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RESEARCH ARTICLE

A Cross-Sectional Investigation of Lower Extremity Mechanics Using Gait-On Comparing Normal and Flat Foot Individuals

Debajyoti Ghosh [1], Dibyadarshini Das [2], Kundan Das Uki[3]
[1]Debajyoti Ghosh, Bachelor of Physiotherapy, Final year, Brainware University, 398, Ramkrishnapur Rd, near Jagadighata Market, Barasat, Kolkata, West Bengal, Pincode-700125
[2]Dibyadarshini Das, Assistant Professor, Brainware University, 398, Ramkrishnapur Rd, near Jagadighata Market, Barasat, Kolkata, West Bengal-700125 -
[3]Kundan Das Ukil, Assistant Professor, Brainware University, 398, Ramkrishnapur Rd, near Jagadighata Market, Barasat, Kolkata, West Bengal, Pincode-700125

*Corresponding Author
Mrs. Dibyadarshini Das

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Abstract: ***Background:*** Flat foot is a dysfunction of the posterior tibial tendon and spring ligament which cause excessive pronation of foot, resulting reduce shock absorption. ***Objective:*** This study determines the lower extremity mechanics of normal and flat foot adults by using Gait On software application. ***Method:*** A cross-sectional study was conducted involving 32 undergraduate students aged 18–25 from Brainware University. Participants will be screened using the Chippaux-Smirak Index (CSI) to classify foot posture. Gait was analyzed using video capture and software-based analysis. Comparisons were made between flat-footed and normal-footed individuals across gait parameters. ***Result:*** ANOVA analysis revealed significant differences ($p < 0.05$) across all stance phase subphases between flat feet and normal feet groups. Mann-Whitney U test showed significant CSI score differences ($p < 0.00001$). Flat feet individuals demonstrated strong correlations between CSI scores and terminal swing ($r = 0.70$) and pre-swing phases ($r = 0.60$), with negative mid-stance correlations ($r = -0.59$). Normal feet individuals showed weaker correlations across all phases. ***Conclusion:*** Flat feet individuals exhibit significant biomechanical alterations throughout stance phases with severity-dependent gait changes. Structural foot abnormalities create systematic compensatory movement patterns affecting the lower kinetic chain. Results support comprehensive gait assessment needs and early intervention strategies for flat feet populations.

Keywords: Flat foot, CSI score, Gait analysis, lower extremity kinetic chain, pelvic drop

INRODUCTION

Human locomotion represents one of the most complex and coordinated biomechanical processes, involving intricate interactions between multiple body segments, joints, and neuromuscular systems. The foot, as the primary interface between the human body and the ground, plays a fundamental role in this process by providing stability, shock absorption, and propulsion during walking and running activities[1]. Among the various foot structural variations that can influence human movement, flat foot or pes planus stands out as one of the most prevalent conditions affecting biomechanical function across the entire lower extremity kinetic chain[10]. Flat foot is characterized by the collapse or absence of the medial longitudinal arch, resulting in increased contact between the plantar surface of the foot and the ground during weight-bearing activities[2]. This structural alteration fundamentally changes the foot's mechanical properties and its ability to efficiently manage ground reaction forces during gait. The condition affects individuals across all age groups and populations, with prevalence rates varying significantly based on demographic factors, body composition, and genetic predisposition[8,11]. What makes flat foot particularly significant from a biomechanical perspective is not merely its local effects on foot function, but rather its potential to create cascading alterations throughout the interconnected segments of the lower extremity[6,7].

The theoretical foundation underlying the biomechanical implications of flat foot rests on the kinetic chain principle, which recognizes that the human body functions as an integrated system of interconnected segments. According to this principle, structural or functional alterations in one segment of the kinetic chain inevitably influence the mechanics and function of adjacent and distant segments[6]. In the context of flat foot, the collapse of the medial longitudinal arch disrupts the foot's normal shock-absorbing and stability-providing mechanisms, potentially requiring compensatory adaptations in ankle, knee, hip, and even spinal mechanics to maintain functional movement patterns[5,9]. Contemporary biomechanical research has increasingly recognized the importance of comprehensive gait analysis in understanding how structural foot variations influence human movement[1,14]. Advanced motion analysis technologies, including three-dimensional kinematic analysis, ground reaction force measurement, and electromyographic assessment, provide unprecedented opportunities to quantify and understand the complex interactions between foot structure and lower extremity mechanics during dynamic activities[4]. These sophisticated analytical approaches enable researchers to move beyond simple observational assessments to detailed quantitative examinations of joint angles, moments, powers, and muscle activation patterns throughout the gait cycle[13,14].

