Effects of Load and Gradient on Energy Cost of Running

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Abstract This study quantified the interaction of electromyography (EMG) obtained from the vastus lateralis and metabolic energy cost of running ($C_r$; mL/(mass+load)−1·meter−1·second), an index of running economy, during submaximal treadmill running. Experiments were conducted with and without load on the back on a motor-driven treadmill on the downhill, level and uphill slopes. The obtained EMG was full-wave rectified and integrated (iEMG). The iEMG was divided into eccentric (ECC) and concentric (CON) phases with a foot sensor and a knee-joint goniometer. The ratio of ECC to CON (ECC/CON ratio) was regarded as the muscle elastic capacity during running on each slope. The $C_r$ was determined as the ratio of the 2-min steady-state $\dot{V}O_2$ to the running speed. We found a significant decrease in the $C_r$ when carrying the load at all slopes. The ECC/CON ratio was significantly higher in the load condition at the downhill and level slopes, but not at the uphill slope. A significant gradient difference was observed in the $C_r$ (down/level/up) and ECC/CON ratio (down=level>uphill). Thus, an alteration of $C_r$ by the gradient and load was almost consistent with that of the ECC/CON ratio. The ECC/CON ratio, but not the rotative torque ($T$) functioning around the center of body mass, significantly correlated with $C_r$ ($r=-0.41$, $p<0.05$). These results indicated that the ECC/CON ratio, rather than $T$, contributed to one of the energy-saving mechanisms during running with load. J Physiol Anthropol 30(4): 153–160, 2011 http://www.jstage.jst.go.jp/browse/jpa2 [DOI: 10.2114/jpa2.30.153]

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Introduction

Running is one of the major styles of bipedal locomotion in humans. It is simply defined as both feet being off the ground during one running cycle. This is in contrast to walking, where one of the feet always keeps contact with the ground. An interesting feature of a running human is characterized by the fact that changes in the kinetic and potential energy in one stride cycle are almost out of phase (Cavagna et al., 1964), meaning that the energy storage accomplished by a muscle-tendon unit and passive muscle elasticity contribute to one of the energy-saving mechanisms during running. From the viewpoint of spring-mass mechanics, running economy (RE), which is described as the ratio of steady-state oxygen consumption at a certain running velocity, has been one of the most important determinants for succeeding in long-distance running events (e.g., Saunders et al., 2004). RE ranged quite widely even in a trained-runners’ group with similar performance levels and/or similar endurance capacities (Abe et al., 1998; Daniels and Daniels, 1992). However, factors determining RE and an appropriate procedure for improving RE are still largely unknown.

It was interesting to note that Bourdin et al. (1995) observed a significant decrease in the energy cost of running ($C_r$) when carrying a load corresponding to 10% of body mass. Cooke et al. (1991) also found a non-significant increase in the $\dot{V}O_2$ even if a load corresponding to 5% or 10% of the subjects’ body mass was added during running. These results might indicate that the utilization of the elastic energy produced in the muscle-tendon unit of the leg extremities increased during running by the load carriage. From another point of view, the energy expenditure during walking with load does not always increase as a function of the carried weight in Eastern African women (Charteris et al., 1989; Maloiy et al., 1986). Those authors named this phenomenon as a ‘free-ride,’ in which the load was carried on the head. Indeed, Abe et al. (2004, 2008) also found a significant decrease in the energy cost of walking when carrying the load on the back. These previous studies showed that carrying the load on the upper back during running and/or walking resulted in a significant decrease in the
energy cost of locomotion, because “rotative torque functioning around the center of body mass (Fig. 1)” could save energy consumption during locomotion. As far as we know, those reports were the only evidence that proposed a significant decrease in the energy cost of locomotion.

With regard to running, it is known that the utilization of the stored elastic energy in a series of muscle-tendon units of the lower leg extremities has been recognized as one of the major determinants of RE (Cavagna et al., 1964). Although it has been quite complicated to measure the utilization of the elastic energy during dynamic exercise in humans (Kaneko, 1990), the electromyography (EMG) technique is a potential tool for measuring the utilization of the stored elastic energy of the vastus lateralis (VL) during dynamic exercise (Aura and Komi, 1986a, b; Bosco et al., 1982). These authors found that the ratio of the eccentric (ECC) to concentric (CON) phases of integrated electromyography (iEMG) obtained from the quadriceps femoris during knee extension exercise significantly correlated with the mechanical efficiency of pure positive work during stretch-shortening cycle exercise. Bourdin et al. (1995) and Abe et al. (2007) applied this surface EMG technique to quantify ‘muscle elastic capacity’ during running and showed a close relationship between EMG characteristics and the energy cost of running per unit distance, which is substantially related to RE.

