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Age-related changes in three-dimensional foot motion during barefoot walking in children aged between 7 and 11 years old

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ABSTRACT

Background: The biomechanical complexity of children's feet changes throughout childhood, yet kinematic development of the feet is poorly understood. Further work exploring the kinematic profile of children's feet would be beneficial to help inform our understanding of the typical development of children's feet.
Research Question: Do three-dimensional segmental kinematics of the feet during gait relate to age in a sample of children age 7–11 years?
Methods: This study was a secondary analysis of an existing database representing one hundred and twenty-one children age 7 – 11 years (90 male, 31 female; mean ± SD: age 9.57 ± , 1.17 years, height 1.37 ± 0.08 m, body mass 35.61 ± 9.33 kg). Fifteen, 9 mm retroreflective markers were attached to the right shank and foot of each participant in, line with the 3DFoot model. Multi-segmental joint kinematics were collected during barefoot walking. Sagittal, frontal, and transverse planar motion was described for the shank-calcaneus, calcaneus-midfoot, and midfoot-metatarsals segment of the right foot. Principal component analysis (PCA) was used to reduce the major modes of variation in the data to fully explore foot segment motion over the entire gait cycle. Correlations and multiple regression between PCA outputs with age, and potential confounding factors are presented.
Results: Significant positive correlations were found between age and greater calcaneus, dorsiflexion, midfoot inversion and adduction, and metatarsal dorsiflexion, plantarflexion and abduction. There were no significant confounding effects of height, body mass, walking speed or gender on the relationships between age and PCA outputs.
Significance: The findings from this study demonstrated a relationship between foot kinematics and age suggesting that the development of foot kinematics is ongoing until at least the age of 11 years. This work offers a comprehensive data set of inter-segmental kinematics which helps to advance understanding of the development of the pediatric foot.

1. Background

Childhood represents a period of substantial change in the structure and function of the feet [1,2]. Yet, our understanding of the kinematic changes during this time of growth and development remain poorly understood. Literature suggests that children's feet undergo structural development by the age of 7 years [3], however there is debate as to when such changes cease [4]. Past studies exploring the development of children's feet have employed a range of measurement techniques including static foot anthropometrics and morphology (for a review, see Uden et al. [4]), dynamic footprints [5–8], plantar pressure assessment [9–11], and three-dimensional gait analysis [12–14]. With respect to the latter, motion capture technology has facilitated greater understanding of the biomechanical interactions of the feet segments during gait, advancing insights on the effects of disease on the foot's structure and function [15–18]. This technology has the capacity to support new knowledge about pediatric foot development. Yet, despite the possibilities offered by this, relatively few studies have examined the angular motion of the foot segments during childhood [15,19–23].

The synthesis of existing research exploring gait kinematics in

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children is hampered by disparity with population, study focus, and resolution at which the segments of the foot were explored [21–23]. Samson et al. [21] sought to improve understanding of the development of joint dynamics during the first six years of independent walking. This investigation reported ankle joint function as demonstrating adult-like gait patterns as early as five years of age. More recently, Deschamps et al. [22] examined the interactions between age and multi-segmental foot motion in 32 males age between 6 and 20 years. The authors identified relationships between calcaneal-midfoot plantarflexion angle and both calcaneal-metatarsal plantarflexion and abduction, with increasing age. Yet while informative, the small sample size (e.g., $n = 8$ for the 8–12-year-old group) and population's large age range highlights the need for further exploration of this topic. Contrasting 58 girls to an adult female control group ($n = 50$), Jang et al. [23] reported changes within multi-segmental foot joint kinematics were ongoing until early adolescence, however the study did not report on midfoot kinematics. Taken together, the literature highlights the need for further work to explore the development of foot kinematics that accompany the structural changes occurring during the pre-adolescent stage of growth.

Previous research on foot development during gait is limited by arbitrary cut-offs for age groups, and reliance on discrete kinematic values. Principal component analysis (PCA) is a classical multivariate statistical technique used for dimension reduction in human movement data, transforming time-series data into components that account for most of variability in the original waveform [24]. Work exploring the kinematic profile of the pediatric foot via motion capture technology, combined with PCA would be beneficial to advance our understanding of the typical development of children's feet. Therefore, this study aimed to determine age-related changes in 3D foot segmental motion during barefoot walking in a sample of children aged between 7 and 11 years old.

