Forefoot pressure response to selected backpack loads and carrying durations in adolescent school-going girls

Respuesta de la presión del antepié a cargas seleccionadas de mochila y duración del porteo en adolescentes escolares

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Abstract

Introduction: Carrying heavy school backpacks has been recognized as a common source of biomechanical stress among children. The forefoot, serving as the primary point of propulsion during walking, frequently experiences the highest pressure. Adolescent girls may be particularly susceptible due to ongoing musculoskeletal development and lower load tolerance during growth.

Objective: To assess the effects of selected backpack loads and walking durations on maximum pressure at the forefoot in adolescent school-going girls using a repeated measures design.

Methodology: Sixty-nine girls aged 10 to 16 years participated in the study. Maximum forefoot pressure was recorded using a pressure plate system across six selected backpack loads and seven walking durations. Descriptive statistics and repeated measures analysis were performed to examine the effects of load, time, and side of the foot.

Results: Backpack load had a statistically significant effect on maximum forefoot pressure, and a significant interaction was found between load and time, indicating a cumulative effect. Walking duration alone and foot side did not show significant effects; however, side and load interaction suggested condition-specific differences.

Discussion: The findings suggested that increasing mechanical demands from heavier loads led to adaptive changes in forefoot loading patterns. The cumulative stress reflected compensatory responses to sustained external weight, highlighting the forefoot's vulnerability during growth and its potential link to long-term musculoskeletal strain.

Conclusions: The study concludes that appropriate backpack load management and periodic gait assessments are essential to reduce excessive forefoot pressure.

Keywords

Adolescent girls; backpack load; carrying duration; forefoot pressure; maximum pressure.

Resumen

Introducción: El transporte de mochilas escolares pesadas ha sido reconocido como una fuente común de estrés biomecánico en los niños. El antepié, al actuar como el principal punto de propulsión durante la marcha, experimenta con frecuencia las mayores presiones. Las adolescentes pueden ser particularmente vulnerables debido al desarrollo musculoesquelético en curso y a una menor tolerancia a la carga durante el crecimiento.

Objetivo: Evaluar los efectos de cargas seleccionadas de mochilas y diferentes duraciones de caminata sobre la presión máxima en el antepié en adolescentes niñas que asisten a la escuela, utilizando un diseño de medidas repetidas.

Metodología: Sesenta y nueve niñas de 10 a 16 años participaron en el estudio. La presión máxima del antepié se registró mediante un sistema de plataforma de presión bajo seis cargas seleccionadas de mochila y siete duraciones de caminata. Se realizaron estadísticas descriptivas y un análisis de medidas repetidas para examinar los efectos de la carga, el tiempo y el lado del pie.

Resultados: La carga de la mochila tuvo un efecto estadísticamente significativo sobre la presión máxima del antepié, y se encontró una interacción significativa entre la carga y el tiempo, lo que indicó un efecto acumulativo. La duración de la caminata por sí sola y el lado del pie no mostraron efectos significativos; sin embargo, la interacción entre lado y carga sugirió diferencias específicas según la condición.

Discusión: Los hallazgos sugieren que el aumento de las demandas mecánicas derivadas de cargas más pesadas condujo a cambios adaptativos en los patrones de carga del antepié. El estrés acumulativo reflejó respuestas compensatorias al peso externo sostenido, lo que resalta la vulnerabilidad del antepié durante el crecimiento y su posible vínculo con tensiones musculoesqueléticas a largo plazo.

Conclusiones: El estudio concluye que una gestión adecuada de la carga de la mochila y evaluaciones periódicas de la marcha son esenciales para reducir la presión excesiva en el antepié.

Palabras clave

Adolescentes; carga de la mochila; duración del transporte; presión del antepié; presión máxima.

Introduction

The human foot is anatomically divided into distinct regions, namely, the toes, metatarsal heads (forefoot), midfoot, and heel, each playing a unique role in load bearing and propulsion during gait (Hutton & Dhanendran, 1979). Among these, the forefoot, particularly the metatarsal region, plays a significant role in propulsion during human gait (Koenraadt et al., 2012) and often sustains the highest pressure loading during dynamic activities such as walking (Cavanagh & Lafortune, 1980). In adolescent school-going populations, the concern is heightened due to repetitive, long-duration schoolbag carriage, which can lead to abnormal loading on the forefoot during developmentally sensitive periods (Barbosa et al., 2021; Perrone et al., 2018). Recent literature has highlighted that the forefoot is one of the most affected foot regions under such loading conditions (Bukowska et al., 2021), where the cumulative stress may predispose children to biomechanical adaptations and musculoskeletal problems including metatarsalgia and plantar fasciitis (Castro et al., 2013; Pau et al., 2015a; Pau et al., 2013; Hennig et al., 1994).

