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Long term gait postural characteristics of children with general foot pain using smartphone connected wearable sensors

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Whether children's general foot pain related to specific foot posture remains unknown. The aim of the study was to determine long-term dynamic foot posture characteristics in children with general foot pain using smartphone-connected wearable sensors. Over a 30-day period, 94 children (37 girls and 57 boys, mean age 9.3 years) completed the study. Children were grouped according to the recent history of foot pain during walking. Static rearfoot alignment was digitally measured. Long-term gait posture was collected using wearable sensors during 10 m of self-selected speed walking per day. There were 81 children in the asymptomatic group and 13 in the foot pain group. Static and gait parameters showed moderate to strong correlations between left and right, but only the left foot parameters showed group differences for foot pain. Increased static rearfoot angle (RA) and decreased coronal movement at toe-off (TOCP) of the left foot were significantly associated with foot pain ($p < 0.05$). This study demonstrates IMU-based identification of gait characteristics in children with foot pain, revealing associations with increased static rearfoot angle and reduced dynamic propulsion posture at coronal plane. These findings provide a foundation for developing IMU-based algorithms to predict musculoskeletal disorders in children, enabling early detection and intervention strategies.

Keywords Pediatric foot pain, Gait propulsion, Rearfoot valgus, Inertial measurement unit

Abbreviations

CD	Cadence
IV	Instantaneous velocity
IMU	Inertial measurement unit
RA	Rearfoot angle
STP	Stance percentage
SWP	Swing percentage
TCCP	Touch coronal projection
TCSP	Touch sagittal projection
TCTP	Touch transverse projection
TOCP	Toe-off coronal projection

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TOSP Toe-off sagittal projection
TOTP Toe-off transverse projection

The prevalence of foot pain in children is often underestimated, primarily due to the assumption that it is less common in this age group than in adults. However, studies have reported that the incidence of lower extremity complaints in children ranges from 15 to 33%, indicating that foot pain may be more prevalent than traditionally believed[1,2]. The etiology of pediatric foot pain is complex, encompassing a wide range of causes and clinical presentations[3]. For example, mid-foot pain can be a symptom of common pediatric conditions, such as pathological flatfoot[4]. Foot posture is considered closely linked to foot muscle and plantar fascia properties, which may contribute to the development of foot pain[5]. One of the most commonly used assessments is static foot posture evaluation, such as measuring the rearfoot valgus angle[6]. In addition to foot posture, gait analysis is essential for understanding foot kinematics. Gait can be described as the process of body weight transitioning through space, with the propulsion phase being the most critical for moving the body forward[7]. Gait propulsion strategy is now considered a marker of gait maturation and elastic energy recycling in children[8]. The propulsion characteristics also reveal the function of the foot in maintaining stiffness and arch coordination with the first MTP joint[9]. Some studies have assessed propulsion function to help identify certain pathological conditions, such as muscular dystrophy, developmental coordination disorder (DCD) and cerebral palsy[10–12]. However, while many studies have focused on gait spatiotemporal parameters, limited research has been conducted on dynamic foot postures, particularly in children.

During childhood development, the kinematics of the human foot undergo significant changes. The arch of the foot develops rapidly, and gait patterns mature to resemble those of adults[13,14]. However, studies suggest that the body weight transition strategy during gait in children is not fully developed by the age of 12[15]. The relationship between evolving gait characteristics in children and associated foot symptoms remains unclear. This highlights the importance of regular assessment of foot function in children to better understand the interplay between pathological factors and clinical symptoms. To facilitate frequent gait assessment, non-laboratory-based methods are essential. Recent advancements have expanded gait analysis beyond expensive, highly specialized laboratory settings, enabling data collection during daily activities[16,17]. Inertial Measurement Units (IMUs) have emerged as a cost-effective, convenient, and efficient tool for gait data acquisition. By leveraging machine learning techniques, researchers can extract gait phases and other relevant parameters from IMU raw data[18]. The accuracy of IMUs has been validated, positioning them as a viable and accessible alternative to optical motion capture systems in gait analysis[19]. In summary, the use of IMUs facilitates the continuous detection of children's daily gait characteristics, representing a promising field for further research.

The primary objective of this study is to examine the relationship between pediatric foot pain and both static and dynamic foot postural parameters, such as rearfoot valgus angle and gait postural parameters derived from IMU. Building on existing evidence, this study hypothesizes that pediatric foot pain is linked to distinct propulsion characteristics during gait.

