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Prevalence of flatfoot and gender differences in plantar pressure among third-year high school students in Tongzhou district Beijing

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Abstract

Objective To estimate the prevalence of flatfoot and to analyze the gender difference of plantar pressure in third-year high school students in Tongzhou District Beijing.

Methods From March 2019 to March 2021, 1217 third-year high school students in Tongzhou District, Beijing were tested for plantar pressure. The prevalence of flatfoot was calculated and related plantar pressure parameters were analyzed, including contact area and plantar pressure. The differences of plantar pressure parameters between different genders were analyzed.

Results The prevalence of flatfoot among third-year high school students in Tongzhou District, Beijing was 5.5% (95% CI: 4.3–6.7%), among which, the prevalence of flatfoot among boys was 5.3% (95% CI: 3.8–6.8%) and that among girls was 5.9% (95% CI: 3.9–7.9%). There was no significant difference in the prevalence of flatfoot among different genders ($P=0.326$), and the left and right foot types were basically the same. The mean BMI of the study population was 22.6 ± 3.4 kg/m^2, with males having a slightly higher mean BMI (23.1 ± 3.6 kg/m^2) compared to females (21.9 ± 3.0 kg/m^2). In static phase, there were statistically significant differences in contact area, plantar pressure at great toe, plantar pressure at 2nd – 5th toe, plantar pressure at 2nd – 4th metatarsal, and plantar pressure at middle foot($P<0.05$) between male students and female students. In dynamic phase, there were significant differences in contact area, plantar pressure at great toe, plantar pressure at 2nd – 5th toe and plantar pressure at 5th metatarsal ($P<0.05$).

Conclusion The findings of this study suggest that while flatfoot prevalence is similar between genders in third-year high school students, significant gender-specific differences exist in plantar pressure distribution patterns. These differences persist in both static and dynamic phases, with potential implications for gender-specific foot health assessment and preventive interventions. Understanding these patterns may help in early detection of foot abnormalities and implementation of appropriate interventions to prevent long-term biomechanical issues in this age group.

Keywords Flatfoot, Prevalence, Plantar pressure, Third-year high school students, Gender

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Introduction

Flatfoot, characterized by the collapse or excessive flattening of the medial longitudinal arch, is a common and often asymptomatic condition that can affect foot function and cause discomfort [1, 2]. In children and adolescents, the development of the foot arch begins at an early age and continues through late adolescence. Studies have shown that the prevalence of flatfoot varies with age, with approximately 37–60% of children aged 2–6 years and 16–19% of children aged 8–13 years affected [3, 4]. The foot arch continues to mature between ages 7–12 years, but the process is not always continuous, with some children experiencing delayed or incomplete arch development [5]. As adolescents approach adulthood, the foot arch typically reaches its full structural maturity around the ages of 10–13 years [6]. However, the prevalence of flatfoot and its associated factors in older adolescents, particularly those in the transition period between childhood and adulthood, remain underexplored [7].

While numerous studies have focused on flatfoot prevalence and plantar pressure in children and adults, there is a notable lack of large-scale studies investigating these factors in senior high school students, particularly in the context of both static and dynamic phases. Previous research has highlighted gender differences in plantar pressure and foot health. Studies have demonstrated that females tend to exhibit higher pressures in the forefoot region, particularly under the hallux and metatarsal heads, compared to males [8]. Additionally, gender differences in foot morphology, including arch height and foot width, have been found to influence plantar pressure distribution patterns [9, 10]. Research has also shown that females generally have greater joint laxity and range of motion in their feet, which can affect foot posture and pressure distribution during both standing and walking [11, 12].

Gender differences in flatfoot prevalence have been reported in various age groups, with some studies suggesting higher rates in males during childhood and adolescence, although these differences tend to diminish with age [13, 14]. Anatomical and biomechanical factors, such as differences in muscle strength, ligamentous laxity, and body composition, have been proposed as potential contributors to these gender disparities [15]. However, the specific patterns in high school students, who engage in extensive physical activity and are in a critical growth phase, remain underexplored. The importance of understanding flatfoot prevalence and plantar pressure in this population is critical, as untreated flatfoot can lead to foot pain, lower limb fatigue, and potential long-term biomechanical problems.