However, we should make some considerations for the complicated interaction effects of the load carriage on RE, because the load carriage will induce increases in both utilization of the stored elastic energy and another factor as described in Fig. 1. For example, interaction effects between the rotative torque (T) functioning around the center of the body mass and a concomitant excessive burden on the lower leg muscles influenced the energy cost of human walking with load (Abe et al., 2004, 2008). The former effect was treated as having a positive nature for saving production of the propulsive force effected by the leg locomotor muscles, and the latter was treated as a negative effect on the energy cost of running (Fig. 2). During running with load, the Cr will possibly be decreased by the load carriage due to effects of both utilization of the stored elastic energy and T. Thus, the effect of either utilization of the stored elastic energy or T on the Cr should be distinctly examined to explain the possible mechanisms of a similar phenomenon to the free-ride during running.

Thus, if a possible decrease in the Cr with load is either T or utilization of the stored elastic energy, then the EMG activities of the leg muscle will be associated with a gradient difference and/or load carriage. It was hypothesized that a possible decrease in the Cr with load could be observed during running and that the alteration pattern of the EMG activities of the leg muscles will be associated with that of Cr. The first purpose of this study was to test whether a similar phenomenon to free-ride could be observed during running. The second purpose was to examine the interrelationship of the EMG activities, T and Cr with load carriage at various slopes.

**Methods**

**Participants**

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 ($\dot{V}O_{2max}$) 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⁻¹·min⁻¹ ranging from 57.3 to 73.5 mL·kg⁻¹·min⁻¹, respectively. Informed consent from each subject and approval from the ethical committee were obtained for all procedures.

Maximal running test

A $\dot{V}O_2_{\text{max}}$ 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). Breath-by-breath oxygen consumption ($\dot{V}O_2$: mL·kg⁻¹·min⁻¹), carbon dioxide output and ventilation were measured using a gas analyzer (AE-300S, Minato, Osaka), which was calibrated before the tests with room air and reference gases of known concentrations. After a warm-up period of about 5 min with the treadmill running at 200 m·min⁻¹ for highly-trained runners and 191.7 m·min⁻¹ for well-trained runners and the soccer player, respectively, the subjects started running at a 0% gradient during the first 2 min of the $\dot{V}O_2_{\text{max}}$ test. At every 1 min, the gradient was increased by 1% until the subjects felt exhausted. When a given criterion was met (a plateau or a drop in $\dot{V}O_2$ and respiratory exchange ratio greater than 1.10), the $\dot{V}O_2$ slow component could be produced if $\dot{V}O_2_{\text{max}}$ test, a submaximal running test was applied. Each subject ran on the treadmill with a freely chosen step cadence. The volunteers ran on the treadmill for 5 minutes at either velocity, and the final 2-min $\dot{V}O_2$ was used to calculate $C_r$. The gradient was set at 0% (level), +5% (uphill) and −5% (downhill) due to a consideration of the practical application for daily outdoor activities. The subjects wore underwear, shirts, socks, gym shorts and the same lightweight training shoes with different sizes (WAVE WING FF, Mizuno, Osaka). The load consisted of small grains of lead packed into a nylon cloth, and it was installed in the upper back of a weight jacket. The net weight of the jacket was 0.3 kg, thus, the total weight of the load was set at 2.3 kg, corresponding to 40±0.2% of each subject's body mass. This load weight seemed to be relatively lighter than that of other studies (Bourdin et al., 1995; Cureton and Sparling, 1980), primarily because habitual distance runners and a soccer player were intermixed. It was also noted that the volunteers ran at 5% uphill with load carriage, indicating that the cardiovascular $\dot{V}O_2$ slow component could be produced if the $\dot{V}O_2$ exceeded the anaerobic threshold (Poole et al., 1988). This was another reason for employing lighter load mass in this study. However, this lighter load mass may bring useful practical application for leisure purposes. We measured a length from the center of the loaded mass to the trochanter major, from which the center of the body mass could be located during running (Cavagna et al., 1964). The length was multiplied by 2 kg, which was the weight of the small grains of lead, to obtain $T$ in each subject ($T$: kg·m). The $T$ can be defined by the following equation:

$$T=AB\times\text{load weight}$$

where $AB$ is the radius of rotation (Fig. 1).

