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：

Chapter 4

Availability of EMG characteristics for evaluating muscle elasticity during 90-min prolonged running

4-1. Introduction

Running is one of the most common movement styles for locomotion. Numerous studies have adopted the surface electromyography (EMG) technique as a noninvasive biomechanical technique for human musculoskeletal system measurement during exercise. Aura and Komi (1986) 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 was significantly correlated with the mechanical efficiency of pure positive work during stretch-shortening cycle exercise. Bourdin et al. (1995) applied this surface EMG technique to quantify ‘muscle elasticity’ during running and showed a close relationship between EMG characteristics and the metabolic energy cost of running (C_r) as a common index to assess running economy, which is substantially related to running efficiency.

Several studies have shown that C_r significantly increased after prolonged running (Brueckner et al. 1991; Candau et al. 1998; Guezennec et al. 1996; Morgan et al. 1996; Xu and Montgomery 1995), and some of these previous studies suspected an alteration in running mechanics during prolonged running (Candau et al. 1998; Morgan et al. 1996). If running mechanics changes during prolonged running, then so does the activation pattern of the working muscles. It was hypothesized that the ratio of the eccentric to concentric (ECC/CON) phases of the leg working muscles during running would change and that this might reflect the alteration in the muscle activity pattern. Even though the surface EMG technique has been viewed as having a great deal of potential to explain several running-related biomechanical questions, little is known regarding its interaction with metabolic responses during prolonged running. The purpose of this chapter was to quantify the interaction of the ECC/CON ratio of the leg working muscles and metabolic energy cost during prolonged running.

For examining whether the *free-ride* phenomenon exists during running in the next chapter, some considerations are required. The energy-saving mechanism for running has been explained by a utilization of the stored elastic energy (Saibene and Minetti 2003). Bourdin et al. (1995) showed that the utilization of the stored elastic energy was significantly increased when running with load. This was not a necessary consideration during walking, because it has been considered that the elastic energy cannot be counted for one of the energy-saving mechanisms during walking (Cavagna et al. 1963). Previous chapters of this thesis employed load carriage model as an experimental set-up for examining the existence of the *free-ride* phenomenon during walking. However, for running, the load carriage could significantly alter not only the utilization of the stored elastic energy (Bourdin et al. 1995) but also the rotative torque functioning around the center of the body mass, defined in the first chapter. Thus, the present chapter focused on the availability of the ECC/CON ratio for evaluating the muscle elasticity during running. In particular, the endurance reliability of the ECC/CON ratio observed from 90-min prolonged running was assessed in this chapter.

4-2. Methods

4-2-2. Subjects

Experiments were performed on seven male novice distance runners. They were recruited on the requirement that their running experience was less than 6 months because it was expected that prolonged running would cause an alteration of the running mechanics of novice runners. The mean age, body weight, and height of the subjects were 19.3±1.1 years, 59.1±5.3 kg, and 169.7±7.2 cm, respectively. Informed consent from each subject and approval from the ethical committee were obtained for all procedures.

4-2-2. Measurements

A $\dot{V}O_{2max}$ test was initially performed on a motor-driven treadmill (Newroad 21S, Takei, Japan) 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. The expired gas volume and concentration were analyzed during the final 30 sec of each minute. The highest value of the 1-min $\dot{V}O_2$ was regarded as the individual's $\dot{V}O_{2max}$.

The submaximal exercise protocol for sampling expired gas and electric signals is described in Fig. 1. The treadmill velocity for the prolonged running was set at 12.0 km/h for middle-distance runners (n = 3) and 13.2 km/h for long-distance runners (n = 4). Those submaximal running velocities corresponded to about 10% slower than the training velocity of each subject. Each subject ran on the same treadmill with a freely chosen step cadence. Submaximal metabolic measurement was performed at the 10th and 90th min during prolonged running using the Douglas bag method (Muraki et al. 1996). The determination of C_r followed previous studies (Bourdin et al. 1995; Abe et al. 1998). In brief, the C_r expressed in ml·kg^{-1}·m^{-1} was determined from the ratio of oxygen consumption ($\dot{V}O_2$; ml·kg^{-1}·min^{-1}) above the resting value (net $\dot{V}O_2$) to the running speed (v: m/min):

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

Five ml·kg^{-1}·min^{-1} 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 respiratory exchange ratio (R: $\dot{V}CO_2/\dot{V}O_2$) was obtained at each sampling session.

