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An analysis of contact time of children's walking gait with progressive backpack weight and selected duration conditions

Sukanya Rawat[1], Rabiya Husain[1], Dhananjoy Shaw[2]

[1] Department of Physical Education and Sports Sciences, University of Delhi, Delhi, India; [2] Indira Gandhi Institute of Physical Education and Sports Sciences, University of Delhi, Delhi, India

Abstract

Study aim: Backpack carriage is a daily necessity for school-going children, but excessive loads and prolonged carrying durations may disrupt gait mechanics, potentially leading to musculoskeletal strain. The present study aimed to analyse the effect of progressive backpack weights and carrying durations on the contact time during the walking gait of school-aged boys. Additionally, it assessed the symmetry between left and right foot contact times under varying conditions.

Material and methods: A total of 85 healthy male students (mean age = 11.06 ± 0.76 years, height 143.50 ± 5.11 cm, body weight 36.00 ± 4.05 kg) from Delhi National Capital Region participated in the study. Contact time was recorded using the Zebris FDM pressure plate under five backpack weights (0%, 8%, 12%, 16%, and 20% of body weight) and five intervals (0, 5, 10, 15, and 20 minutes). A 5 × 5 repeated measures design was used. Descriptive statistics, paired-sample t-tests and two-way repeated measures ANOVA were employed to evaluate the effects of backpack weight and duration.

Results: Progressive backpack weights up to 12% of body weight increased contact time, reflecting biomechanical adjustments to maintain stability. However, loads of 16% and above caused fatigue, disrupting gait patterns. Prolonged carrying durations intensified these effects, leading to greater variability and asymmetry in contact time, particularly under heavier loads. Significant differences in contact time between the left and right foot were observed ($p < 0.05$), indicating uneven weight distribution and compensatory gait strategies. ANOVA findings confirmed a significant main effect of backpack weight, a significant interaction between weight and duration, and a statistically significant main effect of duration for the left foot.

Conclusions: The findings suggest that excessive backpack weight and prolonged carrying duration significantly alter foot contact time and gait symmetry, which may contribute to musculoskeletal stress in school-aged children. A threshold effect emerged, where both backpack weight and duration—independently and interactively—disrupted natural gait stability, particularly in the non-dominant limb. The study supports limiting backpack weight to 10–12% of body weight and reducing prolonged carriage duration. Future studies should incorporate multifactorial models and longitudinal tracking to better understand the long-term impact of load-induced gait adaptations.

Keywords: Backpack weight – School-going boys – Walking durations – Contact time – Gait analysis

Introduction

Understanding walking patterns is fundamentally supported by the critical method of gait analysis (Harris & Wertsch, 1994; Whittle, 1993), offering valuable insights into the biomechanics of movement and identifying factors that affect stability and propulsion (Almeheyawi et al., 2021). Among school-aged children, gait is often influenced by external loads such as backpacks (Song et al., 2014), which are a daily necessity (Pascoe et al., 1997; Sheir-Neiss et al., 2003). While practical, backpacks can impose significant mechanical stress on the body, leading to health issues such as back pain (Skaggs et al., 2006), postural imbalances (Castro et al., 2015), and gait alterations (Hong & Cheung, 2003; Knapik et al., 1996; Knapik et al., 2004; Perrone et al., 2018). The implications of improper backpack use extend beyond temporary discomfort, potentially influencing long-term musculoskeletal development and motor control in children (Connolly et al., 2008; Rose et al., 2016). Despite existing guidelines recommending that school children carry no more than 10-12% of their body weight (Hong & Brueggemann, 2000; Rai & Agarawal, 2013), there is limited research on how progressively increasing loads interact with carrying

Author's address Rabiya Husain, Ph.D. Scholar, Department of Physical Education and Sports Sciences, University of Delhi, Delhi, India rabiyahsn70@gmail.com

duration to affect gait mechanics. Research indicates that carrying loads exceeding the recommended threshold significantly disrupts posture and gait (Hong & Brueggemann, 2000; Rai & Agarawal, 2013), especially during extended durations (Chow et al., 2006; Tomal et al., 2022). Similarly, Kinoshita (1985) reported that both 20% and 40% backpack loads significantly modified normal walking gait in adult males, increasing double support phases and altering temporal-spatial gait characteristics. The study also found that using a doublepack system, which distributed the load between front and back, reduced some of the gait alterations compared to a conventional backpack. This supports our observation that increasing backpack weight alters support dynamics and may affect gait symmetry. Backpacks are associated with discomfort in various body regions, including the head, neck, shoulders, arms, wrists, hands, lower limbs, and even feet and ankles (Rai & Agarawal, 2013). Poor backpack design or improper use can further aggravate these issues, leading to postural alterations and changes in walking patterns (Singh & Koh, 2009). To manage the additional load, children often adopt biomechanical adjustments (Hong & Cheung, 2003), which can contribute to fatigue and increase the risk of developing long-term musculoskeletal problems (Barbosa et al., 2019; Macias et al., 2008; Perrone et al., 2018; Sokhi et al., 2022; Son, 2013). However, previous studies have primarily focused on postural responses rather than dynamic gait parameters such as contact time, which plays a crucial role in maintaining locomotor efficiency and stability (Al-Khabbaz et al., 2008; Behmaram et al., 2022).