With the widespread practice of schoolbag use, multiple studies have identified abnormal shifts in plantar pressure distribution in children. Hennig et al. (1994) reported that although children generally exert lower peak pressures than adults, pressure loading tends to migrate medially in the forefoot with age. Pau et al. (2011a) showed that static load application from backpacks can result in 20–30% increases in peak forefoot and midfoot pressure, along with an anterior shift in the centre of pressure. These findings were later validated under walking conditions, where dynamic trials confirmed elevated forefoot pressure during loaded ambulation, particularly in overweight or physically inactive children (Pau et al., 2013; Pau et al., 2015b; Laštro et al., 2021). Similarly, Balkó et al. (2022) observed that backpack load significantly increased midfoot and forefoot contact areas and pressure impulse in adolescent girls.

While the impact of backpack weight is well documented, the additional effect of walking duration has received comparatively less focused attention. Prolonged walking with a load has been shown to exacerbate musculoskeletal stress accumulation (Wang et al., 2001), potentially intensifying forefoot pressure over time (Pau et al., 2015a; de Paula et al., 2015). This cumulative effect may be more pronounced in adolescent girls due to lower relative muscle strength and biomechanical differences (Jenčíková et al., 2024).

Additionally, asymmetrical plantar loading patterns have been observed, attributed to functional differences between dominant and non-dominant limbs (Guo et al., 2024). The dominant foot often serves a propulsive function, while the non-dominant foot supports body weight, creating inherent pressure asymmetries that may be magnified under load conditions (Fang, 2018; Balkó et al., 2022; Wafai et al., 2015). These asymmetries are particularly critical in adolescent populations undergoing rapid musculoskeletal development.

Despite the growing body of research, most studies have explored backpack-related gait disturbances in broader terms such as general posture (Chansirinukor et al., 2001), balance (Palumbo et al., 2001), and spatiotemporal parameters (Lehnen et al., 2017; Paez-Moguer et al., 2019). Several biomechanical studies have documented the impact of backpack loads on walking gait, particularly in terms of increased ground reaction forces (GRF), altered stride characteristics, and greater joint loading (Liew et al., 2016). The systematic review by Liew et al. (2016) confirms that backpack carriage leads to increased cadence, reduced stride length, and significant changes in lower-limb mechanics. Although these findings are primarily drawn from adult populations, they highlight a consistent biomechanical response to load that may contribute to elevated plantar pressures in specific foot regions, such as the forefoot. These adaptations, when sustained over time, may place excessive stress on the forefoot, especially in younger populations whose musculoskeletal systems are still developing. Moreover, research has also focused on the broader postural effects of schoolbag carriage. Hasbiah et al. (2025) found that Indonesian primary school children carrying backpacks heavier than 10 % of their body weight had a significantly higher prevalence of postural abnormalities, while sitting position was not a significant factor. Their findings emphasize that excessive bag load can compromise spinal alignment, supporting the need to explore region-specific outcomes such as plantar pressure in developing populations. However, only a limited number of studies have explicitly examined region-specific plantar pressure responses, particularly in adolescent girls. Prior studies by the present author and colleagues investigated peak force during gait in schoolboys under similar backpack load and duration conditions (Husain et al., 2024a; Husain et al., 2024b), but the specific effects on maximum forefoot pressure in girls, considering both time and load interactions, remain underexplored.

The current study aims to bridge this gap by evaluating how maximum pressure at the forefoot responds to variations in backpack load, walking duration, and limb (foot) side in adolescent girls aged between 10 to 16 years, using a robust repeated measures design.

It was hypothesized that maximum pressure at the forefoot would significantly vary across the selected different backpack loads, that longer walking durations would result in increased forefoot pressure, and that the interaction between load and time would have a cumulative effect. Additionally, asymmetries between the left and right foot were expected as an effect of selected loads and durations of walk.

