ジュウリョウ フカ オ モチイタ ヒト ノ リクジョウ イドウ ウンドウ ニ カンスル ニンゲン コウガクテキ ケンキュウ

安陪, 大治郎
University of East Asia

https://doi.org/10.15017/10323

出版情報：Kyushu University, 2007, 博士（芸術工学）, 課程博士
バージョン：
権利関係：

Chapter 5

Effects of load carriage on EMG characteristics and energy cost of running on various terrains

5-1. Introduction

Energy expenditure during walking with and without loads has been investigated to examine physiological and/or psychological tolerance by military-related scientists (e.g. Knapik et al. 2004). It has been acknowledged that the energy expenditure during walking with load increases linearly with the carrying load (e.g. Keren et al. 1981), but other studies argued that the energy expenditure during walking with load did not always increase as a function of the carried weight (Charteris et al. 1989b; Maloiy et al. 1986). Those authors named such a phenomenon as '*free-ride*'.

As pointed out in the first chapter, a similar phenomenon to the *free-ride* during running has also been discussed. Bourdin et al. (1995) observed a significant decrease in the energy cost of running (C_r) with load corresponding to 10% of the 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 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, however, the oxygen cost was significantly decreased if the increase in 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. The first chapter has proposed that such a phenomenon during walking 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 (Fig. 1a). The T can be defined using the following equation:

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

where F is the T and AB is a radius of rotation (Fig. 1a). If the possible mechanisms for explaining the *free-ride* are the T as proposed by the first chapter, then the *free-ride* could be also observed during running. It was hypothesized that a similar phenomenon to the *free-ride* could be observed during running. The first purpose of this study was to examine whether a similar phenomenon to the *free-ride* could be observed during running with load.

The energy-saving mechanism for running, such as *free-ride* phenomenon, has mainly been explained by the recoil of the stored elastic energy (Cavagna et al. 1964). The elastic energy can be stored in the stretch phase of the muscle-tendon unit, thus, the utilization of the stored elastic energy would be greater during running with load than without load (Bourdin et al. 1995). Indeed, the fourth chapter has recently found that the ratio of the eccentric (ECC) to concentric (CON) phases of integrated electromyography (iEMG) obtained from the *quadriceps femoris* was significantly correlated with an alteration of C_r during prolonged running. However, the complex interaction effect of the load carriage on the C_r needs some consideration, because the load carriage would affect increases in the utilization of the stored elastic energy and T (Fig. 1b). Therefore, the effect of either utilization of the stored elastic energy or T on the C_r should be carefully investigated when examining the possible mechanisms of the *free-ride* phenomenon during running. The gradient difference may give us a potential solution (Minetti et al. 1994). The experimental set-up of the present study is characterized by the facts that the gradient difference will only contribute to an increase in the utilization of the stored elastic energy and that the load carriage will contribute to an alteration of both utilization of the stored elastic energy and T.

It was also hypothesized that the alteration of the ratio of the ECC to CON phases of the integrated electromyography (ECC/CON ratio) by the gradient and/or load carriage would be consistent with that of C_r, if the mechanism for explaining the *free-ride* during running is either T or utilization of the stored elastic energy. The second purpose of this study was to examine the variation of the ECC/CON ratio and C_r with and without load carriage on various terrains.

