Ergonomics of human land locomotion with load carriage

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Chapter 1

Introduction

1. Introduction

1-1. Walking with load and its relevance to *free-ride*

Walking and running are the most common styles for human land locomotion. In many industrially developing countries or inconvenience areas, walking is the only method for carrying the load in daily activities (Kawahara 1999; Davies and Mackinnon 2006).

Energy expenditure during walking with and without loads has been particularly studied to examine physical and psychological tolerance as well as physiological responses in military research (Datta and Ramanathan 1971; Soule et al. 1978; Jones et al. 1986a, 1986b; Duggan and Haisman 1992; Legg et al. 1992). It has been suggested that the metabolic demand during walking with load carriage increases linearly with the carrying weight (Soule and Goldman 1969; Keren et al. 1981; Gordon et al. 1983; Francis and Hoobler 1986). However, some studies revealed that African women could carry an extra-heavy load that amounts to 40% of the body mass on their head (Maloiy et al. 1986; Charteris et al. 1989b). It was reported that the metabolic cost while walking with loads did not necessarily increase if the load was less than 20% of the subject's body mass (Charteris et al. 1989a). These authors termed the phenomenon '*free-ride*' (Charteris et al. 1989b), and referred to the *free-ride* as carrying loads on the head. They demonstrated that the *free-ride* diminished with an increase of carrying weight.

1-2. Possible hypothesis for explaining *free-ride*

Charteris et al. (1989a) suggested that changes in both step frequency and stride length in the *free-ride* are possible biomechanical mechanisms. However, it is well known that humans naturally select their own optimum step frequency and stride length during walking and/or running (Maloiy et al. 1986). These biomechanical factors did not change significantly in men carrying loads of up to 40 kg (Martin and Nelson 1986), suggesting that the minimum energy cost of walking must be automatically selected to minimize energy expenditure. This means that changes in step frequency and stride length due to load carriage might be an incidental phenomenon to minimizing energy expenditure. Furthermore, the effects of varying loads and load position on an energy-saving phenomenon when walking with loads on the back as a function of speed have not yet been fully studied.

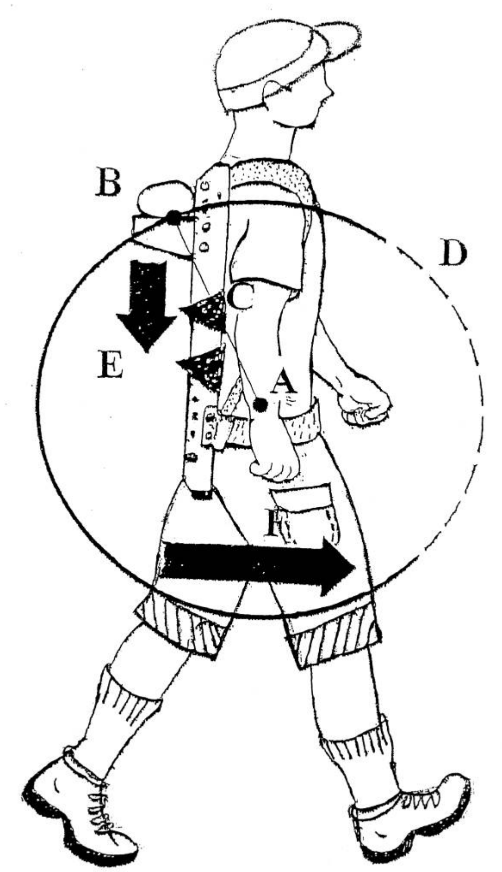

Fig. 1
A schematic description of an interaction between the rotative torque functioning around the center of the body mass (BM) and the excessive burden on the leg muscles during level walking with load on the back. A, center of BM; B, center of mass of load; C, radius of rotation; D, rotation arc; E, excessive burden on the leg muscles; F, rotative torque functioning around the center of BM.

It was hypothesized that the main factors affecting this phenomenon when walking with loads on the back would be due to an interaction between the following two conflicting effects (Fig. 1):

1. Load weight on the back would induce a rotative torque functioning around the center of the body mass (T) as a positive effect.
2. Load weight on the back would also put an excessive burden on the lower body muscles as a negative effect.