A key component of gait analysis is the evaluation of contact time, which refers to the duration a foot remains in contact with the ground during the stance phase of walking. This parameter plays a crucial role in maintaining gait stability and efficiency (Ewins & Collins, 2014). When children carry heavier backpacks, they adapt their walking mechanics to manage the increased load, often resulting in prolonged contact time. While an increased contact time may serve as a compensatory strategy to maintain balance, it may also contribute to inefficient movement patterns and excessive strain on the lower limbs, ultimately leading to fatigue-induced gait instability (Grobler & Kramer, 2023; Husain et al., 2024a; Husain et al., 2024b). Such adaptations may also lead to fatigue and asymmetrical gait patterns (Behmaram et al., 2022; Grobler & Kramer, 2023). Research has shown that these adaptations increase the biomechanical burden on the lower limbs, influencing stability and efficiency during prolonged load carriage (Al-Khabbaz et al., 2008; Husain et al., 2024a; Husain et al., 2024b).

Beyond overall contact time, analysing the difference in contact time between the right and left foot provides deeper insights into gait symmetry and balance. A significant discrepancy in contact time between the two feet may indicate compensatory strategies, uneven load distribution, or the onset of fatigue, all of which can contribute to gait instability. This asymmetry is particularly concerning, as prolonged gait imbalances may increase stress on joints and lead to injury over time. Such asymmetries become more pronounced under the effects of progressive loads and carrying durations, as they reveal subtle biomechanical adjustments children make to cope with external stressors (Tomal et al., 2022). For instance, prolonged stance times on one foot relative to the other can signal uneven weight distribution, which may lead to joint stress and potential injury over time (Barbosa et al., 2019). Understanding these differences is essential for identifying potential risks of musculoskeletal strain and for developing interventions to promote symmetrical and efficient gait patterns. Moreover, discrepancies in contact time have been linked to an increased metabolic cost of locomotion, which may further amplify fatigue and gait instability over prolonged durations (Rose et al., 2016).

While previous research has extensively explored the general impact of backpack weight on posture and walking kinematics, there remains a notable gap in understanding how these external loads influence foot contact time and asymmetry in school-aged children (Perrone et al., 2018; Behmaram et al., 2022). This dual perspective is critical, as it not only captures the overall biomechanical burden but also highlights potential asymmetries that could compromise long-term musculoskeletal health. Moreover, studies have noted the impact of load carriage on ground reaction forces, which affect gait dynamics and increase the risk of postural and joint-related issues, emphasizing the need for a detailed evaluation of gait symmetry under load conditions (Barbosa et al. 2019; Husain et al., 2024a; Husain et al., 2024b). Chow et al. (2005) investigated the effects of backpack loads on adolescent girls and found that increasing load percentages up to 15% of body weight caused a significant increase in double support time and a reduction in walking speed and cadence. These changes were attributed to increased biomechanical demands to maintain balance. The increase in proximal joint movement and reduced pelvic rotation observed in their study closely aligns with our findings that loads above 12% body weight disrupt gait mechanics and increase asymmetry, particularly under longer durations. By addressing these gaps, this study contributes to a growing body of research focused on optimizing load management strategies in children to mitigate potential risks associated with prolonged backpack use.

It is hypothesized that increasing backpack weight and prolonged carrying duration will lead to:

1. An increase in overall contact time due to biomechanical adaptations for stability.
2. Significant asymmetry in left and right foot contact time, indicating uneven weight distribution and compensatory gait strategies.
3. A threshold effect beyond which excessive backpack loads and prolonged durations will result in fatigue-induced gait instability.

The present study aimed to analyse the effects of progressive backpack weights and varying carrying durations on the contact time of both the right and left foot during the walking cycle in boys aged between 10 and 12 years. Using the Zebris FDM pressure plate, we examined contact time under five load conditions (0%, 8%, 12%, 16%, and 20% of body weight) and five recording time intervals (0, 5, 10, 15, and 20 minutes). A specific goal was to identify and interpret differences in contact time between the right and left foot to reveal patterns of asymmetry and their potential implications. Harman et al. (2000) examined gait biomechanics under military backpack loads and found that heavier loads caused significant changes in stride frequency, knee flexion, and trunk forward lean. Although the population and context differ, their finding that the burden of heavier loads shifted toward the knee and hip muscles reinforces our observation that prolonged heavy backpack use may lead to fatigue and postural strain, particularly evident through increased contact time and asymmetry.

By bridging these gaps, this study aims to provide evidence-based recommendations for safe backpack use, while also contributing to the broader understanding of how load and duration impact gait mechanics (contact time) and symmetry. The findings hold significance for parents, educators, and policymakers, offering practical insights for safeguarding the musculoskeletal health of school-aged children.

