Ergonomics of human land locomotion with load carriage

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Chapter 3

Ergonomic effects of load carriage on the upper and lower back on metabolic energy cost of walking

3-1. Introduction

Energy expenditure during bilateral locomotion in humans with and without load in a variety of occupations has been broadly investigated (e.g. Knapik et al. 2004). There have been two completely opposite opinions with regard to the metabolic energy cost of walking during load carriage. One of them is that the energy expenditure during walking increases linearly with the weight of the carrying load (Soule and Goldman 1969; Gordon et al. 1983; Francis and Hoobler 1986). In contrast, other studies have found that the energy expenditure did not necessarily increase in proportion to the weight of the load (Maloiy et al. 1986; Charteris et al. 1989a, 1989b; Heglund et al. 1995; Stuempfle et al. 2004; Bastien et al. 2005a). For example, it was interesting to note that the oxygen consumption did not increase when the load was carried on the head if the load was less than 20% of the subject’s body mass (Charteris et al. 1989a; Heglund et al. 1995). Those authors termed such a phenomenon as ‘*free-ride*’. Bastien et al. (2005a) recently found that a typical Nepalese porter could carry an extraordinary load of up to 60% of the body mass without a significant increase in energy expenditure. These previous studies suggested the importance of the position of the load, and the walking speed closed to the ‘economical speed (ES)’ during load carriage (Bastien et al. 2005b).

The chapter 1 proposed that such a phenomenon could be due to an interaction between the rotative torque around the center of body mass (T) treated as a positive effect and a concomitant excessive burden on the lower extremities treated as a negative effect (Chapter 1). The T can be defined as follows:

$$F = \mathrm{AB} \times \text{Load weight},$$

where E is the T and AB is a radius of rotation (Chapter 1).

Thus, if the load position was located on the upper or lower back, then it could be possible to adjust the T without changing the load weight. If the possible mechanism to explain the *free-ride* is an interaction between T and excessive burden on the lower extremities, then the higher the position of the load, the lower the energy expenditure, because the T will contribute to the forward propulsion (defined as horizontal acceleration of the body) during walking. To test such a mechanism, the first purpose of this study was to examine the effects of load carriage on the lower and upper back at various speeds on the metabolic energy cost of walking. It was hypothesized that the metabolic energy cost of walking was lesser when the load was carried on the upper back of the subjects.

The most important factor of the energy-conserving mechanism during walking has been explained by the transfer efficiency between kinetic energy (E_k) and gravitational potential energy (E_p) (Cavagna et al. 1963). Minetti et al. (1995) reported that the transfer efficiency between E_k and E_p became maximal at around 70 ~ 80 m/min during walking, and it decreased gradually when walking at slower and/or faster than that speed. Thus, it is expected that there exists a specific speed that can minimize the metabolic energy cost of walking. The walking speed corresponding to the minimum energy cost per unit distance has been called ES or optimal speed (Falola et al. 2000; Bastien et al. 2005b). Factors affecting ES seemed to be dependent on the leg length and gravity (Griffin et al. 1999), however, as Bastien et al. (2005b) discussed, little has been unveiled in the relationship between load carriage and the ES. If the T contributes to the forward propulsion during walking, then the ES will also increase during walking with load, in particular, on the upper back. Thus, the second purpose of this study was to examine the effects of load carriage on the ES. It was hypothesized that the ES would be greater during walking with load on the upper back than carrying on the lower back and/or without load.

The ES may be estimated by the physical characteristics using 'Froude number' system (Donelan and Kram 1997). The Froude number system is calculated with leg length, and it is expected that leg length and body height be correlated, suggesting that the body height is expected to correlate to the ES. The third purpose of this study was to examine how to estimate the ES when the load was carried on a hypothesis that the body height will be the factor for estimating the ES.

3-2. Methods

3-2-1. Subjects

Fourteen healthy young male (age 20.9±0.8 years old; height 170.6±6.2 cm; body mass 59.6±3.6 kg) volunteered for this study. These subjects were recruited based on their similar body mass in order to equalize the physical stress imposed by the load. Informed consent from each subject and the approval from the ethical review committee were obtained. One subject was excluded from a series of measurements due to a health issue.

