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Comparison of Plantar Pressure Distribution Patterns during Walking in Female Students Aged 12–14 Years with Flat and Normal Feet: A Cross-Sectional Comparative Study

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Original Article

Abstract

Introduction: Flexible flatfoot is one of the most common musculoskeletal abnormalities during adolescence. It can affect the biomechanical function of the lower extremity by altering plantar pressure distribution, potentially increasing the risk of musculoskeletal injuries. Given these factors, the objective of this study was to compare the plantar pressure distribution during walking in adolescent girls with flexible flatfoot and their counterparts with normal foot arches.

Materials and Methods: In this cross-sectional study, 32 female students aged 12–14 years were divided into two equal groups of 16 (flexible flatfoot and normal foot). Peak plantar pressure and contact area were measured across 10 anatomical regions using the emed® C50 plantar pressure measurement system. The data were analyzed using linear mixed-effects models, and the Bonferroni correction was applied to control for errors arising from multiple comparisons.

Results: The flexible flatfoot group exhibited a significantly greater contact area in the medial midfoot region (M3) than the normal-arch group ($P < 0.001$, Cohen's $d = 1.997$). Although peak plantar pressure in the third to fifth metatarsal region (M7) was lower in the flexible flatfoot group than in the normal-arch group, this difference was no longer statistically significant after correction for multiple comparisons ($P = 0.009$, Cohen's $d = 0.988$). No statistically significant differences were observed between the two groups in the other plantar regions.

Conclusion: The increased contact area in the medial midfoot region may serve as a biomechanical indicator for the early identification of adolescents with flexible flatfoot. These results can inform preventive programs, orthotic designs, and rehabilitation protocols.

Keywords: Pressure distribution patterns; Flat foot; Female students; Walking

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Introduction

Walking is one of the most complex human motor activities, requiring the coordinated interaction of multiple components of the musculoskeletal system (1). Because the plantar surface of the foot is subjected to the greatest mechanical loads during gait, it plays a fundamental role in weight bearing, shock absorption, and locomotor function (2). As the only body structures in direct contact with the ground during walking, the feet and their arches are essential for dissipating impact forces, providing functional support, and bearing a substantial proportion of body weight throughout the gait cycle (3). Therefore, a comprehensive understanding of the biomechanical function of the foot and its arches is essential for analyzing normal gait and identifying pathological movement patterns (4).

The plantar arch consists of the medial longitudinal, lateral longitudinal, and transverse arches. Together, these structures form a dynamic architectural system whose elastic properties enable the foot to adapt to uneven terrain while efficiently transmitting body weight to the ground (4). The present study focuses on the medial longitudinal arch, which plays a pivotal role in shock absorption and provides the flexibility required for efficient gait (5). Pathological alterations in the medial longitudinal arch can substantially impair standing, walking, running, and overall postural alignment. Excessive pronation and abnormal lowering of the medial longitudinal arch may alter plantar pressure distribution and lower-limb kinematics, particularly at the knee and hip, thereby increasing joint loading and the long-term risk of musculoskeletal injury (6, 7).

Previous studies have shown that several factors, including sex, influence foot structure and plantar pressure distribution (8). For example, girls have been reported to exhibit greater plantar pressure beneath the hallux and a shorter time to peak pressure than boys. These differences may reflect underlying biological and physiological characteristics (8, 9). Other contributing factors include muscular imbalance, ligamentous laxity, and abnormalities of the osseous structures that support the plantar arches (10). These factors may result in either reduced or exaggerated arch height, leading to foot deformities such as pes planus or pes cavus (11). Flexible flat foot is commonly associated with ligamentous laxity, overweight or obesity, physical inactivity, occupations involving prolonged standing, hereditary predisposition, weakness or tightness of the lower-leg and intrinsic foot muscles, and inappropriate footwear (12).