This paper is structured as follows: The Materials and Methods section outlines the study design, including participant selection criteria (inclusion and exclusion), study protocol, measurement techniques, and analytical approaches. The Results section presents the experimental findings, comparing static and dynamic gait posture parameters between asymptomatic children and those with foot pain. The Discussion section interprets the clinical significance of the results and addresses potential limitations. Finally, the Conclusion section summarizes the key findings and proposes directions for future research.

The main contributions of this study are summarized as follows:

- Provision of multi-day gait data collected from children in natural, daily settings.
- Facilitation of research on children's dynamic foot posture using Inertial Measurement Units.
- Identification of common gait characteristics in children with foot pain.

Related work

Recently, IMU-based machine learning methods have been applied to gait analysis in children. A study was conducted to test the reliability of machine-learning based three-dimensional gait analysis using IMU compared to optical motion capture. It showed that IMU with machine learning is a qualified alternative to the optical method, and reducing the number of sensors to two does not affect the consistency of the results[20]. Similar findings were reported in a study comparing IMUs with electronic walkways, demonstrating that IMUs are an effective tool for analyzing children's gait[21]. Furthermore, several studies have utilized IMUs to detect pediatric conditions such as cerebral palsy[22,23]. These studies highlight the value of IMUs in analyzing children's daily gait patterns. However, there is a notable lack of research investigating the gait postural characteristics in typically developing children using IMUs.

Materials and methods

Subjects

In this study, a 30-day follow-up was conducted to collect gait data from children using wearable IMU sensors. A total of 120 subjects were recruited from the NanFang Hospital (Guangzhou, China) at the beginning for regular school physical exams. During the developmental period between the ages of 7 and 11, children undergo a significant change in their gait maturation[15]. Inclusion criteria included typically developing children of both sexes between the ages of 7 and 11 years with normal limb appearance, normal range of height and body mass index (BMI), and the ability to understand and follow verbal instructions. Exclusion criteria encompassed any congenital neuromuscular disorders, or history of orthopedic surgery, or developmental issues, or an inability to follow instructions. The sample size calculation was using Power Analysis and Sample Size) 15.0 software

(NCSS, LLC, Kaysville, UT, USA). The sample size was determined based on the effect size calculated from the mean values and standard deviations (SD) of the Toe-off Coronal Projection angle (TOCP). Two-Sample T-Test Allowing Unequal Variance was performed with an alpha level of 0.05 and power of 95%, to solve for sample size. TOCP reflects the foot's frontal movement in propulsion phase, which is important and complies to the hypothesis[24]. These parameters generated a sample size of more than 12 participants in foot pain group with 81 participants in the asymptomatic group.

The Medical Ethics Committee of NanFang Hospital of Southern Medical University granted approval for the study (NFEC-2020-121). Prior to participation, comprehensive information regarding the study's purpose and procedures was conveyed to both parents and children, and written informed consent was obtained. All methodologies employed in this investigation adhere to the principles outlined in the Declaration of Helsinki. This study conforms to all STROBE guidelines and reports the required information accordingly (see Supplementary Checklist).

Basic information

Demographic data were collected by questionnaire at baseline, including age, sex, height (cm), weight (kg), and BMI (kg/m^2). Anthropometric measurements were obtained from the data of the regular school physical examinations, which were carried out by qualified school doctors. At baseline, the general history of foot pain was assessed by asking whether there had been any pain in either foot after walking in the past week (on a scale of 0–10, with 0 being no pain). Foot pain location in this study mainly refers to foot plantar area from metatarsophalangeal joints to heel area.

Static foot assessment

Static foot assessment was using rearfoot angle, which was calculated from digital images according to Ribeiro's method[6]. (Fig. 1) The requirements were as follows: Children stood in a natural rest position. The camera was placed on the floor, approximately 50 cm behind the children's backs. Two photographs were taken for each child focusing on the heels. Eligible photographs were included in the study through quality assessment. AutoCAD 2021® software was used to quantify the rearfoot alignment. A line was drawn from the posterior calcaneal tuberosity to the center of the heel. A second straight line was then drawn from the lower third of the leg through the calcaneal center. The intersection of the extensions of both straight lines gave the rearfoot angle (degrees). Measurements were taken by two assessors and the analysis was based on the average value.

Fig. 1. Measurement of the frontal alignment of the rearfoot in AutoCAD software.

Fig. 2. The placement of the IMU on the shoe: the black arrow points to the IMU, the red arrow points to the longitudinal axis of the foot.