2. Methods

2.1. Selection and description of participants

The data reported in this study represent a secondary analysis of gait data collected from two cohorts of children who participated in investigations exploring foot segment kinematics and physical characteristics. The lead author was responsible for the recruitment, data collection (including all protocols), and the analysis of both cohorts undertaken at two host institutions. Anthropometric, demographic, and spatiotemporal data for the data collected at each institution are presented in Supplementary material Table S1. Data from 121 children aged 7 – 11 years of age were compiled for this analysis (90 male, 31 female; mean ± SD: age 9.6 ± 1.2 years, height 1.4 ± 0.1 m, body mass 35.6 ± 9.3 kg). All participants were recruited from local clubs and schools. Exclusion criteria included medical conditions affecting neuromuscular and orthopedic integrity or any complications contributing to altered foot posture and/or gait disturbance. Ethical approval was obtained from the host institutions, and parental consent was obtained prior to testing.

2.2. Instrumentation and procedures

Fifteen, 9 mm skin-mounted reflective markers were attached to the right foot and shank and tracked using Vicon Nexus motion capture system at 200 Hz (Vicon Motion Systems Ltd, Oxford, UK), walking barefoot at a self-selected speed. A four-segment model of the foot [25] was constructed for calculation of relative intersegment angular motion in Visual 3D software (C-Motion Inc., MD, USA). Previous research has demonstrated the reliability of this foot model in a pediatric population [26]. Two floor-mounted force plates (at Institution A: Bertec, Model MIE Ltd, Leeds, UK; Institution B, Kistler 9287CA Force Platform, Kistler Instruments Ltd. Hampshire, UK) recorded ground reaction forces during gait trials at 1000 Hz. The gait cycle was defined from initial contact (determined as an increase in vertical force above 20 N) through foot-off, and the subsequent initial contact of the same foot. Sagittal, frontal, and transverse planar motion were described for the shank-calcaneus, calcaneus-midfoot, and midfoot-metatarsals segments. 3D intersegment foot angles from each participant were extracted as 101 data points normalized over the gait cycle, representing angular waveform patterns of foot segment motion. Mean 3D intersegment angles were calculated for each participant based on six gait cycles captured. Root mean squared errors of mean angular waveforms between the two institutions were 0.3–2.1 deg, which is within the error reported in repeatability studies [26,27]. All angular data from the foot segment model were collected via the same protocol by one investigator (RM), reducing variation in data capture between the two institutions.

2.3. Statistical analysis

2.3.1. Principal component analysis (PCA)

Principal component analysis (PCA) was used to reduce the major modes of variation in the data, permitting a comprehensive exploration of foot segment motion over the entire gait cycle. Previous research from our group has employed PCA to analyse multiple waveforms utilizing separate matrices [15]. In the current analysis, nine matrices (shank-calcaneus, calcaneus-midfoot, and midfoot-metatarsals, each considered in the sagittal, frontal, and transverse plane) were constructed for 3D foot angle waveforms based on the 121 participants and the 101 data points representing the gait cycle (heel strike to ipsilateral heel strike). The features of variation in the waveform data were extracted using PCA by orthogonally rotating the variables via a varimax rotation [28] into components which maximally explained variability in the original waveforms. Only principal components (PC) that cumulatively explained at least 90% of the waveform variation were included in further analysis [28]. The rotated loadings (describing the proportion of variance explained by the underlying data points) were assessed to determine which data points contributed to each component. Rotated loadings > 0.722 or < -0.722 were considered as contributing to a component [28]. A regression score (estimated coefficient representing a participant's segmental angle within a component within a standardized distribution of all participants [i.e. z-score]; [28]) was calculated for each participant based on their 3D intersegment foot angle within each PC. Positive regression scores indicated dorsiflexion, inversion, and adduction; negative regression scores indicated plantarflexion, eversion, and abduction. Selected mean waveforms for the top 5% and bottom 5% regression scores are shown in Supplementary material. Regression scores were used for subsequent correlation and multiple linear regression analysis.