Method

Study Design

A 6 (load) × 7 (time) repeated measures design was used. The six backpack loads were: B1 = 0%, B2 = 8%, B3 = 12%, B4 = 16%, B5 = 20%, and B6 = 25% of body weight. Recordings were made at T1 = 00 min (at the beginning of the walking gait), T2 = 05th min, T3 = 10th min, T4 = 15th min, T5 = 20th min, T6 = 25th min, and T7 = 30th min. Data for both feet (right and left) were recorded under each condition.

Participants

A total of sixty-nine school-going girls with the mean age 13.04 ± 2.44 years and body weight of 40.34 ± 14.00 kg from Delhi National Capital Territory were selected using random sampling. Participants with any acute or chronic illnesses, including musculoskeletal deformities such as flat feet or knock-knees, which could influence the study findings, were excluded. Individuals with recent physical injuries or a history of cardio-respiratory conditions or systemic disorders were also not included. To ensure eligibility, a medical certificate confirming that participants were medically fit and free from illness was obtained prior to data collection.

Instruments

The Zebris Force Distribution Measurement (FDM) pressure plate system was employed to assess maximum pressure at the forefoot during walking. This sophisticated system delivers high-resolution data on foot-ground contact, enabling accurate detection of ground reaction forces (GRF). Data analysis was conducted using Zebris Win FDM-S software, known for its comprehensive analytical features (User Manual). As noted by Van Alsenoy et al. (2018), the Zebris FDM platform is characterized by high validity and test-retest reliability. To facilitate consistent walking trials, a 10-meter-long wooden walkway was built with the pressure plate embedded at its center, providing a continuous and even surface.

A calibrated digital weighing scale was used to record both the participant's body weight and the weight of the backpack, with calibration verified using a standard reference weight. Participants wore a comfortable, two-strap school backpack, filled with commonly carried items such as books, notebooks, a water bottle, lunch box and stationery items. The backpack load was adjusted according to each participant's body weight, in line with the specific load condition assigned for the trial.

Selection of the Variables

The study examined the impact of selected backpack loads and carrying durations on the walking gait of girls by analysing the following independent and dependent variables:

Independent Variables:

Backpack Loads: B1 = 0%, B2 = 8%, B3 = 12%, B4 = 16%, B5 = 20%, and B6 = 25% of body weight

Time Duration Recordings: T1 = 00 min (at the beginning of the walking gait), T2 = 05th min, T3 = 10th min, T4 = 15th min, T5 = 20th min, T6 = 25th min, and T7 = 30th min. The time duration recording was conducted at five-minutes intervals throughout the continuous 30-minutes walking gait.

Dependent Variable: Maximum pressure (N/cm2) at forefoot of left and right feet.

Procedure of Data Collection

The data collection took place in the Biomechanics Laboratory of the Indira Gandhi Institute of Physical Education and Sports Sciences, University of Delhi, during the school summer vacation period in Delhi. Girls aged between 10 to 16 years who fulfilled the inclusion criteria and submitted written informed consent from their parents or legal guardians were selected for participation. Prior to participation, each subject was required to submit a medical fitness certificate confirming they were free from illness and suitable for inclusion in the study.

Before initiating data collection, body weight was recorded using a properly calibrated digital scale. A fixed starting point was marked, and participants were instructed to walk comfortably and naturally along the walkway. To ensure understanding of the procedure, a familiarization trial was conducted prior to actual recording. All gait trials were performed barefoot, as barefoot walking is widely recognized for its clinical reliability and is compatible with the Zebris platform (Van Alsenoy et al., 2019). Participants walked at a self-selected comfortable pace along the designated walkway. Gait speed was not formally monitored, and standing leg and/or foot dominance was not considered in the present design.

Each participant completed walking trials under six backpack load conditions corresponding to 0%, 8%, 12%, 16%, 20%, and 25% of their body weight. For each condition, walking lasted 30 minutes, and gait data were captured at seven time intervals: at the beginning of the walking gait (0 minutes), and at 5, 10, 15, 20, 25, and 30 minutes. Participants began their walk from a point 4.5 meters before the pressure plate, initiating contact with their left foot. After reaching a point 4.5 meters beyond the plate, they turned around and walked back, leading with their right foot. This sequence was repeated for five trials to ensure each foot made plate contact five times. Data collection was facilitated by the Win FDM-S software integrated with the Zebris pressure plate system.