The T can be defined as follows:

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

where F corresponds to the T, and AB is a radius of rotation, represented as C in Fig. 1. A possible mechanism to save on the energy cost of walking by the T is the saving on production of the propulsive force done by leg muscles, resulting in a decrease in the energy cost of walking. On the other hand, load carriage may put an extra burden on the postural trunk muscles and leg muscles, resulting in an increase in the energy cost of walking. If our hypothesis is correct, then a phenomenon similar to the *free-ride* will be observed when loads are carried on the back when walking. It was also hypothesized that a phenomenon similar to the *free-ride* would not be observed when the loads were carried in the hands and on the legs because the T can not be counted on as an energy-saving mechanism when walking with loads in the hands and on the legs.

1-3. Pilot study

Abe et al. (2004) tried to examine the mechanisms for explaining the *free-ride* phenomenon. The purpose of the pilot study was to examine the effects of load position and walking speed on the energy cost of walking (C_w). For the purpose of the subjects' safety during laboratory testing, they did not attach the loads to the subjects' heads, instead, the load was carried on the subjects' backs. If their hypothesis is correct, then a phenomenon similar to the *free-ride*, which was previously introduced in the early first chapter, will be observed when loads are carried on the back during walking. It was also hypothesized that a similar phenomenon to the *free-ride* would not be observed when the loads were carried in the hands and on the legs because the T can not be counted on as an energy-saving mechanism when walking with loads in the hands and on the legs.

1-3-1. Methods

Exercise tests were performed on eight healthy male subjects (172.1±0.9 cm and 62.1±1.2 kg) using a motor driven treadmill. When the subjects were accustomed to the treadmill walking with the gas collection mask, the optimal step frequency of each subject was selected at each speed, and was then fixed for each trial. The optimum step frequency of each subject at each speed was set with a metronome during the first minute of each trial speed on the treadmill. Walking speeds were set at 40, 50, 60, 70, 80, 90, 100, 110 and 120 m/min. The subjects performed 5-min trials at each speed with and without loads. The subjects wore underwear, shirts, socks, gym shorts, and light-weight training shoes. The measurements were done twice a week for each subject. The load consisted of a sand bag in a backpack. The total weight of the loads were 6, 9 and 12 kg, which corresponded to approximately 10, 15 and 20%, respectively, of the average body mass of all the subjects.

The control condition was performed with no load on the first day of the measurement sessions, and the order of other load trials was randomized. An adjustable ankle weight (Power Age, Mizuno, Tokyo) was attached to both ankle joints. The loads were 1, 1.5 and 3 kg for each leg (Browning et al. 2007), resulting in a total weight for the legs of 2, 3 and 6 kg, respectively. Hand-carried loads were also prepared (Rythm Fighter, Mizuno, Tokyo). The loads were 1.5, 3.0 and 4.5 kg for each hand, resulting a total weight for the hands of

3, 6 and 9 kg, respectively.

Breath-by-breath oxygen consumption ($\dot{V}O_2$) was measured with a gas analyzer. A single sample with an average 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+L]/meter), where BM is the body mass of the subjects, and L is the load carriage. The C_w values were determined from the ratio of the steady-state $\dot{V}O_2$ to the walking speed (v):

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

The results were presented as mean ± standard error (SE). C_w values of each trial as a 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 speed were compared by one-way analysis of variance. When significant F values were present, Bonferroni's multiple comparison was applied to the data to establish the significant mean differences. Statistical significance was established at the 0.05 probability level.

1-3-2. Results

The average C_w values with and without loads on the back are shown in Fig. 2. The average C_w values obtained from the 9 kg and 12 kg load conditions at 40 m/min were significantly lower than those obtained from the control condition ($p < 0.01$). At 50 and 60 m/min, the average C_w values obtained from 9 kg and 12 kg load conditions were also lower than those obtained from the control condition ($p < 0.01$ and $p < 0.05$, respectively). The average C_w values for each load condition from 70 to 120 m/min, except 80 m/min, were not significantly lower than those obtained from the control condition. However, the C_w values of load conditions tend to be closer to those obtained from the control condition as walking speed increased. The C_w values obtained from the 12 kg load condition at 120 m/min tended to be higher than those obtained from the control condition. No significant differences were observed in the C_w values between the control and 6 kg load conditions, although the average C_w values obtained from the 6 kg load condition seemed to be lower than those obtained from the control condition at all speeds.