a

b

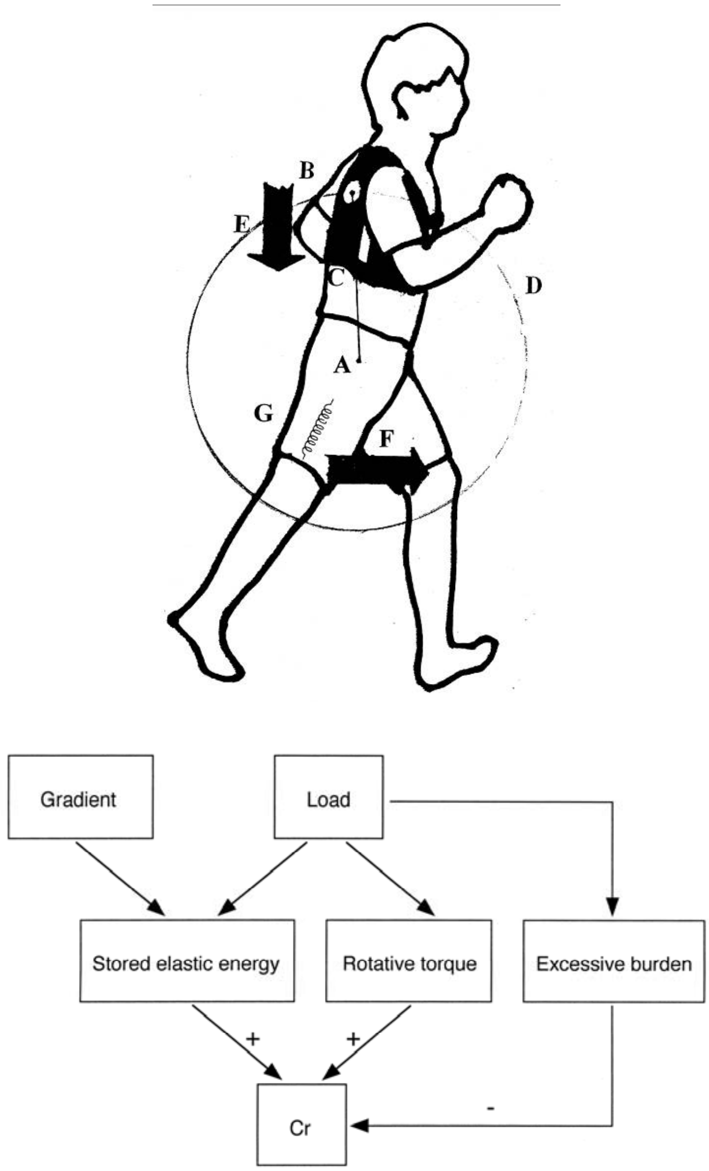


Fig. 2
Panel (a) shows a schematic description of the interaction between the rotative torque functioning around the center of the body mass (BM) and excessive burden on the leg muscles during running with load on the back. A, center of BM; B, center of mass of load; C, radius of rotation; D, rotation arc; E, excessive burden on the leg muscles; F, rotative torque; G, increased utilization of stored elastic energy in the *vastus lateralis*, represented by ECC/CON ratio. Panel (b) represents a complex interaction effect of load carriage and gradient on C_r. Gradient influences ECC/CON ratio only, but load carriage influences both ECC/CON ratio and rotative torque. The load carriage also produces excessive burden as a negative effect on C_r.

5-2. Methods

5-2-1. Subjects

The experiments were performed on eight male volunteers (highly-trained runners = 3, well-trained runners = 4, soccer player = 1). The mean age, body weight, height and maximal oxygen consumption of those subjects were 20.3±0.9 years, 58.2±3.1 kg, 168.6±5.1 cm and 63.7±6.3 ml/kg/min ranging from 57.3 to 73.5 ml/kg/min, respectively. Informed consent from each subject and the approval from the ethical committee were obtained for all procedures.

5-2-2. Measurements

A $\dot{V}O_{2max}$ test was initially performed on a motor-driven treadmill (Biomill BL-1000, S & ME, Tokyo) using a constant velocity, grade incremental protocol (Abe et al. 1998). The subjects ran at 0% gradient during the first 2 min of the $\dot{V}O_{2max}$ test. Every 1-min the gradient was increased by 1% until the subjects felt exhausted. Breath-by-breath expired gas volume and concentration were analyzed from the measurements (AE-300S, Minato, Osaka). The highest value of the 30-sec $\dot{V}O_2$ was regarded as the individual $\dot{V}O_{2max}$.