Material and methods

Participants of the study

This study involved 85 male school pupils, with a mean age of 11.06 ± 0.76 years, mean height of 143.50 ± 5.11 cm, and mean body weight of 36.00 ± 4.05 kg, who were randomly selected from the Delhi National Capital Region. The inclusion criteria required participants to: (i) be male, (ii) fall within the age range of 10 to 12 years, and (iii) be clinically confirmed as healthy. Participants with acute or chronic health conditions, as well as those with incomplete records, were excluded from the study. Importantly, all participants were informed that they had the right to withdraw from the procedure at any point during the data collection process.

All protocols adhered to the ethical guidelines outlined in the Declaration of Helsinki. Data collection was conducted anonymously, with each participant assigned a unique identification code within the software. Ethical approval for this research was obtained from the Biomechanics Laboratory, as part of the research programme (Ref. No.: DPE/2022/1432).

Instrument used for gait analysis recording

In the study, a Zebris FDM pressure plate (dimensions: 40 cm × 30 cm), which operates at a sampling frequency of 120 Hz, was employed to analyse the contact time variable. The measurement accuracy is ±5% within the calibrated range of 1–120 N/cm². It employs capacitive pressure sensors arranged in a matrix format, allowing precise force distribution mapping. The system was operated via the Win FDM-S software provided by Zebris GmbH (Germany), with its detailed user manual available publicly online (Link: https://www.zebris.de/fileadmin/Editoren/zebris-PDF-Manuals/Medizin/Software/Alte_Versionen/Manual_zebris_FDM_1.16.x_R1_EN_web.pdf). The Zebris FDM-S system demonstrated high internal consistency (Cronbach's alpha > 0.90) for gait-related variables, as verified through a double retest protocol over two consecutive days. Previous research, such as the study by Van Alsenoy et al. (2019), has confirmed the platform's validity and reliability for test-retest measurements.

In addition to the pressure plate, a calibrated weighing scale was used to record participants' body weight. Calibration was verified prior to use, employing a standard reference weight to ensure accuracy.

A standard double-strap backpack which is commonly carried by the students was used in the study, filled with commonly carried school materials such as textbooks, notebooks, a water bottle, and a pencil box to simulate a typical student load.

Selection of the variables

The following independent and dependent variables were selected for the study:

1. Experimental variables (independent variables)
   a) Backpack weight
      i. Backpack weight of 0% of the body weight of the subject (no weight in the backpack)
      ii. Backpack weight of 8% of the body weight of the subject
      iii. Backpack weight of 12% of the body weight of the subject
      iv. Backpack weight of 16% of the body weight of the subject
      v. Backpack weight of 20% of the body weight of the subject
   b) Duration of carrying the backpack weight (recording time)
      i. Recording at zero minutes (at the start of the walking gait)
      ii. Recording at fifth minute of the walking gait
      iii. Recording at tenth minute of the walking gait
      iv. Recording at fifteenth minute of the walking gait

v. Recording at twentieth minute of the walking gait
2. Observational variables (dependent variables)
   a) Contact time of the left foot (milliseconds)
   b) Contact time of the right foot (milliseconds)
   c) Contact time of the average of left foot and right foot (milliseconds)
   d) Overall mean contact time of the left foot and right foot (all the cycles) (milliseconds)

Protocol followed for gait analysis

Data collection was conducted in the Biomechanics Laboratory. Prior to the data collection process, participants underwent a trial session to become familiar with the laboratory setup and experimental procedures. Written informed consent was obtained from all participants, and due to the age of the participants, consent from their legal guardians or parents was also secured. Additionally, release-from-liability forms were signed by the guardians to ensure ethical compliance and protect the participants' rights throughout the study.

Participants' body weight was recorded using a calibrated weighing scale, with the calibration verified using standard reference weights. For the gait analysis, a starting line was set 4.5 m before the pressure plate, and participants were instructed to walk barefoot at a natural and comfortable pace. Barefoot walking was chosen as it is considered clinically appropriate and ensures accurate and reliable data for the Zebris FDM pressure plate system (Van Alsenoy et al., 2019).

The Zebris FDM pressure plate (40 cm x 30 cm) was placed at the centre of a 10x5 m walkway, and participants were instructed to maintain a normal gait pattern while avoiding direct aiming at the platform to prevent data inaccuracies. Each trial began with participants stepping onto the platform with their left foot and walking 4.5 m beyond it before turning around and stepping onto the platform with their right foot during their return. This procedure was repeated for five trials, ensuring that each foot made contact with the pressure plate five times. After completing the first protocol, which involved walking without a backpack (0% backpack load), the subject proceeded to the second protocol, where the backpack was introduced. The backpack was comfortably worn and properly adjusted to ensure a secure fit. This adjustment was made once for each subject and remained unchanged throughout the data collection of a particular subject. The backpack load was adjusted five times for each subject (experimental conditions) based on their body weight.