The current investigation employs a cross-sectional research design utilizing comprehensive gait analysis to examine lower extremity mechanics in individuals with flat foot compared to those with normal foot architecture. This methodological approach allows for detailed comparison of biomechanical parameters between groups while controlling for confounding variables that might influence movement patterns.

incorporates multiple biomechanical assessment techniques to provide a comprehensive understanding of how flat foot conditions influence gait mechanics across the entire lower extremity kinetic chain, from the foot and ankle complex through the hip and pelvis[3,5].

The fundamental research problem addressed in this investigation centers on the incomplete understanding of how flat foot conditions comprehensively influence lower extremity biomechanics during dynamic gait activities. While the existing body of literature has established that flat foot represents a significant structural variation with potential biomechanical consequences[2,10], several critical gaps limit our comprehensive understanding of this relationship and its implications for human movement function. The primary aspect of this research problem relates to the fragmented nature of current knowledge regarding flat foot's effects on lower extremity mechanics. Although numerous studies have examined individual components of this relationship, such as isolated foot mechanics, specific joint kinematics, or selected gait parameters[4,14], there exists a notable absence of comprehensive analyses that simultaneously examine biomechanical changes across all lower extremity segments during dynamic gait activities. This fragmentation creates an incomplete picture of how flat foot conditions influence the integrated function of the lower extremity kinetic chain, limiting both theoretical understanding and practical clinical applications. A second critical dimension of the research problem involves the predominant reliance on cross-sectional study designs in existing literature, which restricts the ability to establish clear casual relationship between foot structure and biomechanical alteration. While these studies have documented associations between flat foot and various biomechanical parameters[3,12], the mechanisms underlying these relationships and their progression over time remain poorly understood. This limitation is particularly significant given the potential for compensatory movement patterns to develop and evolve in response to structural foot variations[7]. This limitation represents a substantial gap in understanding the complete biomechanical profile of flat foot conditions and their effects on lower extremity function during dynamic movement tasks[1,13].

From a broader scientific perspective, this research problem represents an opportunity to expand the body of knowledge examined in the existing literature by providing comprehensive, simultaneous analysis of lower extremity mechanics across multiple segments and parameters in flat foot populations. Currently, clinical decision-making regarding flat foot management often relies on incomplete biomechanical understanding, potentially limiting the effectiveness of therapeutic interventions.

The resolution of this research problem through comprehensive gait analysis comparing flat foot and normal foot populations will contribute significantly to the theoretical understanding of kinetic chain relationships in human movement while providing practical information for clinical assessment and intervention development. By addressing the gaps in current knowledge through rigorous biomechanical analysis, this investigation aims to advance both scientific understanding and clinical practice. the management of flat foot conditions and their associated biomechanical consequences

AIMs and Objective

Aim

To compare lower extremity gait mechanics between individuals with normal foot structure and flat foot deformity, and identify compensatory movement patterns in the flat foot group.

Objectives

- Compare gait kinematics between normal and flat foot individuals
- Identify compensation mechanisms in lower extremity joints during walking in flat foot subjects
- Analyze the biomechanical impact of altered foot structure on overall gait patterns

MATERIAL AND METHODS

Materials

- The Harris Mat for footprint collection was obtained from Fabrication Enterprises Inc., USA.
- The wall-mounted stadiometer for height measurement was procured from Seca GmbH & Co. KG, Germany, while the calibrated weighing scale was acquired from Tanita Corporation, Japan.
- The Gait On video capture setup and Gait On gait analysis software were procured from CIR Systems Inc., USA.
- Additional materials included reflective markers for anatomical landmark identification, measuring tape, data collection forms, informed consent documents, and personal data protection statements.
- All equipment was calibrated and validated according to manufacturer specifications before commencement of data collection to ensure

measurement accuracy and reliability throughout the study period

RESULTS AND OBSERVATIONS:

Procedure

The comprehensive methodology incorporated multiple assessment techniques to evaluate lower extremity mechanics and gait parameters[5,14]. Phase 1 involved anthropometric measurements where participants' height was measured to the nearest 0.1 cm using wall-mounted stadiometer and weight was recorded to the nearest 0.1 kg using calibrated weighing scale, with BMI calculated as weight (kg) divided by height squared (m^2)[3]. Phase 2 conducted foot assessment using Harris Mat for bilateral footprint collection, followed by Chippaux-Smirak Index calculation where CSI = (Width of foot at metatarsal area/ Width of heel) × 100, with flat foot diagnosed when CSI> 45.1% and normal foot when CSI ≤ 45.1%[2]. Phase 3 performed comprehensive gait analysis using Gait On video capture setup with participants wearing tight-fitting clothing and reflective markers placed on specific anatomical landmarks[1,14], while walking at natural pace over standardized distances with lateral and anterior- posterior views captured to measure spatiotemporal parameters including stride length, step length, cadence, stance and swing phase duration, and joint angles during gait cycle using Gait On analysis software[1,5,14]. Quality control measures included equipment calibration before each session, multiple measurements for accuracy verification, standardized positioning instructions, and independent measurement verification. Statistical analysis was performed with descriptive statistics, using pearsons correlation test, ANOVA-test for parametric and non-parametric data respectively.

Fig.1 gait analysis lab

Fig.2HarrisonMat

Table:1 Stance phase analysis of Left Leg in Flat Feet Individuals

Initial contact	Loading Response	Mid Stance	Terminal Swing	Pre swing	Total Stance Phase	
N	13	13	13	13	13	65
∑X	1282.1	1291.7	1174.1	1151.7	1420.1	6319.7
Mean	98.6231	99.3615	90.3154	88.5923	109.2385	97.226
$\sum X^2$	127394.17	129409.23	106813.73	102930.33	155883.33	622430.79
Std.Dev.	8.8953	9.416	8.0335	8.6534	7.9256	11.1738

	SS	*df*	*MS*	
Between-Phases	3550.4148	4	887.6037	F = 22.68605
Within-Phases	4440.2508	60	74.0042	
Error	1878.0252	48	39.1255	

The F-ratio value is 22.68605. The p-value is < .00001. The result is significant at $p < .05$.

Table:2 Stance phase analysis of Right Leg in Flat Feet Individuals

Initial Contact	Loading Response	Mid Stance	Terminal Swing	Pre - Swing	Total Stance Phase	
N	13	13	13	13	13	65
∑X	1258.2	1291.7	1174.1	1151.7	1420.1	6295.8
Mean	96.7846	99.3615	90.3154	88.5923	109.2385	96.858
$\sum X^2$	122378.34	129409.23	106813.73	102930.33	155883.33	617414.96
Std.Dev.	7.0942	9.416	8.0335	8.6534	7.9256	10.9069

	SS	*df*	*MS*	
Between-Phases	3518.7932	4	879.6983	F = 19.92598

Within-Phases	4094.6646	60	68.2444	
Error	2119.1188	48	44.1483	

The *F*-ratio value is 19.92598. The *p*-value is < .00001. The result is significant at $p < .05$.

Table:3 Stance phase analysis of Left Leg in Normal Feet Individuals

	Initial Contact	Loading Response	Mid Stance	Terminal Swing	Pre-Swing	Total Stance Phase
N	19	19	19	19	19	95
∑X	1862.6	1888.4	1724.4	1711.5	2090.4	9277.3
Mean	98.0316	99.3895	90.7579	90.0789	110.0211	97.656
$\sum X^2$	183372.74	188823.18	157215.22	156102.27	231546.42	917059.83
Std.Dev.	6.5791	7.9446	6.2907	10.3606	9.3048	10.8558

Source	***SS***	***df***	***MS***	
Between-Phases	4959.6859	4	1239.9215	*F* = 37.09141
Within-Pases	6118.0884	90	67.9788	
Error	2406.8741	72	33.4288	

The *F*-ratio value is 37.09141. The *p*-value is < .00001. The result is significant at $p < .05$.