To obtain the electric signal and $\dot{V}O_2$ during submaximal running, the treadmill velocity was set at 12.0 km/h for highly trained runners and 11.5 km/h for well-trained runners and the soccer player. Each subject ran on the same treadmill with a freely chosen step cadence. The treadmill gradient was set at 0% (level), +5% (uphill) and –5% (downhill) in consideration of the practical application for outdoor sports performance and/or daily activities. The subjects wore underwear, shirts, socks, gym shorts and same lightweight training shoes in five different sizes (WAVE WING FF, Mizuno, Osaka). The load consisted of small grains of lead packed by nylon cloth, and was installed in the upper back of a weight jacket. The net weight of the jacket was 0.3 kg. The total weight of the load was set at 2.3 kg, corresponding to 4.0±0.2% of each subject's body mass. We measured the length from the center of the loaded mass to the *trochanter major*, at which the center of the body mass is located during running (Cavagna et al. 1964). The length was multiplied by 2 kg, the weight of small grains of lead, to obtain T in each subject (T; kg·m).

The determination of the energy cost of running (C_r; ml/kg/meter) followed previous studies (Abe et al. 1998; Bourdin et al. 1993, 1995; Lacour et al. 1991). The C_r expressed in ml/kg/meter was determined from the ratio of oxygen consumption ($\dot{V}O_2$; ml/kg/min) above the resting value (net $\dot{V}O_2$) to the running speed (v: m/min):

$$C_r = \text{net } \dot{V}O_2/v.$$

5 ml/kg/min was used as a resting $\dot{V}O_2$ corresponding to the average y-intercept of the linear $\dot{V}O_2$-v relationship obtained during the treadmill exercise (Medbo et al. 1988). Thus, it corresponds to the $\dot{V}O_2$ of a man standing on the treadmill (Lacour et al. 1991).

The EMG signal from the *vastus lateralis* (VL) was measured with bipolar Ag-AgCl surface electrodes (interelectrode distance = 2 cm) and a polygraph system (LEG-1000, NIHON KOHDEN, Tokyo). As previously reported in the fourth chapter, the electrodes were initially placed over the VL, *vastus medialis* and *rectus femoris*. However, the amplitude of the EMG signal from the VL was found to be the largest. Therefore, only the VL was selected as a target muscle in order not to disturb the individual's natural running mechanics. A small force sensor (PS-10KASF4, KYOWA, Tokyo) was inserted into the running shoes of the dominant leg. The sensor was placed just under the heel to detect the heel contact. Changes in the knee-ankle angle from the dominant leg were recorded with an electric goniometer (SG150, NIHON KOHDEN, Tokyo). The goniometer was secured with an elastic belt to each subject's leg. The electrodes were secured with surgical tape.

The electrode, pressure sensor and goniometer wires were secured with an elastic belt to minimize movement artifacts. Those apparatus made it possible to divide the working muscle activation into three different phases: preactivation (PRE), ECC, and CON. As shown in Fig. 1c, the PRE and ECC phases of VL activation during running could be divided when the pressure signal began increasing from the baseline. The ECC and CON phases could be divided using knee joint angle information. All electric signals were simultaneously sampled at 1 kHz and recorded on a personal computer through an amplifier (CDA-700A, KYOWA, Tokyo) and a 12-bit analog-digital conversion system (PowerLab ML845, NIHON KOHDEN, Tokyo). The observed EMG signals were high-pass filtered at 10 Hz with a second-order Butterworth digital filter and full-wave rectified. Then the rectified EMG was integrated (iEMG) in each phase. To minimize intra-individual variability, the storage of the electric signals was repeated 4 to 6 times at each sampling session. The iEMG of each phase was also evaluated by root mean square value (RMS; iEMG/duration). Total number of analyzed steps ranged from 30 to 50 in each subject. The obtained dependent variables for each session were averaged in each subject. Thus, the observed dependent variables were expressed as the individual representative value.

