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Increased backpack weight might lead to increased trunk stiffness during walking in primary school aged children: A pilot study

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ABSTRACT

Background: Backpacks are essential in the daily lives of children. Carrying a heavy backpack affects trunk posture during standing. It remains unclear, whether this effect is also observed during gait.
Research question: How do different backpack weights affect trunk kinematics during walking in children?
Methods: Sixteen children stood and walked on a 5 m walkway with a custom load-carrying-system simulating unloaded and loaded backpacks (10 %;20 %;30 % of body mass (BM). A marker-based 3D motion analysis system captured whole-body kinematics (Rizzoli model). During walking, the primary outcomes were the maximum ranges of motion (RoM;[°]) of thoracic and lumbar trunk segmental angles in three planes. During standing, the average angles over 5 s were measured in three planes. Secondary measures included stride length, stride time, and velocity during walking. The children's own backpacks' weights were measured and expressed as a percentage of body mass. Statistical analysis was performed using repeated-measures ANOVA (α=0.05) and Tukey-Kramer post hoc test.
Results: The average weight of the children's own backpack was 15.4 ± 7.4 %BM. For the experimental conditions, the average weights added to the load-carrying system were 3.3 ± 0.8 kg (10 %BM), 6.5 ± 1.7 kg (20 % BM), and 9.8 ± 2.5 kg (30 %BM). During standing, the average trunk flexion angles (sagittal plane) of the lumbar trunk segment significantly increased with increased backpack weight ($p = 0.002$). During walking, no changes in sagittal plane RoM but significant decreases in lumbar and thoracic transversal and frontal plane RoM ($p < 0.001$), stride length ($p = 0.047$) and velocity ($p = 0.041$) were observed with additional weight. No significant differences were observed for stride time between the conditions.
Significance: Added backpack weight led to a more flexed trunk posture during standing and reduced transversal and frontal plane trunk movement, stride length, and gait velocity during walking. These adjustments likely compensate for the dorsally displaced center of mass and minimize energy expenditure by reducing trunk-backpack-angular momentum during walking.

1. Introduction

For children of primary school age, the backpack is an indispensable utensil in everyday life. On average, the children carry their backpacks for up to 50 min per day [1], while covering a distance of approximately one kilometer [2]. Therefore, the weight of the backpack takes an important role in the everyday life of school children. Although the WHO recommends a maximum carrying weight of 12.5 % of a child's body mass to prevent overloading of the back, studies have shown that these recommendations are often exceeded and that large differences occur in day-to-day comparisons [3–6]. For instance, Negrini et al. [7] found that the average backpack weight for children at age eleven was 22 % of body mass. It was also observed that at least once a week, the children's backpack weight was even greater than 30 % of body mass [4]. An association between the exceeding of backpack weight recommendations and back pain is often discussed but not confirmed yet. However, a correlation between back pain and the perception of school backpacks as being burdensome and tiring does exist [4,8].

Recent studies indicated a correlation between a heavy backpack and an altered trunk posture during standing and walking, which is mainly

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characterized by a forward tilt of the entire trunk and an enlargement of the craniohorizontal angle to compensate for the additional load on the back [8–10]. In addition, several studies have shown that carrying a heavy backpack while standing and walking affects head and neck posture, shoulder symmetry and spinal curvature, particularly in the lumbar region [10], which can manifest as back pain in the longterm [8]. Yi-Lang et al. [6] studied trunk and whole-body posture of school children in a standing position while wearing a loaded backpack. The main findings were increased head and trunk flexion, decreased lumbosacral angle, and increased trunk muscle activation, even with a backpack weight corresponding to just 15 % of body mass [6]. In a systematic review, Cuenca-Martinez et al. [9] concluded that wearing a backpack in children and adolescents leads to postural changes in standing and affects gait. In detail, they could find decreased walking speed and stride length as well as an increased craniovertebral angle. However, detailed data on segmental trunk motion is lacking throughout the literature. Studies often used only a rigid segment to analyze the kinematic movement of the trunk while carrying a backpack. However, these models neglect the segmental differences between the thoracic and lumbar regions, which can be of elementary relevance when investigating the influence of backpacks on the loading of the different regions of the trunk

It remains unclear, how backpack weight affects the children's segmental trunk posture during gait. The purpose of the current study was to analyze the influence of different backpack weights on segmental trunk kinematics during standing and walking in primary school children.