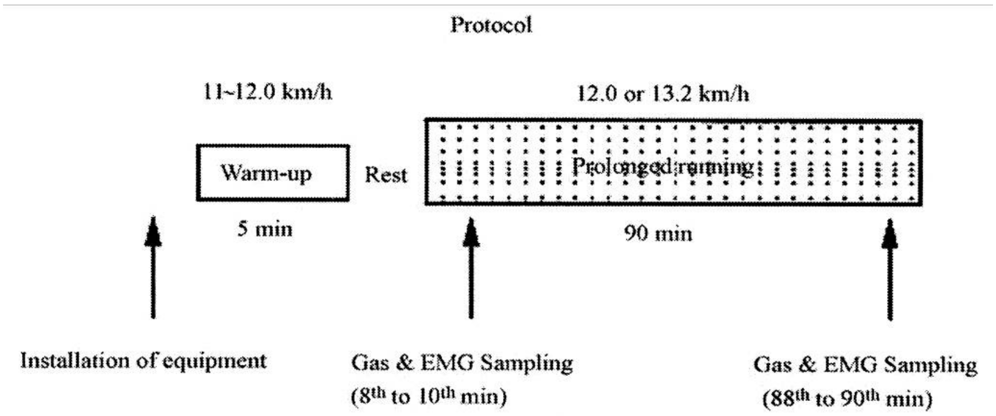

Fig. 1
Experimental protocol for sampling expired gas and electric signals.

The EMG signal from the *vastus lateralis* (VL) was measured with bipolar Ag-AgCl surface electrodes (NM-420S, Nihon Kohden, Japan; interelectrode distance = 2 cm) and a multi-telemetry system (Multi Telemeter System WEB-5000, Nihon Kohden, Japan). In the preliminary work, electrodes were placed over the VL, *vastus medialis*, and *rectus femoris*. However, the amplitude of the EMG signal from the VL was shown 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 force platform (Model 1292, Takei, Japan) was set under the treadmill to detect alterations in contact and flight phases. Changes in the knee-joint angle from the dominant leg were recorded with an electric goniometer (model M-180, P & G, Japan). The goniometer was secured with an elastic belt to each subject's leg. The electrodes were secured with surgical tape, and electrode and goniometer wires were secured with an elastic belt to minimize movement artifacts. These apparatus made us possible to divide the working muscle activation into three different phases: preactivation (PRE), ECC, and CON. As shown in Fig. 2, 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 (PC9801-RA, NEC, Japan) through an amplifier (DSA-601B, Minebea, Japan) and a 12-bit analog-digital conversion system (Analog Pro-2, Canopus, Japan). The observed EMG signals were high-pass filtered at 15 Hz with a second-order Butterworth digital filter and full-wave rectified. Then, the root mean square EMG was integrated (iEMG). To minimize intra-individual variability, the storage of the electric signals was repeated 4 to 6 times at each sampling session. The total number of analyzed steps ranged from 30 to 50 in each subject. The obtained ECC/CON ratio during each session was averaged for each subject. Thus, the ECC/CON ratio was expressed as the individual representative value (see Fig. 3).

4-2-3. Statistical analysis

The observed values were presented as the mean and standard deviation (S.D.). A paired *t*-test was used for the data comparison, and the correlation between C_r and ECC/CON ratio was determined by a linear regression analysis. Statistical significance was set at $p < 0.05$.

4-3. Results

Individual $\dot{V}O_{2max}$ values ranged from 50.8 to 61.7 ml·kg^{-1}·min^{-1} with an average value of 56.8±4.5 ml·kg^{-1}·min^{-1}. The average *R* value at the 10th and 90th min was 0.92±0.04 and 0.93±0.08, respectively.

Fig. 2 shows representative examples of alterations in the knee-joint angle, iEMG in the VL, and the pressure signal from the force platform. The average iEMG value of the CON phase was significantly increased from the 10th min to 90th min during exercise, as shown in Table 1 ($p < 0.05$). In contrast, the average iEMG value of the ECC phase did not significantly alter during running. The ECC/CON ratio at the 90th min of running (1.34±0.19) was significantly decreased compared to that at the 10th min (2.01±0.26, $p < 0.05$). The average C_r value observed at the 90th min was significantly higher than that observed at the 10th min ($p < 0.05$). Therefore, we observed a significant correlation between C_r and the ECC/CON ratio ($r = -0.702$, $p < 0.05$, Fig. 3). That is, a decrease in the ECC/CON ratio depended on an increase in muscle activity during the CON phase.

Table 1
Summary of observed values

	10th min	90th min
Duration of ECC phase (ms)	74.7 (10.6)	75.2 (9.0)
Duration of CON phase (ms)	150.4 (9.5)	151.0 (6.7)
iEMG of ECC phase (mV s)	17.1 (6.4)	15.4 (6.6)
iEMG of CON phase (mV s)	9.0 (3.4)	11.6* (4.1)
ECC/CON ratio	2.012 (0.241)	1.335* (0.145)
C_r (ml kg m^{-1})	0.177 (0.006)	0.205* (0.004)

Values are mean (S.D.).
* Significantly differs from 10th min ($P < 0.05$).