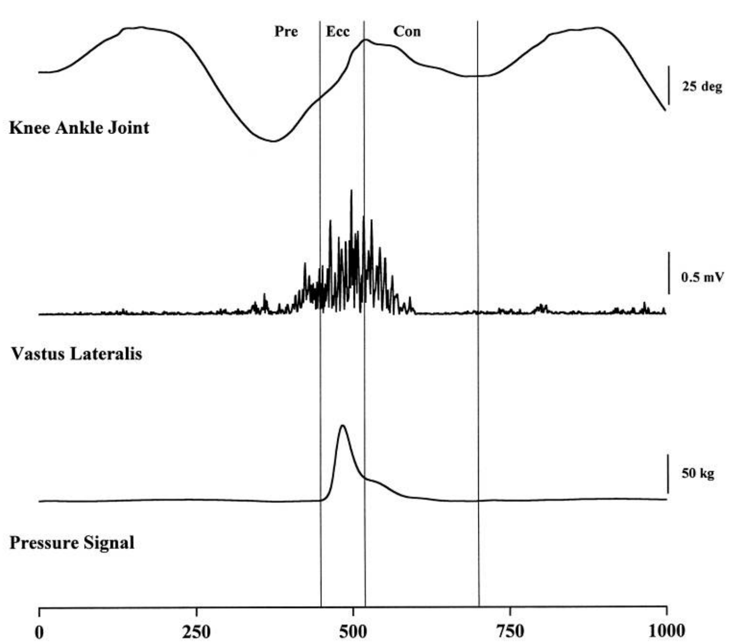


Fig. 1c
A typical trace of EMG for the *m. vastus lateralis* during running. The contact phase was divided into eccentric (E) and concentric (C) phases by an alteration in knee joint angle. Preactivation (P) and E phases were divided by the pressure signal from the foot sensor.

5-2-3. Statistical analysis

A two-way 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. When a significant *F* value was present, 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 relationship of each appropriate data set was evaluated by a single regression analysis. Statistical significance was established at the 0.05 probability level.

5-3. Results

Figure 1c shows representative examples of alterations in the knee-joint angle, iEMG in the VL and pressure signal. Significant main effects of load were found in the ECC/CON ratio, C_r, iEMG and duration of ECC phase in this study (Table 1). A significant main effect of gradient was found in the C_r only (Table 1). There were no significant interaction effects of load and gradient on most of the dependent variables except for the ECC/CON ratio. A further post-hoc test revealed that the ECC/CON ratios obtained from load and unload conditions were significantly different during downhill and level running, but not during uphill running (Table 2). The iEMG of the ECC phase was significantly greater during downhill running with load than without load. The duration of the ECC phase was significantly longer during downhill running with load. There was no significant difference in the RMS (Table 2). Significant relationships of the ECC/CON ratio between load and unload conditions were observed (Fig. 2). No significant relationship was observed between T and ratio of C_r with load to that without load at each terrain (Fig. 3a). The ECC/CON ratio was significantly correlated with C_r in the load condition (Fig. 3b).

Table 1

F and p values for main effects of load and gradient and load-gradient interaction effect of each dependent variable.

	Main effect of gradient (A)		Main effect of load (B)		Interaction of A and B	
Variable	F (2,21)	p value	F (1,14)	p value	F (2,42)	p value
ECC/CON ratio	2.341	0.121	12.733	0.002*	6.111	0.008*
Cr (ml/kg/meter)	72.990	0.000*	25.367	0.000*	0.692	0.512
iEMG of ECC phase (mV・sec)	0.005	0.995	10.265	0.004*	0.381	0.688
iEMG of CON phase (mV・sec)	1.434	0.261	0.039	0.845	2.466	0.109
Duration of ECC phase (msec)	1.797	0.190	12.069	0.002*	2.993	0.072
Duration of CON phase (msec)	1.010	0.381	1.087	0.309	0.160	0.853
RMS of ECC phase (mV)	0.802	0.462	0.161	0.692	0.228	0.798
RMS of CON phase (mV)	0.877	0.431	1.395	0.251	0.308	0.738

ECC and CON mean eccentric and concentric phases, respectively. Cr and RMS mean energy cost of running per unit distance and root mean square, respectively.

Table 2

Summary of observed values at each condition.