Parameter	Abbreviation	Measure unit	Definition
Cadence	CD	steps/min	The number of unipedal gait cycles completed per minute
Instantaneous velocity	IV	cm/s	The instantaneous acceleration of the first metatarsal at the heel landing phase
Stance Percentage	STP	%	The percentage of time between heel landing and toe off in the entire gait cycle
Swing percentage	SWP	%	The percentage of time between toe off and the next heel landing in the entire gait cycle

Table 1. Descriptions of the gait parameters.

IMU data collection
Utilizing the Huawei Research Platform, the IMU data collection used a Huawei foot motion wearable sensor, manufactured by Huawei Technologies Co. Ltd, Shenzhen, China. The hardware specifications of the device comprised a triaxial accelerometer (2048 LSB/g, 200 Hz) characterized by a sensitivity of ± 16 g, and a triaxial gyroscope (16.4 LSB/dps, 200 Hz) with a sensitivity of ± 2000 dps. Each child was given two IMUs to attach to both shoes for data collection (Fig. 2).

The children were instructed to walk about 10 m at a self-selected speed on a straight concrete path for a total of 30 days. Online follow-up was performed daily between 16:00 and 20:00 to track the task completion. Raw data collected by the wearables were simultaneously transmitted to smartphones via Bluetooth, and then parents uploaded the data to Huawei Research's online server. The raw data were then processed to calculate the spatio-temporal parameters according to the algorithm generated from the motion analysis.

Dynamic foot assessment
Dynamic foot assessment includes detection of basic gait parameters and dynamic foot postural parameters. Spatiotemporal parameters were generally normalized by gait cycle (detected according to threshold). Dynamic foot postural parameters were calculated based on accelerometer and gyroscope data, the angles were calculated between the foot's longitudinal axis at toe-off and heel touch phase with respect to the at rest standing position. The definitions of the gait parameters and dynamic foot posture parameters were shown in Tables 1, 2 and Fig. 3. The analysis of the dynamic foot assessment parameters used the mean of the 30-day data to reduce bias.

Taking the line between the second and third metatarsal heads and the heel point as the foot's longitudinal axis, and the axis in the neutral standing position at rest as the reference line (direction is defined as forward in the sagittal plane), the rotation angle of the foot's longitudinal axis to the reference line was calculated during the whole gait cycle. Measurements were taken at the heel touch (the beginning of stance phase) and toe-off (the beginning of swing phase). Definition of dynamic foot posture parameters (degrees). The analysis used the mean of the 30-day data to ensure consistency.

Statistical analysis
All statistical analyses were performed using the SPSS software package, version 25 (IBM Corp. 2017 release. IBM® SPSS® Statistics for windows, Armonk, NY: IBM Corp.). Data were expressed as mean and standard deviation. The normal distribution of the data was tested using the Shapiro-Wilk test, and homogeneity of variance was assessed using Levene's test. Mann–Whitney U test to compare parameters between groups. An

Parameters	Abbreviations	Definition
Touch Coronal Projection	TCCP	The average value of the angles of the projection of foot longitudinal axis on coronal plane at touch phase and at rest standing position
Touch Sagittal Projection	TCSP	The average value of the angles of the projection of foot longitudinal axis on sagittal plane at touch phase and at rest standing position
Touch Transverse Projection	TCTP	The average value of the angles of the projection of foot longitudinal axis on transverse plane at touch phase and at rest standing position
Toe-off Coronal Projection	TOCP	The average value of the angles of the projection of foot longitudinal axis on coronal plane at toe-off phase and at rest standing position
Toe-off Sagittal Projection	TOSP	The average value of the angles of the projection of foot longitudinal axis on sagittal plane at toe-off phase and at rest standing position
Toe-off Transverse Projection	TOTP	The average value of the angles of the projection of foot longitudinal axis on transverse plane at toe-off phase and at rest standing position

Table 2. Definitions of dynamic foot posture assessed with angles between foot longitudinal axis at motion and at rest standing position.