Previous investigations have demonstrated that individuals with flat feet exhibit altered foot function and plantar loading compared with those with normal foot posture. Several studies have specifically highlighted these biomechanical alterations in school-aged children and adolescents (13). Flatfoot is among the most prevalent musculoskeletal deformities in childhood and adolescence, affecting more than half of individuals in some populations. The condition may induce maladaptive compensatory mechanisms, alter foot biomechanics, increase the metabolic cost of movement, and ultimately reduce locomotor efficiency (7).

Evidence further suggests that individuals with flat feet exhibit altered lower-limb muscle activation patterns compared with those with normal arches. These functional changes are accompanied by skeletal malalignment, increased energy expenditure, and elevated mechanical loading during gait (14). Over time, such adaptations may promote adverse compensatory mechanisms and structural musculoskeletal disorders (15). Musculoskeletal pain is also commonly associated with flat foot, with approximately 23% of affected individuals reporting pain-related symptoms (16). Furthermore, individuals with flat feet have demonstrated poorer dynamic balance than their counterparts with normal foot posture (17). Nevertheless, recent evidence indicates that the relationship between medial longitudinal arch height and lower-extremity injury risk in adolescent girls may be moderated by body mass index (BMI) (18).

Advances in pressure-sensing technology have enabled accurate, non-invasive assessment of plantar pressure distribution under dynamic walking conditions (19). These developments have facilitated detailed biomechanical evaluation of plantar loading patterns across different age groups and clinical populations. Given the high prevalence of flat foot among children and adolescents, together with its potential consequences for balance, musculoskeletal pain, prolonged standing, and altered plantar loading, further investigation of plantar pressure characteristics in this population is warranted (5,7).

Despite the clinical importance of this topic, no previous study has specifically compared plantar pressure distribution during walking between Iranian girls aged 12–14 years with flexible flat feet and their age-matched peers with normal foot posture. This developmental period represents a critical stage of musculoskeletal growth, during which the feet are exposed to substantial repetitive loading during daily activities. Accordingly, the present study is novel in two respects. First, it focuses on a specific and understudied population of Iranian adolescent girls

aged 12–14 years. Second, it employs advanced statistical methods, including linear mixed-effects models, the Holm–Bonferroni correction for multiple comparisons, and Hedges' *g* effect size estimation, while adjusting for important confounders such as walking speed and physical activity level.

We hypothesized that: (1) girls with flexible flat feet would demonstrate a greater plantar contact area in the medial midfoot region (M3) than girls with normal feet; and (2) peak plantar pressure in the forefoot, particularly beneath the third to fifth metatarsals (M7), would differ significantly between the two groups. Therefore, the primary aim of this study was to compare plantar pressure distribution during walking, including peak plantar pressure and contact area across ten anatomical plantar regions, between adolescent girls with flexible flat feet and those with normal foot posture. The findings may contribute to improved clinical assessment of pediatric flat foot, facilitate the development of evidence-based orthotic interventions, and support rehabilitation strategies to optimize foot function during adolescence.

Materials and Methods

This cross-sectional comparative study was conducted in October 2023 at the Motion Analysis Laboratory of Kharazmi University, Tehran, Iran. The study population consisted of female middle-school students aged 12–14 years from Qods City, Tehran Province. Initial foot posture screening was performed using the Navicular Drop Test (ICC = 0.92). Plantar pressure measurements were obtained using the emed® C50 pressure platform (Novel GmbH, Munich, Germany), a system with established validity, reliability, and measurement accuracy in plantar pressure assessment (19, 20).

The required sample size was calculated using G*Power version 3.1.5 (University of Düsseldorf, Germany) for an independent-samples *t*-test, assuming an effect size of 0.90, 80% power, and a two-sided significance level of 0.05. A total sample of 32 participants (16 with flexible flat feet and 16 with normal feet) was required (21). A post hoc power analysis indicated 82% power to detect differences in the M3 region. Participants were recruited using purposive convenience sampling.

Inclusion criteria were female sex, age between 12 and 14 years, good general health, leg-length discrepancy <1 cm, absence of lower-extremity musculoskeletal disorders, previous lower-limb injury or surgery, and no history of orthotic insole use.