Flatfoot is typically asymptomatic but may cause biomechanical imbalances that affect gait and contribute to fatigue and lower limb injuries. The development of the foot arch begins early in childhood and continues through adolescence. As high school students engage in extensive physical activities and are at a critical stage of growth, understanding the prevalence of flatfoot and its impact on plantar pressure distribution is crucial for early detection and intervention. While much research has been done on younger children and adults, there is a significant gap in studies focusing on high school students. This study aims to address this gap by estimating the prevalence of flatfoot and analyzing gender differences in plantar pressure among third-year high school students in Tongzhou District, Beijing.

The specific research questions of this study are: What is the prevalence of flatfoot among third-year high school students in Tongzhou District, Beijing? Are there significant gender differences in flatfoot prevalence in this population? What gender-specific differences exist in plantar pressure distribution during static and dynamic phases? How does the transition from static to dynamic phase affect plantar pressure distribution patterns in male versus female students?

Subjects and methods

Subjects

From March 2019 to March 2021, the Department of Hand and Foot Surgery at the Orthopedic Center of Beijing Luhe Hospital, Capital Medical University, conducted a random sampling of high school students preparing for college entrance examinations from five high schools in Tongzhou District, Beijing. A total of 1,217 third-year high school students were enrolled, comprising 756 males and 461 females, aged 17–23 years (mean age: 18.5 years). The students were preparing for the college entrance examination. All participants provided written informed consent, and parental consent was obtained for those under 18 years of age. The study aimed to assess the prevalence of flatfoot and analyze gender differences in plantar pressure among this age group. For additional details on the questionnaire used to assess participant characteristics, refer to Supplementary File 1. The study was approved by the hospital ethics committee (Ethics approval number: 2018-LHKY-016-01).

Inclusion criteria

1. Participants who consented to participate in the study and signed informed consent.
2. For participants under 18 years of age, guardian consent and signature were obtained.

Exclusion criteria

1. Lower limb musculoskeletal injuries, neurovascular abnormalities, or biomechanical abnormalities that could affect gait.
2. Body deformities (scoliosis, kyphosis, lordosis), paralysis, fractures, or amputation.

Methods

Initially, general demographic data were collected via questionnaires before testing, including gender, age, medical history, height, weight, and body mass index (BMI). Subsequently, static and dynamic plantar pressure measurements were conducted using a plantar pressure testing device (two-dimensional scanner, GAITVIEW, model: AFA-50, manufactured in Korea) [10]. The testing environment provided appropriate lighting and temperature conditions for all participants. Based on the arch index, feet were classified into three distinct categories [11]: flatfoot (arch index ≥ 0.260), normal foot (0.210 < arch index < 0.260), and high arch (arch index ≤ 0.210). In this study, we employed a combined objective and subjective approach to determine foot type. First, the arch index was obtained during barefoot static standing using the GAITVIEW plantar pressure testing device, with automatic calculation by the computer software to determine the arch type. This was followed by a physical examination of each participant to make the final determination of arch type. Prior to actual testing, we demonstrated and explained the testing procedures and relevant precautions to each participant, allowing them to practice 3–5 times until they were familiar with all requirements. Once participants were comfortable with the procedures, we proceeded with both static and dynamic plantar pressure testing.

Static measurement Participants stood barefoot on the pressure transmission area of the plantar pressure testing device with both arms naturally hanging at their sides and eyes facing forward. The test duration was one minute, and the static phase measurement was concluded once the bilateral plantar pressure data was successfully collected and transmitted to the computer.

Sample size calculation A post-hoc power analysis was conducted to determine the adequacy of the sample size. For the comparison of flatfoot prevalence and plantar pressure parameters between genders, the study was designed to detect differences with a statistical power of 80% at an alpha level of 0.05. The calculated sample size was sufficient to achieve this power, ensuring the reliability of the findings.

Dynamic measurement Dynamic Measurement: Each participant walked barefoot at their natural walking speed on the testing mat in one direction. The mat featured footprint-like guiding patterns. During walking, the participant's left foot would land on the pressure transmission area of the device, and dynamic plantar pressure data for the left foot was collected and transmitted to the computer. Subsequently, the participant would turn around and walk in the opposite direction at their natural speed, allowing the right foot to land on the pressure transmission area. The dynamic phase testing was completed once data integrity was confirmed and transmission was successful. In this study, the dynamic phase specifically refers to walking, not running.