The contact time variable data were collected using the Zebris FDM-S pressure plate and processed through the Win FDM-S software. In cases where participants missed or partially missed stepping on the plate, they were asked to continue walking, and additional trials were recorded to ensure complete data collection.

Study design

A 5 × 5 (five backpack weights; five recording intervals) repeated measures study design was employed for this research, allowing for comprehensive evaluation of the variables across multiple trials. This design ensured consistency and reliability in data collection by assessing each participant under repeated conditions.

Statistics used

Descriptive statistics, including mean, standard deviation, and coefficient of variation, were calculated to evaluate the contact time data for both feet under various weight and duration conditions. Initially, a paired-samples t-test was conducted to assess the mean differences between the left and right foot contact times. To assess the combined effects of backpack weight and carrying duration, a two-way repeated measures ANOVA was applied. This allowed for the analysis of both main effects and their interaction. Mauchly's test of sphericity was conducted to verify the assumption of sphericity; where violated, the Greenhouse-Geisser correction was applied. The level for significance was set at 0.05 for all statistical procedures.

Results

The results of the study are presented in Tables 1 to 5 and Figures 1 and 2. A detailed analysis of these findings is presented below to highlight significant patterns and their biomechanical implications.

Table 1 presents the descriptive statistics of left foot contact time under different backpack weights and time intervals. An increasing trend in contact time is observed as backpack weight increases to 12% of body weight (B3), indicating compensatory gait adjustments. However, at 16% (B4), a decline in contact time suggests the onset of fatigue, followed by a slight increase at 20% (B5), reflecting biomechanical strain. This fluctuation in contact time suggests that heavier loads induce instability and force the body to adapt differently at higher stress levels.

Table 2 presents the descriptive statistics of right foot contact time, following a similar pattern to the left foot. A consistent increase in contact time is observed with backpack loads up to 12% (B3), followed by a decrease at 16% (B4), similar to the left foot. The observed differences between the left and right foot indicate asymmetric adaptations to increasing loads.

Table 3 provides the overall mean contact time of the average of the left and right foot across different backpack weights and time intervals. However, a significant difference between left and right foot contact times is observed at higher loads (B4 and B5), suggesting compensatory strategies that result in asymmetric gait patterns. This asymmetry is more pronounced at prolonged durations (T3–T5), reflecting fatigue-induced biomechanical adaptations.

Table 1. Descriptive statistics of mean contact time of left foot with selected backpack weights at selected recording time

S.No	Bag/ Time	B1	B2	B3	B4	B5	Mean ± SD	CV
		Contact Time (Milliseconds) of Left Foot						
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD		
1	T1	620.83 ± 61.34	627.53 ± 86.15	644.71 ± 76.27	618.71 ± 76.98	626.59 ± 65.19	627.67 ±73.19	11.6%
2	**T2**	610.95 ± 57.4	612 ± 73.03	627.42 ± 65.49	600.95 ± 76.9	639.3 ± 70.73	618.12 ± 68.71	11.1%
3	T3	599.89 ± 65.81	627.65 ± 83.5	633.18 ± 67.43	618.48 ± 66.06	630.59 ± 81.09	621.96 ± 72.78	11.7%
4	T4	607.89 ± 71.99	632.12 ± 86.6	624.59 ± 74.45	614.59 ± 71.63	628.71 ± 66.17	621.58 ± 74.17	11.9%
5	**T5**	602.12 ± 60.78	629.42 ± 69.96	640.24 ± 80.06	625.3 ± 68.68	635.53 ± 73.19	626.52 ± 70.53	11.2%
		608.34 ± 63.46	**625.74 ± 79.85**	**634.03 ± 72.74**	**615.61 ± 72.05**	**632.14 ± 71.27**		
	CV	**10.43**	**12.76**	**11.47**	**11.7**	**11.27**		

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; B1= 0% of Body Weight (No backpack); B2= 8% of Body Weight; B3= 12% of Body Weight; B4= 16% of Body Weight; B5= 20% of Body Weight.

Table 2. Descriptive statistics of mean contact time of right foot with selected backpack weights at selected recording time

S.No	Bag/ Time	B1	B2	B3	B4	B5	Mean ± SD	CV
		Contact time (milliseconds) of right foot						
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD		
1	T1	616 ± 58.09	625.41 ± 79.17	638.71 ± 85.42	608.24 ± 65.87	616.35 ± 63.92	620.94 ± 70.49	11.3%
2	T2	615.29 ± 56.73	607.41 ± 70.38	618.71 ± 57.75	597.06 ± 77.38	630.35 ± 64.83	613.76 ± 65.41	10.6%
3	T3	601.53 ± 52.34	632.71 ± 70.75	629.76 ± 73.13	607.18 ± 59.49	622.35 ± 84.75	618.71 ± 68.09	11.0%
4	T4	599.65 ± 65.36	632.35 ± 84.95	625.41 ± 73.95	610.59 ± 72.18	625.18 ± 61.09	618.64 ± 71.51	11.5%
5	T5	597.06 ± 54.57	624.71 ± 68.53	634.35 ± 69.39	616.82 ± 69.01	626.47 ± 67.82	619.88 ± 65.86	10.6%
		605.91 ± 57.42	**624.52 ± 74.76**	**629.39 ± 71.93**	**607.68 ± 68.76**	**624.14 ± 68.49**		
	CV	**9.48**	**11.97**	**11.43**	**11.31**	**10.97**		

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; B1= 0% of Body Weight (No backpack); B2= 8% of Body Weight; B3= 12% of Body Weight; B4= 16% of Body Weight; B5= 20% of Body Weight.