2. Material and methods

2.1. Design and ethics

The presented study was conducted as a cross-sectional cohort pilot study with one measurement time point. The local Ethical Commission approved the study including all the described procedures (No. 12-2019).

2.2. Participants

Sixteen children (females/males: 6/10; age: 9.1 ± 1.6 years; height: 137.1 ± 10.2 cm; mass: 32.4 ± 8.4 kg) were enrolled in the current study. They were recruited from local primary schools and sports clubs if they were healthy and aged between 6 and 11 years. Exclusion criteria were: acute and/or chronic pain, injuries of the musculoskeletal system (especially of the spine) that limited normal function, ongoing treatments by a physical therapist, and a skin intolerance for double-sided adhesive tape. If the children were interested in participating, their parents were informed about the study and asked to provide written informed consent.

2.3. Experimental procedures

All children were invited for a single visit to the movement analysis laboratory. After collecting demographic and anthropometric data, their own school backpack, which they brought along packed for the given day, was weighed and expressed as a percentage of body mass. Afterwards, the children were equipped with 43 retro-reflective markers according to the Rizolli full body model [11,12] (Fig. 1) and asked to stand still in an upright position for 5 s and to walk on a 5-meter walkway at a self-selected normal walking speed without and with carrying a custom-built load-carrying system (Fig. 1) with added loads corresponding to 10 %, 20 %, and 30 % of their individual body mass (added in random order). To get accustomed to the different loads, participants were allowed a familiarization trial before each measurement trial. All participants performed about five steps along the 5 m walkway, from which at least three were used for the analysis.

Low back pain was monitored by use of a face pain scale (FPS) [13] in regular intervals throughout the whole measurement day (begin/after

Fig. 1. Kinematic marker set up and backpack-simulating carrying system.

each walk with different weights/end). A face score ≥ 3 at the FPS (acute pain) was defined as termination criterion for the whole measurement.

2.4. Data collection and reduction

Marker data were recorded using a 16-camera optoelectronic 3D-motion analysis system (NaturalPoint, Inc. DBA OptiTrack, Oregon, USA; sampling rate: 120 Hz) and low-pass filtered with a cutoff frequency of 5 Hz using the software Motive 2.0 (Optitrack, Oregan, USA). For analyzing multi-segment trunk kinematics (Fig. 2) an upper thoracic segment (UTS), and a lumbar segment (LS) were built. The UTS segment was built out of the markers on the right/left acromio-clavicular joint, seventh cervical vertebrae (C7), second thoracic vertebrae (T2), midpoint between left and right scapular apex (near T10 vertebrae), jugular notch and xiphoid process of the sternum. The LS segment was built out of the markers on L1, L3 and L5. The pelvis segment was built out of the four markers of the right and left anterior superior iliac spine and the right and left posterior superior iliac spine. The pelvis was built as the basis and the reference segment for the two trunk segments.

All further data reduction steps were conducted using a custom MATLAB routine (R2019b, MathWorks Inc., Natick, MA, USA). This included the automatic detection of the gait events (stride cycles based on heel marker) and the subsequent calculation of relative angles between the UTS and the pelvis as well as the LS and the pelvis in all three planes.

The primary outcome measure during walking was range of motion (RoM [°]) of the UTS vs. pelvis and LS vs. pelvis angles in the sagittal, frontal and transverse planes. The ROM was determined for each segment for three completed step cycles. The average ROM out of the three step cycles was calculated for further analysis. During standing, the UTS vs. pelvis and LS vs. pelvis average angles [°] over the 5 s were calculated in all three planes. Negative angles thereby represented extension, right rotation and left lateral-flexion, and positive values flexion, left rotation and right lateral-flexion.