Previous studies have evaluated the RE using different treadmill velocities (e.g., Conley and Krahenbuhl, 1980; Daniels and Daniels, 1992), which makes it difficult to compare with the obtained results. Thus, the energy cost of running ($C_r$: mL·kg⁻¹·min⁻¹) was used for expressing RE based on the concept used by Minetti et al. (1994) and Ferretti et al. (1991). The $C_r$ was calculated by the ratio of steady-state oxygen consumption ($\dot{V}O_2$: mL·kg⁻¹·min⁻¹) to the running velocity ($v$: m·min⁻¹) as shown in the following equation.

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

EMG sampling and analysis

The EMG signal from the 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 (Abe et al., 2007, 2010), the electrodes were initially placed over the VL, vastus medialis and rectus femoris, however, the amplitude of the EMG signal from the VL was the largest. Therefore, only the VL of the dominant leg was selected as a target muscle not to disturb the individual natural running mechanics. As described by previous studies (Aura and Komi, 1986a, b; Bosco et al., 1982), 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 heel contact. Changes in the knee joint 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. This apparatus made it possible to divide the working muscle activation into three different phases: preactivation (PRE), ECC and CON. As shown in Fig. 3, the PRE and ECC phases of VL activation during running could be divided when the pressure signal began to increase from the baseline. The ECC and CON phases could be divided using knee joint angle information. After the foot contact on the treadmill, the knee joint angle changes from stretch (eccentric for VL) to shortening (concentric for VL). The changing point of the knee joint angle was regarded as a separation between ECC and CON. 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,
ADInstruments, Tokyo). The observed EMG signals were high-pass filtered at 10 Hz with a second-order Butterworth digital filter and were full-wave rectified. Then the rectified EMG was integrated (iEMG) in each phase. The ratio of the ECC to CON (ECC/CON ratio) phases of the obtained iEMG was regarded as the “muscle elastic capacity,” which could be a good index of effectiveness in the stretch-shortening cycle (Aura and Komi, 1986b; Bourdin et al., 1995). To minimize intra-individual variability, the storage of the electric signals was repeated 4 to 6 times in each sampling session. The iEMG of each phase was also evaluated by a root mean square value (RMS). The total number of analyzed steps ranged from 30 to 50 in each subject. The obtained dependent variables at each session were averaged in each subject. Thus, the observed dependent variables were expressed as the individual representative value.

Statistical analysis

The observed values were presented as the mean and standard deviation (S.D.). A two-way repeated measure of ANOVA with two within-subject effects was used to test for the main effects of load (2 levels) and gradient (3 levels) on the dependent variables. When a significant $F$ value was present, 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 relationship of the appropriate data set was evaluated by a single regression analysis. The statistical significance was established at the 0.05 probability level.

Results

A significant main effect of load and/or gradient on other dependent variables is summarized in Table 1. A significant main effect of load was found in the iEMG of the ECC phase at all slopes and in the iEMG of the CON phase between uphill and downhill slopes. Another gradient difference was also observed in the RMS of the CON phase (level<downhill<uphill). There were no significant interaction effects of load and gradient on the dependent variables, except the ECC/CON ratio.

Figure 4A shows a multiple comparison of the $C_r$ values at each slope. The obtained $C_r$ values in the load and unload conditions were $0.165 \pm 0.015$ vs. $0.175 \pm 0.017$ mL·kg$^{-1}$·m$^{-1}$ for the downhill slope, $0.206 \pm 0.015$ vs. $0.215 \pm 0.017$ mL·kg$^{-1}$·m$^{-1}$ for the level slope and $0.255 \pm 0.014$ vs. $0.260 \pm 0.012$ mL·kg$^{-1}$·m$^{-1}$ for the uphill slope, respectively. There were significant differences between load and unload conditions at all slopes. A significant gradient difference was also observed at each slope.