2.3.2. Relationship analysis

The Shapiro-Wilk test revealed all variables with the exception of body mass, shank-calcaneus PC2, and PC3 as meeting assumptions of normality. Pearson's or Spearman's 2-tailed correlation coefficient (r) assessed relationships between participant age, height, body mass, and walking speed, in addition to the relationships with regression scores from PCA. A point biserial coefficient of correlation was used to compute the correlations with gender. Ninety-five percent confidence intervals (95%CI) were calculated for each r value.

To determine the association between age and 3D intersegment foot angles, the regression scores extracted from PCA were entered into multiple linear regression. The regression scores were entered as the predictor variables with age representing the dependent variable. Potential confounding predictor variables (height, body mass, walking speed, and gender) were entered into multiple linear regression. For the exploratory nature of the study, a backward step-wise regression method was used to determine the predictors for the regression scores based on 3D intersegment foot motion. Predictor variables were removed in the order of least significance (i.e., highest p-value) until the remaining predictors (if any) were significantly associated with the regression score. If age and any additional variables were significantly associated with the regression score, further analysis via mixed model linear regression (with interactions to account for the potentially confounding influence amongst the predictor variables), was undertaken. Only those regression scores that were significantly associated with age are presented in the results. All statistical analysis was carried out in SPSS version 24. Statistical significance was set to $p < .05$.

3. Results

3.1. PCA

Table 1 presents PCA results for the three-foot segments, for each of the three planes of motion. Four sagittal (PC1 covers initial stance to midstance, PC2: midstance to toe-off, PC3: late swing, PC4: early swing), three frontal (PC1 covers early to late stance, PC2: late stance to early swing, PC3: late swing), and one transverse (PC1 covers the entire gait cycle) plane shank-calcaneus PCs were extracted from the original waveform, explaining 96.7%, 95.5%, and 96.4% of the variance, respectively. At the calcaneus-midfoot, two sagittal (PC1 covers midswing through to midstance, PC2: midstance to toe-off), one frontal (PC1 covers the entire gait cycle), and one transverse (PC1 covers the entire gait cycle) plane PCs were extracted from the original waveform, explaining 96.7%, 96.4%, and 98.7% of the variance, respectively. Finally, at the midfoot-metatarsal, two sagittal (PC1 covers late swing through to midstance, PC2: midstance to early swing), one frontal (PC1 covers the entire gait cycle), and one transverse (PC1 covers the entire gait cycle) plane PCs extracted from the original waveform, explaining 98.4%, 97.1%, and 98.8% of the variance, respectively.

3.2. Correlations

Table 2 presents the correlations between age, height, body mass, and gender. Age (being older) was significantly associated with both greater height and body mass plus being male (mean ± SD: males 9.7 ± 1.2 years, females 9.2 ± 1.0 years). There was no significant correlation between age and walking speed.

Table 3 illustrates correlations between age and confounding variables with foot segment PCs. There were significant correlations between older children and the following kinematic features: greater dorsiflexion (mid-to-late swing) of the calcaneus; inversion and adduction (both throughout the gait cycle) of the midfoot and dorsiflexion (late swing to midstance), plantarflexion (from the end of stance to mid swing), and abduction (throughout the gait cycle) of the metatarsals.

Fig. 1 presents age plotted against average angles represented by the PCs which were significantly correlated. For a meaningful interpretation of foot segment angles relative to age, a mean angle was extracted over the percentage of gait cycle referred to in each significant PC. The range of angle from the line-of-best-fit of shank-calcaneus sagittal plane PC3 was 1.0 deg from youngest to oldest participant. The range of angle from the line-of-best-fit of calcaneus-midfoot: frontal plane PC1 was − 8.4 deg from the youngest to the oldest participant. The range of angle from the line of best fit of calcaneus-midfoot: transverse plane PC1 was 6.4 deg. Midfoot-metatarsal: sagittal plane range from the line of best fit for PC1 was 2.9 deg and − 1.0 deg for PC2. Midfoot-metatarsal: transverse plane range from the line of best fit for PC1 was − 6.0 deg. For illustrative purposes, Fig. 2 presents mean kinematic data for all children, children ≥ 10 years old, and children < 8 years old.

