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The effect of simulated school load carriage configurations on shoulder strap tension forces and shoulder interface pressure

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Abstract

Recently, several studies have addressed the physical demands of school student's load carriage, in particular the load weight carried, using physical demands indicators such as oxygen consumption, gait, and posture. The objective of this study was to determine the effects of different load carriage configurations on shoulder strap tension forces and shoulder interface pressure during simulated school student's load carriage. A load carriage simulator was used to compare shoulder strap forces and shoulder pressure for 32 combinations of gait speed, backpack weight, load distribution, shoulder strap length and use of a hip-belt. The results showed that the manipulation of backpack weight, hip-belt use and shoulder strap length had a strong effect on shoulder strap tension and shoulder pressure. Backpack weight had the greatest influence on shoulder strap tension and shoulder pressure, whereas hip-belt use and then shoulder strap adjustment had the next greatest effects, respectively. While it is clear that researchers and practitioners are justified in focusing on load magnitude in backpack studies as it has the greatest effect on shoulder forces, hip-belt use and shoulder strap adjustment should also be examined further as they too may have significant effects on the demands placed on backpack users. Based on the present findings, school students should wear their backpacks with the least weight possible, use the hip-belt if present, allow a reasonable amount of looseness in the shoulder straps and should position the heaviest items closest to their back. However, more detailed work using human participants needs to be undertaken before these recommendations can be confirmed.
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1. Introduction

Growing suspicion that the loads school students carry to, around and from school are frequently too high has prompted research into the physical demands of school student's load carriage (Chansirinukor et al., 2001; Cheung and Hong, 2000; Grimmer et al., 2002; Grimmer and Williams, 2000; Hong et al., 2000; Mackie et al., 2003; Malhoutra and Sen Gupta, 1965; Pascoe et al., 1997; Sander, 1979; Voll and Klimt, 1977; Whittfield et al., 2001). However, it is difficult to demonstrate that loads carried by school students are directly associated with reported musculoskeletal pain or discomfort as there are many other factors such as physical capability, other physical activities, poor seating, growing pains or psychosocial factors that may contribute to reported pain or discomfort (Troussier et al., 1994; Watson et al., 2002).

Researchers have therefore tended to study the effects of load carrying on physiological and biomechanical measures in children and adolescents such as oxygen consumption (Hong et al., 2000; Malhoutra and Sen

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Gupta, 1965), gait (Cheung and Hong, 2000; Pascoe et al., 1997; Wang et al., 2001) and posture (Chansirinukor et al., 2001; Grimmer et al., 2002; Grimmer and Williams, 2000; Malhoutra and Sen Gupta, 1965; Pascoe et al., 1997; Wang et al., 2001). Wang et al. (2001) also studied ground reaction forces in order to determine the effects of carrying school-related loads.

Physiological and biomechanical measures such as oxygen consumption and gait are undoubtedly altered as a result of load carriage (Goldman and Iampietro, 1962; Kinoshita, 1985; Knapik et al., 1996; Legg and Mahanty, 1985,1986) but whether these changes are indicative of eventual injury is unknown. Increases in oxygen consumption or increases in support phase time during gait may be the body's natural way of safely accommodating the extra load placed on it.

A more direct method of determining the physical demands of load carriage in school students would be to measure the external forces that directly relate to carrying a backpack, such as the pressure on the shoulders that occur as a result of the tension in the shoulder straps of a backpack. Bryant and Reid (1996) described a biomechanical model for the forces that act within the person/backpack system when load carrying. In this model the weight force of the backpack is resisted mostly by the resistive forces of the shoulders, hips and lower back via the shoulder straps and hip-belt. Given that using the hip-belt to increase the load on the hips is seen as positive during load carriage, measuring the forces at the shoulder during load carriage would provide a relevant indicator of the demands placed on the backpack user.

The magnitude of the loads that school students carry has also been the focus of school load carriage researchers (Cheung and Hong, 2000; Hong et al., 2000; Malhoutra and Sen Gupta, 1965; Pascoe et al., 1997; Voll and Klimt, 1977; Whittfield et al., 2001), and 10% of body weight (BW) is generally accepted as a recommended maximum load for school students (Sander, 1979; Voll and Klimt, 1977). Recently studies have shown that no significant changes in oxygen consumption or gait occur until school students are carrying 15–20% of BW (Cheung and Hong, 2000; Hong et al., 2000; Pascoe et al., 1997), which may support a school load carriage limit of 10% BW. What seems more certain is that 20% BW as a load for school students is excessive (Cheung and Hong, 2000; Hong et al., 2000).

