Effect of backpack load placement on posture and spinal curvature in prepubescent children

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Received 16 January 2008
Accepted 24 May 2008

Abstract. Parents, educators and researchers have expressed concern about the long term impacts of children carrying excessive loads in their backpacks on a daily basis. Although many researchers have investigated appropriate weight limits for children’s packs, little research has been conducted on the design of children’s backpacks. The purpose of this study was to evaluate the changes in children’s trunk forward lean (TFL), cranio-vertebral angle (CVA) and spinal lordosis angle (LA) that occurred with high, medium and low load locations during standing and walking. Ten-year-old children (n = 15) completed a repeated measures designed study while carrying 15% of each child’s body weight in a typical backpack with only shoulder straps. A special instrumented backpack (IBP) was designed that allowed the weight to be placed in the proper location and continuously measure changes in spinal curvature. TFL and CVA postures were captured on digital video at five intervals including: standing without a backpack prior to a 1000 m walk; standing with a backpack at the beginning and end of a 1000 m walk; and walking with a backpack at the beginning and end of a 1000 m walk. Results indicated that significant changes occurred in TFL and CVA when the backpack was loaded to 15% body weight. The low load placement in the backpack produced fewer changes in CVA from the initial standing baseline measure than the high and mid placements. When all measures were assessed collectively, there were fewer changes in LA in the low load placement. These findings indicate that future backpack designs should place loads lower on the spine in order to minimize children’s postural adaptations.

Keywords: Load carriage, backpack design, children, posture, gait, biomechanics

1. Introduction

Within developed nations, backpack use amongst schoolchildren has become the most popular means of transporting belongings to and from school. However, there is a growing public concern that overloaded children’s and adolescent’s backpacks may lead to the development of back pain and other musculoskeletal injuries. Some cross-sectional studies link backpack use with back pain [10,17,18,24,31] and other studies indicate that carrying excessive weight [29,32] or experiencing fatigue [10,23] while carrying a backpack may be linked with back pain and rucksack palsy.

In an attempt to determine a safe weight limit for children’s backpacks, several studies have examined the effects of increasing backpack loads on physiological parameters, including heart rate, VO₂, blood pressure and respiration [14,16,19,20,22], as well as biomechanical parameters, including trunk forward lean, head on neck posture and gait [7,12–15,20]. Based on a critical review, which took into account both physiological and biomechanical findings, Brackley and Stevenson [6] recommend that backpacks should weight no more than 10–15% of a child’s body weight. This conclusion is consistent with recommendations set forth from various health organizations, such as, the America Occupational Therapy Association [2] and the Ontario Chiropractic Association [3].

Although the current accepted weight limit appears to be rather well established, the applicability of this
generic limit is questionable given the lack of investigation and reporting of children’s backpack design [6]. This scarcity of research is concerning, particularly in light of the fact that abundant research exists into larger adult rucksack designs for military and hiking purposes. Research into these adult packs strongly suggests that improved pack design and fit greatly influences the user’s performance, comfort and health [28]. These findings highlight the fact that preventing back pain and injury may be best accomplished not only through children’s compliance with suggested load limits, but also though industry’s improvement of current pack designs.

One of the first and most crucial pack design decisions is load placement. The location of the load must be established before other aspects of the design, such as frame sheets, shoulder straps and hip belts, can be applied. Without knowing where to place the load’s center of mass to minimize postural adaptations and fatigue, altering other design features is premature. Only two studies were found that investigated the effects of load placement on children’s posture [8,11]. Grimmer et al. [11] examined the effects of different loads and load placement on horizontal displacement of various body segments in the sagittal plane. It was found that when the load was placed low on the back (L3) horizontal displacements were minimized, indicating that less postural adjustment was needed when supporting the load. Contrary to studies on children, adult rucksack studies have found that high load placement minimizes postural adaptations, indicating that adult findings cannot be directly transferred to children. Frank et al. [8] also investigated load placement in children’s backpacks. Using biomechanical modeling, it was found that lumbar and shoulder reaction forces were minimized under low load placement. However, contrary to what Grimmer et al. [11] found, posture was adversely affected; low load placement resulted in greater postural adaptations then high load placement. The contrasting results of these two studies indicate a need to further investigate optimal load placement for children’s backpacks.

