# Ergonomics of human land locomotion with load carriage

安陪, 大治郎
University of East Asia

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Chapter 6

# General discussion

## 6-1. Overview of this chapter

The previous chapters examined the effects of load weight, load position, gradient and locomotion speed on the energy cost of walking ($C_w$) and/or running ($C_r$). In particular, this thesis mainly investigated whether a similar phenomenon to the *free-ride* could be observed during walking and running with load on various terrains. The purpose of the final chapter was to summarize the effects of the four factors listed above on a similar phenomenon to the *free-ride* and economical speed (ES) for making a general conclusion and examining the possible practical applicability of the results of this thesis.

## 6-2. Effects of load weight, walking speed, load position and gradient on *free-ride*

### 6-2-1. Effects of load weight

The first chapter introduced the *free-ride* phenomenon and its possible biomechanical and physiological mechanisms. The first chapter established a hypothesis that the *free-ride* could be explained by an interaction effect between the rotative torque functioning around the center of the body mass (T) as a positive effect and an excessive burden on the lower leg muscles as a negative effect. Through the experiment of the pilot study, a similar phenomenon to the *free-ride* could be observed only when carrying a load corresponding to 10 ~ 20% of the body mass on the back. It was worth noting that an extra-heavy load corresponding to more than 40% of the body mass could be carried only when the load was located on the head or on the back (Bastien et al., 2005a; Kinoshita 1985; Maloiy et al., 1986; LaFiandra et al. 2002, 2003). Kinoshita (1985) and Maloiy et al. (1986) reported that the biomechanical gait pattern, particularly in the step frequency and trunk angle, significantly changed when an extra-heavy load was carried on the back or head. However, Martin and Nelson (1986) reported that such a gait pattern did not change significantly in men carrying loads up to 40 kg. It has also been pointed out that many biological systems associated with muscle activity are controlled under the criterion of minimum effort (Sutherland et al. 1994). Thus, the optimum gait pattern at a certain gait speed could be automatically selected to minimize the energy expenditure in humans, and such biomechanical factors could not explain the *free-ride* phenomenon.

LaFiandra et al. (2002) recently reported that the torque produced in the upper body segments increased during walking with an extra-heavy load than without load. In contrast, the torque produced in the lower body segments decreased when carrying the extra-heavy load. These authors speculated that the torque produced in the upper body segments could be transferred to the lower body segments. The chapter 1~3 hypothesized that the rotative torque functioning around the center of the body mass was produced by the load on the back, providing an assistive function for the lower body segments. Thus, LaFiandra's speculation was quite similar to the rotative torque hypothesis of this thesis. The first chapter finally showed that '15%' of the body mass could be the likely requirement for obtaining the largest *free-ride* effect during walking in humans, and this interpretation was further supported by some recent studies (Bastien et al. 2005b; Hong and Cheung 2003; Whittfield et al. 2005).

### 6-2-2. Effects of walking speed

It was of interest to note that a similar phenomenon to the *free-ride* was only observed when carrying the load on the back or head at slower speeds (Bastien et al. 2005a; Charteris et al. 1989a, 1989b; Maloiy et al. 1986). In the first three chapters of this thesis, a similar phenomenon to the *free-ride* was observed only when the walking speed was less than 100 m/min, being consistent with the results of those previous studies. As shown by Willems et al. (1995) and Minetti et al. (1995), the highest transfer efficiency between gravitational potential energy ($E_p$) and kinetic energy ($E_k$) during walking occurred at around 80-90 m/min, being consistent with the appearance of the economical speed (ES). Thus, a possible reason why the similar phenomenon to the *free-ride* occurred only at the slower walking speeds would be associated with an interaction of the rotative torque functioning around the center of the body mass and excessive burden on the lower leg muscles with a further association of the transfer efficiency between $E_k$ and $E_p$.

**6-2-3. Effects of load position**

The first and third chapters referred to the load position. The first chapter compared the $C_w$ values obtained from three different experimental conditions, and concluded that the most economical load position was 'on the back'. However, as explained in the first chapter, the compared load positions were 'on the back', 'on the legs' and 'in the hands', meaning that the results of the pilot study obtained from those experimental set-ups gave us indirect evidence to test the hypothesis of this thesis.

Therefore, the third chapter compared the $C_w$ values obtained from other experimental conditions. In that chapter, the load was carried on the upper back (U condition) or lower back (L condition). A similar phenomenon to the *free-ride* was found in both conditions, and significantly lower $C_w$ values were observed in the U condition than in the L condition at 60 ~ 80 m/min. Thus, the hypothesis of this thesis was supported. It was thereby concluded that a similar phenomenon to the *free-ride* could be observed due to an interaction between rotative torque functioning around the center of the body mass and excessive burden on the lower leg muscles. This result clearly indicated that the load should be carried on the upper back to reduce physiological stress during walking with load, and this will be of benefit to outdoor workers or mountain climbers.