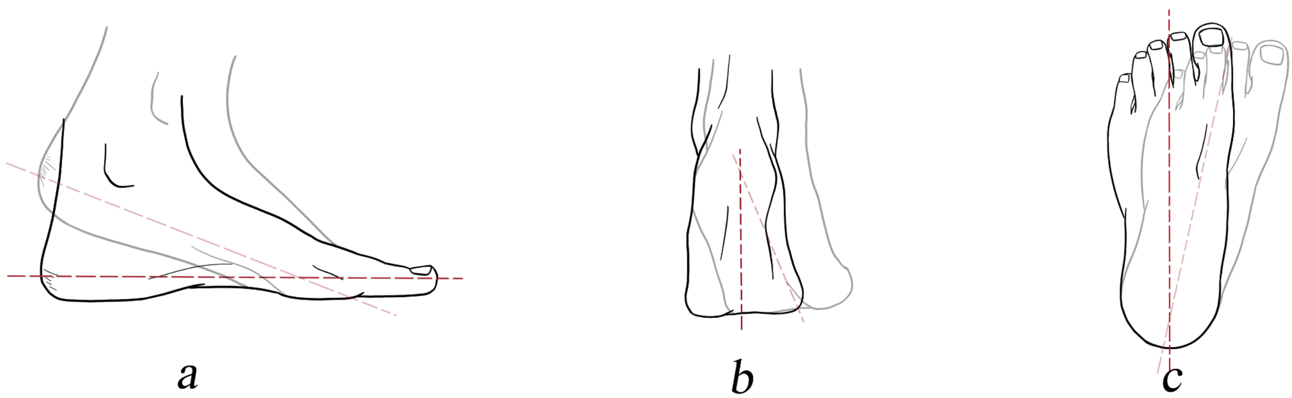

Fig. 3. Diagram of the detection of the dynamic foot posture (take the toe-off phase as an example). The red dotted line (dark) is taken as the foot's longitudinal axis. The axis in the neutral standing position at rest is taken as the reference line (light). The angle between two red dotted lines was calculated in sagittal (**a**), coronal (**b**) and transverse (**c**) projection.

Groups	Parameters				
	N	Age (y)	Weight (kg)	Height (cm)	BMI (kg/m^2)
Total	94	9.3 ± 1.3	27.6 ± 7.2	129.8 ± 9.7	16.2 ± 3.0
Asymptomatic	81	9.2 ± 1.3*	27.0 ± 7.1*	129.1 ± 9.6	16.0 ± 3.2*
Foot-pain	13	10.0 ± 1.2*	31.2 ± 7.1*	134.2 ± 10.0	17.1 ± 2.0*

Table 3. Demographics of participants (Mean ± S.D.) BMI: body mass index. *Mann–Whitney U test showed statistically significant differences in age, weight, and BMI between asymptomatic and foot-pain groups (Age $p = 0.024$, Weight $p = 0.025$, BMI $p = 0.032$).

independent t-test was used to compare the rearfoot angle between groups. Correlations between parameters were calculated using Pearson's method. Based on common classification criteria, correlations were categorized as follows: Strong correlation: $0.7 < |r| < 1$; Moderate correlation: $0.3 < |r| < 0.7$; Weak correlation: $0 < |r| < 0.3$; No correlation: $|r| < 0.3$. Bivariate logistic regression was performed (forward: conditional) with rearfoot valgus angle and all gait posutral parameters in left foot, adjusted for age, height, weight, and BMI. The Hosmer & Lemeshow test was used to test model fit. A p-value of less than 0.05 was considered statistically significant.

Results

Demographics

A total of 120 children were initially enrolled in the study. Of these, 26 dropped out due to personal reasons, as they were unable to complete the 30-day gait data collection. The remaining 94 participants successfully completed the 30-day task and provided valid data, with 39% being female (n = 37). The participants had an average age of 9.3 years (range: 7–11 years), with a mean height of 129.8 cm and a mean weight of 27.6 kg. (Table 3) Among the participants, 81 were asymptomatic, while 13 reported a history of foot pain. Notably, participants in the foot pain group showed slightly higher values for age, weight, and BMI compared to those in the asymptomatic group. These differences were accounted for and adjusted in subsequent regression analysis. The inter-rater agreement for RA measurements between the two operators was excellent, with an ICC of 0.98 (95% CI 0.970–0.989).

Correlations between parameters

The correlation analysis revealed that among all examined parameters, only cadence (CD) demonstrated significant associations with basic anthropometric measures. Specifically, CD showed moderate negative correlations with both age (r = − 0.34, $p < 0.01$) and body height (r = − 0.37, $p < 0.01$). Notably, no other static or dynamic parameters exhibited significant correlations with age, body weight, body height, or BMI (all $p > 0.05$).

The comprehensive correlation matrix, encompassing all examined parameters (RA, CD, IV, STP, SWP, TCTP, TCSP, TCCP, TOSP, TOCP, and TOTP), is visually presented in Fig. 4. This matrix provides a detailed overview of the interrelationships among these gait postural parameters.