	Downhill		Level		Uphill	
	Load	Unload	Load	Unload	Load	Unload
ECC/CON ratio	2.104* (0.613)	1.805 (0.500)	1.838* (0.499)	1.620 (0.437)	1.415 (0.350)	1.469 (0.483)
Cr (ml/kg/meter)	0.165*# (0.015)	0.175# (0.017)	0.206* (0.015)	0.215 (0.017)	0.255 (0.014)	0.260 (0.012)
iEMG of ECC phase (mV・sec)	9.06* (3.00)	8.53 (3.01)	9.31* (3.49)	8.27 (3.17)	9.29* (3.41)	8.56 (3.10)
iEMG of CON phase (mV・sec)	4.67 (1.56)	5.05 (1.69)	5.45 (2.15)	5.62 (2.47)	6.96 (2.60)	6.28 (2.27)
Duration of ECC phase (msec)	68.4* (5.1)	64.3 (4.2)	65.6 (4.1)	64.7 (3.7)	63.1 (4.6)	62.0 (4.2)
Duration of CON phase (msec)	182.4 (14.0)	183.6 (14.0)	186.8 (10.0)	189.5 (10.4)	190.5 (9.0)	191.2 (12.8)
RMS of ECC phase (mV)	131.6 (52.8)	137.8 (47.1)	121.1 (47.9)	126.5 (45.0)	154.1 (34.6)	150.5 (41.1)
RMS of CON phase (mV)	26.9 (9.1)	29.0 (11.1)	26.8 (10.0)	29.6 (11.3)	33.8 (8.8)	34.0 (9.6)

Values are mean and standard deviation. ECC and CON mean eccentric and concentric phases, respectively. C_r and RMS mean energy cost of running per unit distance and root mean square, respectively. * $p < 0.05$ for load vs. unload. # $p < 0.05$ for downhill vs. level.

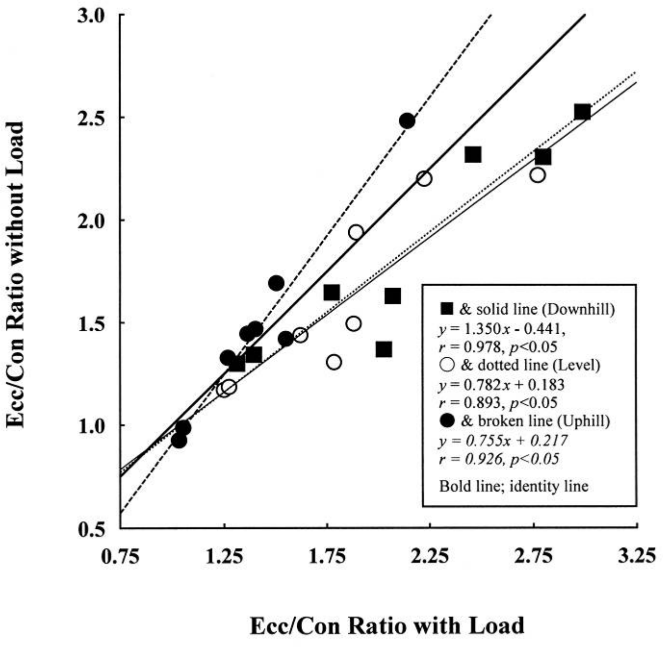
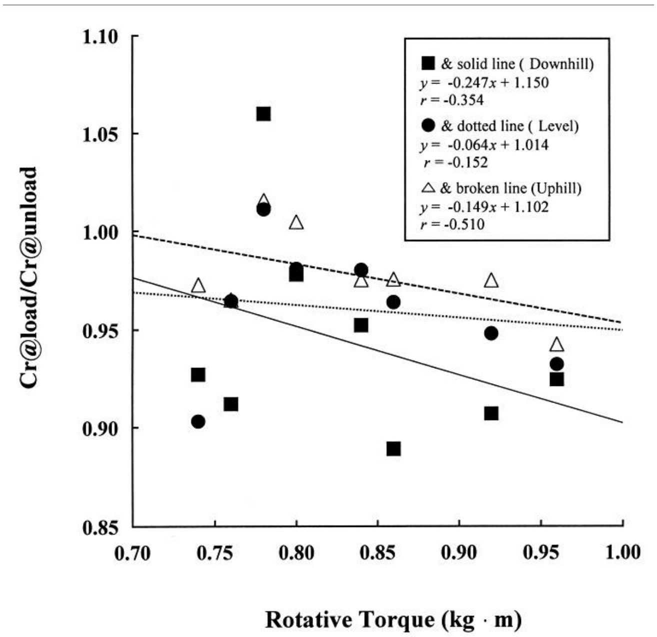