The average C_w values as a function of walking speed with and without loads in the hands are shown in Fig. 3. The average C_w values of the 3 and 6 kg load conditions at 40 m/min were significantly lower than those obtained from the control condition ($p < 0.05$). At 50 m/min the average C_w value of the 3 kg load condition was also lower than that of the 9 kg load condition ($p < 0.05$). The average C_w values of 9 kg were significantly higher than those of the control condition at 120 m/min ($p < 0.05$).

Figure 4 illustrates the average C_w values as a function of walking speed with and without loads on the legs. The average C_w values of the 6 kg load condition were significantly higher than any other condition ($p < 0.01$ except the 2 kg load condition at 40 m/min ($p < 0.05$)). At slower walking speeds the average C_w values obtained from 2 and 3 kg load conditions on the legs were almost the same as those obtained from the control condition. At faster speeds, particularly above 100 m/min, the average C_w values of the control condition tended to be lower than those of the 2 and 3 kg load conditions. These statistically significant results were summarized in Table 1.

When the average C_w values obtained from 6 kg load conditions in the hands, on the legs, and on the back were compared, the C_w values of the leg-load condition were significantly higher than those of hand-load and/or back-load conditions at any walking speed (Fig. 5, $p < 0.01$).

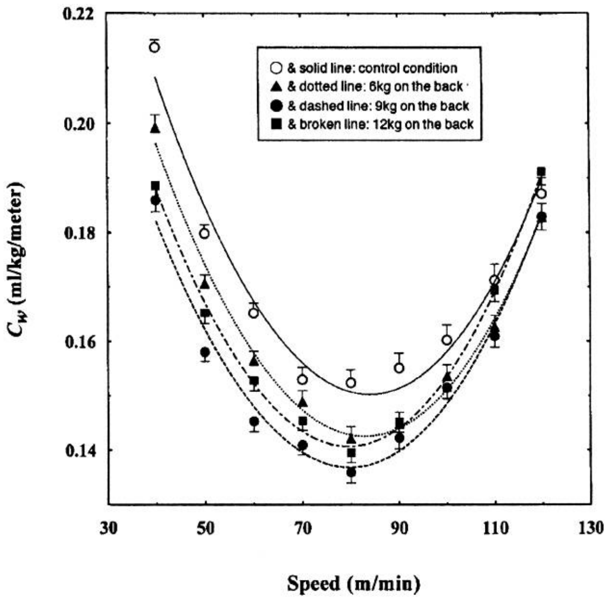

Fig. 2
Energy cost of walking (C_w) with load on the back.

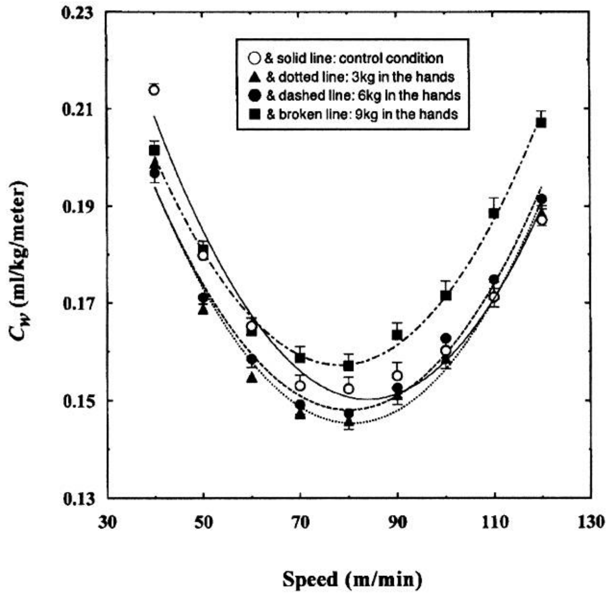

Fig. 3
Energy cost of walking with load in the hands.