Flexible flat foot was confirmed using the Jack test, and only participants with flexible flat foot were included, as this is the most common form during adolescence (22). Foot posture classification was further verified using the Foot Posture Index (FPI) and the Navicular Drop Test, with participants in the flatfoot group demonstrating an average FPI score >6 (23). Pubertal maturation was controlled using the Tanner staging system (mean stage 2–3) to minimize developmental variability (24). Physical activity level was assessed using the International Physical Activity Questionnaire (IPAQ), and footwear habits (standard school shoes) were documented (25). These data were obtained through interviews with the school health nurse and review of students' medical records.

Participants with a rigid flat foot were excluded during the initial screening. None of the enrolled participants presented with leg-length discrepancy, musculoskeletal disorders, previous fractures of the foot, ankle, or lower leg, major orthopedic abnormalities, previous lower-limb surgery, or prior use of foot orthoses.

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Research Ethics Committee of the Sport Sciences Research Institute (Approval No. IR.SSRC.REC.1402.316). Written informed consent was obtained from both participants and their parents or legal guardians before data collection.

Before testing, all participants received standardized instructions regarding the experimental procedures. Height and body mass were measured using a digital stadiometer and a calibrated electronic scale. The emed® C50 system was calibrated according to the manufacturer's recommendations before each testing session. Peak plantar pressure values were normalized to body weight to minimize the influence of inter-individual differences in body mass.

The pressure platform was embedded flush within the center of a 10-m walkway to avoid gait disturbance. Participants completed a 5-minute familiarization period before testing. They were instructed to walk barefoot at their self-selected comfortable walking speed. A metronome was used to maintain a consistent walking cadence throughout testing (26). Walking speed was monitored using timing gates (mean = 1.05 ± 0.15 $m \cdot s^{-1}$), with no significant difference observed between groups (P = 0.68). Walking speed was subsequently included as a covariate in the statistical analyses, along with physical activity level and footwear; BMI was not included as a covariate because no significant between-group difference was observed, and its inclusion would have reduced model parsimony.

Participants initiated walking two steps before reaching the pressure platform so that the tested foot

naturally contacted the center of the platform during the second step (27). For the primary analysis, the dominant foot was selected for each participant, as determined using the preferred kicking-leg test (28). A trial was considered successful when the participant contacted the platform naturally, without visually targeting the platform or altering gait. Thirty seconds of rest were provided between consecutive trials, and the average of five successful trials for each participant was used for analysis (29).

Intra-session reliability was evaluated using the intraclass correlation coefficient (ICC(3,k)), yielding values between 0.85 and 0.95 across the primary plantar regions, indicating excellent repeatability. No observations were excluded as statistical outliers using the three-standard-deviation criterion. Data distribution and homogeneity of variance were assessed before statistical analysis. All variables satisfied normality assumptions except M8, for which a Mann–Whitney *U* test produced results consistent with those obtained from the primary analyses. To account for bilateral measurements, the foot (left/right) was modeled as a repeated within-subject factor. Because the primary analysis focused on the dominant foot, bilateral measurements were not modeled as a repeated within-subject factor.

Following plantar pressure assessment, participants were classified into the flatfoot or normal-foot groups using the Arch Index (AI). The foot axis was defined as the line extending from the center of the heel to the center of the second toe. Foot length (excluding the toes) was divided into three equal regions representing the forefoot (A), midfoot (B), and rearfoot (C). The Arch Index was calculated as:

$$AI = B / (A + B + C)$$

According to established pediatric reference values, AI values between 0.21 and 0.28 were classified as normal, whereas values >0.28 were classified as flat feet (30). It is important to note that the Arch Index is a dimensionless ratio, not a linear measurement in centimeters. Arch Index calculations were performed using the Geometry module within the Novel software package. Only participants with moderately flexible flat feet were included in the flatfoot group.

Plantar pressure variables were analyzed using MultiMask software (Novel GmbH, Munich, Germany). The mean values from five successful dominant-foot trials were calculated automatically. The plantar surface was divided into ten anatomical regions using the PRC AutoMask protocol implemented in the emed software (Figure 1): medial heel (M1), lateral heel (M2), medial midfoot (M3), lateral midfoot (M4), first metatarsal (M5), second metatarsal (M6), third to fifth metatarsals (M7), hallux (M8), second toe (M9), and third to fifth toes (M10) (31).