Fig. 2
Relationships of the ECC/CON ratio obtained from load and unload conditions.

a



b

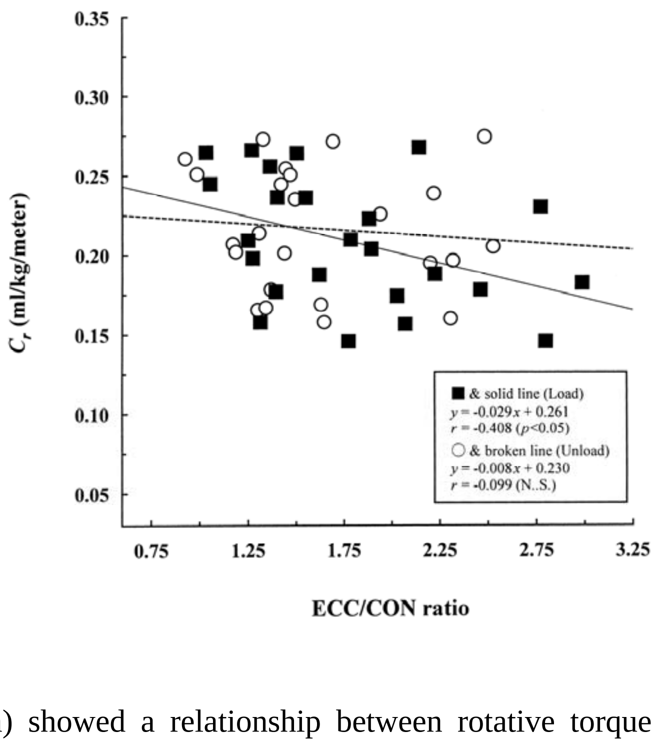


Fig. 3
Panel (a) showed a relationship between rotative torque functioning around the center of the body mass (T) and ratio of C_r with load to that without load at each terrain. Panel (b) also showed a relationship between C_r and ECC/CON ratio in the load and unload conditions. The T was produced only when the load was carried, thus, the presentation style was a little bit different between both panels.

5-4. Discussion

We examined the effects of load and gradient on the metabolic energy cost of running (C_r) and ECC/CON ratio. In support of our first hypothesis, this study was characterized by the fact that significantly lower C_r values were observed during level and downhill running with load than without load, meaning that a similar phenomenon to the *free-ride* could be observed during level and downhill running. Another important finding of this study was that significant differences of the ECC/CON ratio and C_r values between load and unload conditions were observed during level and downhill running, but not during uphill running. However, a trend for an alteration of the ECC/CON ratio was consistent with that of C_r at each terrain (Table 2). The ECC/CON ratio was also significantly correlated with C_r in the load condition (Fig. 3b). That is, our second hypothesis was also supported.

A significant decrease in the C_r was observed when carrying the load on all terrains (Table 2). This result was in line with that of Bourdin et al. (1995), but it conflicted with other studies (Cooke et al. 1991; Cureton and Sparling 1980; Myers and Steudel 1985). An important finding of the present chapter was that the absolute $\dot{V}O_2$ expressed in ml/min obtained from the load condition was not significantly different from that obtained from the unload condition, and this result was further inconsistent with the results of those previous studies (Cooke et al. 1991; Cureton and Sparling 1980; Myers and Steudel 1985). That is, the present results cannot be explained by a difference of the methodology of the evaluation. A possible explanation was that our study added load corresponding to 4.0±0.2% of the subjects' body mass. In contrast, those previous studies added around 7 ~ 10%. Bourdin et al. (1995) chose 10%, but their subjects were very fit. Thus, such a discrepancy would be dependent on the subjects' physical fitness with an association of the loaded weight. An increase in the ECC/CON ratio by the vertical loading contributed to the energy cost of running (Bourdin et al. 1993, 1995). A high ECC/CON ratio of iEMG value observed from the *gastrocnemius* during jumping exercise was associated with a low iEMG to force ratio and a high efficiency (Bosco et al. 1982). These previous studies suggested that the ECC/CON ratio reflected how much the stored elastic energy was utilized. As shown in Table 2, the increased ECC/CON ratio during level and downhill running with load could be mainly derived from an increase in the iEMG of the ECC phase, being consistent with the results of some previous studies (chapter 4; Aura and Komi 1986). However, it was surprising to note that there were no significant gradient differences in the ECC/CON ratio when running without load. This might be partly due to the large inter-individual variation of the ECC/Con ratio (Table 2). However, a strong relationship of the ECC/CON ratio was observed between load and unload conditions on each terrain, indicating that the intra-individual variation of the ECC/CON ratio was quite small (Fig. 2).

