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The Physiological Cost of Carrying Light and Heavy Loads

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Summary. Nine subjects walked on a treadmill with load weights equal to 10% and 40% of body weight carried on the back. Although the speed of the treadmill was selected so that the measured oxygen consumption ($\dot{V}O_2$) was the same for both load conditions, the heavier load placed an extra strain on the cardiopulmonary system and was perceived by all subjects as harder work than the lighter load. When the subjects worked at their own pace, walking on a level road or climbing stairs with load weights equal to 10% and 40% of body weight, they compensated for the heavier load by decreasing walking speed or climbing rate. Although the energy costs calculated from walking speed, body and load weight for self-paced walking and the external work of stair climbing were the same for both load conditions, the heavier load was again perceived as harder work. These findings are discussed as they relate to the definition of acceptable load weights.

Key words: Load-carrying – Energy expenditure – Self-paced work – Perceived exertion

There is a limit to the load a man can carry and still be able to function effectively (Marshall, 1950). Traditionally this limit has been defined in absolute terms (Renbourn, 1952) or as a percent of the body weight (Cathcart et al., 1923). Alternatively, an acceptable load weight may be defined as one for which the energy cost is within limits specified by tolerance for work (Simonson, 1971). The application of this approach to the load carrying situation has been made possible by the development of an equation which predicts the energy cost of carrying different load weights at different walking speeds over different terrain (Givoni and Goldman, 1971; Soule and Goldman, 1972; Pandolf et al., 1977; Soule et al., 1978). However, a fundamental assumption in this definition of acceptable load weight is that weight and speed are essentially "interchangeable". In other words, it is assumed that walking or climbing speed can be adjusted to compensate for heavy loads without any penalty. The objective of this study was to examine this assumption.

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Table 1. Physical characteristics of the test subjects

Experiment	Age (year)	Weight (kg)	Height (cm)	$\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$)
walking (n = 9)	29 ± 5	68.7 ± 6.4	175 ± 5	50.1 ± 9.8
stair climbing (n = 9)	28 ± 5	70.7 ± 5.2	176 ± 6	47.7 ± 9.0

Values are means ± SD

Methods

Subjects

The physical characteristics of the male subjects used in this study are shown in Table 1. Five of the subjects participated in both the walking and the stair climbing experiments.

Aerobic Power

Aerobic power ($\dot{V}O_2$ max) was determined using the protocol of Bruce (1971) on a cardio-exerciser treadmill (model 18–54, Quinton Instruments, Seattle, Washington). Oxygen consumption ($\dot{V}O_2$) and ventilatory parameters were measured using the Beckman Metabolic Measurement Cart (Wilmore et al., 1976) and heart rate (f_c) was measured using a Cambridge ECG. A 10-ml blood sample for lactic acid estimation was drawn from an antecubital vein 5 min after cessation of exercise.

Treadmill and Self-paced Walking

Each subject participated in four experimental sessions, randomly assigned.

Session I

Oxygen comsumption and f_c were measured during 30 min of level treadmill walking with a load equivalent to 10% of the individual's body weight carried on the back. The load carriage system used in this and all other sessions was a conventional backpack to which bags of sand were added to the appropriate load weight. The tradmill was adjusted for each individual to a speed which, according to the equation of Pandolf et al. (1977) would give a $\dot{V}O_2$ equal to 35% of their $\dot{V}O_2$ max. After cessation of exercise, the subject was asked to rate the intensity of the work on the perceived exertion scale of Borg (1970).

Session II

This session was the same as Session I except that the load carried was equal to 40% of body weight and the treadmill speed was adjusted so that each individual worked at 35% of his $\dot{V}O_2$ max. (Pandolf et al., 1977).

Session III

Subjects were asked to walk on a level road for 5 km at the fastest rate they could maintain comfortably. The load carried was equal to 10% of body weight. Walking speed was recorded with the aid of a stopwatch and f_c was recorded every 0.5 km with a Siemens Telecust telemetry system. After completing the walk, subjects were asked to rate the work on the perceived exertion scale (Borg, 1970).