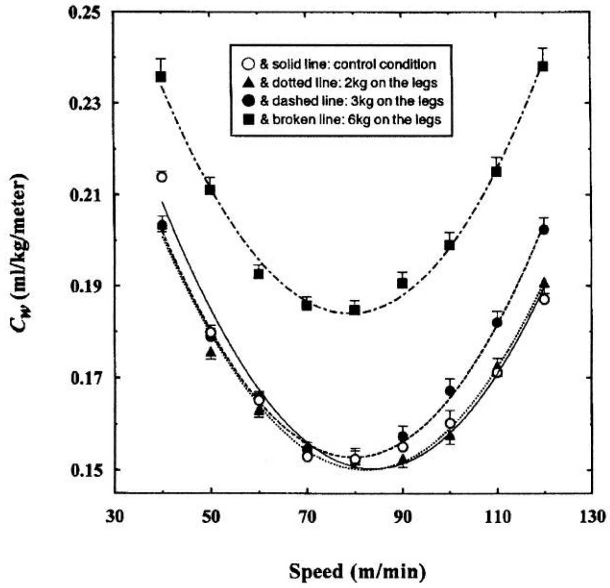

Fig. 4
Energy cost of walking with load on the legs.

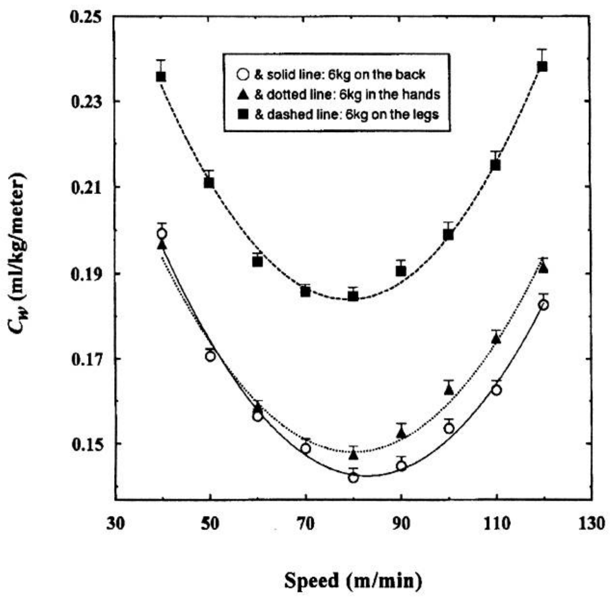

Fig. 5
A comparison of the C_w values obtained from 6kg load conditions on the back, on the legs and in the hands.

Table 1
Summary of statistically significant results

Weight (kg)	Speed (m/min)								
	40	50	60	70	80	90	100	110	120
Load on the back									
6									
9	*	*	*		*				
12	*	*							
Load in the hands									
3	*	*							
6	*								
9									$
Load on legs									
2									
3									
6	#	#	#	#	#	#	#	#	#

Note: *Significantly different from control condition only; # significantly different from other conditions; not significantly different from others; $ significantly different from 3 kg load condition and control condition.

1-3-3. Discussion

The effects of load carriage on the energy cost of walking per unit distance as a function of walking speed were investigated to examine the hypothesis that an energy-saving phenomenon similar to the *free-ride* would be observed during walking with loads on the back due to an interaction between T and an excessive burden on the lower leg muscles (Fig. 1). One of the main findings of this study was that the average C_w values of 9 and 12 kg load conditions significantly decreased at slower speeds when the load was carried on the subjects' back (Fig. 2). This trend was observed until 80 m/min. It was important to note that a phenomenon similar to the *free-ride* was not observed at faster speeds, even though the 'non-significant' energy-saving phenomenon during walking with loads on the back was seen at those walking speeds. In particular, the average C_w values obtained from 12 kg load condition at 120 m/min seemed to be higher than those of the control condition. These results indicated that load weight positively influenced the C_w values, possibly due to an increased T at slower speeds, however, the excessive burden on the lower leg muscles negatively overcame the positive effect of the T at faster speeds. These results indicated that an energy-saving phenomenon similar to the *free-ride* depended on not only load but also walking speed.