Table 2
Correlation analysis between the independent variable (age) and potential confounding variables (height, body mass, walking speed and gender).

	Age	Height		Body mass		Walking speed	Gender	
Age	1	0.467	**	0.302	**	0.025	0.185	*
Height		1		0.447	**	0.131	0.212	*
Body mass				1		0.023	0.060	
Walking speed						1	0.114	
Gender							1	

*Correlation significant at 0.05 level.
**Correlation significant at 0.01 level.

3.3. Multiple regression

There were no significant confounding effects of mass, height, walking speed, or gender in the relationships between age and foot segments PCs. Fig. 2 presents the foot segment angular waveforms of younger and older children (for description purposes only) and marks the boundaries of the gait cycle covered by each PC.

4. Discussion

This study aimed to determine age-related changes in 3D foot segmental motion during barefoot walking in a large cohort of children between 7 and 11 years of age. Findings demonstrated the development of foot kinematics were ongoing until at least the age of 11 years. Of note, sagittal plane motion was significantly related to age despite demonstrating only a small range of motion across the age groups (<3 deg from the youngest to oldest child). The sagittal plane

Table 1
Summary of principle component analysis of 3D foot segment angles.

Segment	Principal component							
	PC1		PC2		PC3		PC4	
	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle	% Variance explained	% of gait cycle
Shank-calcaneus								
Sagittal plane	31.98	7–27	26.95	39–57	21.30	89–97	16.64	63–69
Frontal plane	38.60	15–49	31.29	55–71	25.65	97–101	–	–
Transverse plane	96.39	1–101	–	–	–	–	–	–
Calcaneus-midfoot								
Sagittal plane	57.81	69–43	38.88	47–63	–	–	–	–
Frontal plane	96.39	1–101	–	–	–	–	–	–
Transverse plane	98.76	1–101	–	–	–	–	–	–
Midfoot-metatarsal								
Sagittal plane	54.07	93–45	44.29	51–67 77–89	–	–	–	–
Frontal plane	97.06	1–101	–	–	–	–	–	–
Transverse plane	98.78	1–101	–	–	–	–	–	–

Table 3
Correlations between independent variable (age) and potential confounding variables (height, body mass, walking speed and gender) with regression scores (from principal component analysis).

			Age		Height		Body mass		Walking speed		Gender	
Shank-calcaneus	Sagittal plane	PC1	0.003		0.182	*	0.063		0.342	**	0.135	
		PC2	-0.060		0.014		-0.006		-0.422	**	-0.148	
		PC3	0.193	*	0.092		0.020		-0.078		0.012	
		PC4	-0.067		-0.031		-0.046		-0.046		0.029	
	Frontal plane	PC1	-0.044		-0.003		0.028		-0.099		0.043	
		PC2	0.103		-0.066		-0.105		-0.003		0.040	
		PC3	-0.075		-0.162		-0.140		0.014		-0.048	
	Transverse plane	PC1	-0.030		0.173		0.130		0.098		0.188	*
Calcaneus-midfoot	Sagittal plane	PC1	-0.042		-0.162		-0.231	*	0.273	**	-0.074	
		PC2	0.058		-0.042		0.105		-0.426	**	-0.001	
	Frontal plane	PC1	0.334	**	0.143		0.011		-0.003		-0.029	
Calcaneus-midfoot	Transverse plane	PC1	0.215	*	-0.067		0.025		0.034		-0.001	
Midfoot-metatarsal	Sagittal plane	PC1	0.278	**	0.133		-0.001		0.013		0.231	*
		PC2	-0.238	**	-0.180	*	-0.089		-0.103		-0.359	*
	Frontal plane	PC2	-0.067		0.059		-0.049		0.007		-0.100	
	Transverse plane	PC1	-0.278	**	0.133		-0.203	*	-0.115		0.111	

*Correlation significant at 0.05 level.
**Correlation significant at 0.01 level.

