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# Ergonomics of human land locomotion with load carriage

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Chapter 2

# Ergonomic effects of load carriage on energy cost of gradient walk

## 2-1. Introduction

Recent studies revealed that the energy expenditure during walking with load does not always increase linearly as a function of the carrying weight (chapter 1; Stuempfle et al. 2004). Charteris et al. (1989a, 1989b) and Maloiy et al. (1986) have proposed a '*free-ride*' hypothesis that the energy expenditure during walking with load carried on the head does not necessarily increase in African women if the load is less than 20% of their body mass. Recently, a similar phenomenon to the *free-ride* was also found in Nepalese porters (Bastien et al. 2005a, 2005b).

In relation to such an energy-saving phenomenon during walking with load, it was worth noting that the load was always carried on the upper part of the body, such as on the head (Bastien et al. 2005a; Charteris et al. 1989a, 1989b; Maloiy et al. 1986) and on the back (chapter 1; Stuempfle et al. 2004). Another point in common in previous studies was the fact that such a phenomenon was observed at slower walking speeds only. Thus, the chapter 1 pointed out that a similar phenomenon to the *free-ride* could be found only when the load was carried on the back at slower walking speeds, and further suggested that an interaction between the rotative torque functioning around the center of the body mass (T) and an excessive burden on the lower leg muscles comprehensively affected the energetics of walking (Chapter 1).

If a similar phenomenon to the *free-ride* can be found not only during level walking but also during gradient walking, then the practical benefit will be applicable to a wider range of occupational and leisure tasks. Indeed, as recently discussed by Bastien et al. (2005b), the argument with regard to the energetics of gradient walking with load is still open. We hereby hypothesized that a phenomenon similar to the *free-ride* could be found not only during level walking but also during gradient walking, because the possible explanation for a similar phenomenon to the *free-ride* proposed by the chapter 1 appeared

to be independent of the gradient of the terrain. The first purpose of this study was to examine whether a similar phenomenon to the *free-ride* would be found not only during level walking but also during gradient walking.

It has been reported that there exists a specific walking speed that can minimize the metabolic energy cost of walking per unit distance ($C_w$: ml/kg/meter) in each person (Saibene and Minetti, 2003). The walking speed corresponding to the minimum energy cost per unit distance has been called the economical speed (ES) or optimal speed (Falola et al. 2000). With reference to the ergonomic implications, considerations of ES seems to be significant for an establishment of workers' safety and for a reduction of workers' physical stress, however, as far as we know, no information has been available with respect to the alteration of the ES between level and gradient walking with load. It was interesting to note that the ES was significantly decreased if the load was carried on the back on a flat terrain (Falola et al. 2000), but was not decreased in another study (Bastien et al. 2005b). In a previous study the energy cost of walking reached minimum at a –10% gradient (Margaria 1938). Minetti et al. (2003) indicated that the ES decreased as a function of positive gradient, but the load was not carried in those previous studies.

Here, it was also hypothesized that the ES obtained from each gradient would be slower in the load condition than in the no load condition. However, it was assumed that the percentage decrease in the ES during level and gradient walking with load would not be great so much when compared to the '15%' load of the subjects' body mass, if a similar phenomenon to the *free-ride* appeared not only during level walking but also during gradient walking with load. Therefore, the second purpose of this study was to examine the effects of load carriage on the ES during level and gradient walking.

## 2-2. Methods

### 2-2-1. Subjects

Ten healthy male subjects participated in this study. The physical characteristics of those subjects were 169.9±3.9 cm and 60.5±3.0 kg for body height and body mass, respectively. The average age of the subjects was 20.8±1.1 years old. After being informed of the purpose and possible risks of this study, a written informed consent was obtained from each subject. An approval from the ethical review committee was also obtained for all procedures.