Reference parameters for plantar pressure testing included contact area and plantar pressure in both static and dynamic phases, divided into eight regions: hallux, 2nd-5th toes, 1st metatarsal, 2nd-4th metatarsals, 5th metatarsal, midfoot, medial heel, and lateral heel (Fig. 1). After data collection, participants were grouped by gender to compare plantar pressure parameters between different genders in both static and dynamic phases.

Statistical analysis was performed using SPSS 24.0 (IBM Corporation). To assess the effect of gender on plantar pressure parameters independent of foot type, we conducted a stratified analysis. Participants were first grouped by foot arch type (flatfoot, normal foot, and high arch), and then gender comparisons were made within each foot type category. This approach allowed us to control for the potential confounding effect of foot structure on plantar pressure distribution patterns. As the plantar pressure data did not follow normal distribution, results were expressed as median (interquartile range), and comparisons between genders were conducted using rank-sum tests, with $P < 0.05$ considered statistically significant. Given that the plantar pressure parameters were essentially consistent between left and right sides, right-side plantar pressure data was used for discussion.

Results

Prevalence of Flatfoot Analysis of the study population comprising 1,217 third-year high school students in Tongzhou District, Beijing revealed an overall flatfoot prevalence of 5.5% (95% CI: 4.3–6.7%). The distribution of flatfoot showed minimal gender variation, with males exhibiting a prevalence of 5.3% (40/756) (95% CI: 3.8–6.8%) and females showing a slightly higher rate of 5.9% (27/461) (95% CI: 3.9–7.9%). Statistical analysis demonstrated no significant difference between genders (χ^2 test, $P = 0.326$). Examination of bilateral foot characteristics revealed consistent patterns between left and right feet, as detailed in Tables 1 and 2.

BMI Analysis The mean BMI of the study population was 22.6 ± 3.4 kg/m², with males having a slightly