For each anatomical region, peak plantar pressure (kPa) and contact area (cm²) were calculated.

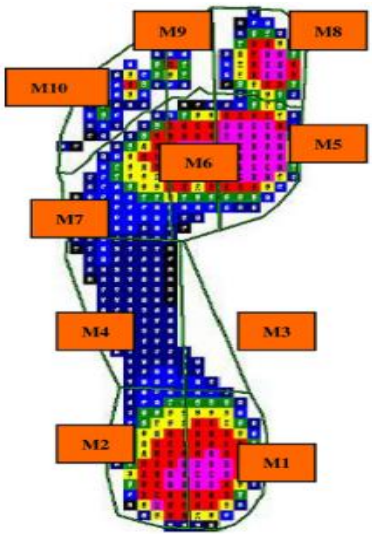


Figure 1. Anatomical plantar regions defined using the PRC masking protocol.
M1 = medial heel; M2 = lateral heel; M3 = medial midfoot; M4 = lateral midfoot; M5 = first metatarsal; M6 = second metatarsal; M7 = third–fifth metatarsals; M8 = hallux; M9 = second toe; M10 = third–fifth toes.

Descriptive statistics are presented as mean ± standard deviation. Normality was evaluated using the Shapiro–Wilk test. Because M8 violated the normality assumption, supplementary analyses using the Mann–Whitney U test were conducted and yielded findings consistent with the primary analyses. Between-group comparisons were performed using linear mixed-effects models (LMMs), with region as the within-subject factor, group as the between-subject factor, and walking speed, physical activity level, and footwear as covariates. To control the family-wise Type I error rate resulting from 20 simultaneous comparisons (10 plantar regions × 2 outcome variables), Holm–Bonferroni correction was applied. Effect sizes were quantified using both Cohen's d and Hedges' g to reduce small-sample bias, and 95% confidence intervals (95% CI) were reported. All statistical analyses were performed using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA), with statistical significance established at $P < 0.05$.

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Table 1. Comparison of demographic characteristics of participants

Variable	Normal Group	Flat Foot Group	Significance Level
Age (years)	13.2 ± 0.84	12.9 ± 0.66	0.430
Height (m)	1.56 ± 0.34	1.53 ± 0.11	0.180
Weight (kg)	47.92 ± 2.30	46.58 ± 3.72	0.624
Body Mass Index (kg/m²)	19.9 ± 2.23	20.13 ± 1.60	0.841
Arch Index	0.24 ± 0.01	0.29 ± 0.02	0.015*
Foot Posture Index	3.4 ± 0.9	7.2 ± 1.1	<0.001*
Navicular Drop (mm)	4.8 ± 1.2	9.5 ± 2.3	<0.001*

*Significant difference at the 0.05 level

Results

The demographic characteristics of the participants are presented in Table 1. No significant differences were observed between the flat foot (FF) and normal (N) groups in terms of age, height, weight, and body mass index (P > 0.05). The Arch Index showed a significant difference between the groups (P = 0.015), confirming the correctness of the group classification based on foot posture. The Arch Index values are presented as ratios (dimensionless), consistent with standard reporting practices. The mean FPI in the FF group was 7.2 ± 1.1, and in the N group was 3.4 ± 0.9 (P < 0.01); navicular drop in the flat foot group was 9.5 ± 2.3 mm, and in the normal group was 4.8 ± 1.2 mm (P < 0.01).

Peak pressure (kPa) and contact area (cm²) were measured in 10-foot regions (M1 to M10) for both the normal (N) and flat-foot (FF) groups. Mean and standard deviation values for each variable, along with the results from mixed linear models for between-group comparisons, are presented in Table 2.