Session IV

This session was the same as Session III except that the load carried was equal to 40% of body weight.

Self-paced Stair Climbing

Each subject participated in two experimental sessions, randomly assigned.

Session I

Subjects were asked to ascend and descend a flight of stairs at the fastest rate they could maintain comfortably for five ascents and descents. The stairs consisted of 58 steps with an average height of 19 cm (total vertical height ascended was 11.02 m) interspersed with six small landings. The load carried was equal to 10% of the individual's body weight. Time to ascend the 58 steps was recorded with a stopwatch while the stepping rate was measured between two pressure plates placed on the 39th and 45th steps with an electronic timer (Hunter Electronics, Iowa). Heart rate was measured during ascent from the 39th to the 45th step by a Siemens Telecust telemetry system. At the finish, subjects were asked to rate the work on the perceived exertion scale of Borg (1970).

Session II

The protocol in Session II was identical to that used in Session I except that the load carried was equal to 40% of the body weight.

Lactic Acid Analysis

Blood lactates were analysed using the kit supplied by Sigma Chemical Co., St. Louis, Mo., USA and the enzymatic method described in Sigma Technical Bulletins Nos. 726-UV and 836-UV.

Results

Treadmill Walking

Heart rate, minute ventilation ($\dot{V}_E$), frequency of breathing (f_b) and ratings of perceived exertion (RPE) were all higher with the heavier load than with the lighter load

Table 2. Treadmill walking with light and leavy loads

Parameter measured	Mean ± SD		Significance of difference
	LW/BW = 0.1	LW/BW = 0.4	
f_c (beats · min^{-1})	118 ± 16	128 ± 21	$p < 0.001$
$\dot{V}_E$ (l · min^{-1})	34.0 ± 5.6	37.5 ± 5.2	$p < 0.005$
f_b (breaths · min^{-1})	26.2 ± 6.2	30.9 ± 9.0	$p < 0.025$
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})	19.9 ± 4.5	20.6 ± 4.0	NS
$\dot{V}O_2$ (watts)	477 ± 108	494 ± 96	NS
% $\dot{V}O_2$ max	39.8 ± 3.6	41.3 ± 4.2	NS
RPE	10.4 ± 1.3	12.8 ± 1.3	$p < 0.001$

Ratio of load weight to body weight is abbreviated as LW/BW and rating of perceived exertion as RPE

weight (Table 2). The energy cost of carrying the two loads, expressed as $\dot{V}O_2$ or as % $\dot{V}O_2$ max, was not different. The energy cost (%$\dot{V}O_2$ max) for both loads was greater than the 35% predicted by the equation of Pandolf et al. (1977) assuming a terrain factor of 1.0 for the treadmill.

Self-paced Walking

Although the mean values were not significantly different, eight of the nine subjects had a lower f_c when walking with the lighter load (Table 3). Although subjects reduced their walking speed with the heavy load, the energy cost calculated from body weight, load weight and walking speed using the equation of Pandolf et al. (1977) was not significantly different for the two load conditions. All subjects perceived walking with the heavier load as harder work than walking with the lighter load (RPE).

Table 3. Self-paced walking with light and heavy loads

Parameter measured	Mean ± SD		Significance of difference
	LW/BW = 0.1	LW/BW = 0.4	
f_c (beats · min^{-1})	117 ± 16	131 ± 26	NS
Velocity (m · s^{-1})	1.86 ± 0.17	1.64 ± 0.15	$p < 0.001$
Metabolic rate (watts)	497 ± 48	523 ± 53	NS
% $\dot{V}O_2$ max	42.3 ± 5.5	44.6 ± 6.8	NS
RPE	10.7 ± 0.71	13.2 ± 0.97	$p < 0.001$

Ratio of load weight to body weight is abbreviated as LW/BW and rating of perceived exertion as RPE. Metabolic rate was estimated by the equation of Pandolf et al.