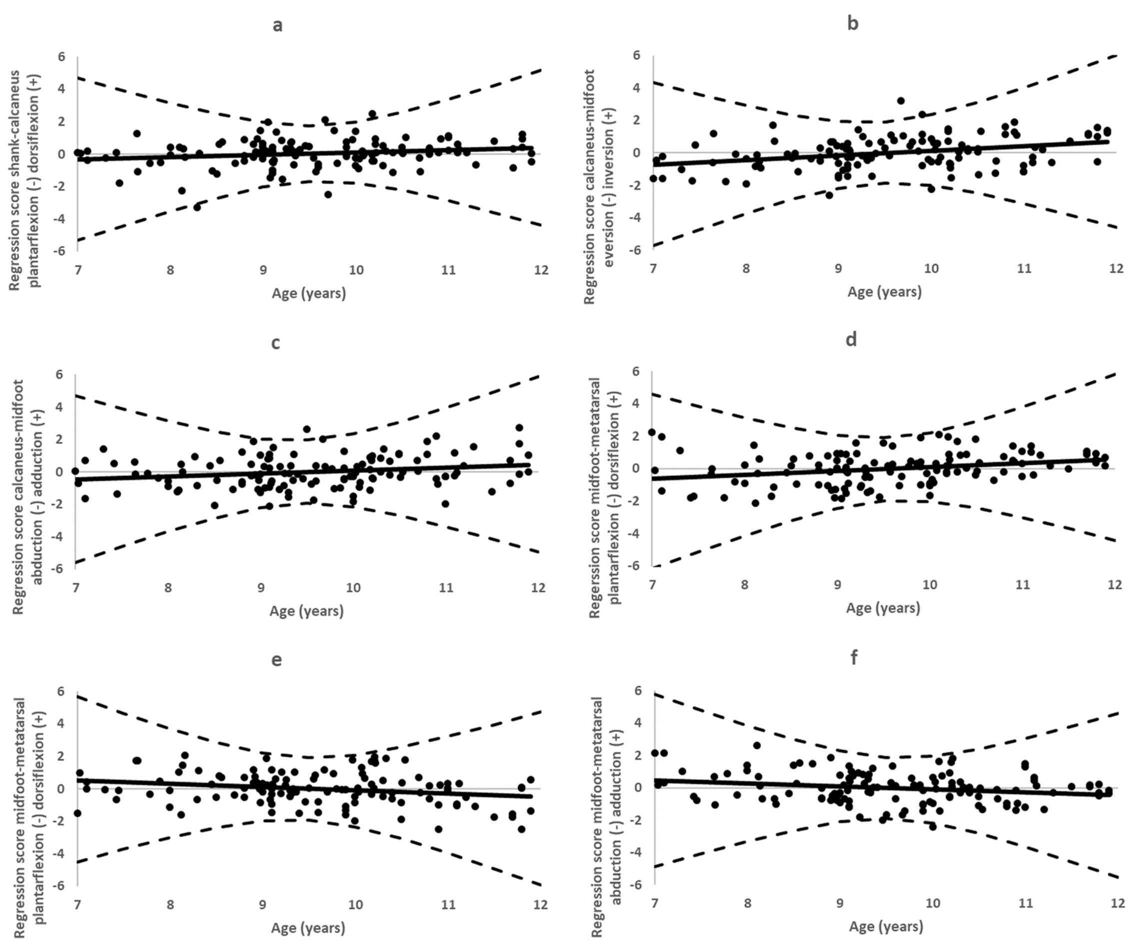

Fig. 1. Scatter plots of significant correlations of age against regression scores from PCA a) shank-calcaneus sagittal plane PC3, b) calcaneus-midfoot frontal plane PC1, c) calcaneus-midfoot transverse plane PC1, d) midfoot-metatarsal sagittal plane PC1, e) midfoot-metatarsal sagittal plane PC2, f) midfoot-metatarsal transverse plane PC1. Dotted lines represent 95% confidence intervals.

relationships should be interpreted with caution as the range fails to exceed the typical error found in test-retest reliability analysis when using the foot model [26]. Frontal and transverse plane motion were also significantly related to age yet demonstrated a larger range of motion across all children (6–8 deg from the youngest to the oldest child). No significant confounding effects of height, weight, walking speed, or gender were found.