3-2-2. Measurements

Walking tests were performed on a motor-driven treadmill (Biomill BL-1000, S & ME, Tokyo). To become accustomed to treadmill walking wearing a gas collection mask, each subject performed at least two preliminary trials on the same treadmill at several speeds. The speeds selected 30 ~ 120 with increments of 10 m/min, meaning that previously employed walking speeds were covered in the present study. The subjects performed 5-min trials at each speed with and without load on the back. The subjects wore underwear, shirts, socks, gym shorts and lightweight training shoes. The measurements were performed once a day on each subject. The load to be carried consisted of a sand bag on a net weight of 2.0 kg position-adjustable lightweight aluminum frame (Carry-Bone EBB003, Evernew, Tokyo) with an elastic belt (Fig. 1). The total weight of the load was set at 15% of each subject's body mass. The sand bag was placed at the upper (U) and lower (L) end of the frame. The control condition (C) was prepared with no load and the order of three load conditions (U, L and C) was randomized. Each subject chose a preferred step frequency at each condition.

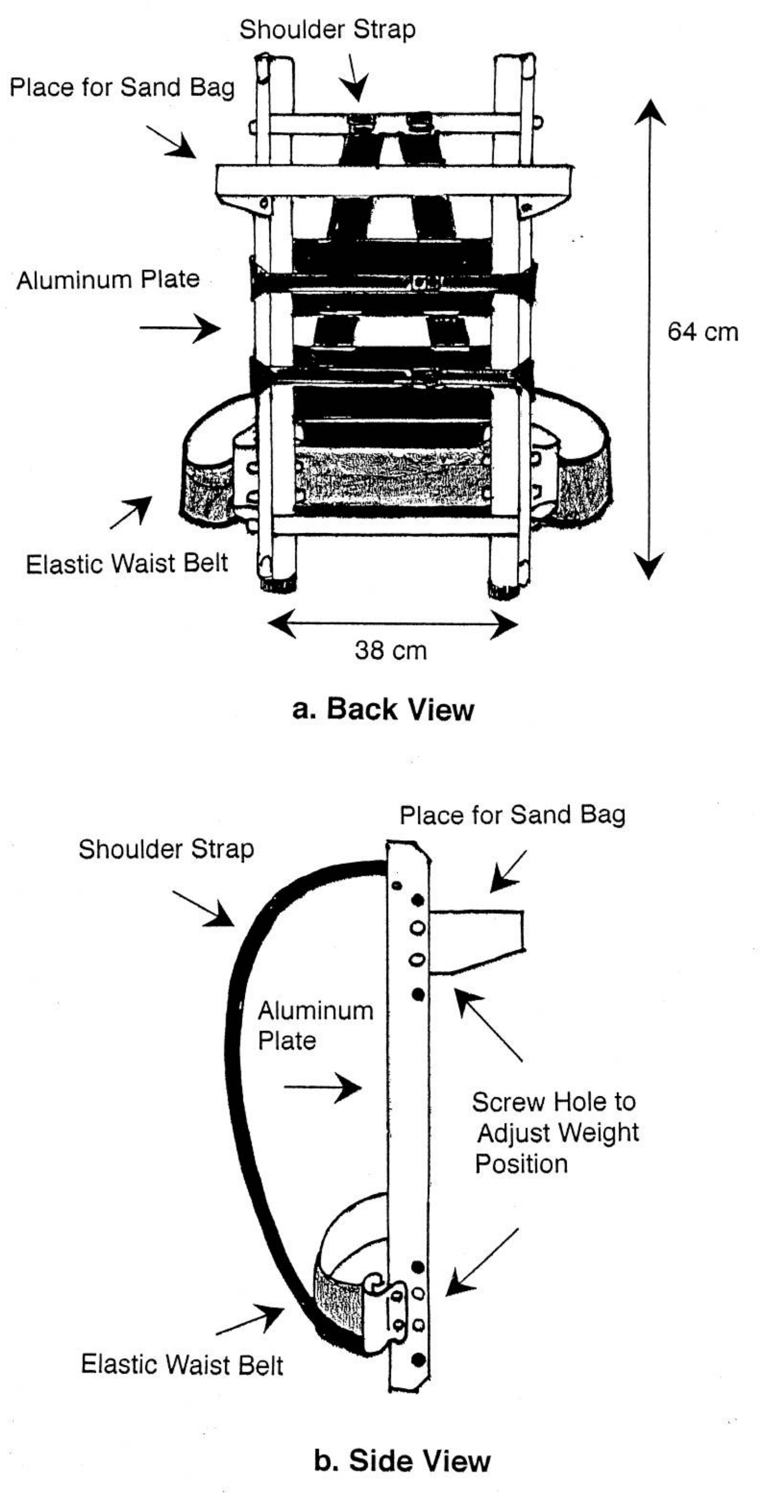

Fig. 1
Position-adjustable aluminium frame. Back view (a) and side view (b).