The analysis revealed moderate inter-correlations among spatial–temporal parameters (CD, IV, STP, SWP) in both feet, with the exception of IV and STP in the right foot, which showed no correlation (r = − 0.26, $p < 0.05$). CD-IV was postively correlated (left r = 0.54, right r = 0.58, $p < 0.01$), while STP-SWP was negatively correlated (left r = − 0.43, right r = − 0.32, $p < 0.01$). Speed-related parameters (IV and CD) demonstrated consistent patterns, showing positive correlations with SWP (IV: left r = 0.45, right r = 0.46, $p < 0.01$; CD: left r = 0.59, right r = 0.61, $p < 0.01$) and negative correlations with STP (IV: left r = − 0.35, $p < 0.01$; CD: left r = − 0.50, right r = − 0.45, $p < 0.01$) across both extremities.

Furthermore, significant relationships were identified between spatial–temporal parameters and gait postural parameters (TCSP, TCCP, TCTP, TOSP, TOCP, TOTP). Specifically, CD and IV exhibited moderate positive correlations with TOSP bilaterally (CD:left r = 0.32, right r = 0.30, $p < 0.01$; IV: left r = 0.54, right r = 0.58, $p < 0.01$), while showing no significant associations with other gait postural parameters. Notably, STP displayed a moderate negative correlation with TOCP exclusively in the right foot (r = − 0.46, $p < 0.01$). Conversely, SWP showed a weak positive correlation with TCTP only in the left foot (r = 0.30, $p < 0.05$).

Static RA demonstrated no significant associations with any dynamic parameters in either extremity ($p > 0.05$ or $|r| < 0.3$ for all correlations). Regarding gait postural parameters during the touch phase, the sagittal plane parameter (TCSP) showed no significant correlation with either coronal (TCCP) or transverse plane parameters (TCTP). However, a moderate positive correlation was observed between TCCP and TCTP bilaterally (left: r = 0.39, $p < 0.01$; right: r = 0.40, $p < 0.01$).

During the toe-off phase, transverse plane parameters (TOTP) exhibited moderate to strong negative correlations with sagittal plane parameters (TOSP) in both feet (left: r = − 0.47, $p < 0.01$; right: r = − 0.60, $p < 0.01$). Notably, coronal plane parameters (TOCP) displayed plane-specific correlations exclusively in the right foot, showing a moderate negative correlation with sagittal parameters (TOSP: r = − 0.43, $p < 0.01$) and a stronger positive correlation with transverse parameters (TOTP: r = 0.57, $p < 0.01$).

Significant inter-phase correlations were observed in gait postural parameters between the touch phase and toe-off phase across both feet. Statistical analysis indicated that TCSP showed a moderate positive correlation with TOSP bilaterally (left: r = 0.52, $p < 0.01$; right: r = 0.55, $p < 0.01$), whereas it demonstrated moderate negative correlations with TOTP (left: r = − 0.33, $p < 0.01$; right: r = − 0.43, $p < 0.01$). A lateralized pattern was evident in TCCP-TOCP correlations, with significant positive association only in the right foot (r = 0.37, $p < 0.01$). Notably, TOTP exhibited the strongest positive correlations with TCTP in both feet (left: r = 0.69, $p < 0.01$; right: r = 0.66,