Figure 1 illustrates the overall mean contact time of the left and right foot across different backpack weights. It shows a steady increase in contact time up to 12% of body weight (B3), a dip at 16% (B4), and a slight rise at 20% (B5), indicating the biomechanical strain imposed by excessive loads.

Figure 2 shows the contact time trends across different time intervals. It is evident that contact time increased progressively as walking duration extended beyond 10 minutes (T3–T5). This prolonged exposure to load exacerbates asymmetry, particularly at heavier weights (B4 and B5).

Table 3. Overall mean contact time of left foot and right foot with selected backpack weights at selected recording time

Backpack Weights	B1	B2	B3	B4	B5
Left Foot	608.34	625.74	634.03	615.61	632.14
Right Foot	605.91	624.52	629.39	607.68	624.14
Recording Time	T1	T2	T3	T4	T5
Left Foot	627.67	618.12	621.96	621.58	626.52
Right Foot	620.94	613.76	618.71	618.64	619.88

Note: Derived from Tables 1 and 2; T1= Recording at 0 minute; T2= Recording at fifth minute; T3= Recording at tenth minute; T4= Recording at fifteenth minute; T5= Recording at twentieth minute; B1= 0% of body weight (No backpack); B2= 8% of body weight; B3= 12% of body weight; B4= 16% of body weight; B5= 20% of body weight.

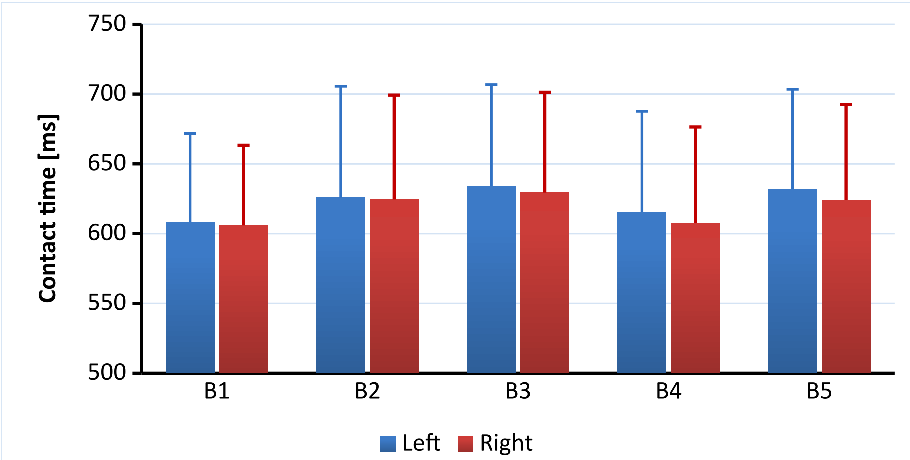

Figure 1. Overall mean contact time of left foot and right foot with selected backpack weights

Note: Derived from Table 3.

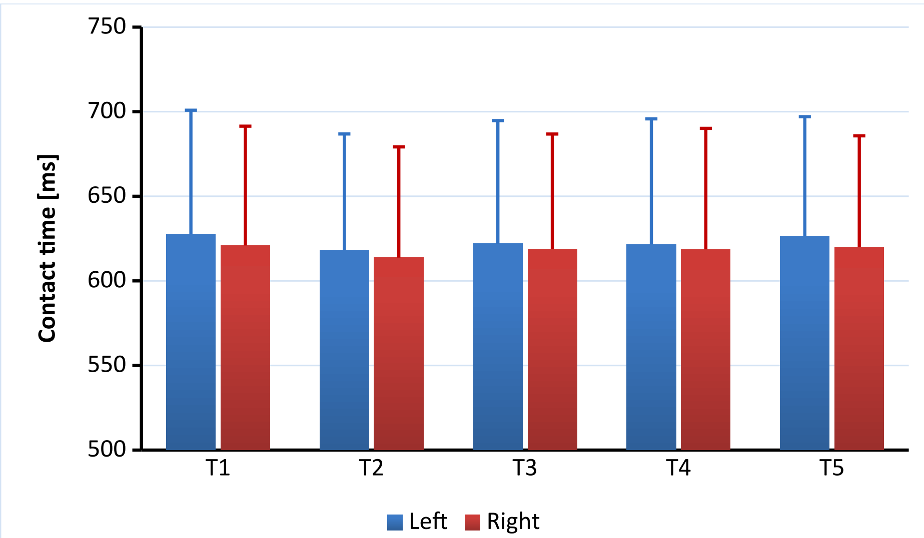

Figure 2. Overall mean contact time of left foot and right foot at selected recording time intervals

Note: Derived from Table 3.