Breath-by-breath oxygen consumption ($\dot{V}O_2$ in ml/kg/min) was measured with a gas analyzer (AE-300S, Minato Co. Ltd, Osaka), which was calibrated before the tests with room air and reference gases of known concentrations. A single sample with an average 2-min $\dot{V}O_2$ value at each walking speed was calculated to obtain the values of energy cost of walking per unit distance (C_w in ml/body mass+Load/meter). The C_w was determined from the ratio of the steady-state $\dot{V}O_2$ to the walking speed (v; m/min):

$$C_w = \dot{V}O_2/v$$

As shown by previous studies (Zamparo et al. 1992; Bastien et al. 2005b), the relationship between v and C_w can be approximated by a U-shaped quadratic equation, meaning that there exists a specific walking speed corresponding to the minimum energy cost per unit distance. The relationship between v and C_w can be mathematically described as the following equation:

$$C_w = \mathrm{a}v^2 + \mathrm{b}v + \mathrm{c}$$

where a, b and c are the constants determined by the least squares with the actually observed C_w values at each v. Therefore, a differential equation of the original quadratic equation of each experimental condition could be described as follows:

$$C_w' = 2\mathrm{a}v + \mathrm{b}$$

The ES was then determined at the speed when C_w' equals zero. That is, the ES could be observed as follows:

$$\mathrm{ES} = -\mathrm{b}/2\mathrm{a}$$

The estimated ES can be obtained using the ‘Froude number’, which has been used to predict the biomechanics of legged locomotion over a wide range of body size, gravity and speed (Donelan and Kram, 1997). For human walking, the inertial force commonly employed is the centripetal force. The Froude number has been considered to be a dimensionless ratio of inertial force to the gravitational force, and is defined as follows:

$$\text{Froude number} = (\text{body mass} \times v^2/l)/(\text{body mass} \times g)$$

where l is the leg length, defined from the *trocanter major* to the ground, and g is the gravitational acceleration (9.81 m/sec^2). Thus, this equation can be shortened as follows:

$$\text{Froude number} = v^2/9.81 \times l$$

The walking speed at which the highest exchange between E_p and E_k occurred when the Froude number was 0.25 (Minetti 2001). The estimated ES was then obtained as follows;

$$\text{estimated ES} = 1.566 \times l^{\,0.5}$$

3-2-3. Statistical analysis

C_w values of each trial as function of speed were interpolated by a quadratic equation as previously done by Zamparo et al. (1992). Differences in the observed C_w values at each walking speed were compared by one-way analysis of variance. When the significant F values were present, Fisher's least squares test was applied as the post hoc test. The relationships between body height and ES in each condition were evaluated by a simple regression analysis. A comparison between the ES obtained from the C condition and the estimated ES was evaluated using a t-test. The statistical significance was established at the 0.05 probability level.

3-3. Results

The statistical results are summarized in Table 1. Figure 2 shows the relationship between the walking speed and C_w for the three conditions. The regression line for the average data did not seem to be an ideal quadratic shape, because the C_w values obtained from four subjects always appeared to be a “collapsed U-shape” in each condition. However, the correlation coefficients of the quadratic relationship between C_w and walking speed ranged from 0.93 to 0.99 in all subjects. At 60 ~ 80 m/min, the C_w values obtained from L and U conditions were significantly lower than those obtained from the C condition. This trend was observed until 60 m/min in the L condition and 100 m/min in the U condition (Fig. 2). The C_w values were significantly lower in the U condition than in the L condition at 60 ~ 80 m/min.

The ESs for U, L and C conditions were 77.8±3.8, 78.1±2.8 and 81.4±3.4 m/min, respectively. A significant difference for the ES was observed between C and other conditions. Compared to the C condition, the percent decreases in the ESs were 4.4±2.9 and 4.1±3.4% for the U and L conditions, respectively. There was a significant linear relationship between the body height and ES obtained during the U and C conditions (Figs. 3a and 3c), but not during the L condition (Fig. 3b). Significant relationships were also observed between the ES obtained during the C condition and estimated ES (Fig. 4), although the average estimated ES (88.4±2.9 m/min) was significantly greater than ES obtained during the C condition.