For the peak pressure variable, although a considerable difference was observed between the two groups in region M7 (P = 0.009, Cohen's d = 0.988), this difference did not reach statistical significance after adjustment for multiple comparisons (adjusted P = 0.099). It is important to note that the flat foot group demonstrated lower peak pressure in the M7 region compared to the normal group (mean difference = 35.5 kPa), indicating a trend toward reduced lateral forefoot loading. No significant differences were found between the groups in other regions for peak pressure (P > 0.05).

For the contact area variable, a significant difference between the normal and flat foot groups was observed only in region M3 (P < 0.001, Cohen's d = 1.977), and this difference remained significant even after adjusting the significance level for multiple comparisons (adjusted P < 0.005). The 95% confidence interval for the mean difference in this region (4.0 to 10.2) also confirmed that it did not cross zero. No significant differences were observed between the groups in other regions for the contact area. The calculated effect size for region M3 in the contact area variable was in the large range, indicating a strong influence of foot type on this variable.

Figure 1 shows the distribution of mean peak pressure across 10-foot regions for the two groups of students: flat feet (gray) and normal feet (light blue).

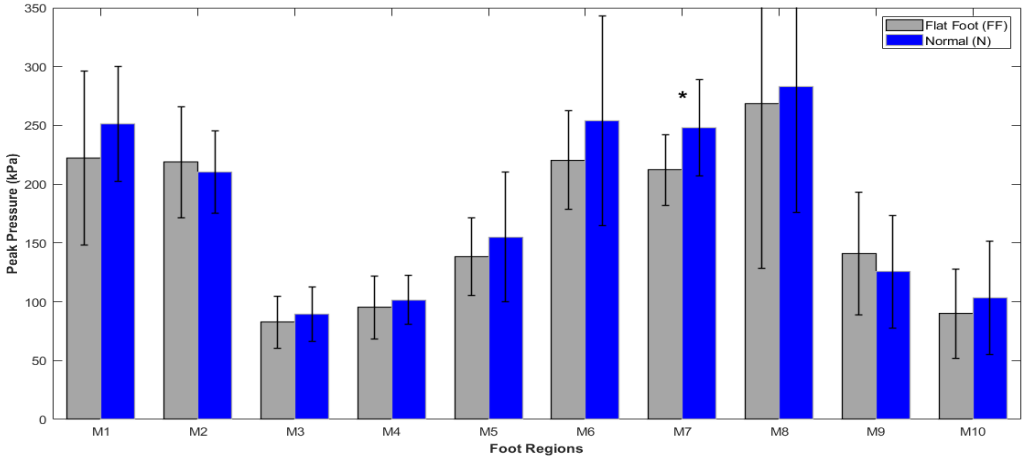


Figure 1. Peak pressure in the ten regions of the foot in students with flat and normal feet (Horizontal axis: regions M1 to M10, Vertical axis: peak pressure in kPa.)
*Significant difference at the 0.05 level

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As observed in the figure, the pressure distribution pattern is similar in both groups, with the highest peak pressure in each group corresponding to region M8 (hallux), followed by regions M6 and M1 (2nd metatarsal head and medial heel edge). Conversely, the lowest peak pressure values are seen in regions M3 and M4 (midfoot).

Although in region M7 the flat foot group shows lower peak pressure values than the normal group (P=0.099), the statistical test results (Table 2) indicate that, after adjusting the significance level using the Bonferroni method, this difference was no longer significant.

Figure 2 shows the contact area (cm^2) in ten-foot regions for the normal and flat foot groups. Examination of the overall trend in the figure indicates that the contact area in both groups is greater in the lateral regions of the foot (M4, M7) than in other regions, which aligns with the normal pressure distribution pattern during standing and walking.