Table 4. Result of *t*-test of contact time of left foot and right foot with selected backpack weights at selected recording time

Variables	Mean (Milliseconds)		*t*-value	*p*-value
	Left Foot	Right Foot		
Backpack Weight #(collectively)	623.18	618.32	3.49*	0.025
Recording Time ##(collectively)	623.17	618.38	5.89**	0.004

Note: Significance level 0.05; #Backpack weight (collectively) = Recorded collectively for B1, B2, B3, B4, B5; ##Recording time (collectively) = Recorded collectively for T1, T2, T3, T4, T5 * – $p < 0.05$, ** – $p < 0.01$ significantly different in regard to backpack weights and recording time intervals.

Table 4 presents the results of the t-test comparing left and right foot contact times. The analysis reveals statistically significant differences ($p < 0.05$) in contact time across varying backpack loads and time intervals. These findings suggest that carrying a heavier backpack for extended durations results in uneven weight distribution and increased biomechanical stress on the lower limbs.

Table 5. Two-way repeated measures ANOVA for contact time of left and right foot

Variable	*df*	*F*	*p*-value
Left Foot			
Weight	4, 81	8.88	< 0.001
Duration	4, 81	2.83	0.030
Weight × Duration	16, 69	2.84	0.001
Right Foot			
Weight	4, 81	12.61	< 0.001
Duration	4, 81	1.59	0.184
Weight × Duration	16, 69	3.07	0.001

Note. *df* = degrees of freedom.

Table 5 presents the results of the two-way repeated measures ANOVA applied to examine the effects of backpack weight, carrying duration, and their interaction on the contact time of the left and right foot. For the left foot, the main effect of weight was statistically significant ($F(4, 81) = 8.88$, $p < 0.001$), as was the main effect of duration ($F(4, 81) = 2.83$, $p = 0.030$). Additionally, the interaction effect between weight and duration was significant ($F(16, 69) = 2.84$, $p = 0.001$). For the right foot, the main effect of weight was also statistically significant ($F(4, 81) = 12.61$, $p < 0.001$), while the main effect of duration was not significant ($F(4, 81) = 1.59$, $p > 0.05$). However, the interaction effect of weight and duration for the right foot was statistically significant ($F(16, 69) = 3.07$, $p = 0.001$). Mauchly's test of sphericity showed that the assumption was violated for all within-subject effects in the left foot (Load: $p < 0.001$, Time: $p = 0.038$, Load × Time: $p < 0.001$), and partially violated for the right foot, where it was met for Load ($p = 0.070$) but violated for Time ($p = 0.022$) and Load × Time ($p < 0.001$). Therefore, Greenhouse-Geisser corrections were applied where necessary to adjust the degrees of freedom for F-tests.

Discussion

The present study analysed the effect of progressive weights and the duration of carrying these loads on the contact time during the walking gait of school-aged boys using a pre-defined and structured protocol. The research focused on understanding how different backpack weights ranging from 0% (no additional backpack) to a weight of 20% of the body weight and walking durations from T1 (zero minutes) to T5 (twentieth minute of the recording) of walking gait affected the contact time of the left and right feet during a gait cycle. A two-way repeated measures ANOVA revealed that, for the left foot, backpack weight had a statistically significant main effect on foot contact time, $F(4, 81) = 8.88$, $p < 0.001$. Additionally, duration also showed a significant main effect on foot contact time, $F(4, 81) = 2.83$, $p < 0.05$. Moreover, the interaction between weight and duration was found to be significant, $F(16, 69) = 2.84$, $p = 0.001$, suggesting that the combined influence of backpack weight and carrying duration plays a critical role in altering gait patterns. In contrast, for the right foot, only the effects of weight ($F(4, 81) = 12.61$, $p < 0.001$) and the interaction were significant ($F(16, 69) = 3.07$, $p < 0.001$), while the main effect of duration remained non-significant ($F(4, 81) = 1.59$, $p = 0.184$). This asymmetry in statistical significance between the left and right foot suggests a differential neuromuscular response to sustained load, possibly reflecting side-dominant fatigue adaptation, where the non-dominant (left) foot is more sensitive to the influence of prolonged load duration. The findings of this study demonstrate the combined effects of progressive weights and carrying durations on children's gait mechanics, particularly the contact time of the left and right feet during the stance phase. As depicted in Figure 1, contact time increased progressively with weights up to 12% of body weight (B3). This aligns with earlier research (Hong & Cheung, 2003), which documented prolonged ground contact under moderate loads as a compensatory strategy to enhance stability. The study also confirms that heavier loads, such as 16% (B4), induce fatigue, as evidenced by a decline in contact time. This suggests that the neuromuscular system struggles to maintain consistent gait patterns under excessive loads, potentially due to muscle fatigue and proprioceptive adjustments, as described in previous research on load carriage and locomotion (Connolly et al., 2008). Fatigue likely disrupts the ability to maintain stable gait patterns, as observed in Figure 1. Interestingly, at 20% load (B5), the contact time rose again, reflecting the body's effort to adapt and stabilize under extreme mechanical stress.