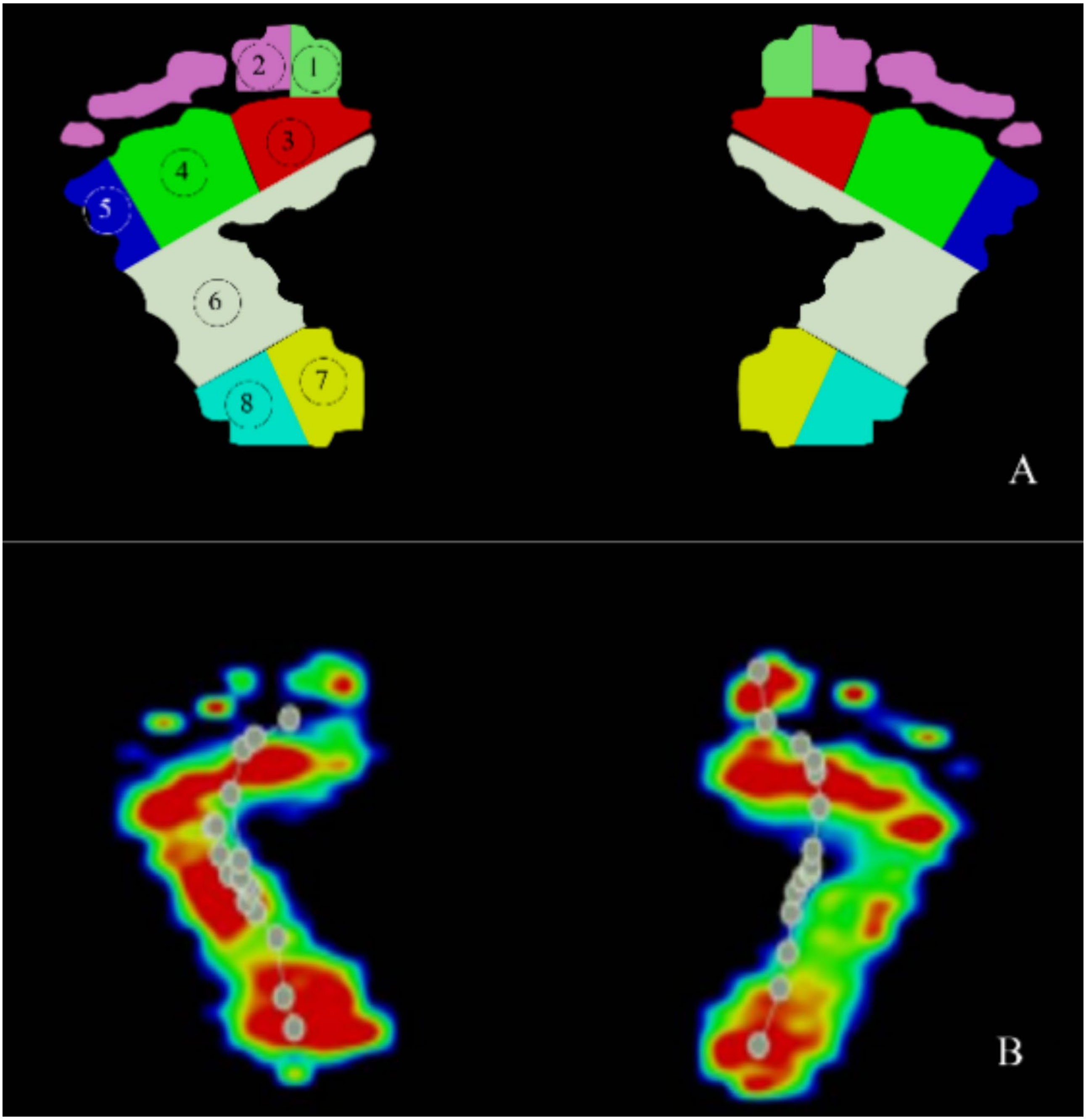

Fig. 1 (**A**) Plantar pressure regions divided into eight areas: ① hallux, ② 2nd-5th toes, ③ 1st metatarsal, ④ 2nd-4th metatarsals, ⑤ 5th metatarsal, ⑥ midfoot, ⑦ medial heel, and ⑧ lateral heel. Note: The dividing lines between regions have been recalibrated for greater precision in this revised figure. (**B**) Dynamic plantar pressure distribution pattern in a third-year high school student with normal foot type

Table 1 Gender differences in foot type prevalence (left foot) in static phase

Foot Type	Male *n*(%)	Female *n*(%)	Total *n*(%)	*P*-value
Flatfoot	40(5.3) **(95% CI: 3.8–6.8%)**	27(5.9) **(95% CI: 3.9–7.9%)**	67(5.5) **(95% CI: 4.3–6.7%)**	0.258
Normal foot	696(91.2) **(95% CI: 89.9–92.5%)**	415(90.0) **(95% CI: 87.5–92.5%)**	1111(91.3) **(95% CI: 89.3–93.3%)**	0.326
High arch	20(2.6) **(95% CI: 1.5–3.7%)**	19(4.1) **(95% CI: 2.3–5.9%)**	39(3.2) **(95% CI: 2.2–4.2%)**	0.03

Table 2 Gender differences in foot type prevalence (right foot) in static phase

Foot Type	Male *n*(%)	Female *n*(%)	Total *n*(%)	*P*-value
Flatfoot	40(5.3) **(95% CI: 3.8–6.8%)**	27(5.9) **(95% CI: 3.9–7.9%)**	67(5.5) **(95% CI: 4.3–6.7%)**	0.145
Normal foot	696(91.2) **(95% CI: 89.9–92.5%)**	414(89.8) **(95% CI: 87.2–92.4%)**	1111(91.3) **(95% CI: 89.3–93.3%)**	0.244
High arch	20(2.6) **(95% CI: 1.5–3.7%)**	20(4.3) **(95% CI: 2.5–6.1%)**	40(3.3) **(95% CI: 2.3–4.3%)**	0.316

Table 3 Comparison of bilateral plantar pressure parameters between genders in static phase, median (interquartile range)