Furthermore, these two studies only examined postural variables in a rested standing posture, which is not consistent with the typical use of a backpack. Children use backpacks to transport loads; therefore, they are frequently walking while donning a pack. Walking requires that the center of gravity be shifted forward, outside the base of support, while maintaining dynamic stability and control. Given these fluctuations in the center of gravity and given that prolonged stresses during walking may lead to fatigue, it seems more appropriate to evaluate postural changes throughout a gait cycle.

The purpose of the present study was to examine the effect of load placement (high, mid, and low) on posture, specifically trunk forward lean (TFL) posture, head on neck (CVA) postures and lordosis angle (LA) for standing and walking in pre-pubescent children.

2. Methods
2.1. Instrumentation

In order to assess spinal curvature, a specialized backpack needed to be designed and validated. The instrumented backpack (IBP) was designed to be a stand-alone system that was housed in a custom designed backpack, based on the technology developed by Orloff and Rapp [25] (Fig. 1a). To assess changes in spinal curvature, sixteen light resistance spring-loaded slide potentiometers with 100 mm of travel (Panasonic, model EVA-JQLR15B14) protruded out of the backpack frame toward the user’s spine (Fig. 1b). The output from the potentiometers was multiplexed to 8 channels and converted to digital form with 0.4 mm resolution. All data were recorded onto an 8-channel AD128 Valitec Analog/Digital Datalogger V5.0 (Valitec Inc, Dayton, OH). Data acquisition was controlled by a radio frequency remote control that enabled the system to be turned on and off in the testing area. All data were collected at 31.25 Hz and downloaded to a personal computer following each testing session.

To determine the validity and reliability of the individual potentiometers and the system as a whole, three sub-studies were completed. In the first study, accuracy and repeatability was found for the individual rods by displacing each rod 20, 40, 60, 80 and 100 mm. Each displacement was completed three times and the average difference from expected and the coefficients of variation (COV) were found. The average difference from the expected displacement was $-1.46$ mm representing a COV was 0.15% across all rods at all distances. The second study evaluated IBP creep with data collection every 5 minutes for 30 minutes with rods at various lengths. No creep existed as the difference between measured and IBP displacements averaged $0.98 \pm 0.87$ mm. To examine its repeatability on a curved surface, the IBP was placed five times onto a block of Styrofoam that was carved into a curved surface. Repeatability was assessed with COV values and
accuracy was compared graphically. The COV varied from 1.4% on flat or gently curving surfaces and 4.9% on rapidly curving surfaces. This higher COV error was caused by the fact that only rods’ endpoint edges made contact with the hard Styrofoam surface. Since the spine has more gently curving surfaces, one would anticipate errors in same range as the flat surface at 1.4%.

2.2. Subjects

All subjects were recruited from the same grade five class at a local public school. Sixteen self-reported healthy students returned complete parental consent forms. One student did not meet the inclusion criteria because her body size was not adequate for high, mid, and low load adjustments. The remaining 15 students (10 females and 5 males) completed all three testing conditions. No significant differences in body anthropometrics were found between males and females. Summary anthropometrics and demographic data on the subjects can be seen in Table 1.

2.3. Procedure

Every child was asked to complete a backpack and activity questionnaire based on the survey created by Grimmer and Williams [11]. The questionnaire assessed backpack use, backpack preferences, weight of load carriage, time of load carriage, activity levels, and experienced pain. Anthropometrics including: standing height, weight, vertical back length, surface back length, waist circumference, and leg lengths were collected prior to the first day of testing.

The study methodology was based on a self-controlled repeated measures design. On three different days each child carried 15% of his/her body weight with the center of mass of the pack located high, mid or low back. The loads were carried in the IBP. TFL and CVA were measured using two-dimensional video and LA was measured using the IBP. Each student was provided with their own black study t-shirt to increase consistency between subjects and provide better contrast for joint markers. A strip of packing tape was placed down the back of each shirt to prevent the rods of the IBP from catching on the subject’s clothing.