Maloiy et al. (1986) reported that the energy cost of walking did not increase significantly when the loads corresponding to 20% of the body mass were carried on the head, however, information regarding walking speed was not reported. The results of the present study were partly consistent with Keren et al. (1981), who investigated the effects of load carriage on energy expenditure during walking and running. Keren et al. (1981) argued that energy expenditure significantly increased when loads were carried on the back during walking and running. However, these authors examined the effects of loads on the energy expenditure at speeds faster than 107 m/min. The results of the present study agreed with their interpretation at faster speeds, but not at slower speeds.

As previously discussed by Saibene (1990) and Willems et al. (1995), one of the most significant factors of the energy-saving mechanisms in walking is explained by the transfer efficiency between kinetic energy (E_k) and gravitational potential energy (E_p). The center of the body mass is located at the level of the *trochanter major* during upright standing, and does not change much during walking (Cavagna et al. 1963). This implies that the center of the body mass must have been increased by the load carried on the back, thus the E_p might have also increased by the carried load in this study. The increased E_p would cause an increase in E_k if the transfer efficiency did not alter regardless of the carrying load. The time course of the E_k is almost out of the phase with that of the E_p during walking (Cavagna et al. 1963). A small phase difference results in the loss of a sum of potential and kinetic energy, suggesting that muscle activities must compensate for the energy loss to maintain walking speed. Based on the above points, if the transfer efficiency between E_k and E_p and the time course of E_p do not alter during walking with loads, then E_k must increase as the increased E_p. In other words, increased E_k caused by T might be equivalent to increased E_p.

The present study also found that the average C_w values for 3 and 6 kg load carriage in the hands were significantly lower than those obtained from the control condition at slower speeds. However, the average C_w values of 9 kg load condition in the hands were significantly higher than those obtained from other conditions at faster speeds (Fig. 3). These results conflicted with several previous studies that reported energy cost of walking increased as a function of carrying load (Soule and Goldman 1969; Keren et al. 1981; Martin and Nelson 1986). In this study, however, the values of energy cost of walking with loads in the hands did not increase as a function of carrying load, at least at slower speeds. To our knowledge, no information is available on load carriage in the hands in addition to load on the back. Legg (1985) reported that the physical and physiological responses during walking abruptly increased when the loads were transferred to smaller muscle groups due to peripheral muscle fatigue. It is important to note that the carrying load of this study was, at most, 20% of the subjects' body mass, however, Legg (1985) subjected a load corresponding to 35% of the subjects' body mass in the hands. The difference in load weight and lack of information regarding walking speed make it difficult to a directly compare Legg's study with the present one.

The E_k necessary to maintain the propulsive motion must be mainly produced by leg muscles, not by arm muscles, meaning that the kinetic motion required to produce propulsive force must not be hindered by the load when loads are carried in the hands. Willems et al. (1995) showed that the energy cost of walking mainly depends on an alteration of internal work done by locomotive muscles, and such internal work done by those muscles linearly increased with an increase in walking speed. In other words, it is assumed that energy expenditure during walking with loads in the hands was mainly spent on propulsive force at faster speeds and holding of gait at slower speeds. As previously discussed, the T may not have been an important factor as an energy-saving mechanism when the load was carried in the hands because the load weight was always located at a lower level than the center of the body mass when walking. Hand and arm muscles might not be direct locomotive muscles yielding propulsive force, but they may contribute to an efficient energy transfer between E_p and E_k when walking. In other words, energy cost in the hand and arm muscles during walking must be negligibly small at slower speeds, resulting in the appearance of an energy-saving phenomenon similar to the *free-ride* when light load is carried in the hands.