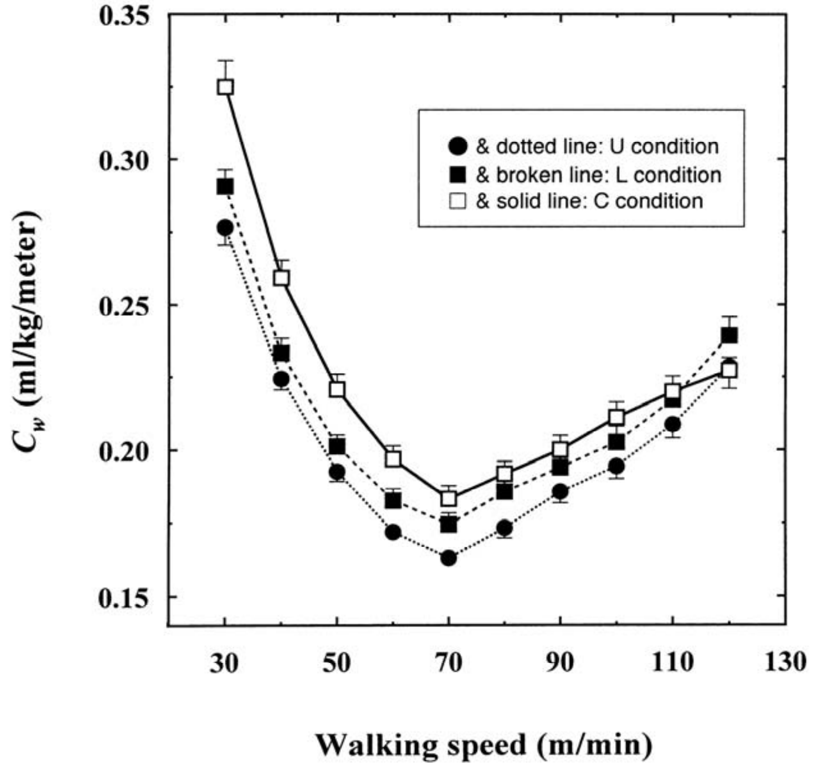

Fig. 2
Metabolic energy cost of walking (C_w) as a function of walking speed. Statistically significant results are summarized in Table 1.

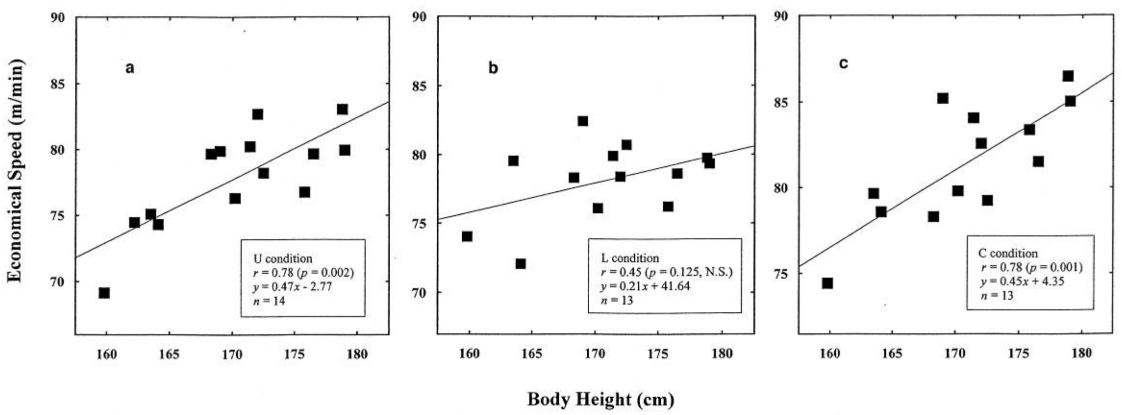

Fig. 3
Relationships between body height and the individual economical walking speed. Each panel represents the U (a), L (b) and C (c) conditions, respectively.