To reduce fatigue and preserve data quality, trials under the six load conditions were distributed across separate days. Participants retained the right to withdraw from the study at any time without consequence. Data from participants who did not complete all required trials were omitted from the final analysis.

Confidentiality was maintained throughout the study by assigning each participant a unique identification code in the data system. All research procedures were conducted in line with the ethical standards of the Declaration of Helsinki. Approval for the study was granted by the institutional ethics committee (advisory committee) and endorsed by the Board of Research Studies at the University of Delhi as part of a doctoral research project (Ref No: DPE/2022/1432).

Data Analysis

Data were exported to Excel and SPSS for statistical analysis. Descriptive statistics were calculated to summarize the data. Repeated measures ANOVA was performed with Load, Time, and Side as within-subject factors. Mauchly's Test of Sphericity and Greenhouse-Geisser corrections were applied. Bonferroni-corrected pairwise comparisons followed where necessary. Significance was set at $p < 0.05$.

Results

The study findings are presented in Tables 1 to 3 and illustrated in Figures 1 and 2:

Table 1. Descriptive Statistics of Maximum Forefoot Pressure (Mean ± SD) Across Selected Backpack Loads and Time Intervals for Left and Right Foot

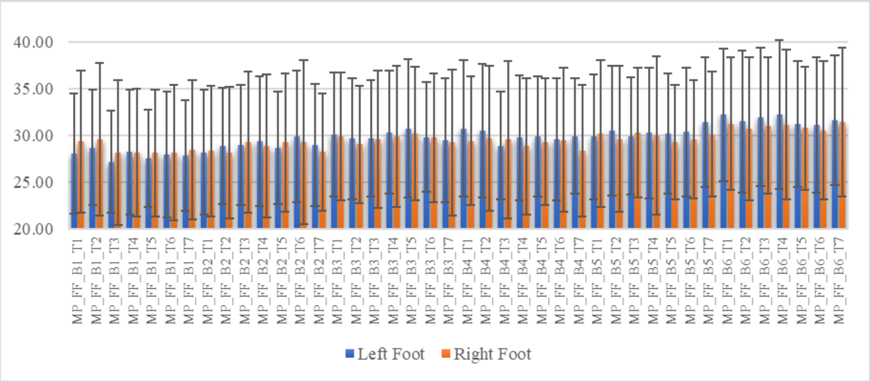
S.No.	Variable Name	Left Foot			Right Foot		
		Mean	±	S.D.	Mean	±	S.D.
1	MP_FF_B1_T1	28.00	±	6.41	29.31	±	7.61
2	MP_FF_B1_T2	28.67	±	6.20	29.58	±	8.17
3	MP_FF_B1_T3	27.12	±	5.46	28.16	±	7.76
4	MP_FF_B1_T4	28.19	±	6.66	28.14	±	6.84
5	MP_FF_B1_T5	27.52	±	5.21	28.09	±	6.76
6	MP_FF_B1_T6	27.93	±	6.75	28.13	±	7.26
7	MP_FF_B1_T7	27.82	±	5.90	28.42	±	7.44
8	MP_FF_B2_T1	28.15	±	6.69	28.29	±	7.02