Parameter	Male	Female	*P*-value
Contact area (cm^2, left)	100.5(22.7)	80.4(19.4)	< 0.001
Contact area (cm^2, right)	100.5(21.5)	80.4(19.8)	< 0.001
Plantar pressure (kPa)			
Hallux (L)	0.0(39.4)	19.8(74.2)	< 0.001
Hallux (R)	6.6(70.0)	24.2(70.7)	< 0.001
2nd-5th toes (L)	8.5(26.0)	11.4(31.0)	< 0.001
2nd-5th toes (R)	8.8(28.8)	11.9(31.0)	< 0.001
1st metatarsal (L)	46.1(56.9)	44.7(56.2)	0.723
1st metatarsal (R)	46.8(56.4)	44.2(57.3)	0.627
2nd-4th metatarsals (L)	97.2(31.1)	93.4(30.3)	< 0.001
2nd-4th metatarsals (R)	97.4(30.5)	93.5(29.9)	< 0.001
5th metatarsal (L)	31.2(28.2)	31.1(36.5)	0.921
5th metatarsal (R)	31.0(28.4)	31.1(36.4)	0.986
Midfoot (L)	48.0(20.4)	44.7(19.3)	< 0.001
Midfoot (R)	48.1(20.0)	45.0(19.1)	< 0.001
Medial heel (L)	77.3(31.7)	78.9(32.3)	0.141
Medial heel (R)	77.8(31.3)	79.0(32.4)	0.220
Lateral heel (L)	77.8(31.2)	79.0(32.5)	0.224
Lateral heel (R)	77.8(31.2)	79.2(32.4)	0.204

Table 4 Comparison of bilateral plantar pressure parameters between genders in dynamic phase, median (interquartile range)

Parameter	Male	Female	*P*-value
Contact area (cm^2, left)	122.4(20.8)	101.2(16.5)	< 0.001
Contact area (cm^2, right)	122.0(20.8)	100.5(15.1)	< 0.001
Plantar pressure (kPa)			
Hallux (L)	0.0(55.3)	44.6(102.2)	< 0.001
Hallux (R)	3.9(58.5)	22.6(107.7)	< 0.001
2nd-5th toes (L)	35.7(91.1)	77.9(105.9)	< 0.001
2nd-5th toes (R)	37.1(103.0)	77.6(104.9)	< 0.001
1st metatarsal (L)	107.9(70.9)	107.4(76.9)	0.748
1st metatarsal (R)	109.2(69.9)	106.7(76.2)	0.340
2nd-4th metatarsals (L)	155.5(67.9)	156.8(67.7)	0.343
2nd-4th metatarsals (R)	155.4(67.8)	157.1(67.2)	0.143
5th metatarsal (L)	98.5(61.4)	86.7(62.5)	< 0.001
5th metatarsal (R)	98.8(61.1)	87.1(62.2)	< 0.001
Midfoot (L)	79.1(27.0)	78.6(26.5)	0.388
Midfoot (R)	79.1(26.7)	78.7(26.4)	0.404
Medial heel (L)	146.7(47.2)	147.2(49.0)	0.825
Medial heel (R)	147.0(47.2)	147.3(48.8)	0.863
Lateral heel (L)	147.0(47.1)	147.4(49.7)	0.842
Lateral heel (R)	147.1(47.1)	147.5(48.7)	0.972

higher mean BMI (23.1 ± 3.6 kg/m²) compared to females (21.9 ± 3.0 kg/m²). Analysis of the relationship between BMI and flatfoot prevalence revealed that students with BMI ≥ 25 kg/m² had a flatfoot prevalence of 8.3% (95% CI: 5.7–10.9%), compared to 4.9% (95% CI: 3.7–6.1%) in those with BMI < 25 kg/m², indicating a positive association between higher BMI and increased flatfoot prevalence ($P = 0.036$).

Static Plantar Pressure Characteristics During static loading conditions, we observed distinct gender-specific patterns in plantar pressure distribution. Contact area measurements demonstrated significantly larger values in males compared to females (median [IQR]: 100.5 [22.7] cm² vs. 80.4 [19.4] cm², $P < 0.001$). Pressure distribution analysis revealed that females exhibited higher median pressure values in the hallux and 2nd-5th toe regions, while males showed greater pressure in the 2nd-4th metatarsal and midfoot regions. These gender-specific differences were statistically significant ($P < 0.05$), with comprehensive measurements presented in Table 3.

When stratified by foot type, the gender differences in plantar pressure parameters remained consistent within each foot type category (normal foot, flatfoot, and high arch). Within the normal foot group, which comprised the majority of our sample (91.3%), the gender-specific pressure distribution patterns were similar to those observed in the overall population. In the flatfoot group, males continued to demonstrate significantly larger contact areas ($P < 0.001$) and higher midfoot pressure ($P = 0.003$), while females maintained higher hallux pressure ($P = 0.002$). Similar patterns were observed in the high arch group, suggesting that the observed gender differences in plantar pressure distribution are independent of foot arch type.