Figure 4B also shows a multiple comparison of the ECC/CON ratio at each slope. The ECC/CON ratio in the load and unload conditions was $2.104 \pm 0.613$ vs. $1.805 \pm 0.500$ for the downhill slope, $1.838 \pm 0.499$ vs. $1.620 \pm 0.437$ for the level slope and $1.415 \pm 0.350$ vs. $1.469 \pm 0.483$ for the uphill slope, respectively. In these comparisons, there were significant differences at the downhill and level slopes, but not at the

Table 1 Summary of observed values at each condition

<table>
<thead>
<tr>
<th></th>
<th>Load</th>
<th>Unload</th>
<th>Load</th>
<th>Unload</th>
<th>Load</th>
<th>Unload</th>
</tr>
</thead>
<tbody>
<tr>
<td>iEMG of ECC phase (mV·sec)</td>
<td>9.06* (3.00)</td>
<td>8.53 (3.01)</td>
<td>9.31* (3.49)</td>
<td>8.27 (3.17)</td>
<td>9.29* (3.41)</td>
<td>8.56 (3.10)</td>
</tr>
<tr>
<td>iEMG of CON phase (mV·sec)</td>
<td>4.67 (1.56)</td>
<td>5.05 (169)</td>
<td>5.45 (2.15)</td>
<td>5.62 (2.47)</td>
<td>6.96* (2.60)</td>
<td>6.28* (2.27)</td>
</tr>
<tr>
<td>Duration of ECC phase (msec)</td>
<td>68.4* (5.1)</td>
<td>64.3 (4.2)</td>
<td>65.6 (4.1)</td>
<td>64.7 (3.7)</td>
<td>63.1 (4.6)</td>
<td>62.0 (42)</td>
</tr>
<tr>
<td>Duration of CON phase (msec)</td>
<td>182.4 (14.0)</td>
<td>183.6 (14.0)</td>
<td>186.8 (10.0)</td>
<td>189.5 (10.4)</td>
<td>190.5 (9.0)</td>
<td>191.2 (12.8)</td>
</tr>
<tr>
<td>RMS of ECC phase (mV)</td>
<td>131.8 (41.8)</td>
<td>132.5 (45.4)</td>
<td>141.8 (51.7)</td>
<td>128.5 (49.5)</td>
<td>147.5 (53.3)</td>
<td>139.6 (53.6)</td>
</tr>
<tr>
<td>RMS of CON phase (mV)</td>
<td>25.6 (8.4)</td>
<td>27.5 (8.7)</td>
<td>29.0 (11.0)</td>
<td>29.3 (11.9)</td>
<td>36.2* (12.4)</td>
<td>32.6* (10.4)</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$)</td>
<td>34.3* (3.6)</td>
<td>34.6* (3.3)</td>
<td>42.9 (3.1)</td>
<td>42.5 (2.9)</td>
<td>52.9 (2.7)</td>
<td>51.5 (18)</td>
</tr>
<tr>
<td>%$\dot{V}O_2_{max}$ (%)</td>
<td>54.4* (7.9)</td>
<td>54.9* (8.0)</td>
<td>67.9 (8.4)</td>
<td>67.2 (7.4)</td>
<td>83.7 (8.8)</td>
<td>81.4 (8.1)</td>
</tr>
</tbody>
</table>

Values are mean and standard deviation. ECC and CON mean eccentric and concentric phases, respectively. RMS is root mean square. $\dot{V}O_2$ is oxygen consumption per body mass. * unload<load; # downhill<uphill; ^ level=downhill<uphill; $ level<downhill<uphill.
uphill slope. A post-hoc test further revealed that there was a significant gradient difference of the ECC/CON ratio between downhill and uphill slopes in the unload conditions. Another gradient difference was also observed in the load condition at all slopes. There was a significant interaction effect of load carriage and gradient difference on the ECC/CON ratio. In particular, the ECC/CON ratio was greater in the load condition at downhill and level slopes, while it had an opposite tendency at the uphill slope.

Figure 5 showed that either $T$ or the ECC/CON ratio had a significant impact on the $C_r$. However, the ECC/CON ratio, but not $T$, was significantly correlated with $C_r$ when carrying the load (ECC/CON ratio; $r = 0.41$, $p < 0.05$). In the unload condition, $C_r$ was not significantly correlated with ECC/CON ($r = 0.10$, n.s.).

**Discussion**

In support of our first hypothesis, we found that significantly lower $C_r$ values were observed at all slopes with load than without load, suggesting that a similar phenomenon to *free-ride* could be observed during running. There was a symmetrical alteration of $C_r$ by the gradient and load carriage with that of the ECC/CON ratio, suggesting that an alteration of $C_r$ values was almost consistent with that of the ECC/CON ratio. Otherwise, $T$ was not significantly correlated with $C_r$.