9	MP_FF_B2_T2	28.84	±	6.26	28.14	±	7.03
10	MP_FF_B2_T3	28.94	±	6.39	29.28	±	7.56
11	MP_FF_B2_T4	29.32	±	6.93	28.84	±	7.67
12	MP_FF_B2_T5	28.64	±	6.05	29.21	±	7.40
13	MP_FF_B2_T6	29.85	±	7.06	29.28	±	8.75
14	MP_FF_B2_T7	28.93	±	6.49	28.18	±	6.30
15	MP_FF_B3_T1	30.09	±	6.64	29.89	±	6.85
16	MP_FF_B3_T2	29.63	±	6.49	29.00	±	6.23
17	MP_FF_B3_T3	29.67	±	6.22	29.57	±	7.33
18	MP_FF_B3_T4	30.27	±	6.57	29.87	±	7.51
19	MP_FF_B3_T5	30.70	±	7.41	30.19	±	7.15
20	MP_FF_B3_T6	29.80	±	5.85	29.73	±	6.90
21	MP_FF_B3_T7	29.48	±	6.62	29.20	±	7.79
22	MP_FF_B4_T1	30.70	±	7.27	29.38	±	6.87
23	MP_FF_B4_T2	30.50	±	7.15	29.67	±	7.74
24	MP_FF_B4_T3	28.89	±	5.79	29.50	±	8.40
25	MP_FF_B4_T4	29.73	±	6.69	28.80	±	7.29
26	MP_FF_B4_T5	29.87	±	6.42	29.28	±	6.75
27	MP_FF_B4_T6	29.54	±	6.49	29.46	±	7.70
28	MP_FF_B4_T7	29.89	±	6.16	28.34	±	7.07
29	MP_FF_B5_T1	29.81	±	6.71	30.19	±	7.83
30	MP_FF_B5_T2	30.47	±	6.95	29.58	±	7.79
31	MP_FF_B5_T3	29.87	±	6.26	30.27	±	6.93
32	MP_FF_B5_T4	30.25	±	6.98	29.94	±	8.45
33	MP_FF_B5_T5	30.19	±	6.44	29.21	±	6.11
34	MP_FF_B5_T6	30.36	±	6.88	29.54	±	6.35
35	MP_FF_B5_T7	31.40	±	6.90	30.11	±	6.71
36	MP_FF_B6_T1	32.16	±	7.08	31.22	±	7.12
37	MP_FF_B6_T2	31.46	±	7.62	30.66	±	7.67
38	MP_FF_B6_T3	31.93	±	7.43	31.03	±	7.26
39	MP_FF_B6_T4	32.20	±	7.95	31.13	±	8.05
40	MP_FF_B6_T5	31.19	±	6.71	30.75	±	6.57
41	MP_FF_B6_T6	31.08	±	7.20	30.50	±	7.39
42	MP_FF_B6_T7	31.63	±	6.94	31.43	±	7.96

Note: N=69; MP= Maximum Pressure; FF= Forefoot; B1= No Backpack Load; B2= Backpack Load of 8% of Bodyweight; B3= Backpack Load of 12% of Bodyweight; B4= Backpack Load of 16% of Bodyweight; B5= Backpack Load of 20% of Bodyweight; B6= Backpack Load of 25% of Bodyweight; T1= Recording at Zero Minute; T2= Recording at Fifth Minute; T3= Recording at Tenth Minute; T4= Recording at Fifteenth Minute; T5= Recording at Twentieth Minute; T6= Recording at Twenty-fifth Minute; T7= Recording at Thirtieth Minute.

The Table 1 presents the mean and standard deviation values of maximum forefoot pressure (MP_FF) for both the left and right foot among 69 participants, recorded across six backpack load conditions (ranging from no load to 25% of bodyweight) and seven walking time intervals (from 0 to 30 minutes). The table details the variations in pressure responses at each condition, helping to identify pressure trends and asymmetries under increasing mechanical load and prolonged walking duration.

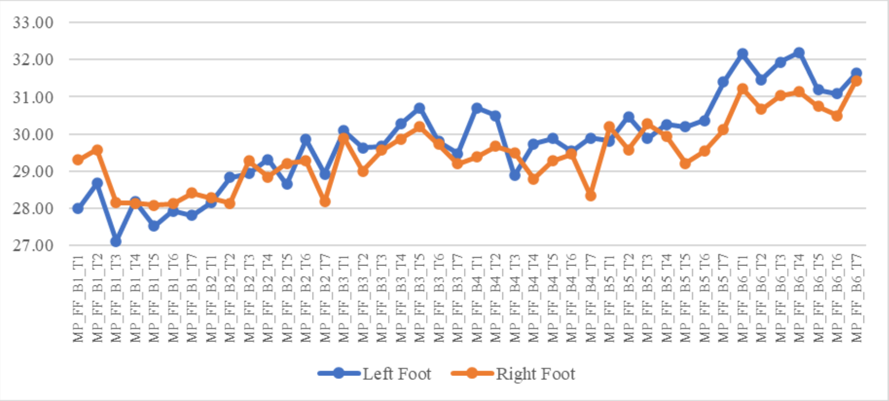
Figure 1. Bar Graph Representing Maximum Pressure at Forefoot (MP_FF) Across Six Backpack Loads and Seven Walking Durations for Left and Right Foot



Note: MP_FF= Maximum Pressure at forefoot (N/cm^2); Derived from Table 1.