The variations reported in school student's responses to carrying loads may be because a person's carrying capacity is affected not only by the magnitude of the load they carry but also by the way the load is carried, the duration of carriage, the frequency of carriage and the physical capabilities of the person. These other factors must also be considered when attempting to determine the overall physical demands placed on the user.

Bygrave et al. (2004) appear to be the only authors to have studied the adjustment of a single backpack in adults. They found that the tightness of fit of a backpack (adjustment in the shoulder straps, chest strap and hip-belt of 3 cm) had an effect on lung function in 12 healthy males wearing a 15 kg backpack. Using different backpack designs Lloyd and Cooke (2000) and Kinoshita (1985) both found that distributing the weight of the backpack between the front and the back of the body lead to improvements in gait measures. In children, Grimmer et al. (2002) found that more loose shoulder straps allowed a more upright, natural posture than tighter shoulder straps where the backpack is carried higher on the back.

Although these studies have addressed backpack configuration, no studies to date have attempted to study the effects of many different backpack adjustments on the backpack forces that directly affect school students. However, in order to carry out such a study, a large number of trials would need to be performed in order to test different combinations of backpack adjustments for each individual from a sample group large enough to account for the variation of results expected from human participants.

Bryant et al. (2001) recommend that a load carriage simulator is useful in screening a large number of backpack designs or configurations prior to more detailed analyses using human participants. A load carriage simulator might, therefore, be an efficient way of evaluating a large number of school load carriage configurations, prior to a more detailed evaluation of potentially beneficial configurations using school students in the future. The objective of this study, therefore, was to determine the effects of load weight, shoulder strap length, load distribution, gait speed, and the use of a hip-belt on shoulder strap tension forces and shoulder interface pressure during simulated school student's load carriage.

2. Methods

All trials were conducted on a load carriage simulator that was designed and built by the Ergonomics Research Group at Queens University, Ontario, Canada and is the property of Defence Research and Development Canada (Stevenson et al., 2004). The load carriage simulator (Fig. 1) consists of a programmable three degree of freedom pneumatically driven platform, which supports interchangeable rigid mannequins. Vertical displacement, rotation about the anterior/posterior axis (side lean), and rotation about the medial/lateral axis (forward lean) are user programmable from a menu. A skin analogue (Bocklite®) covers the surface of the mannequin.

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Fig. 1. Load carriage simulator used for data collection (tight shoulder straps configuration shown).

Anterior/posterior lean of the mannequin is typically set by balancing the anterior–posterior moment due to backpack loads. In previous studies (Cheung and Hong, 2000; Malhoutra and Sen Gupta, 1965; Pascoe et al., 1997) the change in anterior lean of the trunk in school children when carrying different loads has been shown to be very small or negligible until a load change of 17–20% BW was administered. Therefore, in this study, the mannequin was fixed to the motor of the simulator with an anterior tilt of 5° (balanced in the anteroposterior plane) to maintain consistency between trials.

A mannequin representing a 5th percentile Canadian armed forces female (weight 52.8 kg and height 1.55 m) was used (Fig. 1) as it most closely resembled the anthropometric characteristics of 13 year old school students, which have been reported as carrying the greatest loads across all school students (Grimmer and Williams, 2000, Pascoe et al., 1997; Whittfield et al., 2001) and therefore may be at the greatest risk of injury. A commercially available school backpack (Fig. 1), with no internal or external frame, but with adjustable shoulder straps and waist belt was used for the study. The backpack was modified to accommodate custom built load cells at the top and at the bottom of the shoulder straps so that tension could be measured at these points, giving an indication of the shoulder reaction force. The linearity of the load cells' response to loading was tested up to 50 N. Correlation coefficients of $r = 0.999$ and 0.998 were determined for the bottom and top shoulder strap load cells, respectively. Forces were measured on the right side of the backpack while dummy load cells of identical dimensions were used on the left side to ensure the symmetry of the school backpack. The load cells were hardwired to an amplifier and personal computer and force data were collected at 20 Hz, which was the limit of the capability of the system.

Shoulder pressure during load carriage has previously been measured using Tekscan pressure sensors (Martin and Hooper, 2000). A pressure sensor (Fscan 9811, Tekscan) was placed over the most superior aspect of the right shoulder of the mannequin so that changes in pressure due to forces from the shoulder straps could be measured. Gathering absolute quantitative data using this sensor when placed on a curved surface proved ineffective as the bending of the sensor created an offset, so only changes in raw pressure (the sum of the pressures measured in each of 96 pressure sensitive cells) was used. Raw pressure measurements were collected at 50 Hz using the same data acquisition software as the load cells. Extra precautions were taken by collecting unloaded baseline data from the Tekscan system before and after each trial, to account for any drift in the signal from the sensor.

