Backpack load positioning and walking surface slope effects on physiological responses in infantry soldiers

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Abstract

The primary purpose of this study was to survey a sample of infantry soldiers to determine their preferred backpack load distribution. The second objective was to examine the effect of backpack load position, walking speed and surface grade on the physiological responses of infantry soldiers. In the first phase of the study, analysis of 500 questionnaires indicated that backpack item arrangement was typically determined by convenience and habit. About 33.6% and 30.6% of the soldiers reported placing heavier items in the lower and higher positions, respectively. In the second experimental phase of the study, five male infantry soldiers who had completed basic training (including 30 km tactical road march) each performed eight treadmill walking bouts at one of two speeds (i.e., 3.2 and 6.4 km/h) and two surface grades (0% and 6%) carrying 15% of their body weight in a backpack with two chambers (upper and lower). Respiratory frequency, minute ventilation, oxygen consumption and heart rate were recorded using the Quark pulmonary system. The MANOVA results indicate that the effect of walking speed was strongly significant for all physiological indices. In addition, as might be expected, walking on a 6% grade was associated with higher oxygen consumption and heart rate compared to level going. In terms of load position, the mean respiratory frequency was significantly higher where the load was carried in the upper position. Furthermore, there was a significant interaction between load position and walking grade on oxygen consumption. Where participants were walking at zero incline, there was no significant difference in mean oxygen consumption. By contrast, the mean oxygen consumption was significantly higher where loads were carried in the upper position and negotiating the 6% grade. Previous research has found that, ideally, load carriage should complement stability, bringing the load’s center of gravity as close to the body as possible and making use of the larger muscles. However, carrying heavy loads close to the trunk can affect lung function. Thus, load placement is an important factor in physiological response to load carriage, and optimum choice of upper or lower position when distributing items in a backpack may be dependent on the walking grade.

Relevance to industry

The need to carry heavy loads for long distances is common to a range of human endeavor, with physical transport used by soldiers, various types of workers and recreational hikers. Load distribution and walking gradient are important factors in terms of the efficiency of load carriage and should be taken into consideration in both the design and loading of backpacks. Thus, the findings of the present study will be relevant to infantry soldiers, mountain climbers or of manual material handling (MMH) in industry, providing practical implications for tasks associated with exposure to uneven walking/working surfaces.

Keywords: Load carriage; Physiological workload; Backpack; Load position; Grade

1. Introduction

Carrying heavy loads over unpredictable terrain for long distances is a requirement common to military personnel, various types of workers and recreational hikers. Knapik et al. (1992, 1996) have indicated that 50% of soldiers were unable to complete a strenuous 20 km march, reporting problems associated with the back. A majority of the published studies are concerned with the effects of load weight, walking speed, gradient and other factors during carriage. The energy cost of load carriage increases...
progressively with higher load mass, walking speed and surface grade (Martin and Nelson, 1986; Holewijn, 1990; Knapik et al., 1996; Jacobson et al., 2003).

Datta and Ramanathan (1971) compared seven modes of load carriage and found that a double pack is the most physiologically efficient. Liu and Chou (2004) also compared three carriage modalities (backpack, satchel and handbag) and found that backpack carriage of loads equivalent to 10% body weight by incurred the lowest physiological cost while walking at 6.4 km/h. Aside from the method used to carry the external load, an additional technique to decrease physical stress is to alter distribution of the load within the backpack (Stuempfle et al., 2004). The general principle is that lighter weight items should be placed at the bottom of the backpack, while heavier items should be located at the top to compliment stability, bringing the load center of gravity as close to the body as possible and making use of the larger muscles (Legg, 1985; Howe and Getchell, 1995). By contrast, however, placement of the load high in the pack tends to further destabilize posture, especially in taller individuals, as measured by the amount of body sway while standing (Hellebrandt et al., 1944; Knapik et al., 1996). Bloom and Woodhull-McNeal (1987) have suggested that low load placement might be preferable for stability on uneven terrain while a higher alternative may be best over relatively even terrain because it keeps loaded body posture more similar to the unloaded analog. While the static moments are similar for these high and low load placements, the dynamic moments are about 40% greater for the former, an effect attributed to the greater rotational inertia associated with the higher load (Bobet and Norman, 1984). Some of the controversial statements and findings in the literature with respect to load distribution may be sufficient rationale for further study.