The bar graph displays the variation in maximum pressure at forefoot (MP_FF) recorded across six backpack load conditions, namely at 0% (B1), 8% (B2), 12% (B3), 16% (B4), 20% (B5), and 25% (B6) of body weight, and seven time intervals (T1 to T7: 0 to 30 minutes at 5-minute intervals) for both left and right foot. The height of each bar represents the average MP_FF (in N/cm^2) for the respective load-time combination. The graph indicates a progressive increase in MP_FF with increasing load and walking duration, with distinct differences in loading between the left and right foot at higher stress levels.

Figure 2. Line Graph Showing Trends in Maximum Pressure at Forefoot (MP_FF) Over Time Across Six Backpack Loads for Left and Right Foot



Note: MP_FF= Maximum Pressure at forefoot (N/cm^2). Derived from Table 1.

The line graph illustrates the progression of maximum pressure at forefoot (MP_FF) over seven walking durations (0 to 30 minutes in 5-minute intervals) and under six backpack load conditions, namely, 0% (B1), 8% (B2), 12% (B3), 16% (B4), 20% (B5), and 25% (B6) of body weight, for both the left and right foot. For each load condition, MP_FF is plotted over time to visualize cumulative pressure effects. At lower loads (B1 and B2), the right foot initially shows slightly higher MP_FF than the left. However, from around B2_T5 onward, the left foot exhibits progressively higher MP_FF, particularly at heavier loads (B4–B6) and later time points (T5–T7). This shift may reflect adaptive compensations or emerging fatigue, especially during prolonged load carriage.

Table 2. Multivariate Comparison (Pillai's Trace) for Within-Subjects Effects: Side, Load, Time, and Their Interactions on Maximum Pressure at Forefoot

Effect	F	df (Hyp., Error)	Sig. (p-value)	η^2 (Partial Eta Squared)
Side	0.659	(1, 68)	0.42	0.01
Load	38.906*	(5, 64)	<.001	0.752
Time	0.6	(6, 63)	0.729	0.054
Side × Load	5.109*	(5, 64)	0.001	0.285
Side × Time	1.848	(6, 63)	0.104	0.15
Load × Time	8.704*	(30, 39)	<.001	0.87
Side × Load × Time	3.107*	(30, 39)	0.001	0.705

Note: *Significant at 0.05 Level.

The Table 2 presents the results of the multivariate repeated measures ANOVA using Pillai's Trace for the within-subjects effects of foot side (left vs. right), backpack load (six levels), walking duration (seven intervals), and their interactions on maximum pressure at forefoot (MP_FF). The analysis reveals a statistically significant main effect of load ($p < .001$, $\eta^2 = 0.752$) and a significant load × time interaction ($p < .001$, $\eta^2 = 0.870$). Additionally, side × load ($p = .001$, $\eta^2 = 0.285$) and side × load × time ($p = .001$, $\eta^2 = 0.705$) interactions were significant, indicating dynamic pressure differences across limbs depending on load and time combinations. In contrast, side alone and time alone did not reach statistical significance.

Table 3. Within-Subjects Effects with Greenhouse-Geisser Correction for Maximum Forefoot Pressure Across Side, Load, Time, and Their Interactions

Source	df	F	p-value	η^2 (Partial Eta Squared)
Side	1	0.659	0.42	0.01
Load	2.59	38.668*	<.001	0.363
Time	4.59	0.879	0.488	0.013
Side × Load	4.41	3.942*	0.003	0.055
Side × Time	3.86	2.163	0.076	0.031
Load × Time	11.26	3.042*	<.001	0.043
Side × Load × Time	11.41	1.11	0.349	0.016

Note: *Significant at 0.05 Level.

The Table 3 displays the within-subjects effects after applying the Greenhouse-Geisser correction to address violations of sphericity. Results confirm a significant main effect of load (F(2.59) = 38.67, $p < .001$, $\eta^2 = 0.363$) and a significant side × load interaction ($p = .003$), while time ($p = .488$) and side ($p = .42$) were not statistically significant on their own. The load × time interaction remained statistically significant ($p < .001$), although with a smaller effect size ($\eta^2 = 0.043$) compared to the Pillai's Trace results in Table 2. The side × time interaction approached significance ($p = 0.076$), suggesting a potential trend in how pressure differs between sides over time. However, the three-way interaction (side × load × time) remained non-significant, indicating that side differences were not consistently influenced by both load and time together.