Another important finding of this study was that the average C_w values with 2 and 3 kg loads on the legs tended to be higher than those obtained from the control condition, but values were not significant. However, at slower speeds, the average C_w values with those loads on the legs were almost consistent with those obtained from the control condition (Fig. 4). These results were partly similar to those reported by Jones et al. (1984, 1986) and Legg and Mahanty (1986). These studies found increments in the energy cost of a 0.7 to 0.9% per 100-g increase in the weight of footwear. It was worth noting that the average C_w values at any speed abruptly increased when a 6 kg load was carried on the legs (Fig. 4). An excessive burden on leg muscles obstructed the rhythmic swinging motion, particularly in the ‘lifting up’ motion, resulting in an abrupt increase in the internal work done by the leg muscles. Lejeune et al. (1998) suggested that there was a decrease in the efficiency of the positive work done by the muscles and an increase in the external work done when subjects walked on sand. Zamparo et al. (1992) showed that the energy cost of walking on sand increased linearly as a function of speed. Those authors concluded that a reduction of the transformation of the E_p into kinetic energy and vice versa induced an increase in the energy cost of walking on sand. In the present study, a curvature of the C_w-v relationship did not alter regardless of the carrying loads on the legs, thus, a mechanism to explain the abrupt increase in the energy cost of walking when 6 kg was loaded on the legs in this study may be different from that of Lejeune et al. (1998). It is possible, however, that the energy cost of walking abruptly increases when the mechanical work is done by the leg muscles.

Figure 5 clearly showed that the energy cost of walking with loads on the legs was significantly higher than other conditions at any speed. This result supported our interpretation that an increment of the mechanical work done by the leg muscles induced an abrupt increase in the energy cost of walking. In view of the anatomy of Japanese adult men, the mass of the lower leg and thigh is four-fold larger than that of the hand, forearm and upper arm (Kaneko 1994), suggesting that the energy cost of walking with the same extra load on the legs must be larger than that of the load carriage in the hands and/or on the back at any walking speed.

1-3-4. Conclusion

An energy-saving phenomenon similar to the *free-ride* was observed when a load was carried on the back at slower walking speeds. A load of 9 kg (~ 15% of the body mass) yielded the largest energy-saving phenomenon at slower speeds only when the load was carried on the back. The energy-saving phenomenon diminished at faster speeds, particularly when walking faster than 90 m/min. At slower speeds, it was also observed when the load was carried in the hands, not on the legs. These findings partly supported our biomechanical hypothesis that an energy-saving phenomenon similar to the *free-ride* would be observed due to an interaction between rotative torque functioning around the center of the body mass and an excessive burden on the lower leg muscles. It was also suggested that a phenomenon similar to the *free-ride* was dependent on walking speed.

1-4. Overview of pilot study

1-4-1. Unsolved problems of pilot study

The pilot study mainly investigated the effects of loaded mass on the energy cost of walking, and suggested that a load corresponding to 10 ~ 15% of the body mass would be a necessary requirement for a similar phenomenon to the *free-ride* during walking. This study also insisted on the importance of the load position. However, it is noted that the compared load positions were 'on the back', 'on the legs' and 'in the hands'. Thus, the result of the pilot study obtained from such an experimental set-up cannot be direct evidence for examining the established hypothesis. Other unsolved problems also remain. The gradient challenge is an inevitable part in the human land locomotion at daily work or leisure. However, little information about physiological responses during gradient locomotion is available (Minetti 1995; Minetti et al. 1993, 2002).

1-4-2. Argument of economical speed

The economical speed (ES), corresponding to the walking speed at which the metabolic energy cost of walking per unit distance becomes minimum, was not measured in the pilot study. With reference to the ergonomic implications, considerations of the ES could be significant for a reduction of workers' physical stress and early onset of fatigue. However, no information is available with respect to an alteration of the ES by the gradient. 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 it was not decreased in another study (Bastien et al. 2005b). Minetti et al. (2003) indicated that the ES decreased as a function of positive gradient, but no load was carried in these previous studies.

1-4-3. Does the *free-ride* exist in running?

It is also pointed out that the question of a similar phenomenon to the *free-ride* during running has not been solved yet. Bourdin et al. (1995) observed a significant decrease in the energy cost of running (C_r) when carrying a load corresponding to 10% of the subjects' body mass. In contrast, Myers and Steudel (1985) observed that a loaded mass of 3.7 kg during running resulted in a 3.7% increase in the oxygen consumption ($\dot{V}O_2$). Cureton and Sparling (1980) showed that the addition of 7.5% body weight to the trunk during submaximal running significantly increased $\dot{V}O_2$ by 0.16 l/min. Cooke et al. (1991) observed a similar result to that of Cureton and Sparling (1980). However, the oxygen cost was significantly decreased if such an increase in the oxygen consumption was expressed as ml/kg/min. These conflicting results regarding the existence of a similar phenomenon to the *free-ride* during running may depend on the methodology of evaluation. Thus, a similar phenomenon to the *free-ride* would be observed even in running.