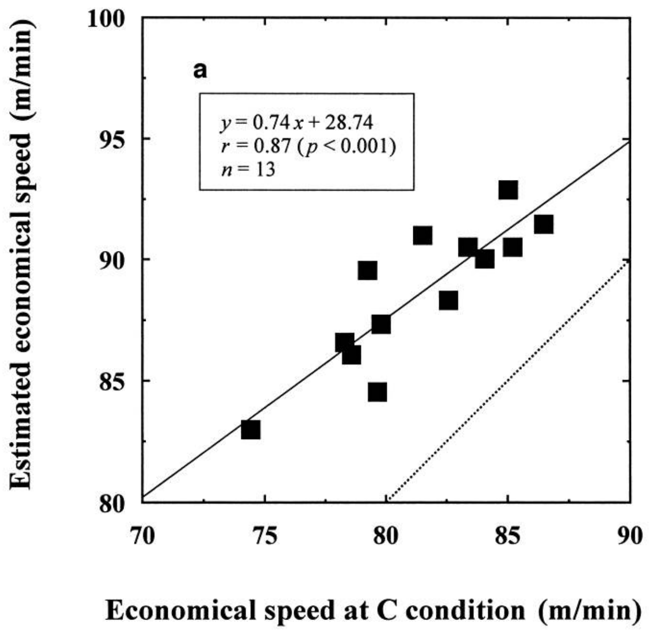

Fig. 4
Relationship of the economical speeds obtained during the C condition and Froude number system. Dotted line indicated identity line.

Table 1 Summary of statistically significant results.

	Speed (m/min)	30	40	50	60	70	80	90	100	110	120
C_w	L Condition	*	*	*	*#	#	#	—	—	—	—
	U Condition	*	*	*	*#	*#	*#	*	*	—	—

* Significantly different from the control condition; # significantly different between 'lower' and 'upper' conditions; — not significantly different from other conditions.

3-4. Discussion

We examined the effects of load position on the energy cost of walking per unit distance as a function of speed. In support of our first hypothesis, the result of the present study was primarily characterized by the finding that significantly lower C_w values were observed in the U condition than in the L condition at 60 ~ 80 m/min (Fig. 2 and Table 1). These results are partly consistent with that of Stuempfle et al. (2004). The result of the present study also confirmed that lower C_w values were observed in the loaded conditions than in the unloaded condition (chapter 1).

Previous studies have examined the metabolic responses for different carrying methods and the weight of the load carriage (Soule and Goldman 1969; Kinoshita 1985; Francis and Hoobler 1986; Hong and Cheung 2003; Stuempfle et al. 2004). As reported by Cavagna et al. (1963), the time courses of the gravitational potential energy (E_p) and the kinetic energy (E_k) were almost out of phase during walking, and it was assumed that the most significant factor affecting the energy-conserving mechanism during walking was explained by the pendulum-like energy transfer efficiency between E_p and E_k. In the present study, both the total mass and height of the center of mass in the U and L conditions increased compared to that of the C condition because the load was carried on the back, indicating that the E_p must have also increased in the U and L conditions than in the C condition. It goes without saying that the increased E_p could be larger in the U than in the L condition, because the load was located relatively higher in the U condition than in the L condition. The difference between these conditions was expected to yield a difference in the production of the T (chapter 1). The increased E_p could cause an increase in E_k if the transfer efficiency between E_p and E_k did not alter regardless of the load carriage. Indeed, it was well known that the highest transfer efficiency between E_p and E_k was observed at around 60 ~ 80 m/min in adult men (Minetti et al. 1995; Willems et al.

1995), assuming that the increased E_p could, to a greater or lesser extent, have contributed to an increase in E_k in our study. In other words, the increased T would contribute to an increase in E_k in the U condition than in the L condition, and it would save energy expenditure during walking with load on the upper back at around 60 ~ 80 m/min.

It was recently reported that the recoil of the elastic energy acted as one of the energy-conserving mechanisms (Fukunaga et al. 2001; Lichtwark and Wilson 2006; Orendurff et al. 2005; Sasaki and Neptune 2006). Our first hypothesis was that the vertical load as an excessive burden could induce a negative effect for the forward propulsion due to the requirement of more energy expenditure by the lower leg muscles. However, if the recoil of the elastic energy could be counted on as one of the energy-conserving mechanisms during walking regardless of the walking speed, then the vertical load might also contribute as one of the energy-conserving factors during walking by way of such physiological mechanisms.