Secondary outcome measures to characterize the gait of the children were spatio-temporal parameters such as stride length (m), stride time (sec) and velocity (m/s). Three completed step cycles were used to calculate the average results for each outcome. Furthermore, the weight of childrenś own backpacks was measured and expressed as percentage of body mass (% BM).

2.5. Statistical analysis

After plausibility and extreme value check, outcome data were presented descriptively (means, standard deviations) and checked for normal distribution with the Shapiro-Wilk test. Since the majority of the main outcomes were normally distributed, one-way analyses of variance with repeated measures and Tukey-Karmer post-hoc tests were applied to statistically examine the differences of the outcome parameters between the experimental conditions. Statistical analyses were conducted using the JMP Statistical Software Package 14 (SAS Institute®, Cary, NC, USA). The alpha level was set to 0.05 for all tests.

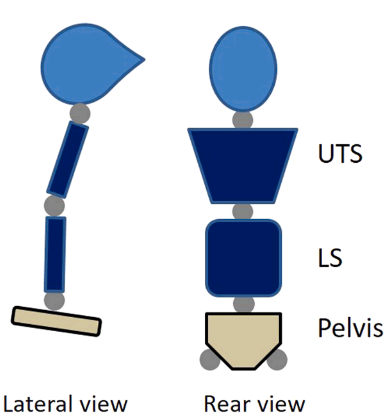

Fig. 2. Schematic representation of the pelvis and trunk segments (UTS: upper thoracic segment; LS: lumbar segment).

3. Results

3.1. Trunk kinematics during walking

The average loads added to the load-carrying system were 3.3 ± 0.8 kg (range: 2.1–5.0 kg), 6.5 ± 1.7 kg (range: 4.4–10.0 kg), and 9.8 ± 2.5 kg (range: 6.5–14.8 kg) in the 10 %, 20 %, and 30 % of body mass conditions.

No changes in average range of motion in the sagittal plane (Table 1) but significant decreases in transversal and frontal plane for lumbar (LS) and thoracic (UTS) range of motion ($p < 0.001$) were observed during walking with different backpack loads compared to walking without a backpack (Fig. 3: UTS). Detailed results are displayed in Table 1.

3.2. Trunk kinematics during standing

The average trunk flexion angle (sagittal plane) of the lumbar trunk segment (LS) significantly increased with increased backpack weight ($p = 0.002$) (Fig. 4). Moreover, the average trunk rotation angle in the UTS segment was statistically significant different between 30 % BM and 20 % BM. Detailed results are displayed in Table 1.

3.3. Spatio-temporal parameters

Significant decreases in stride length ($p = 0.047$) and gait velocity ($p = 0.041$) were observed in the loaded conditions versus the unloaded condition. No significant differences were observed for stride time between tested conditions. All results are displayed in Table 2.

3.4. Weight of childrenś own backpacks

The average weight of the childrens' own backpacks was 4.7 ± 1.9 kg (range: 2.5 and 8.8 kg), corresponding to 15.4 ± 7.4 % (range: (5.6–34.0 %)) of their body mass.

4. Discussion

The presented study investigated the influence of different backpack loads on segmental trunk kinematics during both walking and standing among primary school children. All load conditions led to reduced UTS vs. pelvis and LS vs. pelvis ranges of motion in the frontal and transversal planes compared to the unloaded condition during walking. During standing, only the 30 % load condition showed increased LS flexion. Stride length was reduced at 20 % load, but no consistent effects were found across all loads. While gait speed tended to decrease with load, this was not statistically significant.