The data suggests that the midfoot segments displays greater inversion and adduction in older children, reflecting the expected changes in the profile of the medial longitudinal arch [4]. Rather than a change in movement patterns, the findings highlight an angular offset in midfoot inversion and adduction and forefoot (metatarsal) abduction, possibly

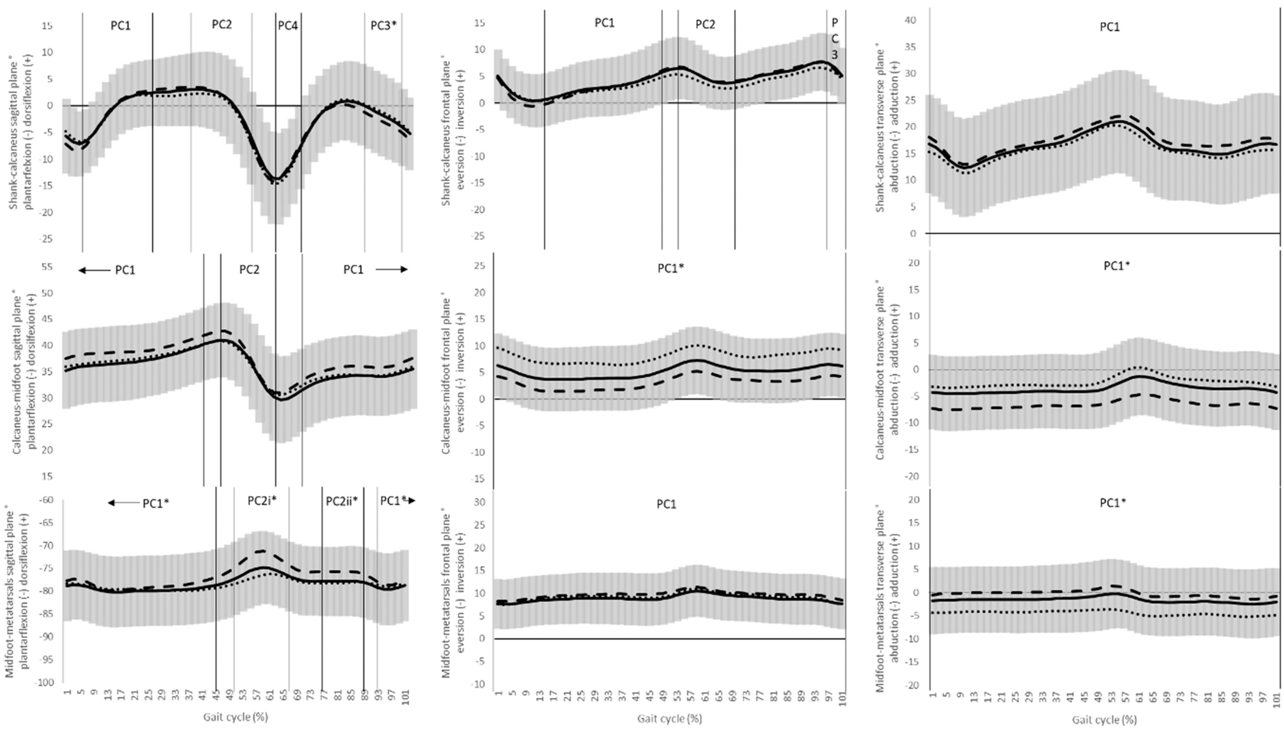

Fig. 2. Mean (black line) and SD (gray shaded area) of foot segmental angular data over the gait cycle (1–101%). * refer to PCs significantly correlated with age. For descriptive purposes mean lines are shown for children ≥ 10 years old (dotted line) and < 8 years old (dashed line).

due to structural changes in the older children (Fig. S2). Bosch et al. [10] reported forefoot and medial longitudinal arch development continues until at least 10 years of age, and that further structural and functional development may extend into adolescence. Phethean et al. [9] postulated that elevated pressures across the central metatarsals may relate to greater inclination (plantarflexion) of the metatarsals; the findings of the present study (greater midfoot-metatarsal plantarflexion in older children) would concur with this notion. Indeed, younger children demonstrated a flatter forefoot during stance.