An increase in the ECC/CON ratio by vertical loading has been shown to contribute to a decrease in the energy cost of running (Bourdin et al., 1995), which means a substantial increase in RE. A high ECC/CON ratio of the iEMG value observed from the gastrocnemius during the jumping exercise has been associated with a low iEMG to force ratio and a high efficiency (Aura and Komi, 1986a, b; Bosco et al., 1982). These previous studies suggested that the ECC/CON ratio reflected the utilization of stored elastic energy. The increased ECC/CON ratio during level and downhill running with load in this study may be primarily derived from an increase in the iEMG of the ECC phase (Table 1), being consistent with the result of a previous study (Aura and Komi, 1986a), even though no significant difference in the ECC/CON ratio between load and unload conditions was observed at the uphill slope (Fig. 4). Our present study employed freely chosen step frequency at each condition, however, the duration of CON and ECC phases was almost constant (Table 1). This result suggested that the internal work due to the movement of body segments during running with and without load must be almost constant at each condition.
Minetti et al. (1994) suggested that the positive work, which consisted of concentric muscle contractions in the major locomotor muscles, abruptly increased during uphill running, being consistent with our results exhibiting a significant increase in the iEMG and/or RMS of the CON phase (Table 1). This result was partly supported by the results of Abe et al. (2007). Prior studies have reported that the elastic energy could be stored only in the ECC phase, and the energy expenditure in the CON phase was 3-5 times greater than that of the ECC phase (Aura and Komi, 1986a, b; Bosco et al., 1982; Minetti et al., 1994). In our study, no significant difference in the ECC/CON ratio was observed between load and unload conditions at the uphill slope (Fig. 4B). This finding may be due to a significantly larger iEMG of the CON phase than that at other slopes (Table 1). Because locomotor muscle activities of the ECC phase were relatively greater than those of the CON phase at the downhill and level slopes (Minetti et al., 1994), the elastic energy stored in the ECC phase would play a crucial role in the determination of \( C_r \) during downhill and level running.

We observed that an alteration of \( C_r \) by the gradient and load was almost consistent with that of the ECC/CON ratio (Figs. 4A and 4B). A significant negative relationship was observed between \( C_r \) and ECC/CON ratio \((r = -0.41, p<0.05, \text{Fig. 5B})\), while \( T \) was not significantly correlated with \( C_r \) (Fig. 5A). Thus, our second hypothesis was partly supported. During both running and walking, utilization of the stored elastic energy contributes to propelling the body upwards during the stance phase (Fukunaga et al., 2001; Lichtwark and Wilson, 2006; Sasaki and Neptune, 2006). Notably, the stretch of the Achilles tendon does not differ so much regardless of the gait speed (Fukunaga et al., 2001) and/or gradient (Lichtwark and Wilson, 2006), indicating that production of the elastic energy by the Achilles tendon for contributing to the energy-saving phenomenon during running could be limited. Our present result shown in Fig. 4 supported this speculation. Leg muscles have the ability to either produce elastic energy or absorb shock from the ground at different periods of the stride depending on the conditions of locomotion (Lichtwark and Wilson, 2006). This follows the assumption that not only lower leg muscles but also upper leg muscles and their accompanying tendons contribute to store and/or utilize the elastic energy during running, and this storage potential will be greater when carrying a load.

It was particularly important to note that the experimental setup of the present study presupposes that the gradient difference will contribute to an experimental manipulation of the utilization of the stored elastic energy and that the load carriage will contribute to an increase in not only the utilization of the stored elastic energy but also \( T \) (Fig. 2). Figure 2 showed a schematic description of our hypothesis that the gradient difference contributed only to an experimental manipulation of the ECC/CON ratio, and the added load contributed to an increase in both the ECC/CON ratio and \( T \), because the added load could produce a propulsive torque as shown in Fig. 1. In other words, this setup can clarify the impact of either load or gradient on \( C_r \). In our study, a non-significant relationship was observed between \( T \) and \( C_r \) (Fig. 5A), while a significant negative relationship was observed between the ECC/CON ratio and \( C_r \) (Fig. 5B). It was also important to note that the correlation coefficient seemed to be low \((r = -0.41)\), although this value was possibly dependent on a relatively smaller range of \( T \) values in our study. However, previous studies of walking (Abe et al., 2004, 2008; LaFiandra and Harman, 2004) and running (Bourdin et al., 1995; Cooke et al., 1991; Cureton and Sparling, 1980; Myers and Steudel, 1985) employed more heterogeneous \( T \) values than those of the present study.