The decreases in transverse and frontal plane RoM in the lumbar and thoracic segments during walking suggest that additional backpack load may restrict rotational and lateral trunk motion, possibly as a compensatory strategy to maintain stability and reduce energy expenditure. This likely reflects a stabilization priority in the non-sagittal planes, where uncontrolled motion could challenge balance and postural control in children under load. Moreover, such regulation may help counteract the dorsally displaced center of mass by reducing angular momentum of the trunk–backpack system. Prior research has shown that trunk motion in these planes is tightly controlled to manage angular momentum and maintain dynamic stability, particularly via coordinated joint actions and counter-rotation strategies [14,15]. Excessive motion in the frontal and transverse planes has also been associated with increased spinal

Table 1
Results of average angle [°] during standing and range of motion [°] during walking for both segments (UTS, LS) in all three planes.

Segment	Plane	Average Angle [°] during standing				ROM [°] during walking			
		0	10 %	20 %	30 %	0	10 %	20 %	30 %
UTS	**E/F**	7.8 ± 5.7	9.3 ± 4.2	8.1 ± 3.3	4.6 ± 7.1	4.8 ± 1.2	4.3 ± 1.1	4.1 ± 0.7	4.6 ± 1.2
	LF	1.6 ± 1.6	3.0 ± 1.5	2.9 ± 2.5	0.3 ± 2.8	8.0 ± 1.1	5.6 ± 0.8``	5.1 ± 0.7§	5.0 ± 0.9*
	Ro	0.3 ± 1.1	0.4 ± 1.1	1.1 ± 0.5	−0.3 ± 1.1+	8.1 ± 1.5	4.3 ± 0.9``	3.7 ± 0.6§	3.9 ± 0.7*
LS	**E/F**	−1.0 ± 2.9	−0.1 ± 2.6	2.4 ± 1.7	3.8 ± 3.4*,#	3.9 ± 0.8	4.3 ± 0.7	4.1 ± 0.9	5.1 ± 1.5
	LF	−0.7 ± 1.4	−0.5 ± 1.2	−0.6 ± 0.5	−0.3 ± 1.9	6.8 ± 1.1	5.3 ± 0.9``	5.0 ± 0.5§	5.1 ± 0.8*
	Ro	0.3 ± 1.1	0.2 ± 1.0	1.0 ± 0.5	−0.3 ± 1.1	8.5 ± 1.3	4.6 ± 0.9``	4.0 ± 0.7§	4.3 ± 0.7*

E/F = extension /flexion; LF = lateral flexion; Ro = rotation;
UTS = upper thoracic segment, LS= lumbar segment;
negative values represent flexion, left-sided rotation and left-sided lateral flexion for all 3 segments;
positive values represent extension, right-sided rotation and right-sided lateral flexion;
BM = body mass;
statistical significant difference $p < 0.05$:
* (30 % BM vs. 0);
# (30 % BM vs. 10 % BM);
+ (30 % BM vs. 20 % BM);
§ (20% BM vs. 0);
`` (10% BM vs. 0).

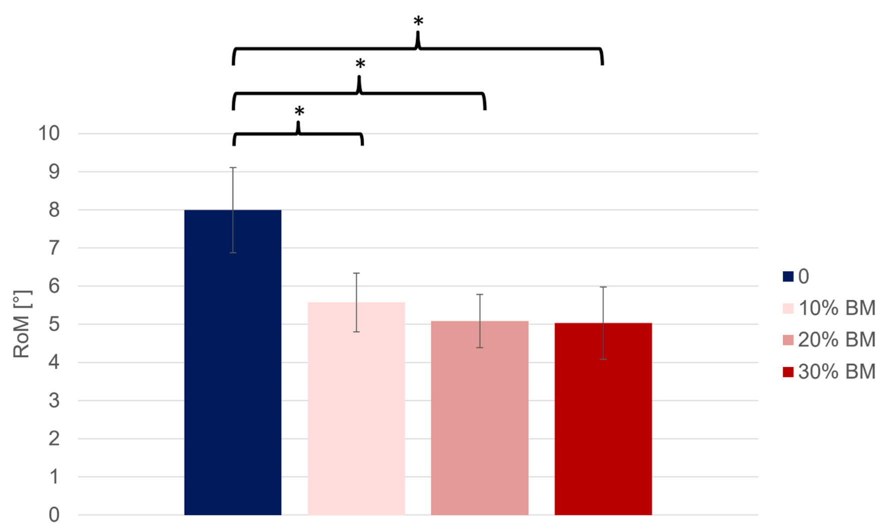

Fig. 3. UTS RoM [°] in frontal plane during walking (*$p < 0.05$).