There are, however, very few investigations of the relationship between load distribution within the backpack and physical stress (Obusek et al., 1997). Physical transport of heavy loads over long distances can result in high injury incidence, with 36% of soldiers reportedly injured during a 161 km march (Reynolds et al., 1999). Thus, the present study has focused on the issue of load carriage in infantry soldiers. It has been hypothesized that, apart from load mass, walking speed and surface grade, load distribution within the backpack might be an important contributor to physiological workload during burden carriage, and there were some associations have been demonstrated between load distribution, walking speed and surface grade. Thus, the initial objective of the present study was to survey different load arrangements as determined by the distribution of military paraphernalia and utensils, such as the washbowl, clothes, sleeping bag and miscellaneous military tools. The secondary goal of this research was to examine the effect of backpack load position, walking speed and surface grade on physiological response in infantry soldiers.

2. Methods

The present investigation consisted of two stages. In the first, a questionnaire was used to survey infantry soldiers and determine preferences with respect to backpack load arrangement. In the second phase, a treadmill-based experiment was used to measure physiological response to walking speed, grade level and load position conditions in five trained soldiers.

2.1. Survey and questionnaires

2.1.1. Participants

The sample was drawn from members of a Taiwanese army base. A total of 700 questionnaires were dispatched by post to the base, with a response rate of 71% (n = 500) obtained from the all-male sample. Mean age was 22.5 years (range 18–38), mean stature 171.7 cm (range 156–190) and mean body mass 66.2 kg (range 45–100).

2.1.2. Questionnaire

The questionnaire was designed to determine background information, typical backpack weight, average march distance and preferred carriage method. In addition, the backpack was divided into six separate layers, and load arrangement determined according to the positioning of military paraphernalia and utensils such as the metal washbowl, shoes, clothes, sleeping bag, washing utensils and shoes.

2.2. Experimental study

2.2.1. Participants

The study was approved by the Research Ethics Committee of the researcher’s institution. Five male infantry soldiers that had undergone basic training (including a 30 km tactical road march) participated in the experiments after providing informed consents with respect to the investigative procedures. The mean age of the sample population was 24.4 years (range 21–28), mean stature 176.6 cm (range 172–182) and mean body mass 74 kg (range 61–93). All subjects were healthy and reported no musculoskeletal problems or cardiovascular diseases which might be detrimental to physical performance. In addition, all recruits were instructed to avoid vigorous physical activity and alcohol consumption during the 12 h prior to the experiment.

2.2.2. Apparatus and materials

A Taiwanese army uniform backpack (27 × 27 × 72 cm, L × W × H) was used in this study (Fig. 1). In addition, the backpack was separated into two chambers (high and low) using a wooden frame and filled with books to obtain a total pack weight equivalent to 15% of body weight for each subject. A facemask was used to measure respiratory frequency (RF), minute ventilation (MV), respiratory exchange ratio (R) and oxygen consumption (VO₂)
on the treadmill using the Quark Pulmonary Function Test system (Cosmed, Italy). In addition, a Polar electrode belt placed around the chest was utilized to continuously measure heart rate (HR) (Polar, Finland).

2.2.3. Experimental procedures
The participants were dressed in an army uniform during the trials, which were performed in a temperature-controlled laboratory (20 °C). Before commencement of the actual experiment, participants were given an opportunity to warm-up and practice walking on the motor-driven treadmill (Sports Art Model 3185, Taiwan) and asked to perform known all experimental tasks until they were able to produce steady manipulation. A rest period of at least 10 min was provided for each subject (longer if required) before resting physiological measurements were collected to serve as baseline. A total of eight treadmill trials were performed at two velocity levels (3.2 and 6.4 km/h), two grade levels (0% and 6%) and carrying 15% of individual body weight in a backpack in two chambers (high or low position). The order of these trials was randomly assigned for each subject. In addition, each trial involved walking for at least 10 min or more (if required) until physiological measurements stabilized. A minimum rest period of 30 min (more if required) was provided between trials until baseline physiological indices were restored. During the rest periods, participants were asked to stay seated, relax and remain silent. If baseline measurements could not be achieved after a rest period, the experimental session was resumed the next day.