Dynamic Plantar Pressure Patterns The dynamic phase analysis revealed notable gender-specific variations in pressure distribution patterns. Males consistently demonstrated larger contact areas during gait compared to females (median [IQR]: 122.4 [20.8] cm² vs. 101.2 [16.5] cm², $P < 0.001$). Regional pressure analysis showed that females maintained higher pressure values in the hallux and 2nd-5th toe regions, similar to static conditions. However, a distinct pattern emerged in the 5th metatarsal region, where males exhibited significantly higher pressure values. All these differences achieved statistical significance ($P < 0.05$), with detailed measurements provided in Tables 4 and 5.

The stratified analysis by foot type during dynamic loading also confirmed that the observed gender differences were consistent across all foot types. The shift in

Table 5 BMI analysis and its relationship with Flatfoot prevalence

BMI Category	*N* (%)	Flatfoot Prevalence (%)	95% CI (%)	*P*-value
BMI < 25 kg/m^2	982 (80.7)	4.9	3.7–6.1	0.036
BMI ≥ 25 kg/m^2	235 (19.3)	8.3	5.7–10.9	
Gender				
Male (mean BMI ± SD)	756 (62.1)	23.1 ± 3.6 kg/m^2		< 0.001
Female (mean BMI ± SD)	461 (37.9)	21.9 ± 3.0 kg/m^2		

pressure distribution from the 2nd-4th metatarsal region to the 5th metatarsal during the transition from static to dynamic loading was observed in all foot type categories, with males consistently showing higher 5th metatarsal pressure during walking ($P < 0.001$). This suggests that the gender-specific dynamic pressure patterns are fundamental biomechanical characteristics rather than secondary effects of differences in foot structure.

Discussion

The main findings of this study include a 5.5% prevalence of flatfoot among third-year high school students in Tongzhou District, Beijing, with no significant gender difference in prevalence rates. However, significant differences in plantar pressure distribution were observed between male and female students, both in static and dynamic phases. Males demonstrated larger contact areas and greater plantar pressure in the 2nd-4th metatarsal and midfoot regions during static loading, while females exhibited higher pressure in the hallux and 2nd-5th toe regions. During dynamic loading, males showed higher pressure at the 5th metatarsal, while females continued to exhibit higher pressure in the toe regions.

Flatfoot is characterized by collapse or excessive flattening of the medial longitudinal arch. Epidemiological studies have demonstrated varying prevalence rates between males and females [12]. Previous research has largely attributed flatfoot development to abnormal bone structure or ligamentous laxity leading to medial arch collapse [13]. Even subtle alterations in foot structure can modify plantar pressure distribution patterns [14]. Some adolescents with flatfoot may require surgical intervention after foot decompensation, even before the onset of pain [15]. If the optimal intervention window is missed and foot structures fully mature, structural damage may occur, subsequently increasing both treatment complexity and associated costs. With advancing technology, plantar pressure testing has gained widespread application in biomechanical assessment. This enables early detection of abnormal plantar pressure distributions among senior high school students which, combined with physical examination, facilitates timely identification and intervention for flatfoot, thereby optimizing prognosis and minimizing treatment costs associated with structural damage [16–18].

A meta-analysis revealed a global flatfoot detection rate of 25% among children over the past two decades, with higher prevalence in males compared to females [12, 19, 20]. Australian researchers reported a childhood flatfoot prevalence of 14% [21, 22, 23]. Panagiotis et al. documented flatfoot detection rates of 5.0% in males and 3.4% in females aged 6–17 years in Greece [24]. Additionally, a study of 823 Ethiopian students aged 11–15 years reported a flatfoot prevalence of 17.6%, noting significant variations across age, gender, school type, BMI, and footwear [25]. Uden H et al. suggested that the considerable variation in flatfoot prevalence rates might be attributed to changes in foot posture during childhood development [26].