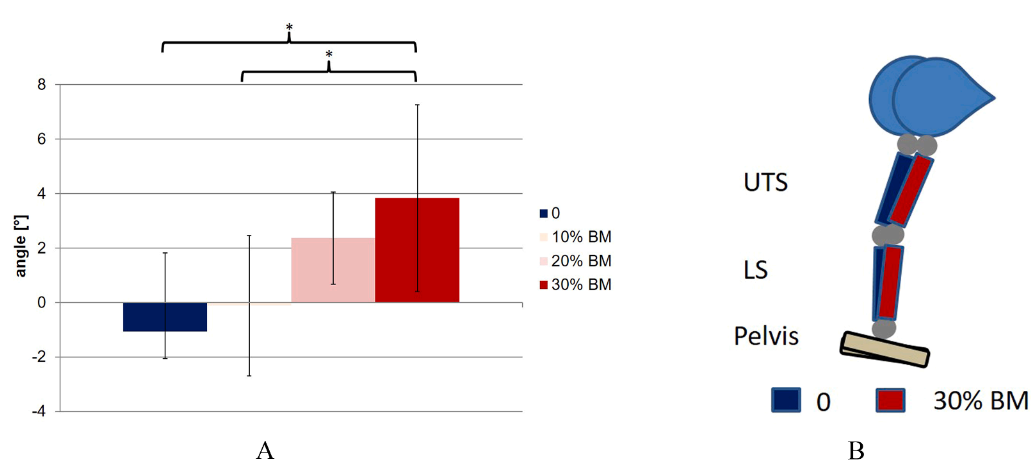

Fig. 4. Trunk flexion angle [°] during standing for (A) LS segment and (B) LS and UTS segment (flexion = positive values; extension = negative values; * $p < 0.05$).

loading [16], underscoring the potential relevance of these compensatory adjustments. Recent studies have already reported alterations in 3D trunk kinematics under backpack load, but these investigations have been conducted exclusively in adult populations [17,18]. For example, Sturdy et al. [17] demonstrated that during walking with additional load, trunk motion – particularly in the transverse plane – was reduced,

Table 2
Spatio-temporal parameters for all four conditions during walking.

Gait parameter / condition	0	10 % BM	20 % BM	30 % BM
Stride length (m)	0.99 ± 0.07	1.00 ± 0.04	0.94 ± 0.03[%,§]	0.95 ± 0.05
Gait velocity (m/s)	0.97 ± 0.08	0.96 ± 0.05	0.91 ± 0.05	0.91 ± 0.06
Stride time (sec.)	1.06 ± 0.07	1.08 ± 0.12	1.08 ± 0.10	1.05 ± 0.09

statistical significant difference $p < 0.05$:
§ (20% BM vs. 0);
% (10% BM vs. 20%).

and that kinematic adaptations varied depending on carrying configuration. Similarly, Liew et al. [18] examined trunk–pelvis coordination during load carriage running in young adults and found systematic shifts across planes: sagittally, trunk-only coordination increased; frontally, anti-phase coordination increased; and axially, trunk-only coordination decreased, with coordination variability increasing significantly in all three planes. Both studies therefore support our observation of reduced transverse plane motion under load. However, it is important to note that these findings were derived from adult participants.

The increased lumbar flexion with added backpack weights during standing implies that as the load of the backpack increases, there is a corresponding increase in forward bending of the lower trunk. This forward tilt, particularly in the lower back, intensified with increasing backpack load. This finding aligns with previous research indicating that heavier loads lead to greater trunk flexion [9,19,20], potentially due to the need to counterbalance the load and maintain equilibrium. As schoolchildren carry their backpacks all day while walking and standing, it is important that these loads can be compensated for by trunk muscles. Otherwise, altered or compensatory trunk movements and postures may result.