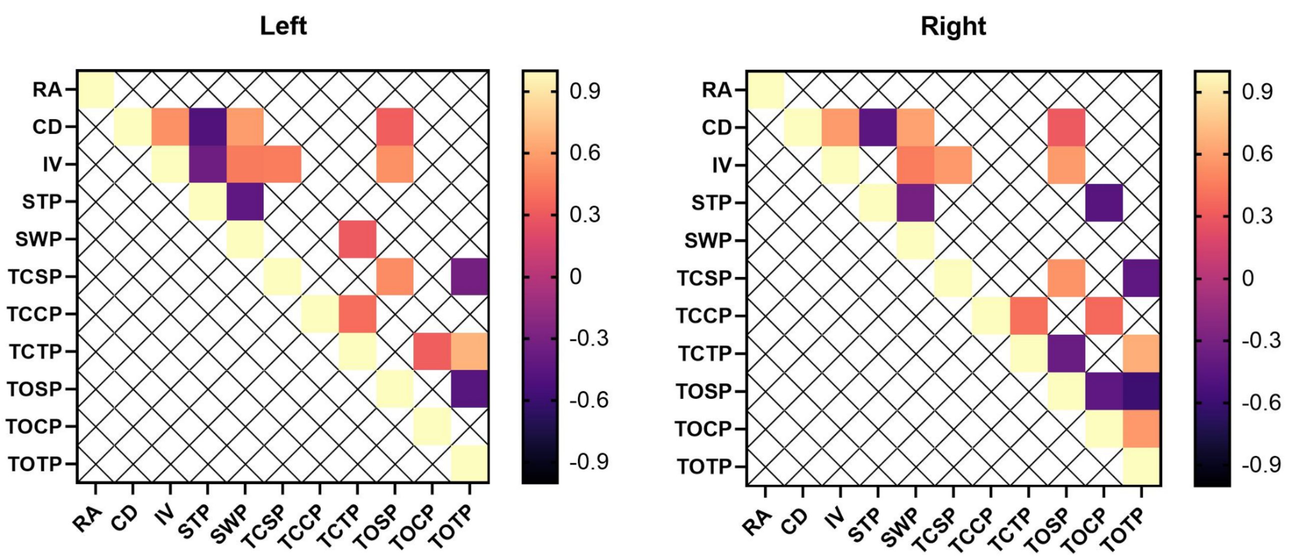

Fig. 4. Heat map of the correlation (− 1 ≤ r ≤ 1) between static and dynamic parameters in the left and right foot ($p < 0.05$).

Parameters	Left		Right	
	Asymptomatic	Foot-pain	Asymptomatic	Foot-pain
RA (degrees)[a]	10.0 ± 4.8[#]	13.9 ± 6.8[#]	11.0 ± 5.3	9.8 ± 3.9
CD (steps/min)	116 ± 9	113 ± 14	116 ± 9	115 ± 13
IV (cm/s)	78 ± 12	80 ± 14	78 ± 11	80 ± 14
STP (%)	62 ± 2	63 ± 2	62 ± 2	63 ± 2
SWP (%)[b]	41 ± 7*	38 ± 8*	41 ± 6	38 ± 8
TCSP (degrees)	13.2 ± 3.9	13.3 ± 3.9	13.6 ± 4.1	13.8 ± 3.7
TCCP (degrees)	6.5 ± 2.1	6.3 ± 2.5	6.8 ± 2.3	6.6 ± 2.7
TCTP (degrees)	5.4 ± 2.0	4.8 ± 1.5	5.6 ± 2.0	5.4 ± 2.2
TOSP (degrees)	52.2 ± 7.5	49.7 ± 7.9	51.3 ± 8.2	49.3 ± 7.7
TOCP (degrees) [b]	13.6 ± 7.5*	9.4 ± 2.5*	13.8 ± 8.6	12.0 ± 4.1
TOTP (degrees)	14.0 ± 7.2	11.8 ± 4.7	14.1 ± 6.8	12.0 ± 4.5

Table 4. Gait parameters and rearfoot angle in asymptomatic and foot pain groups (Mean ± S.D.). [a]Independent t-test showed statistically significant differences between asymptomatic and foot-pain groups ([#]RA, $p = 0.011$). [b]Mann–Whitney *U* test showed statistically significant differences between asymptomatic and foot-pain groups (*SWP, $p = 0.041$; *TOCP, $p = 0.004$).