### 2-2-2. Experimental set-up and measurements

All exercise tests were performed on a motor-driven treadmill (Biomill BL-1000, S & ME, Tokyo). To become accustomed to the treadmill walking wearing a gas collection mask (AMA-102, Minato Medical Science Co. Ltd., Osaka) with and without load, each subject performed at least two preliminary trials on the same treadmill at several speeds. The walking speeds were set at 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 m/min, meaning that the employed walking speeds covered with those of the previous studies (Chapter 1). As suggested by Minetti et al. (1993), the mechanical work done by the leg muscles consisted of both positive and negative muscular work up to a 15% gradient, however, the $C_w$ expressed per unit of vertical distance seemed to be non-linear in the 5-15% gradient zone. It was assumed that either the positive or negative work was no longer functional at more than ±10% gradient. Thus, the treadmill gradient was set at 0% (level), +5% (uphill) and –5% (downhill) due to a consideration of the practical application for daily activities in this study.

In all conditions, each subject walked on the treadmill for 5-min with a freely chosen

step frequency at each walking speed with and without load. The subjects wore underwear, shirts, socks, gym shorts and lightweight training shoes. The measurements were performed once a day on each subject. The load consisted of a sand bag on a lightweight aluminum frame (Carry Bone BB-003, Evernew, Tokyo) with an elastic belt located around the waist. The net weight of the aluminum frame was 2.0 kg. The total weight of the load was set at 15% of each subject's body mass. The sand bag was placed on the upper part of the frame.

Breath-by-breath oxygen consumption ($\dot{V}O_2$; ml/kg/min) was measured with a gas analyzer (AE-300S, Minato Medical Science Co. Ltd., Osaka), which was calibrated before each measurement with room air and reference gases of known concentrations. A single sample with an average final 2-min $\dot{V}O_2$ value at each speed was calculated to obtain the values of energy cost of walking per unit distance ($C_w$; ml/BM+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):

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

The relationship between walking speed and $C_w$ can be approximated with a U-shaped quadratic equation (Chapter 1; Zamparo et al. 1992). Thus, it was apparent that there existed 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:

$$C_w(v) = a\,v^2 + b\,v + c \qquad (eq.\ 1)$$

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

$$C_w'(v) = 2av + b \qquad (eq.\ 2)$$

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

$$ES = -b/2a \qquad (eq.\ 3)$$

**2-2-3. Statistical analysis**

A 2×3 repeated measures analysis of variance with two within-subject effects was used to test for the main effects of load (2 levels) and gradient (3 levels) condition on the dependent variables. A Ryan's multiple comparison as a post-hoc test was applied to the appropriate data set to establish the significant mean differences (Hsu 1996). The statistical significance was established at the 0.05 probability level.

## 2-3. Results

### 2-3-1. Effects of load and gradient on $C_w$

Figure 1 shows a quadratic relationship between the walking speed and $C_w$ values obtained on each terrain. A significant interaction effect between load and gradient condition was found for $C_w$ values at 40, 50 and 60 m/min. A non-significant interaction effect between load and gradient condition was found for $C_w$ values at 30 m/min only. A post-hoc test revealed that the $C_w$ values were significantly lower when the load was carried on the back only at slower speeds during level walking (Table 1 and Fig. 1). Such a trend was also found at 70 m/min ($p = 0.084$), but not significant.

### 2-3-2. Effects of load and gradient on ES

The ESs without load were 82.1±2.7, 78.3±3.8 and 84.7±2.9 m/min for level, uphill and downhill walking, respectively. The ESs with load were 78.3±2.6, 75.1±4.7 and 83.7±3.0 m/min for level, uphill and downhill walking, respectively. Non-significant interaction effect between load and gradient was observed in a multiple comparison of the ES ($F = 3.19$, $p > 0.05$). A post hoc test also revealed that significant differences were observed between load and no load conditions in each gradient. Significant gradient differences were also observed in the load and no load conditions ($p < 0.05$, Fig. 2).