Both the load cells and the pressure sensors proved to be highly reliable. Correlation coefficients for test/re-test mean and peak forces were $r = 0.986$ and 0.979, respectively. Correlation coefficients for test/re-test mean and peak pressures were $r = 0.945$ and 0.956, respectively.

The validity of the load carriage simulator's ability to predict musculoskeletal discomfort in soldiers has been established by Bryant et al. (2001). Significant positive correlations were shown between shoulder pressure and forces on the simulator and soldier's reported musculoskeletal discomfort. In the present study, statistically significant ($P < 0.01$) correlation coefficients of $r = 0.556$ and 0.635 for mean and peak load cell/pressure sensor comparisons, respectively, demonstrated the validity of the overall measurement system. There appear to be no studies that demonstrate the validity of the simulator's ability to reproduce human movement.

Before each trial the backpack was placed on the mannequin in a standardised manner. Measurements between markers on the side and back of the neck of the mannequin and the shoulder strap and the top of the backpack were used to ensure consistent backpack placement.

Five load carriage adjustment parameters were determined based on the variations of load carriage

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that school students were considered to most commonly experience. Gait speed ('Walking' and 'running'), backpack weight, load distribution, shoulder strap length and use of a hip-belt were manipulated so that 32 possible combinations of load carriage configuration were evaluated.

Simulator walking and running step rates (1.3 and 1.5 steps per second, respectively) and centre of mass vertical displacements (4.5 and 6.0 cm, respectively) were used based on gait kinematics information from Unnithan and Eston (1990) and Rose and Gamble (1994). Step rate and centre of mass vertical displacement were the only programmable components of the simulator's gait speed. It is acknowledged that only manipulating these two variables is not sufficient to realistically differentiate between real walking and running, however they are likely to have the greatest effect on the forces that effect the shoulder during load carriage.

Backpack weights used were 10% (5.3 kg) and 15% (7.9 kg) of the representative BW of the mannequin. These weights were chosen as they represented the current recommended load carriage limit for school students (10% BW) and 5% greater than the recommended limit, so that the effects of heavier, yet realistic loads could be examined. Load distribution was termed as 'close' and 'distant'. Five text books were used to pack the school backpack with the heaviest books closest to the back of the mannequin for the 'close' load distribution condition (centre of mass 5.5 cm from inner backpack wall) and the heaviest books farthermost from the back of the mannequin for the 'distant' load distribution condition (centre of mass 11 cm from inner backpack wall). The shoulder straps were adjusted and checked using a tape measure before each trial, with the 'tight' straps condition defined as a distance of 7 cm from the tip of the shoulder strap adjustment buckle to the lower connection of the shoulder strap to the backpack. This adjustment represented the backpack fitting close to the upper back (Fig. 1). The 'loose' straps condition, representing the backpack sitting lower on the back of the mannequin, was defined as a distance of 24 cm from the tip of the shoulder strap adjustment buckle to the lower connection of the shoulder strap to the backpack. The hip-belt was either used or not used. When it was used the hip-belt tension was standardised to 13.6 kg using a Shimpo tensiometer before each trial.

For each trial, the simulator was allowed to run for 10 gait cycles, prior to data collection. Two 10 s trials were collected for each backpack configuration so that the reliability of the system could be evaluated. Between each trial, the backpack position on the mannequin was checked and adjusted if necessary.

Pressure and force data were analysed using SPSS statistical analysis software. Data from the two trials for each load carriage configuration were combined and means and standard deviations were calculated both for the overall data and for the peaks in each cycle for each trial. Separate, single factor, within groups, analyses of variance (ANOVA) with an alpha level of 0.05 were used to compare the data between each variation of walking/running, backpack weight, load distribution, strap length and use of a hip-belt. Between groups ANOVA were used to test for interactions between backpack configurations.

3. Results

Tables 1 and 2 show the mean and standard deviation (SD) overall and peak shoulder strap forces and shoulder pressures for each variation of backpack weight, use of hip-belt, strap length, load distribution and walking/running. The percentage difference between the means of each variation of overall and peak force and pressure is also shown along with the p-value, demonstrating the level of statistical significance of the differences between the means of each variation.

Load weight had the greatest influence on shoulder strap forces with a load of 15% BW producing 50% greater overall force ($p<0.001$) and 36% greater peak force ($p<0.001$) than a load of 10% BW. This was followed by hip-belt use where the non-use of the hip-belt produced 40% greater overall forces ($p<0.001$) and 41% greater peak forces ($p<0.001$) than when a hip-belt was used, and shoulder strap length where tight straps produced 37% greater overall forces ($p<0.001$) but only 10% greater peak forces ($p = 0.151$) than loose shoulder straps.