The ES without load obtained from the C condition was 81.4±3.4 m/min, and was consistent with the result of Bastien et al. (2005b). The results of the present study were secondly characterized by the fact that the ES was significantly lower by around 4% when the load was carried on the back. Thus, the second hypothesis of this study was rejected. When obtaining the ES from the quadratic relationship between walking speed and C_w values (Fig. 2), the C_w values were significantly lower in the U and L conditions at slower speeds than in the C condition, but not at faster speeds. It resulted in a leftward shift of the U-shaped curved line for the relationship between C_w values and walking speed. As discussed before, the experimental setup of this study was especially characterized by the fact that the difference of the load position could induce an experimental manipulation of the T without a difference of the vertical load on the legs (chapter 1). There were no significant differences in the ES between U and L conditions, although the ES obtained from the C condition was significantly higher than that obtained from other conditions. It was considered that the ES obtained from each condition ranged around 80 m/min, meaning that the change in the ES by the load carriage could be practically negligible.

It was also interesting to note that the ES was significantly correlated with body height in the U and C conditions (Figs. 3a and 3c), but not in the L condition (Fig. 3b). Thus, the third hypothesis of this study was partly supported. The present study suggests that the ES was influenced by the body height. This was a logical outcome because the body height and leg length were correlated ($r = 0.93$, $p < 0.05$).

Figure 4 further showed a significant relationship between the ESs obtained from the C condition and estimated ES. There has been no information available for a conventional estimation of the ES. The Froude number system could be a potential tool for estimating the ES. A conventional estimation of the individual ES will be useful for reducing the early onset of fatigue. However, it was pointed out that the ES obtained from estimation by the Froude number system was considerably higher than that obtained from the control condition. The relationship of the ES obtained from the control condition and estimation resulted in predictions considerably higher (Fig. 4). Note that the Froude number at 0.25 might not be appropriate to estimate the ES at 1 times gravity. If the average leg length (0.901 m) and ES (1.357 m/s), which were observed in our study, were used to calculate the Froude number, then the average value of the Froude number became 0.208. This lower Froude number was further supported by the results of Bastien et al. (2005b). Based on the dynamic similarity hypothesis, previous studies neglected the subjects' muscle strength of the lower extremities and/or the difference of the body dimension in relation to the racial difference when assessing the Froude number (Donelan and Kram 1997; Griffin et al. 1999; Minetti 2001). The Froude number system derived from the dynamic similarity hypothesis was established based on the simulated reduced gravity environment.

That is, it is assumed that the relative importance of the muscle strength necessary to fight against the gravity could be smaller in the simulated reduced gravity environment than that on the earth. A conventional estimation for the ES was also possible in the U condition (Fig. 3c), but was not in the L condition (Fig. 3b). These results suggest that the estimation of the ES in the simulated added gravity environment needs some attention.

The carrying method with load on the back and in front of the body is called ‘doublepack system’ (Kinoshita 1985). Here, it is important to note that the *free-ride* phenomenon requires a particular condition that the load weight was less than 20% of the body mass carried on the head or on the back (chapter 1-3; Charteris et al. 1989a). If the doublepack system is employed during walking with load, the forward propulsion due to the T will be cancelled. However, the body posture and gait pattern for the doublepack system were quite similar to those for the normal walking (Kinoshita 1985), suggesting that the doublepack system, rather than the normal backpack system, can be recommended for carrying the load if the load weight exceeds more than 20% of the body mass. That will be also available for reducing early onset of fatigue. For another practical application of the result of the present study for occupational safety and/or military purposes, the heavier load should be located on the upper back during walking, being associated with slower walking speeds at around 60 ~ 80 m/min. In particular, this study showed possible information to estimate the individual’s ES based on the body height and/or leg length. Information about the alteration of the energy expenditure by the load position could be available for reducing early onset of fatigue during working.

3-5. Conclusion

Significantly lower values of the energy cost of walking per unit distance were observed when the load was carried on the upper back than on the lower back at 60 ~ 80 m/min. A significant decrease in the ES was observed when the load was carried on the back regardless of the location of the load. The observed ES was significantly correlated with the simulated ES obtained by the Froude number system, however, this resulted in overestimates of ES. The present results indicated that the load should be carried on the upper back at speeds of 60 ~ 80 m/min to reduce physiological stress.