Carrying duration played a crucial role in shaping gait patterns, with its effects becoming increasingly pronounced over time. Figure 2 shows that at the zero-minute mark (T1), the contact time remained relatively stable across all loads, suggesting a minimal initial impact. However, by the fifth minute (T2), significant variations appeared, especially under heavier loads (B3–B5). This pattern continued as the duration extended to twenty minutes (T5), highlighting the cumulative impact of fatigue on gait stability. The progressive increase in asymmetry suggests a neuromuscular compensatory mechanism, where the dominant leg likely absorbs more impact over time, leading to higher disparities between left and right foot contact times (Rose et al., 2016). These results align with findings of Perrone et al. (2018), who noted that prolonged load carriage exacerbates gait instability and biomechanical asymmetry. The significant interaction between backpack weight and carrying duration supports the hypothesis that biomechanical burden intensifies over time when higher loads are carried, with the present study analysis also showing that duration independently influenced the contact time of the left foot. This is consistent with the findings of Grobler & Kramer (2023) and Tomal et al. (2022), who emphasized the compounding effects of prolonged exposure under excessive loads.

The *t*-test analysis underscores the asymmetry in gait mechanics induced by these factors. Statistically significant differences in contact time between the left and right foot were observed for both weights ($t = 3.49$, $p = 0.025$) and durations ($t = 5.89$, $p = 0.004$). Such asymmetries, depicted in Figures 1 and 2, indicate uneven weight distribution and compensatory strategies that increase the biomechanical burden on the lower limbs. These asymmetries align with the findings of Behmaram et al. (2022), as well as Chow et al. (2005), who observed increased double-support time and reduced stride length in adolescents carrying moderate to high backpack loads—markers of compensatory gait adjustments. Moreover, the significant cubic and quadratic trends observed in the within-subject contrasts from the ANOVA suggest that the response of contact time to increasing weight and duration is non-linear, meaning the effects are not just incremental but may spike beyond certain thresholds. This echoes the findings of Barbosa et al. (2019), who described fatigue-induced gait disturbances under prolonged load carriage, and it reinforces the call for limiting both the load and the time it is carried, particularly in light of the observed sensitivity of the left foot to prolonged duration. The observed changes in gait mechanics further align with research by Grobler & Kramer (2023) highlighting alterations in children's posture and gait mechanics due to weighting. Their findings emphasize the detrimental effects of loads exceeding 15% of body weight, consistent with this study's results showing significant disruptions at and beyond 16% load (B4). Furthermore, it was documented that excessive backpack loads increase ground reaction forces and force children to exert additional effort to maintain stability, thereby elevating metabolic costs and increasing fatigue rates (Tomal et al., 2022), which corresponds with the increased contact time observed in this study.

The significance of the main effect of duration for the left foot indicates that even when considered independently, prolonged carrying time influences contact time and may contribute to altered gait mechanics. However, this effect was not observed in the right foot, suggesting a possible asymmetry in fatigue or adaptation responses between limbs. This nuance adds depth to our understanding and supports recent biomechanical models of cumulative fatigue (Almeheyawi et al., 2021). The effects of carrying duration also align with the biomechanical fatigue model described by Barbosa et al. (2019), who noted that prolonged load carriage leads to fatigue-induced gait disturbances. In the present study, the interplay between load and duration is evident in Figure 2, which illustrates that higher loads combined with longer durations magnified the fluctuations in contact time. These findings reaffirm the importance of load and duration management to safeguard children's musculoskeletal health.

Overall, the study confirms that weights above 12% of body weight and carrying durations exceeding ten minutes significantly disrupt gait mechanics. The additional statistical evidence from ANOVA strengthens this conclusion, showing that such disruptions are not only visible descriptively but also statistically validated. The findings underscore the need for actionable guidelines to limit backpack weight and duration, reducing risks associated with musculoskeletal strain and asymmetrical gait patterns. This is further supported by Harman et al. (2000), who found that increasing load shifted the muscular burden toward the knees and hips, paralleling the gait fatigue patterns observed in this study. By corroborating previous research and providing new insights into the load-duration interaction, this study contributes to a comprehensive understanding of gait biomechanics in school-aged children. The findings further reinforce the sensitivity of the non-dominant limb (left foot) to both load and duration, and emphasize the need to consider side-specific responses when evaluating gait adaptations under backpack stress in children.

Conclusions

The study results suggest that progressive weights and extended carrying durations significantly affect the contact time during the walking gait of school-aged boys. These effects are evident in both the left and right feet, leading to notable changes in gait mechanics and symmetry. Loads up to 12% of body weight resulted in increased contact times, reflecting the body's natural compensatory mechanisms to maintain balance under moderate stress. However, loads exceeding 12% caused disruptions, with 16% and 20% loads inducing fatigue and biomechanical strain, destabilizing gait patterns.