**6-2-4. Effects of gradient**

Little information has been available in reference to the physiological responses during gradient locomotion with load in humans. It was surprising to note that there was a non-significant gradient effect on the $C_w$ values (second chapter). In the second chapter, it was assumed that the possible reasons for non-significant gradient effect on the metabolic $C_w$ values were dependent on the limitation of the utilization of the stored elastic energy with an association of the muscle contraction pattern. However, some previous studies focusing on African women and Himalayan porters carrying loads on their head revealed curious information. The African women and/or Himalayan porters' metabolic economy when carrying extra-heavy loads on level terrain was higher than in Caucasians but the reasons are still unknown (Minetti et al. 2006). Heglund et al. (1995) and Minetti et al. (2006) showed a remarkable difference of the time course of the $E_p$ and $E_k$ during level walking between African and Caucasian women, suggesting that the African women’s and/or Himalayan porter’s lower metabolic energy cost of gradient walking may be dependent on a higher exchange between $E_p$ and $E_k$. A different oscillation pattern of the loaded head-trunk segments of the African women and/or Himalayan porters suggested that the motor skills in balancing the loaded body segment would contribute to a determination of the lower energy cost of walking. In the second chapter, a similar phenomenon to the *free-ride* could not be observed during both uphill and downhill terrains. Further kinematic study will be necessary in the future.

## 6-3. Effects of load position and gradient on ES

### 6-3-1. Effects of load position

The relationship between energy cost of walking per unit distance and walking speed shows a quadratic shape, indicating that the minimum energy cost occurs at around 80-90 m/min in adult men. The walking speed, at which the minimum energy cost appears, has been called optimal speed (Cavagna et al. 2000; Falola et al. 2000) or economical speed (ES) (Bastien et al. 2005b). There has been no information available with regard to the ES when carrying a load. In this thesis, the third chapter mainly referred to the effect of load position on the ES. The chapter 1 previously demonstrated that a difference of the load position significantly affected $C_w$. However, that study added a load on the back, on the legs and in the hands. In contrast, the load was placed on the lower and upper back of the subjects to directly test the hypothesis that the ES would be increased when the load was carried on the back. It was further hypothesized that the ES observed in the U condition would be faster than that observed in the L condition. In hardly support of such hypotheses, the ES was significantly decreased by around 4% in both load conditions, being consistent with the result of Falola et al. (2000).

Cavagna et al. (2000) suggested that the gravity significantly affected the ES. These authors revealed that the transfer efficiency between $E_p$ and $E_k$ in the simulated added gravity environment (1.5 g) was not significantly different from that on the Earth (1.0 g). Furthermore, it was surprising to note that the economical speed, at which the maximum transfer efficiency between $E_p$ and $E_k$ could be observed, was significantly faster in the simulated added gravity environment than on the Earth. Our experimental set-up (load condition) must be quite similar to the simulated added gravity experiment, suggesting that the ES would be independent of the load position. It was also suggested that the ES when carrying the load could be determined by an interaction of the transfer efficiency between $E_p$ and $E_k$, rotative torque functioning around the center of the body mass and excessive burden on the leg muscles.

**6-3-2. Effects of gradient**

The second chapter mainly referred to the effects of positive and negative gradient on the ES. There has been no information available for the ES during gradient walking with load. The second chapter showed that there was no significant interaction effect of gradient and load carriage on the ES. Instead, a significant main effect of gradient on the ES will provide a simple interpretation.

As theoretically argued in the second chapter, the constant '*c*' of *eq.* 1, which was defined in the second chapter, is the critical factor for determining the ES (Bastien et al. 2005b). The constant '*c*' reflects the *y*-intercept of the $C_w$-$v$ relationship and corresponds to a subject standing on the treadmill. In contrast, the ES obtained in the second chapter was dependent only on the constants '*a*' and '*b*' as described in *eqs.* 2 and 3, which were also defined in the same chapter. The constant '*c*' seemed to be independent of the calculation of the ES. However, all constants are obtained from least square regression analysis, suggesting that the constant '*c*' is still affecting the determination of the constants '*a*' and '*b*'. That is, the main factors determining the ES in our method are 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 the second chapter, the curvature constants '*a*' and '*b*' of the U-shaped $C_w$-$v$ relationship seemed to be quite similar regardless of the gradient in this study. In contrast, a remarkable difference was found only in the constant '*c*', resulting in a significant gradient difference of the ES. This result clearly showed that the constant '*c*' had a significant impact on the ES. Further research is necessary.

### 6-4. *Free-ride* in running

The existence of a similar phenomenon to the *free-ride* has been argued in the first and fifth chapters. As explained in the fifth chapter, the effects of load carriage on the energy cost of running ($C_r$) need some consideration. At first, the load carriage influences the rotative torque functioning around the center of the body mass as a propulsive nature. However, it also provides an excessive burden on the leg muscles as a negative nature. These interactions in running are the same as for walking. An influence of the utilization of the stored elastic energy as another positive nature cannot be avoided. Thus, the fourth chapter focused on how to characterize the utilization of the stored elastic energy during running, and found that the ratio of the integrated electromyography obtained from eccentric and concentric phases (ECC/CON ratio) of the *vastus lateralis* would be useful. The fifth chapter referred to an interaction effect of load carriage and gradient on the $C_r$. Here, the gradient challenge induced an alteration of the utilization of the stored elastic energy. In contrast, load carriage induced alterations of the utilization of the stored elastic energy and rotative torque.