Table 4. A comparison of treadmill and self-paced exercise

Parameter measured	Mean ± SD			
	LW/BW = 0.1		LW/BW = 0.4	
	TM	SP	TM	SP
f_c (beats · min^{-1})	118 ± 16	117 ± 16	128 ± 21	131 ± 26
Velocity (m · s^{-1})	1.66 ± 0.21	1.86 ± 0.17*	1.40 ± 0.20	1.64 ± 0.15*
$\dot{V}O_2$ (watts)	477 ± 108	497 ± 48	494 ± 96	523 ± 53
% $\dot{V}O_2$ max	39.8 ± 3.6	42.3 ± 5.5	41.3 ± 4.2	44.6 ± 6.8
RPE	10.4 ± 1.3	10.7 ± 0.71	12.8 ± 1.3	13.2 ± 0.97

Values for self-paced exercise (SP) which are significantly different ($p < 0.05$) from treadmill exercise (TM) are indicated with an asterisk. Ratio of load weight to body weight is abbreviated as LW/BW and rating of perceived exertion as RPE. Metabolic rate for TM was measured, metabolic rate for SP was estimated by the equation of Pandolf et al.

Self-paced (SP) walking can be compared with treadmill (TM) walking (Table 4). Heart rates for TM and SP exercise were not different for either the 10% or the 40% load weight. Although subjects walked faster when allowed to set their own pace, energy cost and RPE were the same for SP and TM exercise at both load conditions.

Stair Climbing

Although the subjects climbed the stairs at a slower pace with the heavier load, they performed the same amount of external work (calculated for ascent only) when carrying both loads (Table 5). Heart rates and RPE values were higher for the heavy load condition.

Table 5. Self-paced stair climbing with light and heavy loads

Parameter measured	Mean ± SD		Significance of difference
	LW/BW = 0.1	LW/BW = 0.4	
f_c (beats · min^{-1})	145 ± 12	155 ± 7	$p < 0.05$
Ascent time (s)	31.0 ± 4.6	38.0 ± 6.3	$p < 0.001$
External work rate (watts)	275 ± 48	286 ± 49	NS
Climbing speed from 39th to 45th step (m · min^{-1})	26.2 ± 4.8	21.7 ± 3.8	$p < 0.001$
RPE	10.7 ± 1.1	15.0 ± 1.0	$p < 0.001$

Ratio of load weight to body weight is abbreviated as LW/BW and rating of perceived exertion as RPE

Discussion

Walking

The objective of this investigation was to determine whether load weights and walking speeds in the practical range can be "interchanged" as required by the definition of acceptable load weight in terms of mobility and as indicated by the equation of Pandolf et al. (1977). It appears that, although a heavier load can be carried at a slower walking speed without any extra energy cost, there is an extra cost to the cardiopulmonary system and the heavy load condition is perceived by the individual as harder work than the light load condition.

Ekblom and Goldberg (1971) proposed that RPE reflects feelings of strain derived from two sources, the working muscles and the cardiopulmonary system. This model explains why the RPE values in this study were consistently higher for the heavier load in spite of the fact that the $\dot{V}O_2$ was the same. It may safely be assumed that walking with the heavier load involved a greater degree of muscular strain which may also have contributed to the higher f_c (Lind and McNicol, 1968). The higher $\dot{V}_E$ and f_b demonstrated with the heavier load may have been due to a restriction of chest movement (Lippold and Naylor, 1950).

The results for self-paced exercise complement those obtained using the treadmill. Although mean values of f_c were not significantly different, eight of the nine subjects had a higher f_c with the heavier load and all of them perceived it as harder work according to the RPE values. Since the equation of Pandolf et al. (1977) reliably selected combinations of load and weight with the same $\dot{V}O_2$ for the treadmill experiments, it was used to estimate the energy cost of the self-paced exercise. Although the subjects walked slower to accommodate the heavier load, their metabolic rate (Table 3) was the same for the two loads and was in a range equivalent to 40–50% of $\dot{V}O_2$ max. Workloads of 40–50% of $\dot{V}O_2$ max have been categorized by Hughes and Goldman (1970) as "hard work" for easonably fit young men.

