less hallux flexion at heel strike but only on the right side. A significant difference was also evident at heel strike on the left side for hallux abduction, with the low arched group more abducted. No significant differences were found in the within subjects analyses for any of the kinematic parameters.

3.2. Temporo-spatial parameters

Temporo-spatial means were calculated over the five trials bilaterally for each participant and averaged over the participants within each group. A summary of the temporo-spatial values for the two groups is presented in Table 3.

There were no significant differences between any of the temporo-spatial parameters within subjects or between the normal and low arched groups, with the exception of the left stride length. A significant difference ($p < 0.05$) was found between the two groups for left stride length, with the low arched group having longer strides, but no significant difference within the participants over the five trials. After normalizing stride length for the participant's height, this difference was non-significant.

3.3. Bilateral differences

Significant bilateral differences ($p < 0.05$) were found for 6 of the 47 variables examined; lateral arch angle at heel strike and

Table 3
Summary of the temporo-spatial characteristics across the two groups.

	Normal arched (n = 25)		Low arched (n = 27)		Total (n = 52)	
	Mean	SD	Mean	SD	Mean	SD
Right stride length (m)	1.16	0.13	1.22	0.14	1.19	0.14
Left stride length (m)	1.15	0.12	1.23	0.15	1.19	0.14
Right stride time (s)	1.03	0.08	1.05	0.07	1.04	0.08
Left stride time (s)	1.04	0.10	1.04	0.08	1.04	0.09
Right stride velocity (m/s)	1.13	0.16	1.17	0.10	1.15	0.13
Left stride velocity (m/s)	1.12	0.17	1.18	0.19	1.15	0.18
Right stride cadence (/min)	58.45	4.47	57.21	3.90	57.83	4.19
Left stride cadence (/min)	58.18	4.85	57.28	3.19	57.73	4.02
Right stride toe-off (%)	59.38	1.62	59.45	1.68	59.42	1.65
Left stride toe-off (%)	59.73	1.54	59.54	1.56	59.64	1.55

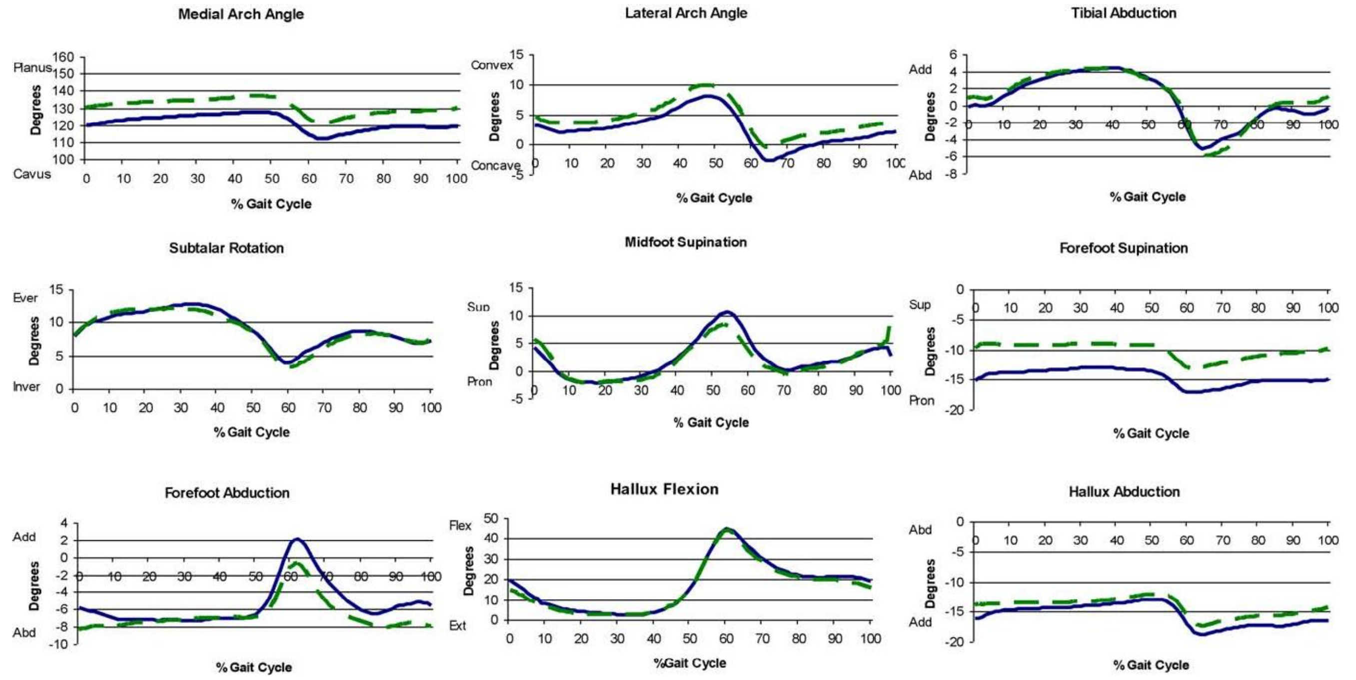

Fig. 2. Graphical representation of the averaged kinematics for the normal and low arched group throughout the gait cycle. Normal arched are represented by solid line and low arched by dotted line.

minimum value, hallux flexion at heel strike, and the maximum, minimum and initial midfoot angle. The angles were consistently greater on the right foot, with a 3–48difference for the lateral arch, hallux flexion and minimum midfoot angles and 4–58for the initial and maximum midfoot angles.