Discussion

The present study investigated the effects of varying backpack loads and walking durations on maximum forefoot pressure in adolescent girls using a repeated measures design. The results showed that backpack load had a significant impact on maximum forefoot pressure, and this effect became stronger when combined with longer walking durations. In contrast, walking duration alone did not produce a statistically significant effect. Multivariate analysis (Table 2) confirmed these findings, showing a highly significant main effect of load ($p < .001$, $\eta^2 = 0.752$) and a strong load × time interaction ($p < .001$, $\eta^2 = 0.870$). These outcomes suggest that the forefoot is more sensitive to increases in load, especially during extended walking, indicating a cumulative effect of load and time on forefoot pressure.

This aligns with the findings of Pau et al. (2015a), who documented a 25% increase in forefoot pressure under backpack load, particularly when walking durations were extended. Laštro et al. (2021) similarly reported that longer walking with a backpack significantly elevated forefoot pressure, especially among children with lower physical activity levels. As visualized in Figure 2, present study shows a clear upward trend in MP_FF with increasing load and time, particularly under the 20% (B5) and 25% (B6) load conditions beyond 15 minutes (T4–T7), further confirming this cumulative effect. These studies collectively support the current result that time alone may not always produce a significant pressure rise, but when combined with load, its impact becomes evident. The additive stress placed on the musculoskeletal system over time may surpass the foot's natural shock-absorbing capacity, especially in developing children.

The significant main effect of load is also in line with the early work of Hennig et al. (1994), who showed that as children grow, there is a shift toward more pressure on the inner forefoot. It also agrees with the findings of Chow et al. (2005), who reported that carrying heavier loads changes walking patterns, including more pressure on the forefoot and midfoot areas. These changes in walking often happen as a way for the body to adjust, such as leaning the upper body forward and spending more time with the foot on the ground, which pushes the force more toward the front of the foot. In the present study, Table 3 shows that the effect of load remained strong even after applying the Greenhouse-Geisser correction (F(2.59) = 38.67, $p < .001$, $\eta^2 = 0.363$). This shows that even carrying a moderate weight can clearly affect how pressure is placed on the foot. Similar changes were also reported by Liew et al. (2016), who found that backpack loads regularly change walking patterns. However, their review also pointed out the need for more detailed studies on specific parts of the foot, such as the forefoot, when under load, which the present study focuses on directly.

No significant side-based (left vs. right foot) differences were detected in the present study. While Fang (2018) and Balkó et al. (2022) described asymmetrical loading patterns associated with leg dominance, particularly under load, such asymmetries may be less pronounced in the current population, possibly due to generalised bilateral gait strategies or the absence of athletic-specific adaptations. However, the significant side × load interaction ($p = .001$, $\eta^2 = 0.285$; Table 2) and the trend reversal observed in Figure 2—where the left foot MP_FF surpasses the right from B2–T5 onward—suggest a possible fatigue-driven redistribution of plantar stress over time. Notably, Pau et al. (2011a) observed that side-based differences became evident primarily in static or high-load contexts, implying that side asymmetry might only emerge under more extreme conditions or in highly trained individuals.

Compared to Jenčíková et al. (2024), who reported significant alterations in both temporal and spatial gait parameters in Czech schoolchildren walking with schoolbags, our study reinforces the notion that backpack loads—even when within recommended limits—can disrupt normal gait biomechanics. Their use of the Zebris platform showed increased foot rotation, longer step times, and slower gait speeds under load, which likely contribute to altered plantar pressure distributions similar to what was seen in our data.

Our results also resonate with the work of Kasović et al. (2018) and Ahmad & Barbosa (2019), both of whom demonstrated load-induced shifts in plantar pressure, particularly under the toes and midfoot. Ahmad and Barbosa (2019) also highlighted increases in the contact area and force-time integrals, indicating sustained forefoot engagement during loaded walking, especially in children with higher BMI or lower activity levels—factors which may influence the current findings.

The bar graph (Figure 1) further illustrates this cumulative impact, with visible pressure elevation at each time interval for higher load conditions. The contrast between B1 (0%) and B6 (25%) is especially pronounced by the 30-minute mark, providing visual evidence of the compounding pressure response noted in the statistical tables.