On each test day, randomized for high, medium and low load locations, five data samples were evaluated. The first sample was a baseline of unloaded standing posture, which was used to normalize subsequent data so that each child’s adaptation to the backpack condition could be compared statistically. The second sample was a loaded standing posture, which allowed an assessment of adaptation due to the backpack alone. Then, each child was accompanied by an adult escort during the walking phase in order to keep attention on the task and ensure that markers adhered to the clothing or skin. Each child walked 100 m around an interior course in the school before walking through the testing area, for the third data sample, where simultaneous video and curvature data were collected. Each child then walked for 1000 m to simulate a typical distance traveled by children of that age. This distance is an approximate average of the distances used by Hong and Cheng [13]. Ratings of perceived exertion (RPE) were collected every 250 m. At the completion of the 1000 m walk, video and spinal curvatures were taken again during walking, followed by a final 100 m loop.
Table 1
Subject anthropometrics

<table>
<thead>
<tr>
<th>Variables</th>
<th>Boys (n = 5)</th>
<th>Girls (n = 10)</th>
<th>Combined (n = 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>143.8 ± 4.9</td>
<td>146.1 ± 6.1</td>
<td>145.7 ± 5.7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>37.8 ± 5.1</td>
<td>42.3 ± 10.2</td>
<td>41.8 ± 9.0</td>
</tr>
<tr>
<td>Surface Back Length (C7 – L5) (cm)</td>
<td>38.7 ± 2.0</td>
<td>40.2 ± 3.7</td>
<td>39.9 ± 3.3</td>
</tr>
<tr>
<td>Vertical Back Length (C7 – L5) (cm)</td>
<td>37.8 ± 1.7</td>
<td>38.7 ± 3.0</td>
<td>38.5 ± 2.6</td>
</tr>
<tr>
<td>Waist Circumference (at Navel) (cm)</td>
<td>67.4 ± 3.8</td>
<td>73.5 ± 8.6</td>
<td>72.1 ± 7.8</td>
</tr>
<tr>
<td>Leg Length (GT to floor) (cm)</td>
<td>74.2 ± 5.0</td>
<td>77.7 ± 4.9</td>
<td>76.7 ± 5.1</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>18.3 ± 1.8</td>
<td>19.7 ± 3.9</td>
<td>19.6 ± 3.4</td>
</tr>
</tbody>
</table>

before the final standing posture was measured. For simplicity, these samples will be referred to as: (1) standing baseline (SB), (2) initial standing (IS), (3) initial walking (IW), (4) final walking (FW) and (5) final standing (FS). All standing trials were recorded for five seconds and evaluated for 1 second at 30 Hz. All walking trials were evaluated for 2 complete strides. Upon completion of the daily testing, the child was asked to complete a body map diagram with the Wong-Baker Faces pain scale [35] to determine any areas of discomfort. A summary of daily testing can be seen in Fig. 2.

2.4. Data processing

Video data were digitized using Peak MOTUS v.3 (Peak Performance Technology, Centennial, CO). The ankle, hip, C7 spinal process, base of neck, tragus of the ear, and top and bottom of the pack were digitized for one second of each standing trial and two strides of each walking trial. TFL was used to evaluate trunk posture and was defined as the angle between the vertical and a line passing from the hip to the base of the neck. CVA was used to evaluate head-on-neck posture and was defined as the angle between the horizontal and a line passing from the spinal process of C7 and the tragus of the ear. These angles were averaged within each testing condition.

The IBP was used to assess the LA. IBP data were decoded and converted from voltage to displacement. The data were checked in Excel to ensure that L5 and rod 16 were aligned. The data were then imported into MatLab and the spinal curvature profile was rotated and aligned with the trunk to prevent TFL angle from confounding spinal curvature data. The data were then fitted with a 4th order polynomial.