Table 2. Descriptive values (mean ± standard deviation) and results from mixed linear models for between-group comparison of peak pressure and contact area variables in the normal (N) and flat foot (FF) groups

Region	Group	Peak Pressure (kPa)	Mean Difference	t	P	Cohen's d	Adjusted P	Cohen's d (Hedges'g)	95% CI
M1	FF	222.1 ± 74	29.1	1.31	0.200	0.464	1.000	0.464, 0.450	-15.2, 73.4
	N	251.2 ± 49							
M2	FF	218.6 ± 47	-8.1	-0.63	0.534	-0.223	1.000	-0.223, -0.220	-34.8, 18.6
	N	210.5 ± 35							
M3	FF	82.7 ± 22	6.7	0.88	0.386	0.311	1.000	0.311, 0.300	-8.5, 21.9
	N	89.4 ± 23							
M4	FF	95.1 ± 27	6.5	0.76	0.453	0.269	1.000	0.269, 0.260	-10.9, 23.9
	N	101.6 ± 21							
M5	FF	138.3 ± 33	16.8	1.05	0.303	0.370	1.000	0.370, 0.360	-16.4, 50.0
	N	155.1 ± 55							
M6	FF	220.4 ± 42	33.4	1.36	0.185	0.480	1.000	0.480, 0.47	-8.5, 75.3
	N	253.8 ± 89							
M7	FF	212.2 ± 30	35.5	2.80	0.009*	0.988	0.099	0.988, 0.96	9.2, 61.8
	N	247.7 ± 41							
M8	FF	268.5 ± 140	14.2	0.31	0.759	0.110	1.000	0.110, 0.11	-48.3, 76.7
	N	282.7 ± 107							
M9	FF	141.1 ± 52	-15.6	-0.90	0.376	-0.318	1.000	-0.318, -0.31	-50.2, 18.9
	N	125.5 ± 48							
M10	FF	90.1 ± 38	13.2	0.89	0.382	0.315	1.000	0.315, 0.31	-16.4, 42.8
	N	103.3 ± 48							
				Contact Area Variable					
M1	FF	15.6 ± 0.8	0.0	0.00	1.000	0.000	1.000	0.000, 0.000	-0.6, 0.6
	N	15.6 ± 1.0							
M2	FF	15.9 ± 0.65	0.5	0.49	0.629	0.173	1.000	0.173, 0.17	-1.5, 2.5
	N	16.4 ± 3.8							
M3	FF	8.4 ± 4.8	7.1	5.65	*<0.001	1.977	*<0.005	1.977, 1.95	4.0, 10.2
	N	1.5 ± 1.3							
M4	FF	22.1 ± 2.2	1.6	1.84	0.076	0.651	0.912	0.651, 0.63	0.1, 3.1
	N	23.7 ± 2.3							
M5	FF	12.3 ± 1.7	0.6	0.82	0.419	0.290	1.000	0.290, 0.28	-0.9, 2.1
	N	12.9 ± 2.2							
M6	FF	10.2 ± 1.04	0.9	1.52	0.139	0.538	0.973	0.538, 0.52	-0.3, 2.1
	N	11.1 ± 1.9							
M7	FF	23.5 ± 2.6	-1.0	-1.12	0.273	-0.395	1.000	-0.395, -0.38	-2.8, 0.8
	N	22.5 ± 2.7							
M8	FF	10.1 ± 1.8	-0.3	-0.51	0.615	-0.180	1.000	-0.180, -0.18	-1.4, 0.8
	N	9.8 ± 1.2							
M9	FF	4.4 ± 0.8	-0.5	-1.74	0.092	-0.615	0.736	-0.615, -0.60	-1.1, 0.1
	N	3.9 ± 0.8							
M10	FF	7.75 ± 3.2	0.45	0.40	0.692	0.141	1.000	0.141, 0.14	-1.8, 2.7
	N	8.2 ± 3.3							