A comparison of treadmill and self-paced exercise (Table 4) indicates that, at each load weight, a lower walking speed on the treadmill elicited the same $\dot{V}O_2$, f_c and RPE as self-paced walking on the road surface. This implies that the terrain factor assigned to the treadmill used in this study was higher than the value of 1.0 used by Pandolf et al. (1977) for their treadmill. This would explain why the measured energy cost of treadmill walking (Table 2) was higher than the 35% of $\dot{V}O_2$ max calculated using the equation of Pandolf et al. (1977).

Stair Climbing

The experimental sessions in which subjects climbed stairs were included to extend observations made with self-paced walking. Stair climbing was different from the other conditions in that neither steady-state conditions for f_c were obtained nor were energy costs estimated. However, as occurred with self-paced walking, subjects adjusted their climbing speed to accomodate the heavier load (Table 5). Although the external work performed in ascent was the same for both load conditions, f_c and RPE were higher with the heavier load.

Adjusting the energy cost of load carrying by manipulating either the load weight or the walking speed has obvious application to experiments in which subjects of widely differing fitness levels must be assigned work of the same intensity relative to their $\dot{V}O_2$ max. This study confirms that the equation of Pandolf et al. (1977) can reliably select combinations of load and speed with the same energy cost as measured by $\dot{V}O_2$. On the other hand, f_c must be used with caution as a measure of energy expenditure for subjects walking with different load weights.

If load weights equal to 10–40% of body weight can be considered typical of those carried by the military and by civilian backpackers, then the definition of acceptable load weight in terms of mobility, using the equation of Pandolf et al. (1977) to calculate energy cost, seems to be feasible. The extra strain placed on the cardiopulmonary system by the heavier load is not excessive and the higher RPE values do not seem to affect self-pacing.

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References

Borg, G.: Perceived exertion as an indicator of somatic stress. Scand J. Rehab. Med. **2,** 92–98 (1970)

Bruce, R. A.: Exercise testing of patients with coronary heart disease. Principles and normal standards for evaluation. Ann. Clin. Res. **3,** 323–332 (1971)

Cathcart, E. P., Richardson, D. T., Campbell, W. C.: The maximum load to be carried by the soldier. J. R. Army Med. Corps **40,** 435–443, **41,** 12–24, 87–98, 161–178 (1973)

Ekblom, B., Goldberg, A. N.: The influence of physical training and other factors on the subjective rating of perceived exertion. Acta Physiol. Scand. **83,** 399–406 (1971)

Givoni, B., Goldman, R. F.: Predicting metabolic energy cost. J. Appl. Physiol **30,** 429–433 (1971)

Hughes, A. L., Goldman, R. F.: Energy cost of hard work. J. Appl. Physiol. **29,** 570–572 (1970)

Lind, A. R., McNicol, G. W.: Cardiovascular responses to holding and carrying weights by hand and shoulder harness. J. Appl. Physiol. **25,** 261–267 (1968)

Lippold, O. C. J., Naylor, P. F. D.: The design of load carriage equipment for the soldier in battle order. A.O.R.G. Rep. 11/50. London: War Office 1950

Marshall, S. L. A.: The soldier's load and the mobility of a nation. Washington: The Combat Forces Press 1950

Pandolf, K. B., Givoni, B., Goldman, R. F.: Predicting energy expenditure with loads while standing or walking very slowly. J. Appl. Physiol. **43,** 577–581 (1977)

Renbourn, E. T.: The knapsack and pack. An historical physiological study with particular reference to the British soldier. J. R. Army Med. Corps **100,** 1–15, 77–88, 193–200 (1952)

Soule, R. G., Goldman, R. F.: Terrain coefficients for energy cost prediction. J. Appl. Physiol. **32,** 706–708 (1972)

Soule, R. G., Pandolf, K. B., Goldman, R. F.: Energy expenditure of heavy load carriage. Ergonomics **21,** 373–381 (1978)

Simonson, E.: Recovery and fatigue. In: Physiology of Work Capacity and Fatigue, ed. E. Simonson, pp. 440–458. Springfield: Thomas 1971

Wilmore, J. H., Davis, J. A., Norton, A. C.: An automated system for assessing metabolic and respiratory function during exercise. J. Appl. Physiol. **40,** 619–624 (1976)

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