Following normalization of the data, ensemble averages, that provide the average curve shape, were calculated for each load placement and each testing condition. To evaluate the differences in the curves, the angle around the inflection point of the lumbar curve was calculated based on the Cobb angle system for lumbar lordosis with sagittal view x-rays [5]. Because locations of bony landmarks were not available, the greatest rates

Fig. 2. Schedule of data collection procedures within a testing day.
Fig. 3. a) Cobb angle system for lordosis angle; b) LA on curvature data collected; c) Rotate curvature data 90° to prevent indiscriminate slopes; d) Mathematical equations used to calculate lordosis angle.

of change within the lumbar curve were the points used to determine the tangent line to the lumbar curve. The angle between the two tangents was termed the lordosis angle (LA). This methodology can be seen in Fig. 3 and is similar to that used by Willner and Johnson [34] with pantograph data.

2.5. Statistical analysis

Two way repeated measures ANOVAs (initial/final x load placement) were completed for standing and walking postures, for TFL, CVA, LA, and perceived discomfort. Post hoc analyses for significant results were completed using paired t-tests with a Bonferroni correction.

3. Results

The standing baseline (SB) with no backpack was compared to initial standing (IS) with backpack across all subjects and indicated that between-subject variability was high in all postural measures thus causing high standard deviations. However, within-subject variability was small by comparison and showed logical patterns of postural change. Average trunk forward lean (TFL) significantly increased \((p < 0.001)\) from \(1.7° \pm 2.6°\) without the pack to \(8.5° \pm 1.9°\) with the pack loaded to 15% BW. Cranio-vertebral angle (CVA) significantly decreased \((p < 0.01)\) from \(45.8° \pm 9.3°\) to \(38.1° \pm 7.6°\) indicating a forward head-on-neck posture when the pack is worn. Lordosis angle (LA) did not significantly change when the pack was applied.

3.1. Effect of load placement

The changes in posture (TFL, CVA, and LA) caused by various load placements (high, mid, and low) were evaluated for initial and final standing (IS, FS) and walking (IW, FW) samples.
3.1. Effect of load placement on the changes in mean trunk forward lean (TFL), cranio-vertebral angle (CVA) and lordosis angle (LA) from unloaded standing to final standing. Significant difference between high and low load placement for CVA was found. (∗indicates \( p < 0.05 \)).

3.1.1. Trunk Forward Lean (TFL)

The changes from the standing baseline (SB) in TFL were positive for all load placements, indicating a forward trunk lean. However, no significant differences were found between load placements for TFL within any sample, standing (IS, FS) or walking (IW, FW).

3.1.2. Cranio-vertebral Angle (CVA)

The changes in CVA from standing baseline (SB) to initial standing (IS) were negative, indicating a forward head-on-neck posture. For initial standing (IS) there were no significant differences between the high, mid, and low load placements \( (p > 0.05) \). However, during final standing, CVA under the low load placement was significantly less than the high load placement. The mean changes from standing baseline (SB) for CVA with high, mid, and low load placements in the FS testing condition were \(-12.52° \pm 7.80°, -8.39° \pm 11.58°, \) and \(-3.79° \pm 11.24°\), respectively (Fig. 4). No significant differences in CVA were found between load placements in either initial or final walking testing conditions.

3.1.3. Lordosis Angle (LA)

The changes from standing baseline (SB) to initial standing (IS) and final standing (FS) in LA were negative, indicating a flattening of the lumbar curve. The mean changes from standing baseline (SB) to final standing (FS) were \(-12.40° \pm 9.14°\) and \(-14.5° \pm 10.65°\) in the initial walking (IW) and final walking (FW) conditions, respectively (Fig. 4).

3.2. Effect of 1000 m walk

Main postural effects of the 1000 m walk were examined by collapsing all load placements (high, mid, and low) for both standing (Fig. 5: IS vs. FS) and walking postures (Fig. 6: IW vs. FW).

3.2.1. Trunk Forward Lean (TFL)

The mean difference in TFL from standing baseline over all three load placements was \(6.82° \pm 3.13°\) for the initial standing (IS) condition. This angle significantly increased following the walk to \(8.24° \pm 3.88°\) in the final standing (FS) condition \( (p = 0.03) \) (Fig. 5). Conversely, no significant differences in TFL were found between initial and final walking conditions \( (p > 0.05) \) (Fig. 6).