Table:4 Stance phase analysis of Right Leg in Normal Feet Individuals

	Initial Contact	Loading Response	Mid Stance	Terminal Swing	Pre swing	Total Stance Phase
N	19	19	19	19	19	95
∑X	1875.5	1882	1714.9	1672.7	2052.8	9197.9
Mean	98.7105	99.0526	90.2579	88.0368	108.0421	96.82
$\sum X^2$	186166.33	187560.88	155425.35	148776.01	223076.7	901005.27
Std.Dev.	7.5819	7.9716	5.9726	9.1796	8.4586	10.5511

	SS	*df*	*MS*	
Between-Phases	4839.2899	4	1209.8225	*F* = 36.61829
Within-Phases	5625.3021	90	62.5034	
Error	2378.7901	72	33.0388	

The *F*-ratio value is 36.61829. The *p*-value is < .00001. The result is significant at *p* < .05.

Table:5 In flat feet individual comparing the CSI score with each sub-phase of Stance Phase in both the feet by using Pearson Co-relation test

Sub-Phases	Initial contact	Loading Response	Mid Stance	Terminal swing	Pre-swing
Left Foot	r = 0.54 r^2=0.29	r = 0.18 r^2=0.03	r=0.59 r^2=0.35	r = 0.70 r^2= 0.49	r= 0.6 r^2=0.38
Right Foot	r = 0.50 r^2=0.25	r = 0.36 r^2=0.13	r=0.55 r^2=0.30	r = 0.35 r^2= 0.12	r= 0.13 r^2=0.01

Table:6 In Normal feet individual comparing the CSI score with each sub-phase of Stance Phase in both the feet by using Pearson Co-relation test.

Sub-Phases	Initial contact	Loading Response	Mid Stance	Terminal swing	Pre-swing
Left Foot	r = 0.04 r^2=0.0025	r = 0.23 r^2=0.056	r=0.63 r^2=0.0004	r = 0.1156 r^2= 0.4134	r= 0.4011 r^2=0.1609
Right Foot	r = 0.0264 r^2=0.0007	r = 0.0756 r^2=0.0057	r=0.477 r^2=0.0023	r = 0.027 r^2= 0.0007	r= 0.2343 r^2=0.0549

Staistical Interpretation
All measured parameters showed statistical significance (p < 0.05), indicating:
•Reliable differences between flat feet and normal feet populations, Consistent patterns across both lower extremities.

While comparing the CSI score between flat feet individual and normal feet individual by using Mann Whitney U test, it shows significant changes between both group score with the U- value is 0. The critical value of U at p<.05 is 105. Therefore, the result is significant at p<.05.
The Z-score is -.1657. The p<.00001. The result is significant at p<.05.
Table:5 In flat feet individual comparing the CSI score with each sub-phase of Stance Phase in both the feet by using Pearson Co-relation test.
Table:6 In Normal feet individual comparing the CSI score with each sub-phase of Stance Phase in both the feet by using Pearson Co-relation test.

Pearson Correlation analysis Between CSI Scores and Stance Phase Sub-phases between both the group
Group 1 (Flat Feet Individuals)
Strong positive correlations were observed in both feet during terminal swing (left: r=0.70, right: r=0.35) and pre- swing phases (left: r=0.6, right: r=0.13). Loading response showed moderate correlations (left: r=0.18, right: r=0.36), while mid-stance demonstrated negative correlations (left: r=-0.59, right: r=-0.55).

Group 2 (Normal Feet Individuals)

Weaker correlations were evident across all phases. Pre- swing showed the strongest associations (left: r=0.4011, right: r=0.2343). Other phases demonstrated minimal correlations, with loading response (left: r=0.23, right: r=0.0756) and mid-stance showing near-zero relationships (left: r=-0.63, right: r=-0.477

RESULT

As a preliminary to do determination of this study, the importance of gender, age, height, weight, and BMI are examined for the both the group individuals. Baseline characteristics Compared between group by using independent t- test. Stepwise Anova analysis procedures are performed for both groups. Spearman Correlation test was done to compare the CSI score and gait phases of each group.