The results of the fifth chapter clearly showed that the $C_r$ values were significantly decreased in the load condition compared with the unload condition during level and downhill running, demonstrating that a similar phenomenon to the *free-ride* was observed even in running. In the early part of the fifth chapter, some previous studies were carefully checked for discussion of the existence of the *free-ride* phenomenon during running with load. It was speculated that the conflicting opinions with regard to the existence of the *free-ride* during running might be dependent on the methodology of the evaluation. It was important to note that the alteration of the ECC/CON ratio by the gradient and/or load carriage was consistent with that of $C_r$ on each terrain. The ECC/CON ratio but not rotative torque was significantly correlated with $C_r$. These results indicated that the utilization of the stored elastic energy was the determinant factor for explaining the mechanism of the similar phenomenon to the *free-ride* during running with load.

## 6-5. Practical applicability

In many areas of the world lacking a transportation infrastructure, load carriage during human land locomotion is an inevitable part of daily life at work or leisure, sometimes at military operations (Birrell et al. 2007; Heglund et al. 1995; Knapik et al. 2004). For example, infantry soldiers’ training has been conducted by road march with load carriage (Attwells et al. 2007; Christie and Scott 2005; Johnson et al. 1995; Quesada et al. 2006; Reynolds et al. 1999). However, a variety of walking speeds were employed in the previous studies regardless of the load weight and physical fitness of the subjects. The second and third chapters employed load carriage corresponding to 15% of the body mass only, because the metabolic demands during walking did not abruptly increase if the load weight was less than 15% of the body mass (chapter 1; Bastien et al., 2005b; Charteris et al. 1989a). It was also reported that the gait pattern altered when the load weight was increased from 15 to 20% of the body mass (Hong and Cheung 2003). However, this load weight seemed to be acceptable for long-distance military road marching in soldiers (Quesada et al. 2000) and for a safety assessment of school bags (Hong and Cheung 2003; Whittfield et al. 2001, 2005).

Information about the load carriage during running may contribute to the athletes. As discussed in the fifth chapter, load carriage induced increases in the utilization of the stored elastic energy and rotative torque functioning around the center of the body mass. This will result in an increase in the running economy (= decrease in the energy expenditure at the same running speed) and in the exhibition of the explosive power. These benefits will particularly contribute to the distance runners, jumpers and most of the ball game players. It is assumed that too much load weight during land locomotion will result in a high risk of injuries. The second and third chapters showed an alteration of the ES by the load carriage during level and gradient walking. Information about the alteration of the ES by the load carriage will be available for reducing early onset of fatigue in the occupational and/or leisure tasks, contributing to a reducing risk of injuries. Thus, the assessment of the ES for each individual will be highly recommended for the military populations, sports athletes and outdoor workers.

**6-6. General conclusion**

The results of the second and third chapters demonstrated that an energy-saving phenomenon similar to the *free-ride* was observed only when carrying the load on the back at slower walking speeds. Such an energy-saving phenomenon diminished at faster speeds, being consistent with the result of the first chapter. The third chapter clearly demonstrated that the larger the rotative torque, the lower the $C_w$ values. The gradient difference did not have a significant impact on the $C_w$ except for level walking at 40-60 m/min (chapter 2). These findings suggested that an energy-saving phenomenon similar to the *free-ride* would be observed due to an interaction between rotative torque and an excessive burden on the lower leg muscles.

With regard to the ES, both the second and third chapters showed that the ES obtained from load condition on any terrain significantly decreased by around 4% compared to the unload condition. As discussed before, such a percent decrease in the ES in the load condition (around 4%) seemed to be smaller than that of the added load (15% of the body mass), suggesting that the rotative torque could function as a positive effect as a propulsive nature. The third chapter also indicated that body height could be a useful tool for estimating the individual ES. Information about the alteration of the ES by load carriage will be available for reducing early onset of fatigue at work or leisure.

The fifth chapter employed the ratio of ECC to CON phases (ECC/CON ratio) defined in the fourth chapter. This chapter was particularly characterized by the fact that the alteration of the ECC/CON ratio by the load was consistent with that of $C_r$ on each terrain. The ECC/CON ratio but not the rotative torque was significantly correlated with $C_r$. These results suggested that the energy-saving mechanism during running mainly depended on the utilization of the stored elastic energy. This study could not find a significant relationship between rotative torque and $C_r$ due to a fact that a quite small range of rotative torque was imposed to the subject. LaFiandra et al. (2002) showed that an extra-heavy load carriage during walking induced a decrease in the pelvic rotation and an increase in the thoracic rotation, suggesting that torque transfer between upper and lower body may occur. Future research will focus on the torque transfer among the body segments during locomotion with load carriage.