Our findings agree with previous data [22] reporting significantly greater shank-calcaneus dorsiflexion and calcaneus-midfoot adduction in older children. However, Deschamps et al. [22] reported significantly greater plantarflexion at both the calcaneus-midfoot segment and calcaneus-metatarsal segments during early stance. In contrast, our study reports greater plantarflexion at the midfoot-metatarsal segment during late stance and swing. Furthermore, Deschamps et al. [22] reported significantly greater abduction at the calcaneus-metatarsal segment, in contrast to midfoot-metatarsal segment reported in the present study. While both studies are generally in agreement with regards to segment motion, the differences appear to be a consequence of the description of segment motion in relation to the proximal segment; Deschamps et al. [22] report on calcaneus-metatarsal motion, omitting midfoot articulations. Indeed, increasing the number of articulating joints between the motion of two segments can alter the interpretation of which joint rotations are occurring and increases violation of rigid body assumptions [29].

Our data reports greater shank-calcaneus dorsiflexion with age and these findings are consistent with a previous study [23]. However, Jang et al. [23] reported greater inversion at the calcaneus relative to the shank, whereas our study reports greater inversion at the midfoot relative to the calcaneus. Furthermore, Jang et al. [23] reported greater adduction and plantarflexion at the calcaneus-metatarsal segment as age increased. Yet, the previous study found adduction and plantarflexion to occur at the midfoot-metatarsal segment. These differences between studies can be attributed to the use of different kinematic models and their definition of foot segments.

Sagittal plane motion of shank-calcaneus and calcaneus-midfoot foot segments were correlated with walking speed and this was consistent with previous studies [30]. Correlations between gender and foot motion were also reported in this study and may be explained by sexual dimorphism [3,31]. However, no confounding variable was significant in the association between foot segment motion and age. Age demonstrated the strongest correlation with foot segment motion. Of note, height was less of a factor in explaining foot kinematics compared to age. This indicates that processes associated with generating and controlling patterns of intersegmental coordination (e.g., neuromuscular and musculoskeletal development) deserve attention in contrast to focusing merely on the influence of linear growth.

The study findings must be viewed with respect to limitations. The work represents a secondary analysis of existing data pooled from earlier studies. Therefore, future research should consider a longitudinal design to explore the development of foot kinematics across childhood. Such investigation would be further enhanced by the inclusion of additional kinematic and kinetic measures with focus on specific anatomical structure such as the medial longitudinal arch, the metatarsophalangeal angle, and plantar pressures. We have reported a large spread of the data around the line-of-best-fit indicating high variability within participants. It is also acknowledged that additional factors (such as biological rather than chronological measures of maturity) may account for changes in foot kinematics, therefore the present results can be utilized to indicate trends in contrast to predicting precise individual values.

5. Conclusion

The development of multi-segment foot kinematics during childhood and adolescence is an area demanding exploration. The present study determined age-related changes in 3D foot segmental motion during gait in a sample of children between 7 and 11 years of age. The findings demonstrated that changes in the kinematics of pediatric foot segments continued until at least 11 years of age. Our data suggest that sagittal plane kinematics were consistent between the oldest and youngest children by the age of 7 years and were related to walking speed.

However, the development of frontal and transverse segment motion was ongoing until (at least) 11 years of age. This work offers a comprehensive data set, highlighting the ongoing development of joint kinematics accompanying the period of growth characterizing childhood. Furthermore, this work helps to advance understanding about the kinematic development of the pediatric foot.

Conflict of Interest

The authors declare no conflict of interest. Lincoln Blandford is employed by Comera Movement Science. The research was funded by the Dr William M. Scholl Podiatric Research and Development Fund.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2022.04.001.

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