The changes in spatio-temporal gait characteristics are in line with previous studies [9,19,21–24], indicating that heavier backpack loads adversely affect the efficiency and dynamics of walking, potentially due to increased biomechanical demands and altered posture [9,21]. In our study, stride length was significantly reduced at 20 % load compared to the unloaded condition, while walking speed showed a non-significant decreasing trend across load levels. Although the direction and magnitude of these changes are comparable to earlier findings, previous studies have reported statistically significant reductions in both stride length and walking speed, even at similar load levels. However, no significant differences were observed in stride time between the tested conditions, suggesting that temporal aspects of gait remain unaffected by the investigated backpack loads. This discrepancy may be due to higher inter-individual variability in our sample, a relatively small sample size, and/or methodological differences such as costumized backpack construction, habituation time, or walking conditions. Additionally, the conservative statistical approach applied in our analysis may have contributed to non-significant results despite observable trends.

The average weight of the children's own backpacks in our study exceeded the WHO's recommendation of 12.5 % of body mass, ranging from 5 % to 34 % body mass. These findings underscore the variability in backpack loads carried by children, highlighting the need for the promotion of appropriate load management strategies. Notably, the upper range of 34 % body mass is nearly three times higher than the recommended limit, emphasizing the importance of continued research and public outreach regarding backpack use and spinal health in children. As the foundations for back health are laid during childhood, the influence of backpack weight on a child's trunk kinematics during walking and standing should not be ignored — even if current evidence linking backpack weight and childhood back pain remains inconclusive [24].

4.1. Limitations

A relatively small and pain-free sample was used, which might limit the transfer to a clinical population of children (e.g. back pain). A customized load-carrying system was used, since several regions of the back and the entire upper body had to remain uncovered for the marker placement. This carrying system might not have fully represented a standard school backpack and brought some restrictions with itself. In some cases, it was observed that the side pockets of the backpack shifted slightly further laterally as the weight increased, due to the bulk and placement of added weight plates. This may have caused a slight lateral displacement of the overall load, potentially affecting trunk kinematics. However, it is unclear whether this resulted in a more lateral or anterior displacement of the load's center of mass, both of which could differentially affect trunk kinematics. Future studies should consider a more standardized fixation of additional weights to better control for load distribution and its biomechanical effects. Furthermore, the children's activity levels were not assessed and hence, possible influences of different activity levels on compensatory strategies cannot be excluded. The specific walkway configuration used in this study, compared to gait measurements with longer walking and measurement distances, could have influenced the results (e.g. gait speed, trunk posture). It might therefore be that this controlled and standardized measurement situation cannot entirely be transferred to free walking over longer distances.

5. Conclusions

This study provides valuable insights into the biomechanical consequences of backpack loading on trunk kinematics and gait characteristics among primary school children. Added backpack weights might lead to increased trunk stiffness, which could predispose the children to low back pain. The findings underscore the importance of considering backpack weight as a potential risk factor for musculoskeletal discomfort and injury, emphasizing the importance of ergonomic guidelines and education in promoting the health and well-being of primary school-aged children. Further research is warranted to explore the long-term implications of backpack use on spinal health and functional outcomes in pediatric populations. A focus on the analysis of age-specific differences appears to be worthwhile, particularly with regard to the previously discussed aspect of the onset of back pain at the age of 14.

CRediT authorship contribution statement

Juliane Mueller: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia Simmer:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stefan Schmid:** Writing – review & editing, Writing – original draft, Validation, Supervision, Formal analysis. **Christoph Zinnen:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis. **Steffen Mueller:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Ethical approval

The Ethics Committee of the Department of Computer Sciences of Trier University of Applied Sciences approved this study (No. 12-2019). All participants and their legal guardian gave written informed consent before data collection began.

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agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Main data generated or analysed during this study are included in this published article. Furthermore, the datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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