The interaction effect (load × time) observed in this study further supports the conclusions of de Paula et al. (2015) and Castro et al. (2013), who emphasised that repeated exposure to moderate loads over time can have compounding biomechanical consequences, including increased risk of forefoot overuse injuries such as plantar fasciitis or metatarsalgia.

This study also aligns with the authors' previously published work. In an earlier investigation (Husain et al., 2024b), similar patterns of increased peak forces under backpack loads were observed. A follow-up study (Husain et al., 2024a) further examined load-duration interactions and found a clear buildup of pressure over time. However, those studies were conducted on school-going boys, while the present research adds new insight by focusing on adolescent girls—a group potentially more susceptible to altered loading patterns due to differences in structural and muscular development (Chow et al., 2005; Grimmer et al., 2002).

These findings partially support the study’s original hypotheses. The hypothesis that maximum forefoot pressure would significantly vary across backpack load conditions was supported. Although walking duration alone was not statistically significant, its interaction with load produced a strong cumulative effect, confirming the second hypothesis. The third hypothesis, predicting consistent differences between the left and right foot, was not supported, as the main effect for side was non-significant. However, the significant side × load interaction suggests that foot-specific pressure differences may occur under certain load conditions. Although the main effects for side and time were not statistically significant, the interaction between side and time approached significance ($F = 2.163$, $p = 0.076$, $\eta^2 = 0.031$), suggesting a possible trend indicating that the influence of time on pressure may differ between the left and right foot. While this result does not meet the conventional threshold for statistical significance, the observed effect size reflects a small yet noteworthy interaction that warrants further investigation.

From a public health perspective, the present study reinforces ongoing recommendations that backpack loads should not exceed 10–15% of body weight and that prolonged walking with such loads should be minimised or counterbalanced with physical activity to enhance load tolerance. The observed trends in both statistical tables and figures support these guidelines and underscore the importance of regular biomechanical screening in schools to prevent long-term overuse injuries. Moreover, biomechanical screening and gait analysis may be beneficial during routine school health evaluations to identify children at risk of excessive forefoot loading.

Conclusions

The present study showed that increasing backpack load leads to a significant rise in maximum pressure at the forefoot in adolescent school-going girls and this effect becomes more noticeable as walking duration increases. Although walking time alone did not show a significant effect, it became important when combined with backpack load. A strong interaction between load and time was found, showing that both factors together increase stress at the forefoot more than either factor alone. While there was no consistent difference between left and right foot overall, some differences were seen under certain load conditions, suggesting that the body may adjust its walking pattern based on the weight carried and duration. These results highlight the sensitivity of the forefoot to backpack-related stress and support the recommendation that schoolbags should not exceed 10–15% of body weight. The study suggests that heavy loads carried for long periods can lead to extra pressure on the forefoot.

The strength of the present study is its focus on the forefoot, a part of the foot that plays a key role in walking and is highly affected by backpack load. The use of a repeated measures design with a reliable pressure plate system allowed careful tracking of how forefoot pressure changed under six different loads and seven walking durations. The study also adds to existing research by focusing on adolescent girls, who are often underrepresented in such studies.

However, the study had some limitations. All walking trials were done barefoot, which may not fully reflect how forefoot pressure behaves when wearing shoes. The study did not measure foot dominance or physical activity levels, which might help explain why some side-related changes were seen under certain load conditions. Additionally, the study did not monitor gait speed during trials, which may influence plantar pressure outcomes. These aspects should be addressed in future research to strengthen the interpretation of results. Finally, as the participants were from one geographic area, the findings may not apply to all children or school environments.

The findings of the study suggest important future directions for both research and school health practices. Schools should consider regular monitoring of students' backpack weight and walking duration, particularly in younger age groups where musculoskeletal development is ongoing. Interventions such as awareness programs for students and parents, structured locker use, and adjustments in schoolbag design (e.g., wider straps, better weight distribution) may help reduce forefoot pressure.

Future studies should explore the long-term impact of forefoot pressure buildup caused by daily backpack carriage, especially in relation to pain, fatigue, or the development of foot disorders. Including variables such as foot dominance, physical activity levels, and footwear type would provide a more comprehensive understanding of pressure distribution patterns. There is also potential to examine pressure responses in school-going boys, children with foot deformities, or those engaged in sports, to compare load tolerance and biomechanical adaptation across populations. Lastly, follow-up studies using in-shoe pressure systems in real-life school environments could help validate these findings under more natural conditions.

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