It was interesting to note that the trend for an alteration of the ECC/CON ratio was consistent with that of C_r (Table 2) and that the ECC/CON ratio was significantly correlated with C_r in the load condition (Fig. 3b), being consistent with the result of Bourdin et al. (1995). Figure 1b showed a schematic description of our hypothesis that the gradient difference could contribute only to the alteration of the ECC/CON ratio. The added load could also contribute to an increase in the ECC/CON ratio and T. No significant relationships were observed between T and the ratio of C_r with load to that without load at all terrains (Fig. 3a). This result suggested that a similar phenomenon to the *free-ride* observed in running was dependent not on the contribution of T but the utilization of the stored elastic energy. However, it was also found that the T produced in the present study was much more homogeneous than that of previous studies in walking (chapter 2 ~ 4; LaFiandra et al. 2002) and running (Bourdin et al. 1995; Cooke et al. 1991;

Cureton and Sparling 1980; Myers and Steudel 1985). In fact, LaFiandra et al. (2002) suggested that a torque transfer from the upper body segments to the lower body segments would possibly occur during walking with an extra-heavy load. As shown in Fig. 1a, it may be possible that the produced torque in the upper body segments by the load may also transfer to the lower body segments even during running. Here, it is proposed that the load on the back during running may contribute to reverse the torque produced from the upper body segments to the lower body segments, and it will provide an assistive function during running in humans. Regardless of such an argument, it was of interest to note that a trend towards a negative relationship was found between T and the C_r, suggesting that the contribution of T to the energy-saving mechanism during running will be a potential focus in future locomotion research.

The present study observed a non-significant main effect of gradient on the ECC/CON ratio (Table 1). During both running and walking, utilization of the stored elastic energy is considered to contribute to propelling the body upwards during the stance phase (Fukunaga et al. 2001; Lichtwark and Wilson 2006; Sasaki and Neptune 2006). It is interesting to note that the stretch of the Achilles tendon does not differ so much regardless of the locomotion speed (Fukunaga et al. 2001) and/or gradient (Lichtwark and Wilson 2006), suggesting that the contribution of the recoil of the elastic energy to the energy-saving phenomenon during running could be limited to some extent. Our present results shown in Table 2 supported this speculation. Leg muscles have the ability to either produce or absorb shock from the ground at different periods of the stride depending on the conditions of locomotion (Lichtwark and Wilson 2006), assuming that not only the lower leg extremities but also the upper leg extremities and their accompanying tendons might also contribute to store and/or utilize the elastic energy during running, and this will be greater when carrying a load.

5-5. Conclusion

This study was characterized by the fact that a similar phenomenon to the *free-ride* could be observed even during running. Significantly different ECC/CON ratio and C_r values were observed during level and downhill running between load and unload conditions. During uphill running, there were no significant differences in the ECC/CON ratio and C_r values between load and unload conditions. These results indicated that the alteration of the ECC/CON ratio by the load carriage was consistent with that of C_r. The ECC/CON ratio but not T was significantly correlated with C_r. Thus, it was suggested that a similar phenomenon to the *free-ride* observed in running was dependent on the utilization of the stored elastic energy