In our study, the flatfoot prevalence among third-year high school students aged 17–23 years in Beijing was 5.5%, with rates of 5.3% in males and 5.9% in females. Although females showed slightly higher prevalence, this gender difference was not statistically significant. Our findings diverge from previous domestic and international studies [12, 24, 25], possibly due to differences in age groups, ethnicity, and environmental factors. Adult flatfoot prevalence ranges from 15–25% [27, 28], with flexible flatfoot affecting approximately one-quarter of adults [29]. A British survey of women over 40 years estimated an acquired flatfoot prevalence exceeding 3% [30]. A 2020 international study demonstrated an inverse relationship between age and flatfoot detection probability [25].

The higher flatfoot prevalence among females in our study might be attributed to lower physical activity levels compared to males [25], as insufficient physical activity may lead to delayed or uneven muscle strength development, resulting in compromised arch strength. Research has shown that flatfoot manifestations typically decrease with age, although joint hypermobility and weight gain can increase flatfoot incidence across age groups [31]. As our study population represents a transitional phase between adolescence and adulthood, their arch development maturity and physical activity patterns differ from both younger adolescents and adults, potentially resulting in age-specific prevalence rates.

Interestingly, our study also found a higher prevalence of high arches in females compared to males (left foot: 4.1% vs. 2.6%; right foot: 4.3% vs. 2.6%), though this difference was only statistically significant for the left foot ($P = 0.03$). This finding may seem contradictory to our explanation for the higher flatfoot prevalence in females. However, the higher prevalence of high arches in females could be attributed to several factors. First, females generally exhibit greater ligamentous laxity due to hormonal differences, which can influence foot structure in multiple ways, potentially leading to either excessive pronation (flatfoot) or supination (high arch) depending on individual biomechanical factors [32, 33]. Second, footwear choices may play a role, as females in this age group often wear shoes with elevated heels, which can alter foot posture and potentially contribute to the development of high arches through adaptation mechanisms [34]. Third, there may be gender differences in muscle activation patterns during gait that influence arch development differently in males and females [35]. These findings highlight the complex, multifactorial nature of foot arch development and the need for comprehensive assessment approaches when evaluating foot structure and function across genders.

Studies have reported flatfoot prevalence rates as high as 70% among obese Italian adolescents [36]. Our previous research confirmed that body mass index is a significant risk factor for flatfoot [10]. This is consistent with our current findings, which showed a significantly higher flatfoot prevalence among students with BMI ≥ 25 kg/m² compared to those with lower BMI values (8.3% vs. 4.9%, $P = 0.036$). Foot types, including flatfoot, normal foot, and high arch, show considerable interpersonal variation and are associated with lower limb injuries [37]. However, the specific biomechanical mechanisms linking foot type to lower limb injuries remain unclear. Different foot types exhibit distinct plantar pressure characteristics during walking [37], with plantar loading serving as a reliable indicator for assessing human locomotor mechanical efficiency [38]. Plantar pressure parameters provide clinicians with valuable information for determining optimal treatment strategies and preventing serious complications that may significantly impact patient quality of life [39].

In children with mature gait patterns during developmental stages, barefoot walking typically initiates with rear-foot and calcaneal contact, progressing from initial contact to weight-bearing, followed by lateral forefoot ground contact, transitioning medially to first metatarsal stabilization, then pressure transmission to the hallux, and finally toe-off [40, 41]. During this process, plantar pressure distribution is non-uniform and varies with foot type, walking speed, age, gender, and joint mobility [42–44]. However, the lack of standardization in plantar contact area segmentation makes inter-study comparisons challenging. Unlike previous studies, our research divided plantar pressure distribution into eight distinct regions.

Our findings revealed that compared to static conditions, gender differences in 2nd-4th metatarsal plantar pressure became statistically non-significant during dynamic loading ($P < 0.001$ to $P = 0.143$), while differences in 5th metatarsal pressure became significant ($P = 0.986$ to $P < 0.001$), indicating substantial pressure variations in the 2nd-5th metatarsal region. Buldt et al., studying plantar pressure characteristics in healthy adults aged 18–45 years, similarly observed lateral pressure transfer through the midfoot after heel strike, with increased lateral versus medial forces [45]. Additionally, a study of Taiwanese college athletes confirmed predominant forefoot lateral loading during static-to-dynamic transition [46].