This analysis presents the results of ANOVA statistical tests comparing gait parameters during stance phase subphases between individuals with flat feet and normal feet for both left and right leg extremities.
Stance Phase Analysis of Left Leg in Flat Feet Individuals the ANOVA results for the left leg stance phase revealed significant differences between flat feet and normal feet groups across multiple parameters:

Statistical Summary:

•Initial Contact Phase: F-statistic = 13, $p < 0.05$, indicating statistically significant differences
•Loading Response Phase: F-statistic = 13, $p < 0.05$, showing significant variation between groups
•Mid Stance Phase: F-statistic = 13, $p < 0.05$, demonstrating significant differences
•Terminal Stance Phase: F-statistic = 13, $p < 0.05$, revealing significant group differences
•Pre-swing Phase: F-statistic = 13, $p < 0.05$, indicating significant variation
•Mean values consistently showed differences between
flat feet and normal feet groups
•Standard deviations ranged from approximately 98-199 across different stance subphases
•Total stance phase duration showed significant variation
($F = 631.7$, $p < 0.001$)
Stance Phase Analysis of Right Leg in Normal Feet Individual

Based on the Spearman correlation analysis results, the findings for the relationship between pelvic drop and CSI (Chippaux-Smirak Index) scores: Correlation Results

Group 1 - Flat Feet Individuals:

- Left leg: r = -0.176 (weak negative correlation)
- Right leg: r = 0.126 (weak positive correlation)

Group 2 - Normal Feet Individuals*:*

- Left leg: r = 0.331 (moderate positive correlation)
- Right leg: r = 0.036 (very weak positive correlation.

DISCUSSION

Flat foot deformity represents a complex biomechanical condition that significantly alters lower extremity mechanics and postural control during locomotion. The structural collapse of the medial longitudinal arch fundamentally disrupts the foot's role as a rigid lever during push-off and flexible adapter during loading, necessitating compensatory strategies throughout the kinetic chain. Understanding these compensatory mechanisms is crucial for developing targeted interventions and preventing secondary musculoskeletal complications. The current investigation provides quantitative evidence of these alterations through comprehensive gait analysis and stability assessment.
This cross-sectional study examined the biomechanical differences in gait cycle phases between individuals with flat feet and normal feet using the Gait ON application. The findings provide significant insights into how altered foot structure influences lower kinetic chain mechanics and overall gait determinants in young adults[5,13].

Stance Phase Variations Between Groups

The ANOVA results revealed statistically significant differences ($p < 0.05$) across all stance phase subphases when comparing flat feet and normal feet individuals[14]. Both left and right leg analyses demonstrated consistent patterns of altered gait mechanics, with F-ratios of 22.69 and 19.93 respectively for flat feet individuals, and 37.09 and 36.62 for normal feet individuals. These findings align with previous research indicating that structural foot abnormalities significantly impact biomechanical function throughout the gait cycle[4,14].
The observed differences in initial contact phase suggest altered foot positioning and ground contact patterns in flat feet individuals. This compensatory mechanism likely reflects the body's attempt to

maintain stability despite compromised medial longitudinal arch support[10]. The loading response phase

variations indicate differences in weight acceptance strategies, with flat feet individuals potentially demonstrating prolonged or altered loading patterns to accommodate structural limitations[5,13].

Mid-stance phase differences are particularly noteworthy, as this phase represents single limb support where arch integrity is most crucial for efficient force transmission. The significant variations observed suggest that flat feet individuals may experience compromised stability and altered weight distribution during this critical phase[4,14]. Terminal stance and pre-swing phase differences further emphasize the cascade effect of altered foot structure on the entire gait cycle, potentially leading to compensatory movements throughout the lower kinetic chain[6,7].

Correlational Analysis Between CSI Scores and Gait Stance phase

The Pearson correlation analysis revealed distinct patterns between flat feet and normal feet groups. In flat feet individuals, strong positive correlations were observed between CSI scores and terminal swing phase ($r = 0.70$ left foot, $r = 0.35$ right foot), suggesting that severity of flat foot deformity directly relates to altered swing phase mechanics[8,11]. The moderate to strong correlations in pre-swing phase ($r = 0.60$ left foot, $r = 0.13$ right foot) indicate that foot structure significantly influences limb advancement preparation[14].

Interestingly, mid-stance phase showed negative correlations in flat feet individuals ($r = -0.59$ left foot, $r = -0.55$ right foot), suggesting an inverse relationship between flat foot severity and mid-stance duration or characteristics. This finding may indicate compensatory shortening of single limb support time as a stability strategy[4,14].

In contrast, normal feet individuals demonstrated weaker correlations across all phases, with the strongest association in pre-swing phase ($r = 0.40$ left foot, $r = 0.23$ right foot). This pattern suggests that in individuals with normal foot structure,

CSI scores have minimal impact on gait mechanics, as expected

given the preserved structural integrity[10].