3.2.2. Cranio-vertebral Angle (CVA)

No significant differences between initial and final standing postures were found for CVA (Fig. 5). However, the mean CVA significantly \( (p = 0.041) \) decreased following the 1000 m walk for walking postures. The mean change from SB for CVA was \(-12.40° \pm 9.14°\) and \(-14.5° \pm 10.65°\) in the initial walking (IW) and final walking (FW) conditions, respectively (Fig. 6).
3.2.3. Lordosis Angle (LA)

The mean change in LA from the unloaded standing for the initial standing (IS) condition was $-4.65^\circ \pm 12.71^\circ$. This angle significantly increased following the 1000 m walk (FS) ($p < 0.001$), creating a hyperlordotic curve. The mean change in LA from initial to final standing was $12.87^\circ \pm 18.56^\circ$ (Fig. 5). Similarly, under walking conditions, the mean difference from unloaded standing for LA following the 1000m walk (FW) was $10.15^\circ \pm 18.16^\circ$, which is significantly greater than the initial walking (IW) value of $-3.79^\circ \pm 14.76^\circ$ (Fig. 6).

3.3. Interaction effects between 1000 m walk and load placement

3.3.1. Trunk Forward Lean (TFL) and Cranio-vertebral Angle (CVA)

No interaction effects between load placement and the 1000 m walk were found for the TFL and CVA outcome measures in either standing or walking conditions.

3.3.2. Lordosis Angle (LA)

In standing postures a significant increase was found in LA with mid pack placement only ($p = 0.03$). However, in walking postures a significant increase was found in LA with high pack placement ($p = 0.02$). No significant differences were noted in LA with low load placement in either standing or walking postures.

3.4. Perceived exertion and discomfort

Ratings of perceived exertion increased linearly with no significant differences between load placements. Using a 10 point scale, average exertion ratings significantly increased ($p < 0.05$) from 1.58 after 250 m to 4.03 after 1000 m. However, very few students reported discomfort with the use of the instrumented backpack following the 1000 m walk. No differences were found between load placements in the perceived discomfort data.

4. Discussion

Regardless of load placement, wearing the pack with a 15% BW load caused significant increases ($p < 0.05$) in TFL and CVA when comparing the unloaded standing baseline (SB) to initial standing (IS). These findings support the results of many load carriage studies [7, 12, 14, 26]; however, other studies did not find a significant increase until loads were increased to 20% BW [13, 15]. These postural deviations may perhaps indicate that the previously recommended load limit of 15% BW could be too heavy for ten-year-old children. These changes were present without any activity or substantial time of wearing the pack. Shifts in neck alignment may result in imbalanced muscle performance along with strain on cervical joints and soft tissue. After comparing radiographic angles and CVAs of adults, Pirunsan et al. [27] asserted that changes in the position of the cervical spine may result in additional stresses on the structures of the upper and lower cervical spine. Furthermore, other investigators have found links between subjects with smaller CVAs (more forward head on neck lean) and headaches [33]. The results of the current study cannot however state conclusively that the 15% weight limit is too high. Although postural adaptations were evident, the children did not perceive significant pain or discomfort.

As the purpose of backpacks is to transport loads, both walking and a significant exposure time provide a more realistic test of the 15% load than a rested standing evaluation. It was evident that walking with the backpack elicited greater trunk forward lean (TFL) and head poke (CVA) when compared to initial standing postures. Following the 1000 m walk, TFL postures did not significantly increase during walking; however, there was a significant decrease in CVA. This may be explained by the ceiling effect on TFL previously suggested by Goodgold et al. [9]. When walking, system
(pack + person) centre of gravity (C of G) must fall outside the base of support for a person to accomplish forward movement, and therefore increased TFL is required to shift the system C of G forward and balance the backwards moment created by the posterior load. The maximum TFL for an individual may be required even in a rested state to satisfy these requirements, thereby preventing the child from increasing TFL to compensate for fatigue. If this is true, following the 1000 m walk, postural accommodation to balance the load may occur by altering the head-on-neck posture and subsequently decreasing the CVA. An additional compensation strategy used by the children was to increase lordotic curvature of the spine, which would shift the trunk C of G forward.