The carrying duration intensified these effects, with prolonged walking times leading to increased variability in contact time and accentuating asymmetry between the feet. Significant differences in contact time between the left and right foot, confirmed through *t*-test analysis, highlight the uneven weight distribution and compensatory adjustments required under these conditions. This asymmetry may also be reflected in the differential statistical response to duration observed between the two feet. It is important to note that all participants were right-handed, suggesting greater strength on their right side. This may have contributed to the longer contact time recorded for the left foot, with mean differences of 4.86 s for backpack weight and 4.79 s for recording time.

The findings are supported by both descriptive and inferential statistics, including two-way ANOVA results, which identified a significant effect of weight and a significant interaction between weight and duration on contact time. These findings confirm that the combined influence of weight and time poses a biomechanical challenge to normal gait function. While the effect of carrying duration alone was not significant for the right foot, it was statistically significant for the left foot, suggesting that prolonged duration independently contributed to changes in gait mechanics in the non-dominant limb.

To minimize risks, it is recommended that backpack weight be limited to 10–12% of body weight and that carrying durations be kept short. These precautions are especially important given that prolonged duration independently affected left foot contact time, suggesting limb-specific fatigue responses. Such measures can help reduce the likelihood of fatigue, gait instability, and long-term musculoskeletal issues in school-aged children.

Strengths and limitations

This study has several notable strengths. It employed a robust 5x5 repeated measures experimental design, ensuring consistency and reliability in data collection across multiple conditions. The use of the Zebris FDM pressure plate provided precise and reproducible measurements, enhancing the validity of the findings. By examining the combined effects of progressive weights and varying carrying durations, the study addressed a critical gap in the literature and contributed novel insights into gait biomechanics. Furthermore, the incorporation of two-way repeated measures ANOVA allowed for a more rigorous statistical interpretation of the interactive effects of load and duration on foot contact time. However, the study has some limitations. The exclusive focus on male participants aged 10 to 12 years limits the generalizability of the findings to females and other age groups. Additionally, the controlled laboratory setting may not fully replicate real-world conditions, such as walking on uneven surfaces or during outdoor activities. The study does not establish the precise neurological mechanisms contributing to gait asymmetry under load. Future research should incorporate electromyography (EMG) and motion capture analysis to identify muscle activation patterns and joint kinematics under varying backpack loads. Additionally, a more detailed examination of postural control and stride variability could offer further insights into how schoolchildren adapt to prolonged backpack use. The short-term nature of the study does not account for potential long-term musculoskeletal impacts of prolonged backpack usage. While initial analysis used t-tests for pairwise comparison, the application of ANOVA enhanced the understanding of multifactorial influences and helped identify both significant main effects and interaction effects, most notably the independent effect of carrying duration on left foot contact time. The finding that carrying duration independently influenced only the left foot underscores the importance of considering side-specific responses in gait analysis. Potential issues such as non-sphericity were addressed by applying Greenhouse-Geisser corrections where assumptions were violated, further strengthening the statistical robustness of the study. The potential influence of non-normal distribution was acknowledged, and the results were interpreted taking this into consideration.

Future implications

The study highlights several directions for future research. Including females and a broader age range could improve the generalizability of the results. Examining gait dynamics on uneven terrains or at varying speeds may offer practical insights into backpack usage. Longitudinal studies are essential to assess the long-term effects of heavy backpacks on musculoskeletal health. Interventional research on ergonomic backpacks, load distribution methods, or educational programmes could help reduce biomechanical strain. Using advanced motion capture and wearable sensors could enhance gait analysis, enabling personalized recommendations to optimize children's health and performance. Future studies should also continue employing multifactorial statistical models, such as repeated-measures ANOVA, to examine complex interactions between load and duration across different populations. This approach has proven effective in highlighting significant interaction effects in the present study, which may have otherwise remained undetected using simpler methods. Additionally, incorporating effect size measures would strengthen the interpretation of the results. The practical implications of these findings are noteworthy. While the study reinforces the existing recommendation to limit backpack weight to 10–12% of body weight, it also suggests that prolonged carrying durations particularly for the non-dominant (left) foot, amplify the biomechanical strain. Therefore, schools and policymakers should focus not only on reducing backpack weight but also on encouraging students to take regular breaks when carrying heavy loads. However, the study falls short in offering detailed suggestions for backpack design improvements or load distribution strategies, which would enhance its real-world applicability. Ergonomic adjustments, such as padded shoulder straps, waist belts, and evenly distributed compartments, could be explored in future studies to mitigate the negative effects observed. Furthermore, investigating alternative carrying methods, such as rolling backpacks or cross-body bags, could provide valuable alternatives for reducing asymmetrical gait adaptations. Lastly, expanding this line of research to explore real-world application in school settings, such as implementing safe load policies and evaluating their outcomes, would greatly increase the translational value of these findings. Additionally, future research could examine whether left-side gait deviations persist under modified load configurations or load-balancing interventions.

Conflict of interest: Author state no conflict of interest

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