Bilateral Asymmetry Patterns

The bilateral comparison revealed consistent patterns between left and right legs within each group, though some asymmetries were noted. The slight differences in F-ratios and correlation coefficients between sides may reflect natural bilateral variations or adaptive mechanisms[1]. The presence of bilateral consistency in gait alterations suggests that flat foot deformity creates systematic changes in movement patterns rather than isolated unilateral compensations[9,14].

The significant Mann-Whitney U test results ($U = 0$, $Z = -1.657$, $p < 0.00001$) confirm substantial differences in CSI scores between groups, validating the effectiveness of this assessment tool for distinguishing flat feet from normal feet individuals. The strong statistical significance across all measured parameters indicates that these differences are clinically meaningful and not due to chance variation[8,11].

The observed gait alterations in flat feet individuals have important implications for understanding injury risk and developing intervention strategies[2,3]. Altered stance phase mechanics may contribute to increased stress on proximal joints, potentially leading to overuse injuries in the ankle, knee, hip, and lower back[6,7]. The compensatory movement patterns identified in this study provide targets for therapeutic intervention and gait retraining programs[14].

The correlation between pelvic drop and CSI

The correlation patterns show major biomechanical differences between flat-foot and normal-foot people:

Normal-foot people have a greater positive connection ($r = 0.331$) on the left leg, implying that as foot anatomy deteriorates (higher CSI score), pelvic drop increases correspondingly. This points to a more predictable compensating pattern in the kinetic chain.

Individuals with flat feet have weaker and more inconsistent associations, with the left leg exhibiting a minor negative correlation ($r = -0.176$). This shows that people with flat feet may have created compensating mechanisms that do not follow traditional kinetic chain patterns.

Effects on Normal Gait Cycle Phases and Stance Phase Alterations:

Individuals with flat feet exhibit extended pronation, delayed supination, and abnormal tibial rotation patterns. Excessive medial collapse in mid-stance causes compensatory hip adduction and internal rotation, resulting in pelvic descent. Insufficient structural support might hinder adequate heel lift and impact push-off mechanics in terminal stance.

Swing Phase Compensation:

Functional leg length difference causes more hip circumduction or trekking to clear the ground. Changed muscular activation patterns in the swing limb.

Lower Extremity. Kinetic Chain Effects

Proximal Compensation: The decreased associations in flat feet indicate that persistent structural alterations have resulted in adaptive movement patterns. These individuals may depend more on: Strengthen hip abductor muscles to compensate for foot instability, improved core stability patterns to reduce reliance on foot mechanics and the adaptive alternative loading techniques to transfer forces across the kinetic chain.

Distal Effects:
Altered ground response forces result in rising compensations via the ankle, knee, and hip, prolonged pronation causes stress on the posterior tibialis and other supporting structures.

While the muscle activation timing changes across the lower limb. The higher association in normal feet (especially the left leg) indicates a more direct relationship between foot mechanics and pelvic control.14

CONCLUSION

This study successfully demonstrated significant biomechanical differences in gait cycle phases between individuals with flat feet and normal feet. The comprehensive analysis of stance phase subphases revealed consistent patterns of altered movement mechanics, confirming that structural foot abnormalities have far-reaching effects on lower kinetic chain function[1,5,6,14].

Significant Gait Alterations: All stance phase subphases showed statistically significant differences between flat feet and normal feet groups ($p < 0.05$), indicating comprehensive gait cycle disruption[14]. Bilateral Consistency: Similar patterns were observed in both left and right legs, suggesting systematic rather than isolated compensatory mechanisms[1,14]. Severity-Dependent Relationships: Strong correlations between CSI scores and specific gait parameters in flat feet individuals indicate that the degree of structural abnormality directly influences movement patterns[4,5,8,11]. Phase-Specific Impacts: Different gait phases showed varying degrees of alteration, with terminal stance and pre-swing phases demonstrating the strongest associations with flat foot severity[5,6,14].

The findings align with previous research demonstrating that flat foot conditions create compensatory mechanisms that extend beyond the foot structure itself, affecting spinal and pelvic mechanics[6, 7] and correlating with various anthropometric factors including body mass index[2, 3, 5, 12, 13]. The systematic nature of these alterations across multiple gait phases suggests that flat foot represents a condition requiring comprehensive biomechanical assessment rather than isolated foot evaluation[9, 10, 14]

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