2.2.4. Data analysis
A randomized complete block design (blocks as individual subjects) with three within-subject factors (speed, grade and load position) was used for this study. The Quark Pulmonary Function Test system was utilized for breath-by-breath determination of physiological response including RF, MV, R, VO₂ and HR. All trial data files were exported in Microsoft Excel format, with the mean values for dependent variables then calculated over the final 2 min of each trial, by which time observed variables were deemed to have achieved a steady state for each participant. Furthermore, multivariate analysis of variance (MANOVA) was utilized to identify significant differences between conditions for dependent variables. Statistical significance was set at a probability level of 0.05.

3. Results
3.1. Survey for load arrangement
A summary of the questionnaire data is presented in Table 1. Comparing carriage methods, soldiers preferred double-shoulder portage (54.2%) to single-shoulder (27.6%), and hand-held (18.2%) analogs. In terms of load mass, soldiers typically carried 6–10 kg during their marches, usually over a distance of 5–10 km. In terms of arrangement of the heavier items, low or high backpack position was reported by 64.1% and 35.9% of the respondents, respectively.

The results for reported load arrangement are presented in Table 2. The backpack was separated into six levels (1–6), with higher number representing higher position. In increasing order of layer height, the most common items for each level were (I) metal washbowl (33.6%) and sleeping bag (15.4%); (II) shoes (33.8%) and clothes (19.8%); (III) shoes (34.2%) and washing utensil...
(24.2%); (IV) shoes (35%) and clothes (26.6%); (V) shoes (30%) and washing utensil (23%) and (VI) mental washbowl (30.6%) and washing utensil (28.2%) metal washbowl (30.6%). Interestingly, the metal washbowl was most commonly placed at both the lowest and highest levels, reflecting fundamentally opposed views with respect to load arrangement.

3.2. Results of experimental study

The mean (S.D.) values for RF, MV, R, VO2 and HR during load carriage are presented in Table 3. MANOVA was conducted for the five measures. Further results have been presented as follows.

3.2.1. Effect of walking speed

Results of MANOVA reveal a significant main effect for walking speed (Pillai’s trace = 0.733, F(5,24) = 13.2, p < 0.001, partial η² = 0.733) on 0.99 of statistical power (alpha = 0.05, two-tail). Univariate F tests show significantly increases for RF (F(1,28) = 7.85; p < 0.01), MV (F(1,28) = 22.34, p < 0.001), VO2 (F(1,28) = 38.82, p < 0.001) and HR (F(1,28) = 32.1, p < 0.001) when walking speed was doubled from 3.2 to 6.4 km/h.

3.2.2. Effect of grade level

Results of MANOVA also revealed a significant main effect for grade level (Pillai’s trace = 0.672, F(5,24) = 9.85, p < 0.001, partial η² = 0.672) on 0.99 of statistical power (alpha = 0.05, two-tail). Analysis of the physiological data for the 0% and 6% grades reveals significant differences in mean R (F(1,28) = 16.82, p < 0.001), mean VO2 (F(1,28) = 16.82, p < 0.001) and mean HR (F(1,28) = 23.5, p < 0.001). In addition, these were significantly greater for mean respiratory exchange (0.92 versus 0.82), mean VO2 (16.0 versus 12.1 ml/kg min) and mean HR (110.2 versus 100.9 beats/min) comparing the 6% grade to level going.

3.2.3. Effect of load position

Analysis of the physiological data reveals significant differences comparing load position for mean RF (F(1,28) = 5.87, p < 0.05; statistical power = 0.65) and R (F(1,28) = 5.64, p < 0.05; statistical power = 0.63). The mean RF was significantly higher when the load was carried in the upper position as compared to the lower (22.0 versus 20.1 breaths/min). In addition, load carriage in the upper position was also associated with significantly higher R.