CI: Confidence Interval
*Significant difference at the 0.05 level

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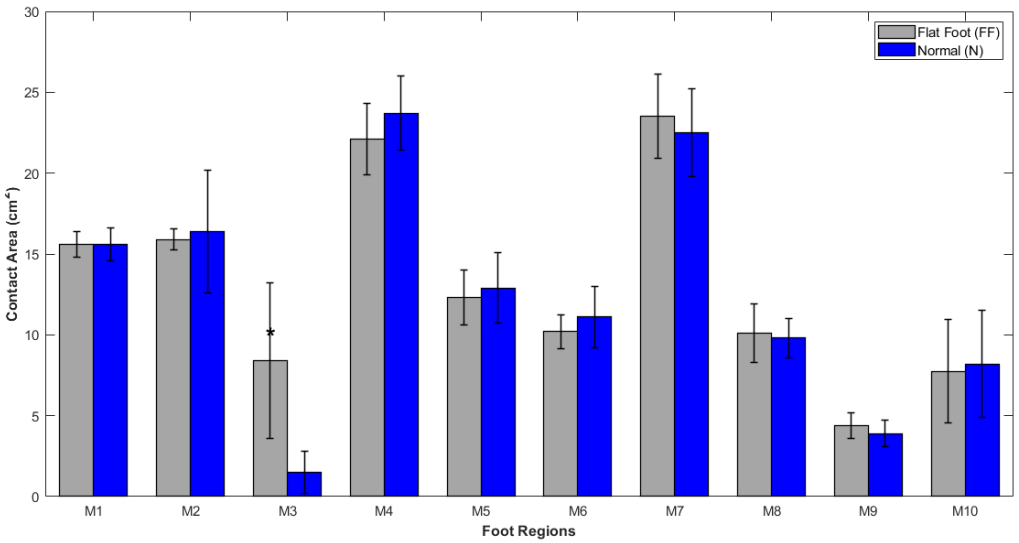


Figure 2. Contact area in the ten regions of the foot in students with flat and normal feet (Horizontal axis: regions M1 to M10, Vertical axis: contact area in cm²).
*Significant difference at the 0.05 level

The most prominent difference between the two groups is observed in region M3, where the flat foot group (approximately 8.4 cm²) has a substantially larger contact area than the normal group (approximately 1.5 cm²). This considerable difference indicates that the flatfoot structure increases the contact area in the lateral midfoot region. In other regions, such as M1 and M2, the two groups have very similar values, and the lines almost overlap. In the forefoot regions (M8 to M10), both groups also exhibit low, similar contact areas. Overall, except in region M3, where a notable difference is observed, the contact area pattern is similar across the other regions.

Discussion

The present findings show that adolescents with flat feet have a complex pattern of plantar pressure redistribution compared to peers with normal arches. Specifically, while the flat foot group demonstrated lower peak pressure in the M7 region (third to fifth metatarsals) with a large effect size (Cohen's d = 0.988), this difference did not reach statistical significance after correction for multiple comparisons. However, the contact area in the medial midfoot region (M3) was significantly increased ($P < 0.001$, Cohen's d = 1.977). This pattern reflects structural and functional changes in the medial longitudinal arch: reduced arch height and excessive pronation not only alter foot geometry and cause navicular bone drop but also affect force transmission from the heel to the forefoot and lower-limb coordination.

The observed changes in pressure and contact area may arise from load redistribution towards the medial foot and internal pressure center, which, by altering the ground reaction force vector, affects the function of the lower extremity kinetic chain. This finding is consistent with mechanisms proposed in previous research, which have shown that individuals with flat feet exhibit altered foot-loading patterns during the stance phase, thereby disrupting controlled force adaptation and effective load transfer (32, 33).

From a biomechanical perspective, excessive pronation increases internal rotation of the leg and knee and changes the ankle joint angle. These alterations can disrupt the coordination of the closed kinetic chain of the lower extremity. These changes can place additional stress on the knee, hip, and lumbar spine joints, increasing the likelihood of soft-tissue and bone injuries over the long term (20–22). Furthermore, disruption of the closed-kinetic-chain coordination of the lower extremity can impair control of the calf and foot muscles, potentially increasing the risk of chain-reaction injuries. Therefore, evaluating plantar pressure not only aids in the early diagnosis of abnormalities but also provides a basis for designing targeted training and corrective programs.

Previous studies indicate the highest pressure in the heel and metatarsal head regions (14-16), and our findings align with this pattern. However, the key difference in adolescents with flat feet is a significant increase in contact area at the medial midfoot (M3), indicating a need for greater stability and control in this

area and the potential for long-term functional impairment. These changes may result from a combination of structural factors (arch height, bone positioning) and functional factors (timing and activity of the muscles supporting the arch and ankle).