Standing postures following the 1000 m walk (FS) indicated TFL significantly increased ($p < 0.05$) from the SB posture; however, CVA did not significantly change. This is logical based on the same ceiling effect theory stated above. In standing the required TFL is less because the system C of G only needs to remain within the base of support. Therefore, TFL can be increased with the increased demands with fatigue. These changes in TFL are sufficient to maintain equilibrium and CVA does not need to be altered.

In addition to the above postural changes, significant increase ($p < 0.01$) in hyperlordotic spinal postures was found in the final standing (IS) posture. The changes in LA for both walking and standing postures indicate that spinal postural changes are present after the 1000 m walk. These findings are similar to that of Orloff and Rapp [25] who found a significant change in spinal curvature following a 15 minute walk with young women. It is hypothesized that the hyperlordotic curvature in the lumbar spine is associated with tension on the anterior aspect of the vertebral column and compression on the posterior aspect, with uneven distribution of forces on the disc and vertebral body. This posture could lead to musculoskeletal discomfort and possibly increased risk of injury because of increased compressive force on the zygapophysial joints and stresses to the inferior margins of the articular surfaces [1].

Although the level of physiological fatigue cannot be determined, the increase in ratings of perceived exertion as the amount of activity increased can be equated to the self-report of fatigue used by Negrini and Carabalona [23]. These researchers found that reporting fatigue while carrying a backpack corresponded to an odds ratio of 3.8 for experiencing pain while carrying the backpack and 5.6 for experiencing at least one episode of back pain. The changes found following the 1000 m walk in this study may explain these findings.

Comparisons across load placements indicate that low load placement may minimize changes in posture and spinal curvature. Although there were no differences between load placements for TFL in any of the testing conditions, CVA results indicated low load placement was better than high for standing postures following a 1000 m walk. LA results demonstrated a trend indicating high and low might be better than mid load placement. Examining the interaction effects of load placement and the 1000 m walk indicated that LA was affected the most by high placement after activity for walking and for mid placement for standing postures. The only load location that did not affect LA in some manner was the low load placement.

Low load placement (at the spinal level of L3) was recommended by Grimmer et al. [11] when looking at horizontal displacements of various anatomical landmarks with only a rested standing posture and 10% BW loads. Additionally, Frank et al. [8] found that the forces on the shoulder and back were minimized with low load placement; however, a postural analysis found less changes with high placement. Mackie et al. [21] found that load weight, use of a waist belt and longer strap lengths resulted in less shoulder pressure, thus advocating lower load placement. Other researchers have advocated higher load placements as the forward lean is less than with low placements [4]; however, this study was completed with rucksacks in adults where waist belts were also used and may not be transferable to children’s backpacks without a waist belt.

Although there are now several studies that suggest a low placement is best, moderating factors in pack design such as fit, sternum straps, frame sheets or hip belts may make other designs advantageous. The results of an isolated load placement study provide a starting point for future backpack designs and help to understand the interactions between backpack use and postural and spinal curvature changes.

5. Conclusions

Altering the load placement of backpacks was found to affect the body posture (TFL and CVA) and spinal curvature (LA) of children. Low load placement appears to minimize these postural changes as compared to mid or high load placement, indicating that backpacks that rest lower on the spine may be best suited for children. However, future work needs to be completed before design changes can be recommended with confidence. The findings of this study are limited in
that a lack of statistical significance was found between load placements for TFL in all testing conditions and in LA and CVA for most testing conditions. This indicates that a follow-up study should be conducted that includes more than 15 subjects. Furthermore, these results are restricted to only one factor of backpack design namely, load placement. Other features of pack design may affect these results, such as adding sternum straps, frame sheets or waist belts. The finding that low load placement minimizes postural adaptations in children provides the foundation for developing a safer backpack for children.

Acknowledgements

The authors would like to thank the Ontario Chiropractic Association for funding this project. Thanks are also extended to Alexander Perry (MSc), and Susan Reid (MSc, PEng) of the Queen’s Ergonomics Research Group for construction of the Instrumented Back Pack. Final thanks to the children in grade 5 of the Kingston Rideau Public School.

References