Table 2
Arrangement of utensils within backpack

<table>
<thead>
<tr>
<th>Main utensils Arrangement position</th>
<th>Lowest</th>
<th>Median</th>
<th>Highest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1 (%)</td>
<td>33.6</td>
<td>4.4</td>
<td>10.2</td>
</tr>
<tr>
<td>Layer 2 (%)</td>
<td>2.2</td>
<td>5.4</td>
<td>30.6</td>
</tr>
<tr>
<td>Layer 3 (%)</td>
<td>3.4</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Layer 4 (%)</td>
<td>4.6</td>
<td>9.2</td>
<td>10.4</td>
</tr>
<tr>
<td>Layer 5 (%)</td>
<td>8.6</td>
<td>15</td>
<td>28.2</td>
</tr>
<tr>
<td>Layer 6 (%)</td>
<td>16.8</td>
<td>24.2</td>
<td>23.1</td>
</tr>
<tr>
<td>Total (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: Main utensil arrangement for each layer is underlined. N = 500

Table 3
Mean, standard deviation and statistical comparison for physiological responses stratified by experimental condition

<table>
<thead>
<tr>
<th>Walking speed (mph)</th>
<th>RF (breaths/min)</th>
<th>MV (L/min)</th>
<th>RQ (VCO2/VO2)</th>
<th>VO2 (ml/kg/min)</th>
<th>HR (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>19.9 ** (6.1)</td>
<td>18.3 *** (4.3)</td>
<td>0.88 (0.12)</td>
<td>11.5 *** (3.2)</td>
<td>100.2 *** (11.6)</td>
</tr>
<tr>
<td>4</td>
<td>22.2 (6.3)</td>
<td>23.3 (6.8)</td>
<td>0.86 (0.09)</td>
<td>16.6 (5.1)</td>
<td>110.5 (11.4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade level (%)</th>
<th>RF (breaths/min)</th>
<th>MV (L/min)</th>
<th>RQ (VCO2/VO2)</th>
<th>VO2 (ml/kg/min)</th>
<th>HR (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.4 (6.8)</td>
<td>20.1 (5.4)</td>
<td>0.92 *** (0.11)</td>
<td>12.1 *** (3.4)</td>
<td>100.9 *** (11.3)</td>
</tr>
<tr>
<td>6</td>
<td>20.8 (5.8)</td>
<td>21.4 (6.9)</td>
<td>0.82 (0.07)</td>
<td>16.0 (5.4)</td>
<td>110.2 (10.4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load position</th>
<th>RF (breaths/min)</th>
<th>MV (L/min)</th>
<th>RQ (VCO2/VO2)</th>
<th>VO2 (ml/kg/min)</th>
<th>HR (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>22.0 * (6.7)</td>
<td>21.7 (6.4)</td>
<td>0.9 * (0.07)</td>
<td>14.3 (5.3)</td>
<td>105.7 (13.1)</td>
</tr>
<tr>
<td>Low</td>
<td>20.1 (5.6)</td>
<td>19.9 (5.9)</td>
<td>0.85 (0.13)</td>
<td>13.8 (4.6)</td>
<td>104.9 (12.2)</td>
</tr>
</tbody>
</table>

*p<0.05; **p<0.01; ***p<0.001.
Standard deviation in bracket.
an experiment was used to measure physiological response to practice. Thus, in the further study, a treadmill-based load arrangement and that these guidelines should be put military personnel should receive instruction on proper endurance, therefore, it appears reasonable to suggest that tactically. Given the demonstrated effects on efficiency and arrangement, soldiers generally arrange items idiosyncratically. Interestingly, 30.6% of the soldiers placed the soldiers were placing the heaviest items in the lowest position. Interestingly, 30.6% of the soldiers placed the metal washbowl in layer 6, the highest position. In addition, as there is no regulation of backpack load position. Furthermore, the center of mass within the backpack depends on the arrangement of contained items. In our sample population of military personnel, however, backpack arrangement was determined primarily by convenience or habit. The weight, volume and distribution of the burden all appear to be important variables (Holewijn, 1990; Holewijn and Lotens, 1992). In general, locating the load center of mass as close possible to the body center of mass results in the lowest energy cost when loads are carried on the upper torso as this tends to keep the body upright as in unloaded walking (Knapik et al., 1996, 2004). Furthermore, the center of mass within the backpack depends on the arrangement of contained items. In our sample population of military personnel, however, backpack arrangement was determined primarily by convenience or habit. The results of our survey show that 33.6% of soldiers were placing the heaviest items in the lowest position. Interestingly, 30.6% of the soldiers placed the metal washbowl in layer 6, the highest position. In addition, as there is no regulation of backpack load arrangement, soldiers generally arrange items idiosyncratically. Given the demonstrated effects on efficiency and endurance, therefore, it appears reasonable to suggest that military personnel should receive instruction on proper load arrangement and that these guidelines should be put into practice. Thus, in the further study, a treadmill-based experiment was used to measure physiological response to walking speed, load position and grade conditions in five trained soldiers.