1-5. Overall purpose

The main purpose of the earlier part of this thesis was to examine the effects of load position, gradient and walking speed on the energy cost of walking. This thesis particularly investigated whether a similar phenomenon to the *free-ride* could be observed during walking with load on various terrains. Another purpose of this study was to examine the effects of load carriage on the ES on various terrains. This thesis also tried to estimate the ES using physical characteristics of the subjects.

With regard to running with load, the structure of this thesis was divided into two parts, because the complex nature of the load carriage affects both rotative torque functioning around the center of the body mass and utilization of the stored elastic energy. Thus, the reliability of the methodology to monitor the utilization of the stored elastic energy during running was primarily validated in the fourth chapter. The purpose of the later part of this thesis was to examine the interaction effect of load carriage and gradient on the energy cost of running and utilization of the stored elastic energy. The later part of this thesis particularly investigated whether a similar phenomenon to the *free-ride* could be observed even in running with load on various terrains and whether the alteration of the energy cost of running by the load carriage and gradient was consistent with that of utilization of the stored elastic energy.

Energy-saving mechanisms have been explained mainly by the transfer efficiency between kinetic energy and gravitational potential energy for walking and utilization of the stored elastic energy for running (Saibene and Minetti 2003). However, some new evidence against these well-known energy-saving mechanisms has recently been reported (Fukunaga et al. 2001; Lichtwark and Wilson 2006; Sasaki and Neptune 2006). Experiments using load carriage and gradient can reveal the further functional potential of human beings during land locomotion. Thus, the whole results of this thesis will be practically useful for outdoor workers, athletes, military populations and school children.

1-6. Structure of this thesis

This thesis was composed of 6 chapters. The second chapter mainly referred to the effects of gradient on the energy cost of gradient walking and ES. The third chapter referred to the effects of load position on the energy cost of walking and ES. The experimental set-up of this chapter was particularly characterized by the fact that the T could be artificially manipulated without changing the load weight and/or radius of rotation (AB), represented in Fig. 1. This chapter also referred to how to estimate the ES using physical characteristics of the subjects. The fourth chapter examined the relationship between electromyography (EMG) characteristics and the metabolic energy cost of running. In this chapter, the EMG signal obtained from the working muscle was divided into eccentric (ECC), concentric (CON) and pre-activation (PRE) phases and full-wave rectified. The ratio of the integrated EMG of ECC to that of CON phase (ECC/CON ratio) was regarded as an indicator of the utilization of the stored elastic energy. The ECC/CON ratio could be highly useful in the fifth chapter when assessing the utilization of the stored elastic energy during running. The fifth chapter referred to the interaction effect of load carriage and gradient on the energy cost of running and the ECC/CON ratio. This thesis consisted of the following articles.

Chapter 1: Daijiro Abe, Kazumasa Yanagawa, Shigemitsu Niihata. 2004. Effects of load carriage, load position and walking speed on energy cost of walking. *Appl. Ergonomics* 35, 329-335.

Chapter 2: Daijiro Abe, Satoshi Muraki, Akira Yasukouchi. 2008. Ergonomic effects of load carriage on energy cost of gradient walking. *Appl. Ergonomics* 39, 144-149.

Chapter 3: Daijiro Abe, Satoshi Muraki, Akira Yasukouchi. 2008. Ergonomic effects of load carriage on the upper and lower back on metabolic energy cost of walking. *Appl. Ergonomics* 39, 392-398.

Chapter 4: Daijiro Abe, Satoshi Muraki, Kazumasa Yanagawa, Yoshiyuki Fukuoka, Shigemitsu Niihata. 2007. Changes in EMG characteristics and metabolic energy cost during 90-min prolonged running. *Gait & Posture* 26, 607-610.

Chapter 5: Daijiro Abe, Satoshi Muraki, Akira Yasukouchi, Yoshiyuki Fukuoka, Shigemitsu Niihata. Effects of load carriage on EMG characteristics and energy cost of running on various terrains. under review