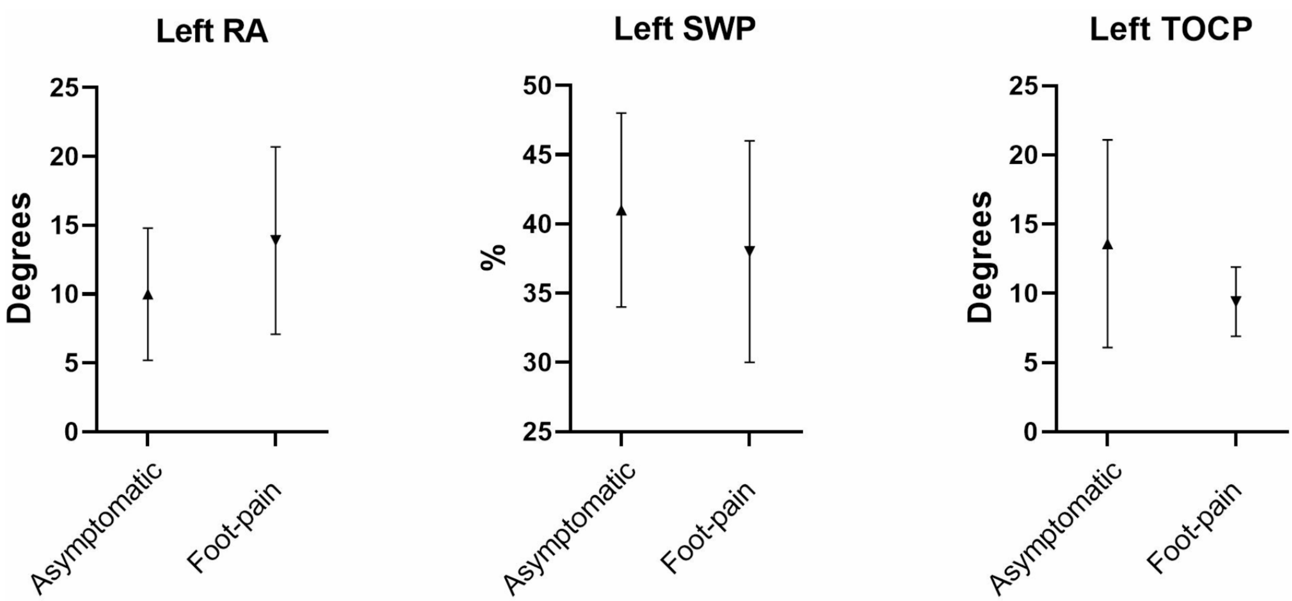

Fig. 5. Measurement with significant group differences. RA, Rearfoot angle; SWP, Swing percentage; TOCP, Toe-off Coronal Projection.

$p < 0.01$). Furthermore, TCTP displayed asymmetric correlations, showing a moderate negative association with TOSP in the right foot (r = – 0.38, $p < 0.01$) but a positive correlation with TOCP in the left foot (r = 0.32, $p < 0.01$).

Analysis of group differences in static and dynamic parameters

The analysis revealed a notable lateralization effect, with only left foot parameters demonstrating significant group differences across both static and dynamic measures (Table 4). Comparative analysis between the foot-pain and asymptomatic groups showed distinct gait postural alterations. Specifically, the foot-pain group exhibited a significantly higher mean rearfoot angle (RA) (13.9° ± 6.8°) compared to the asymptomatic group (10.0° ± 4.8°; $p < 0.05$). Conversely, the foot-pain group displayed reduced mean values in both swing percentage (SWP) (38% ± 8% vs. 41% ± 7%; $p < 0.05$) and toe-off coronal projection angles (TOCP) (9.4° ± 2.5° vs. 13.6° ± 7.5°; $p < 0.05$) relative to the asymptomatic group. (Fig. 5) These findings suggest distinct gait postural alterations associated with foot pain, particularly in the left extremity.

Bivariate logistic regression analysis

A bivariate logistic regression analysis was performed to identify potential predictors of foot pain. The model incorporated foot pain group as the dependent variable, with all gait postural parameters and rearfoot angle (RA) in the left foot as independent variables, while controlling for age, height, weight, and BMI as covariates.

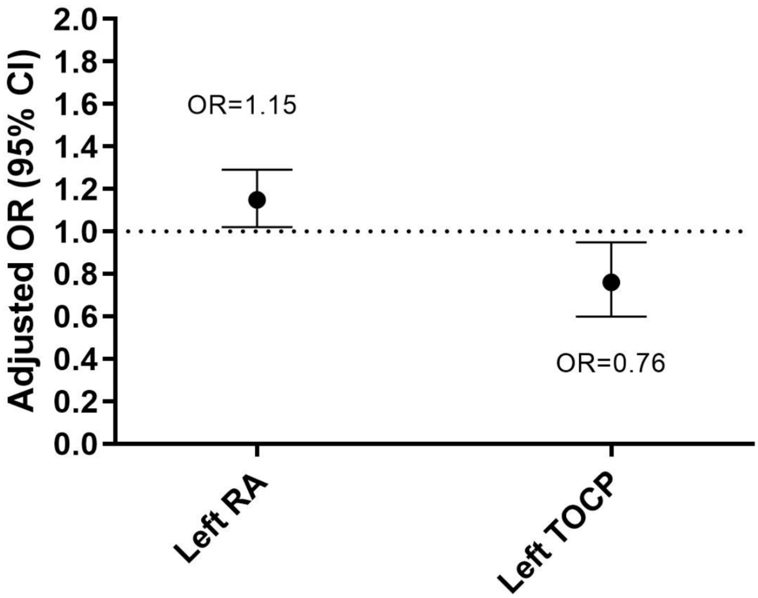

Fig. 6. Adjusted OR (95% CI) for foot pain in a bivariate logistic regression analysis. RA, Rearfoot Angle; TOCP, Toe-off Coronal Projection. OR < 1.0 indicates a protective effect, OR > 1.0 indicates a promotive effect.