3.4. Range of motion

Fig. 2 presents the time-histories for the nine HFMM variables for the low and normal arch groups. An average calculated over the ten trials for each person and then for the group, low or normal arch, is presented and the standard deviation is omitted for ease of visual interpretation.

Medial arch motion was similar for both groups; the angle reached its maximum value during stance and decreased slightly at toe-off as the ankle moved to plantar flexion. However, the magnitude of this angle was significantly different between the two groups throughout the gait cycle (10.78). Despite the significant differences between maximum and minimum values between the two foot types, the timing of these differences in the medial arch angle was not significant. No significant differences existed between the normal and low arched foot for the lateral arch angle, and the frontal plane movement of both the midfoot and the tibia. CMCs were calculated for the time-histories of the nine selected variables. Intra-participant consistency over ten trials within a test session was calculated (Table 4). The high r-values obtained demonstrated highly consistent intra-participant patterns, particularly in sagittal plane motion ($r > 0.76$).

Table 4
Summary of intra-subject coefficients of multiple correlations (CMC) values.

	Intra-CMCs	
	Normal arch (n = 25)	Low arch (n = 27)
Medial arch angle	0.77	0.83
Lateral arch angle	0.76	0.77
Hallux flexion	0.88	0.93
Tibial abduction	0.72	0.70
Subtalar rotation	0.73	0.74
Midfoot supination	0.74	0.67
Forefoot supination	0.68	0.62
Forefoot abduction	0.61	0.65
Hallux abduction	0.78	0.72

4. Discussion

This study contributes to knowledge on foot kinematics in children and provides a comprehensive account of the differences between the kinematics of normal and low arched feet in children. Relatively few kinematic differences were observed between normal and low arched feet in the sample of asymptomatic children studied. In this study decreased forefoot pronation was the only kinematic variable associated with the lower arch, unlike previous studies [16,18,19], where increased rearfoot eversion and forefoot abduction were associated with an increased medial arch angle, particularly during the stance phase.

Some similarities exist between the findings of this study and previous work [6,8,27–30]. Comparisons of the kinematic values in sagittal plane movement generally compared better than motion in the frontal or transverse planes. The subtalar joint, consisting of the articulation between the talus and the calcaneus, can be difficult to measure due to the anatomical position of the talus. In the HFMM, this motion is defined as the rotation of the calcaneus around a predefined non-individualised subtalar axis [6]. The subtalar joint angle at heel strike in the frontal plane was similar in pattern to previous studies [6,8,29] but the range throughout the gait cycle was greater in the present study. Subtalar joint pronation and supination are generally measured clinically by the amount of calcaneal inversion and eversion. The extent of the motion that occurs in the joint has been quantified as 68during level walking for an individual with a normal foot and 98 for a flatfooted individual [31]. Contrary to previous research on PTTD patients [16,17,19], no evidence of an increased rearfoot motion in the low arched group was observed in this study. This finding is in agreement with Hunt and Smith [15] who also reported a lack of difference between the frontal plane rearfoot motion between the low and normal arched foot. However, the rearfoot segment was modeled differently, with the main difference occurring in definition of the axes. In addition, the HFMM uses a heel alignment device to locate the calcaneal markers in an unloaded posture to remove the individual attitude of the hindfoot, as described in Simon et al. [6].

Frontal plane motion of the forefoot was similar in pattern and range to that presented by MacWilliams et al. [8] and Stebbins et al. [5] and only in pattern to Leardini et al. [28]. Leardini et al. [28] reported a smaller range throughout the stance phase of the gait cycle. The motion of the forefoot in this study was difficult to compare with others, as it was relative to the midfoot and in most studies the midfoot was not considered as a separate segment [27,29,32] and hence has previously been reported relative to the rearfoot. However, the most significant kinematic difference between the normal and low arched foot in this study was found in the decreased pronation angle of the forefoot relative to the midfoot in the low arched feet. In support of the hypotheses, the results of this study suggest that the compensation for a lower medial arch angle results in decreased forefoot pronation rather than excessive rearfoot motion.

The magnitude and pattern of the hallux flexion angles found in this study were in agreement with those reported previously [5,6,8,28–30]. Maximum flexion occurred just prior to toe-off in all studies. This was similar for both groups in this study which was surprising as many of the low arched group were observed to begin hallux flexion prior to this stage of the gait cycle. In the frontal plane, the hallux abduction angle increased at toe-off which compared well to the findings of Leardini et al. [28] and Mac Williams et al. [8] and one of the patterns found by Simon et al. [6].

Interestingly, the differences found in the left stride length disappeared once the data were normalised for participants' height. This helped to substantiate the notion that height plays a role in the temporo-spatial gait patterns in the maturing child. Scope remains for further research on this topic. Although a number of significant bilateral differences were found, the absolute difference was small in all instances. Therefore, the data in this study would suggest that bilateral data can be pooled for analysis or it may be sufficient to capture one side only depending on the research or clinical topic. Moreover, the consistency in the time history patterns over the five trials captured in this study advocate the reduction to three trials in future work.

In conclusion, the kinematic differences in the foot between the two groups during walking were relatively small, except for the medial arch angle and forefoot supination (relative to the midfoot). The most significant difference between the two foot types was in the motion of the forefoot. The results of this study support the use of the HFMM for quantification of multi-segment foot motion, provide normative values for children's feet and highlight the mechanical differences in flexible flat feet in this age group. This information will be valuable for future work in structure, function and potential treatment of low arched feet.

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Conflict of interest

The authors declare that there is no conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2010.01.021.

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