The discrepancies observed with some studies that did not report significant differences (17, 18) could be due to different methods of diagnosing flat feet, participant age, walking protocols, equipment used, and the failure to differentiate between flexible and rigid flat feet. This highlights the necessity for more precise analysis and classification based on structural and functional characteristics.

Detailed pressure and contact area analysis suggests that increased M3 contact area could serve as a screening index for the early identification of flat feet. These findings align with the study by Buldt et al. (33), which examined the relationship between foot arch posture and pressure distribution during walking, as well as with research on orthotic interventions in children by Evans and Rome (34), suggesting that changes in pressure and the medial arch of the foot during the growth period are monitorable and correctable. Another important point is the consistency of these findings with mechanical models of the foot. Reduced medial longitudinal arch height and increased pronation cause the talar motion axis to tilt medially, shifting the center of pressure towards the medial side, which coincides with increased contact area in the medial midfoot. This change could explain the tendency of flat feet to cause abnormal loading over time (20, 22).

Also, the observed increase in contact area in the medial midfoot region and the trend toward reduced pressure in the lateral forefoot may indicate impaired force transfer function and ankle joint stability. This impairment can affect the control of calf and foot muscles, increasing the likelihood of chain-reaction injuries in the lower extremity. Therefore, assessing plantar pressure not only aids in early diagnosis but can also serve as a basis for designing targeted training and corrective programs.

Ultimately, the present findings indicate that flat feet in adolescents not only alter pressure and contact area but also reflect functional and structural changes in the foot and lower extremity kinetic chain. These results underscore the importance of detailed plantar pressure assessment, evaluation of movement mechanics, and the design of preventive and corrective interventions. They provide a foundation for future longitudinal and multidimensional studies, specifically aimed at preventing lower-extremity chain injuries, improving foot stability, and enhancing motor performance during the growth period.

Limitations

This study has several limitations. The relatively small sample size (n=16) limited the power to detect differences. It may have increased the risk of Type I error, although this was partially controlled for with multiple-comparison corrections. Flat feet were classified solely by static pressure (arch index), and the functional status of the foot during dynamic tasks was not assessed independently. Additionally, supplementary criteria such as pressure-time integrals and COP trajectories were not recorded, so the present findings cannot address temporal aspects of loading. Changes in foot structure maturation during adolescence might influence plantar pressure patterns, although the Tanner stage was considered. Shoe type and participants' physical activity level were included as covariates in the statistical model.

Furthermore, the convenience sampling limits the generalizability of the results. To improve future studies, increasing the sample size and adding temporal measures, such as pressure-time integrals, are recommended. Also, using multivariate statistical models and longitudinal follow-up of participants could be beneficial in predicting pain and functional changes in the foot.

Recommendations

It is recommended that future studies use larger sample sizes to improve the generalizability of the findings to a wider population. Furthermore, employing longitudinal designs could provide a more comprehensive view of changes in plantar pressure distribution over time and clarify the developmental trends of these variables. Moreover, evaluating interventional approaches such as strengthening exercises or corrective insoles and comparing their effectiveness in improving pressure distribution patterns is of particular importance. Investigating gender differences and including a broader range of age groups could also lead to a deeper understanding of the biological factors affecting plantar pressure.

Conclusion

The findings of the present study indicate that structural alterations associated with flexible flat foot, particularly reduced medial longitudinal arch integrity, are reflected more prominently in the plantar contact area than in peak plantar pressure during walking. Specifically, the increased contact area observed in the medial midfoot region (M3) may serve as a potential biomechanical marker for the early identification of

adolescents with flexible flat foot. These findings may contribute to clinical assessment, the design of customized foot orthoses, and the development of evidence-based rehabilitation and corrective exercise programs for the management of flexible flat foot. Furthermore, the results underscore the importance of early screening for foot posture abnormalities during adolescence, which may help prevent long-term musculoskeletal complications and promote optimal lower-limb function and quality of life.

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Conflict of Interest

The authors did not have a conflict of interest.

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