Model adequacy was confirmed through the Hosmer–Lemeshow test, which indicated satisfactory model fit at all stages ($p > 0.05$). The analysis revealed two significant independent predictors of foot pain: left rearfoot angle (RA) (OR 1.15, 95% CI 1.02–1.29, $p = 0.021$) and left toe-off coronal projection (TOCP) (OR 0.76, 95% CI 0.60–0.95, $p = 0.016$). These associations were visually represented in Fig. 6.

Discussion

This study reveals distinct long-term gait postural characteristics in children with foot pain, particularly in rearfoot angle (RA), swing phase percentage (SWP), and toe-off coronal projection angle (TOCP). These findings provide valuable insights into the biomechanical alterations associated with pediatric foot pain and highlight the potential of IMU technology for early detection and intervention.

The significantly larger rearfoot angle observed in children with foot pain suggests potential rearfoot valgus or eversion, indicating a pronated rearfoot posture. While rearfoot valgus is often associated with biomechanical alterations and increased risk of lower extremity injuries during intense movement, its clinical significance in children remains debated[25,26]. Some researchers consider foot pronation in children as a developmental variation, whereas others argue it may predispose to biomechanical issues[27,28]. Our findings support the latter perspective, indicating that altered foot posture in children warrants attention due to its potential to contribute to biomechanical problems, such as elevated plantar load under the medial foot—a known feature of plantar fasciopathy[29].

Swing phase duration, a critical parameter for assessing balance control and propulsion function, was significantly reduced in children with foot pain. However, regression analysis did not identify SWP as a significant predictor of foot pain, suggesting that foot pain may not markedly alter overall gait patterns. This finding aligns with previous studies showing that children with foot pain maintain a regular gait cadence under self-selected speed conditions[17,30]. Nevertheless, subtle changes in gait posture, particularly during the toe-off phase, were detected, underscoring the importance of propulsion function in pediatric foot pain.

Significant differences in coronal plane motion during the toe-off phase were observed in children with foot pain, with reduced motion range compared to asymptomatic individuals. This finding challenges the traditional mid-foot rigid lever theory, which posits that the foot should become stiff during gait propulsion. Recent studies suggest that normal midfoot motion should exhibit a range close to 15° in the coronal and transverse planes[31]. Our results support this revised perspective, indicating that restricted coronal motion during propulsion may impair the midfoot's ability to transfer body weight and propel the center of mass forward. To our knowledge, this is the first study to report propulsive coronal foot movement in a pediatric population, offering new insights for future research.

Consistent with previous studies, no significant correlation was found between static rearfoot angle and dynamic postural parameters[32]. This suggests that static and dynamic foot postures may independently influence foot pain outcomes. Regression analysis identified static rearfoot angle as a promotive factor for foot pain, while dynamic TOCP acted as protective factors. This highlights the complex interplay between static and dynamic biomechanical factors in pediatric foot pain.

The findings underscore the potential of IMU technology for detecting foot pain risks in children, particularly through the evaluation of static foot posture and dynamic propulsion function. Continuous gait data recording could further enhance the identification of pathological gait patterns, enabling earlier intervention. However, this study has limitations. First, significant results were observed only in the left foot, potentially due to laterality effects or sampling bias. However, previous studies have noted that the left foot may be more sensitive to postural changes[33]. Second, the relatively small sample size in the foot pain group may have influenced model estimates, although the use of long-term data partially mitigated this issue. Third, the study employed a standardized protocol rather than continuous daily activity monitoring, which was meant to better normalize the gait pattern collection. Future studies should prioritize continuous data collection to validate these findings and provide more pragmatic solutions.

Conclusions

This study demonstrates the utility of IMU technology in characterizing long-term gait patterns in children with foot pain. The findings indicate that pediatric foot pain is associated with two distinct biomechanical features: increased static rearfoot angle and reduced dynamic propulsion posture in the coronal plane. Furthermore, the results corroborate the relationship between restricted foot motion range during propulsion and foot pain in pediatric populations. The observed lateralization effect, with significant differences primarily evident in the left foot, suggests the potential influence of functional laterality in pediatric gait pathology. These findings provide a scientific foundation for developing IMU-based algorithms to predict musculoskeletal disorders in children, offering potential for early detection and intervention strategies.

Data availability

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

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Author contributions
ZYF contributed to the design of the study, data reduction/analysis and drafted the first draft; JYL contributed to the design of the study, data curation and supervision; HJW, FHL, YKL, CC contributed to the design of the study, data curation and supervision, revision of the manuscript. YWL, YWW, CZG, SYX, XLP, LGZ, MSF, KRZ, WL, KZ contributed to data collection and analysis. All authors contributed to drafting the manuscript. All authors read and approved the final version of the manuscript and agree with the order of authorship. ZYF is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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