4.2. Effect of load carriage on physiological response

Previous research has found that the energy cost of walking with a backpack increases progressively with increases in load and body mass, walking speed or surface grade (Legg, 1985; Knapik et al., 1996). Laursen et al. (2000) measured VO₂ of individuals while walking either horizontally or up and downhill at an 8% slope under carrying loads in hands. Their study showed that VO₂ rate of walking uphill increased by more than 70% compared with carrying loads horizontally. Navalta et al. (2004) also reported that cardiovascular and metabolic responses were highest at 5% grade compared with level and downhill walking. The results of the present study also show significant increases in VO₂ and HR with increases in walking speed and grade.

In addition, in an experimental study of the effect of load position in a backpack with an internal frame during even walking, Stuempfle et al. (2004) determined that VO₂, HR and MV were significantly lower for the high position. By contrast, although the present investigation also showed that mean VO₂ was lower with the load in the higher position, no significant differences were demonstrated for the level grade. Walking on more severe gradients certainly alters the mechanics of load carriage (Gordon et al., 1983), with additional loads forcing the subjects to lean further forward. Thus, load and gradient are associated with forward postural inclination. Load carriage mainly produces a vertical force on the shoulders to maintain an erect trunk. However, the lateral force of backpack load may act directly on the rear part of the trunk during inclination (Fig. 3). This appears to produce greater restriction of the thorax, particularly while walking up an inclined grade with the load in the high position. In addition, Bobet and Norman (1984) have reported that higher load placement (shoulder level) results in significantly elevated levels of muscle activity (below mid-back).

Carrying heavy loads close to the trunk can affect lung function, however (Bygrave et al., 2004; Legg and Cruz, 2004). In comparison with a loose pack, tight fit has been associated with significantly lower forced vital capacity (FVC) and forced expiratory volume in 1 s (FEV₁). The present investigation has shown that carrying loads in the high position is associated with significantly higher RF and R, particularly when walking on the 6% grade. Knapik et al. (2004) indicated that high load placement may be best for even terrain, while low or mid-back load placement might be preferable over uneven going. Thus, optimum load placement in the backpack should be dependent on terrain characteristics.

The current study has several limitations, however. Only five infantry soldiers were recruited for the experimental stage; however, they had all completed basic training.
In the treadmill experiment, each of the eight subject trials involved walking for at least 10 min until the physiological measurements had stabilized. Furthermore, the present study did not investigate the physiological responses of downhill transport. Thus, future research should clarify, confirm and expand on our findings using experiments involving prolonged marches, uneven terrain and mixed positive and negative grades.

5. Conclusion

In conclusion, load placement is an important determinant of efficient carriage, and it should be an important consideration in both backpack design and subsequent load distribution. Although the general principle pronounced in the popular press (e.g., Howe and Getchell, 1995) is that heavier items should be placed nearer the top of the pack and closer to the body, restriction of lung function must also be taken into account in distribution optimization. As potential interaction between load position and walking grade should be assessed when optimizing spatial distribution of the carried items, operational conditions should ultimately determine arrangement. On level ground, locating heavy items higher in the backpack may improve performance during sustained load carriage. By contrast, lung function appears to become somewhat restricted when carrying loads uphill. Thus, the findings of the present study will have wide-ranging practical implications wherever human physical transportation takes place over uneven walking/working surfaces, with increased efficiencies potentially affecting infantry soldiers, mountain climbers and hikers, and workers involved in manual material handling (MMH) tasks in industry. Instruction in proper load arrangement should be provided to all relevant personnel, with complementary measures instituted to ensure that this education is put into practice.

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References