Although training-induced improvement of RE has been investigated in many studies (e.g., Saunders et al., 2004), no agreement for an appropriate method for it has been established. For example, strength training for lower leg extremities improved RE (Saunders et al., 2006; Støren et al., 2008; Turner et al., 2003), but other studies were opposed to this (Palmer and Sleivert, 2001; Vassilis et al., 2008). Our present study has not specified a longitudinal alteration of RE by using a load carriage during training, however, as far as we know, vertical loading could be the only procedures for a temporal alteration of RE due to an increase in the utilization of the stored elastic energy. This study showed a mechanism for explaining a possible decrease in the \( C_r \) with load was mainly dependent on the increase in the utilization of the stored elastic energy, but not on \( T \). Thus, future research should focus on the longitudinal training effect of load carriage on the individual \( C_r \) without load.

Several previous studies have denied the possible existence of a similar phenomenon to free-ride during running. Relatively less information with regards to running with load has been available for leisure applications, because previous studies in terms of walking with load were mostly aimed at workers’ safety and/or military purposes (e.g., Knapik et al., 2004). Thus, the existence of a similar phenomenon to free-ride during running is still open. Cureton and Sparling (1980) showed that the addition of 7.5% body weight to the trunk during submaximal running significantly increased \( VO_2 \) by 0.16 L·min\(^{-1}\). However, it was important to note that the oxygen cost significantly decreased if such an increase in the \( VO_2 \) was expressed as mL·{mass+load}\(^{-1}\)·min\(^{-1}\). Myers and Steudel (1985) observed that a loaded mass of 3.6 kg during running resulted in a 3.7% increase in the energy consumption. However, it was interesting to note that these authors added load around waist, each upper shank or each ankle, meaning that \( T \), described in Fig. 1, never functioned in those conditions. In our study, a significant decrease in the \( C_r \) was observed when carrying the load at all slopes (Fig. 4A), being partly consistent with the results of Bourdin et al. (1995). It was also interesting to note that our present study added load corresponding to 4.0±0.2% of the subjects’ body mass, being almost consistent with that of Myers and Steudel (1985), whereas other previous studies added 10% of the subjects’
body mass in well- or highly-trained athletes (Bourdin et al., 1995; Cooke et al., 1991). It was assumed that such a heavy load was not always necessary to add for investigating the existence of a similar phenomenon to free-ride during running, because steady-state \( \dot{V}_O_2 \) could not be obtained due to the cardiovascular \( \dot{V}_O_2 \) slow component. In the present study, a high \( %\dot{V}_O_{2max} \) was observed during uphill running with load (Table 1). Such a high \( %\dot{V}_O_{2max} \) would exceed the “anaerobic threshold,” suggesting that the cardiovascular \( \dot{V}_O_2 \) slow component might occur. Indeed, the average \( \dot{V}_O_2 \) increased 67.3±72.2 mL·min\(^{-1}\) (2.4±2.5%) between the 3rd minute (2880.8±354.5 mL·min\(^{-1}\), from 3’00” to 3’20” for 20-sec duration) and the 5th minute (2948.0±349.3 mL·min\(^{-1}\), from 4’40” to 5’00” for 20-sec duration) during uphill running with load. This slight increase in the \( \dot{V}_O_2 \) was in association with a “quasi” steady-state even if the exercise intensity exceeded the “anaerobic threshold” (Poole et al., 1988). It should be noted that the obtained \( C_t \) during such a hard condition (i.e., uphill running with load) could be assessed by both aerobic and anaerobic metabolism, which was a limitation of this study.

The results of the present study showed the existence of a similar phenomenon to free-ride during running, even though it was necessary to point out that it was highly dependent on the methodology of evaluation and load position. Another notable finding of this study was that a mechanism for explaining such a phenomenon during running was not by a rotative torque functioning around the center of body mass (\( T \)) but by an increase in the recoil of the stored elastic energy.

In conclusion, we found that a similar phenomenon to free-ride was observed during running with load at all slopes (Fig. 4A). An alteration of \( C_t \) by the gradient and load was almost consistent with that of the ECC/CON ratio (Fig. 4B). The ECC/CON ratio, rather than \( T \), significantly correlated with \( C_t \) (Figs. 5A and 5B). These results indicated that the ECC/CON ratio rather than \( T \) had a stronger impact on the energy cost of running.

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