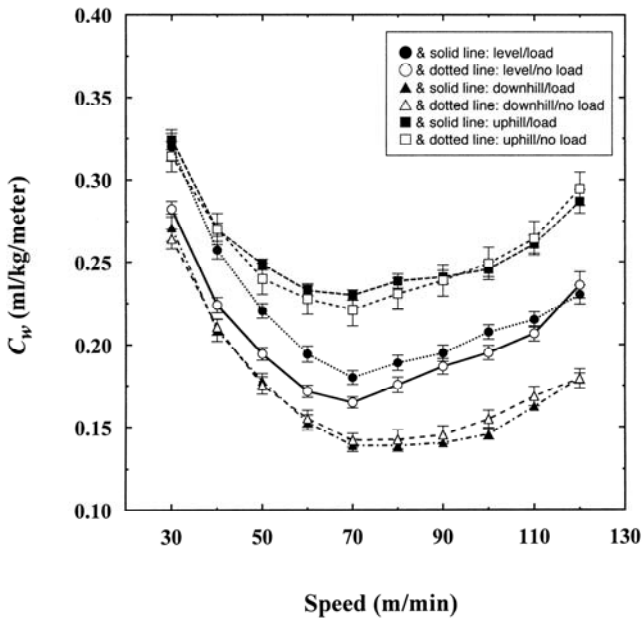


Fig. 1
Energy cost of walking ($C_w$) as a function of walking speed. □and ■ represented load and unload conditions at an uphill terrain. ○ and ● represented load and unload conditions at a level terrain, respectively. △ and ▲ represented load and unload conditions at a downhill terrain, respectively. Statistically significant results are summarized in Table 1. Values are mean and standard error.

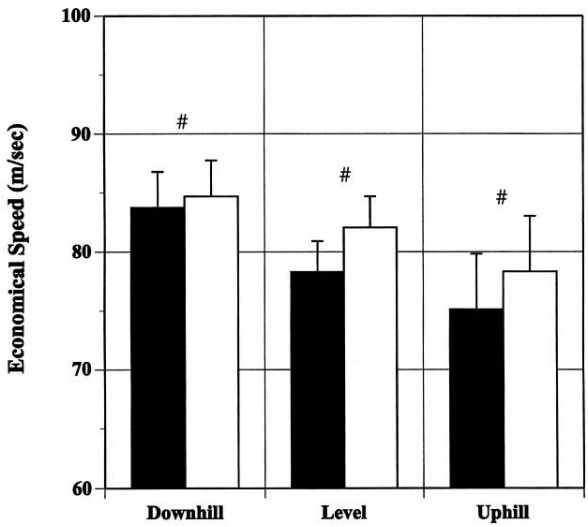


Fig. 2
Comparisons of economical walking speed (ES). Significant differences between load and no load conditions were observed at each gradient. Significant gradient differences were also observed in both conditions. Values are mean and standard deviation.

Table 1

Summary of statistically significant results.

| | Speed (m/min) | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_w$ | Level | * | *# | *# | *# | * | — | — | — | — | — |
| | Uphill | — | — | — | — | — | — | — | — | — | — |
| | Downhill | — | — | — | — | — | — | — | — | — | — |

* Significantly different between load and unload conditions; — not significantly different from others.
# interaction of load and gradient effects was significant.

## 2-4. Discussion

### 2-4-1. Effects of load carriage on $C_w$

This study was particularly characterized by the fact that a similar phenomenon to the *free-ride* could be observed during level walking at slower speeds only, but not during gradient walking (Fig. 1 and Table 1). That is, our first hypothesis was rejected.

Little information has been available with respect to a similar phenomenon to the *free-ride* during gradient walking. The energy-saving mechanism during level walking has been mainly explained by the transfer efficiency between gravitational potential energy ($E_p$) and kinetic energy ($E_k$) (Cavagna et al. 1963; Saibene 1990; Saibene and Minetti 2003). It was interesting to note that the results of the present study showed the ergonomic effects of load were not substantially identical to the energy expenditure during walking obtained from each gradient (Table 1, Fig. 1).