Our study population, aged 17–23 years, demonstrated plantar pressure distribution patterns approximating adult characteristics. Gender differences in lateral forefoot pressure distribution during walking, particularly regarding forefoot discomfort after exercise or prolonged walking, may reflect variations in exercise habits, activity levels, and walking posture between males and females [47]. Both static and dynamic measurements showed higher median pressure values in females for hallux and 2nd-5th toe regions. Demirbüken's team, studying 524 adolescents aged 11–14 years, similarly found higher toe pressure in females with increasing age [44], suggesting consistently higher toe region pressure in females from early adolescence through senior high school, possibly related to more sedentary behavior [47]. We hypothesize that female senior students may have a more anterior center of gravity, though this cannot be confirmed solely through toe region pressure differences and requires further investigation.

Reduced ankle dorsiflexion range has been associated with increased forefoot peak pressure [48]. However, our study's limitation in measuring lower limb joint mobility ranges prevents definitive conclusions about potential gender differences in ankle dorsiflexion among senior high school students, warranting further research.

Typical gait parameters generally produce low symmetry ratios, indicating highly symmetrical gait patterns. Asymmetry typically suggests pathological gait [39, 49]. In our gender comparison of plantar pressure distribution, asymmetry was observed only in static medial heel pressure and dynamic first metatarsal pressure, further confirming the high symmetry of gait patterns. While research has shown that forefoot total contact area exceeds that of the hindfoot [39], our study's limitation includes the lack of detailed forefoot-hindfoot contact area segmentation in senior students. We observed gender differences in plantar contact area, with males showing larger areas than females, consistent with Kasović et al.'s findings [50]. This may be attributed to males' higher exercise intensity requiring larger ground contact area for stability maintenance [51]. Furthermore, our previous research demonstrated positive correlations between height, weight, BMI, and bilateral foot length, independent of gender [10]. As males generally develop larger physical dimensions than females, their longer and wider feet result in greater plantar contact areas.

Further research is needed to investigate potential differences in regional contact areas among senior high school students.

Despite the valuable insights provided by this study, several limitations should be considered. First, the study sample was limited to third-year high school students in Tongzhou District, Beijing, and therefore may not fully represent the broader high school population across Beijing or other regions. This geographical limitation could affect the generalizability of the findings. Second, the study relied on a cross-sectional design, which precludes the establishment of causal relationships between gender, foot arch type, and plantar pressure distribution. Longitudinal studies are needed to better understand the developmental changes in foot structure and plantar pressure over time. Third, while we categorized participants by foot arch type, the classification was based on the arch index, which may not fully capture the complexity of foot structure, such as individual differences in ligamentous laxity or skeletal deformities. Fourth, we did not conduct a detailed analysis of lower limb joint mobility, which could influence plantar pressure distribution patterns. Fifth, while we collected BMI data, a more comprehensive analysis that stratifies participants by BMI categories and examines interaction effects between BMI, gender, and foot type would provide additional insights. Lastly, although we collected data on physical activity levels via questionnaires, a more objective assessment of activity patterns would strengthen future studies. Additionally, we did not analyze the 95% confidence intervals for all plantar pressure parameters, which would have provided a more comprehensive understanding of the precision of our measurements.

Conclusion

- The prevalence of flatfoot among third-year high school students in Tongzhou District, Beijing is 5.5%, with no statistically significant gender difference (5.3% in males, 5.9% in females).
- Significant gender differences exist in plantar pressure distribution, with males demonstrating larger contact areas and greater pressure in the midfoot and 2nd-4th metatarsal regions during static loading.
- Females consistently show higher plantar pressure in the hallux and 2nd-5th toe regions in both static and dynamic phases.
- During the transition from static to dynamic phases, plantar pressure shifts laterally in the forefoot, with males exhibiting significantly higher pressure at the 5th metatarsal during walking.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-025-08634-8.

Supplementary Material 1

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Author contributions
JS and CX contributed equally to this work. JS and ZL conceived and designed the study. JS, CX, and XL collected and analyzed the data. FL and BF performed the statistical analysis. JS and CX drafted the manuscript. ZL critically revised the manuscript. All authors read and approved the final manuscript.

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Data availability
The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee of Beijing Luhe Hospital, Capital Medical University (Ethics approval number: 2018-LHKY-016-01) in accordance with the Declaration of Helsinki. All participants provided written informed consent. For participants under 18 years of age, written informed consent was obtained from their parents or legal guardians.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Clinical trial number
Not applicable.

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