Variations in load placement and walking/running had much less effect on shoulder strap forces than load weight, hip-belt use and shoulder strap adjustment. For load placement, having the weight distributed farthermost away from the back only increased overall shoulder strap forces by 6% ($p = 0.494$) and peak shoulder strap forces by 10% ($p = 0.143$). For walking and running, running only increased overall shoulder strap forces by 1% ($p = 0.914$) and peak shoulder strap forces by 8% ($p = 0.286$).

The pattern of results for shoulder pressure was similar to those shown for shoulder strap forces. Load weight had the greatest influence on shoulder pressure with a load of 15% BW producing 70% greater overall shoulder pressure ($p<0.001$) and 65% greater peak shoulder pressure ($p<0.001$) than 10% BW. This was followed by hip-belt use where the non-use of the hip-belt produced 44% greater overall shoulder pressure ($p = 0.001$) and 47% greater peak shoulder pressure ($p<0.001$) than when the hip-belt was used. For strap length, tight straps produced 40% greater overall shoulder pressure ($p<0.001$) and 28% greater peak shoulder pressure ($p = 0.020$) than loose straps.

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Table 1
Mean and standard deviation (SD) overall and peak shoulder strap forces (Newtons) for different load carriage configurations

Load carriage variable	Adjustment 1		Adjustment 2			
Load weight	10% of body weight		15% of body weight		% Diff overall	% Diff peak
	Overall	Peak	Overall	Peak		
	22.5 (7.0)	38.0 (10.1)	33.8 (8.4)	51.7 (9.6)	50***	36***
Hip belt	Used		not used			
	Overall	Peak	Overall	Peak		
	23.5 (10.1)	37.2 (10.6)	32.9 (6.2)	52.5 (7.7)	40***	41***
Straps	Loose		Tight			
	Overall	Peak	Overall	Peak		
	23.8 (9.4)	42.7 (14.1)	32.5 (7.7)	47.0 (9.1)	37***	10
Load placement	Close to back		Distant from back			
	Overall	Peak	Overall	Peak		
	27.4 (10.8)	42.7 (13.1)	29.0 (8.3)	47.1 (10.5)	6	10
Gait speed	Walking		Running			
	Overall	Peak	Overall	Peak		
	28.1 (9.8)	43.2 (11.4)	28.3 (9.5)	46.5 (12.5)	1	8

*Difference statistically significant ($p<0.05$). **Difference statistically significant ($p<0.01$). ***Difference statistically significant ($p<0.001$).

Table 2
Mean and standard deviation (SD) overall and peak shoulder pressure (Raw pressure) for different load carriage configurations

Load carriage variable	Adjustment 1		Adjustment 2			
Load weight	10% of body weight		15% of body weight		% Diff Overall	% Diff Peak
	Overall	Peak	Overall	Peak		
	222 (95)	271 (112)	378 (128)	446 (136)	70***	65***
Hip belt	Used		Not used			
	Overall	Peak	Overall	Peak		
	246 (138)	290 (143)	355 (114)	427 (129)	44**	47***
Straps	Loose		Tight			
	Overall	Peak	Overall	Peak		
	250 (138)	315 (165)	350 (117)	402 (125)	40***	28*
Load placement	Close to back		Distant from back			
	Overall	Peak	Overall	Peak		
	295 (151)	352 (164)	305 (122)	365 (140)	3	4
Gait speed	Walking		Running			
	Overall	Peak	Overall	Peak		
	336 (141)	390 (147)	264 (124)	326 (152)	−21*	−16

*Difference statistically significant ($p<0.05$).**Difference statistically significant ($p<0.01$).***Difference statistically significant ($p<0.001$).

For shoulder pressure, variations in load distribution again had much less effect on shoulder pressure than load weight, hip-belt use and shoulder strap adjustment. Having the weight distributed farthermost away from the back only increased overall shoulder pressure by 3% ($p = 0.772$) and peak shoulder pressure by 4% ($p = 0.720$). Walking and running had the opposite effect on shoulder pressure than it did on shoulder strap forces. Walking produced 21% more overall shoulder pressure ($p = 0.031$) and 16% more peak shoulder pressure ($p = 0.096$) than running.

One interaction between load carriage adjustments was statistically significant. The interaction between the shoulder strap adjustment hip-belt use was statistically significant ($p<0.001$) for overall and peak shoulder strap forces and shoulder pressure. The interaction meant that the loose shoulder strap adjustment was more effective in reducing shoulder forces when the hip-belt was worn.

4. Discussion

Load weight was clearly the most influential of the load carriage variables that were studied. This seems reasonable as the gravitational pull on the contents of

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