In fact, the fascicles and tendon of gastrocnemius medialis were fully stretched during walking even at slower walking speeds (Fukunaga et al. 2001). The recoiled elastic energy was absolutely released during push-off, even though there was very little change in the function of the muscle fascicles at different gradients or speeds (Lichtwark and Wilson 2006), despite an existence of the differences in the required external work. It is important to note that those previous studies revealed a similar degree of the released elastic energy contributed to the energetics of walking regardless of the gradient. That is, those previous studies could explain a potential mechanism of a fact that a similar phenomenon to the *free-ride* was observed only at slower walking speeds on a flat terrain cannot be explained by the utilization of the released elastic energy.

For the uphill walking, the positive work done by the leg muscles could be much more dominant than that during level walking (Minetti et al. 1993), suggesting that the

ergonomic benefit derived from the T while carrying loads could be canceled by the increased excessive burden on the leg muscles during uphill walking. It is assumed that such an imbalance between the positive and negative effect on the energetics of walking would be more apparent when the load was carried on the back. For downhill walking, the negative work done by the leg muscles could be more dominant during downhill walking than level walking (Minetti et al. 2002), and it was assumed that such a trend would be greater when the load was carried on the back due to the assisted torque derived from load carriage. The energy requirement for the positive muscular work was about three-fold greater than that for the negative muscular work (Aura and Komi 1986), suggesting that the $C_w$ values obtained from downhill walking with load were expected to be less than those obtained from downhill walking without load. In fact, a similar observation to our finding can be found during pushing a wheelchair on the downhill gradient in nursing. Brubaker et al. (1986) reported that a nurse needed to push the wheelchair to go forward while braking against gravity with his or her hands and legs. Judging from those considerations, a similar phenomenon to the *free-ride* could not be observed during gradient walking, but the biomechanical and physiological mechanisms behind the phenomenon would be different between uphill and downhill walking.

### 2-4-2. Effects of load carriage on ES

In support of our second hypothesis, the ES was significantly lower when the load was carried on the back (Fig. 3). The percent decrease in the ES during level and uphill walking was about 4% in a comparison between load and no load conditions, being consistent with a previous study (Falola et al. 2000), while conflicting with another study (Bastien et al. 2005b). These conflicting results could be dependent on how ES is calculated. As discussed by Bastien et al. (2005b), the constant '*c*' in the *eq.* 1 is the

determining factor for the ES when calculating based on the net $\dot{V}O_2$. The constant '*c*' reflects a *y*-intercept of the $C_w$-*v* relationship, meaning a subject standing on the treadmill. In contrast, the ES obtained in this study was dependent only on the constants '*a*' and '*b*' (*eqs.* 2 and 3). Here, the constant '*c*' seemed to be independent of the ES. However, all constants are obtained from least square regression analysis, indicating that the constant '*c*' is affecting the determination of the constants '*a*' and '*b*'. In other words, the constant '*c*' secondary affected determining the ES. That is, the main factor to determine the ES in our method is the constants '*a*' and/or '*b*' with an association of the constant '*c*', meaning that the curvature of the U-shaped $C_w$-*v* relationship determines the ES.

In either case, it was worth noting that the variation of the ES seemed to be small regardless of the gradient variation if the ES was compared between load and no load conditions. In particular, only 1.2% difference was observed during downhill walking, suggesting that the practical application of this observation would be directly applied for military purposes and/or outdoor work management, such as training for fire fighters and mountain rescues (Griefahn et al. 2003). There was no information available with regard to the alteration of the ES during gradient walking with load, thus, further research will be necessary.

## 2-5. Conclusion

A similar phenomenon to the *free-ride* could be observed only when the load was carried on the back during level walking at slower speeds. The ES was significantly decreased by less than 5% when the load was carried on the back. Those results would be induced by different mechanisms, but the information about the alteration of the ES during gradient walking with load will be useful for the outdoor work management.