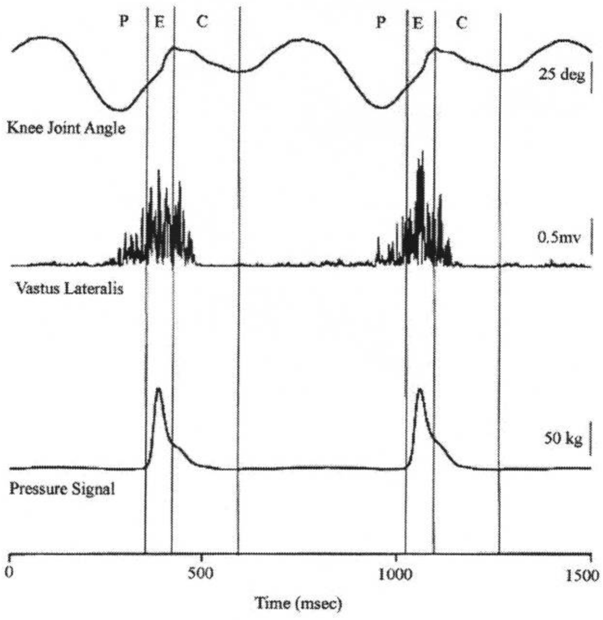

Fig. 2
A typical trace of EMG for the *m. vastus lateralis* during prolonged running at 12.0 km/h. The contact phase was divided into eccentric (E) and concentric (C) phases by an alteration in knee joint angle. Preactivation (P) and E phases were divided by the pressure signal from the force platform.

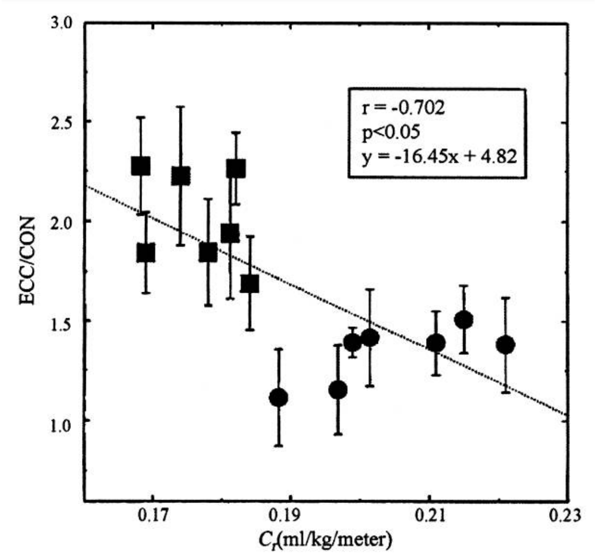

Fig. 3
Relationship between individual C_r values and ECC/CON ratio. Filled squares and circles represent 10th and 90th min, respectively.

4-4. Discussion

In support of the focus of this chapter, the EMG signals were successfully collected during 90-min prolonged running. Thus, the endurance reliability of the ECC/CON ratio was hereby confirmed.

We found that the ECC/CON ratio obtained from the VL was significantly decreased during 90-min prolonged running, corresponding with an increase in C_r (Table 1). Therefore, we found a very close relationship between C_r and the ECC/CON ratio during prolonged running (Fig. 3). Bosco et al. (1982) indicated that a high ECC/CON ratio of the iEMG value observed from the *gastrocnemius* during jumping exercise was associated with a low iEMG to force ratio and a high efficiency, suggesting that the ECC/CON ratio reflected the utilization of stored elastic energy. Bourdin et al. (1995) also showed that the ECC/CON ratio during temporal running remained unchanged between loaded and unloaded conditions. They speculated that the ECC/CON ratio could explain a large part of the interindividual variations in C_r. Judging from those findings, if Bourdin's speculation is correct, then the observed change in the ECC/CON ratio in our study would also be significantly correlated with the change in C_r. In the present study, novice distance runners were employed so that the mechanics of running (e.g., duration of ECC and/or CON phase) would alter during 90-min prolonged running. However, the results of the present study clearly showed that the duration of neither ECC nor CON phases altered during 90-min prolonged running (Table 1). That is, the ECC/CON ratio was not affected by an alteration of the duration of each phase. The change in the ECC/CON ratio observed in this study might be associated with a decrease in the utilization of stored elastic energy, resulting in an increase in iEMG during the CON phase, although the iEMG during the ECC phase did not alter (Table 1). Kouzaki et al. (2002, 2004) recently reported that fluctuations in force production occurred in the knee extensor synergistic muscles during low-level sustained contractions. It was unfortunately noted that the present study did not measure synergistic muscle activities, but the results of the present study and Kouzaki's studies (2002, 2004) suggest the following mechanisms:

1. A decrease in the utilization of stored elastic energy occurred in the VL during prolonged running.
2. Further force production by the VL became necessary to maintain running at a constant speed, resulting in an increase in muscle activation during the CON phase.
3. The metabolic energy cost of running increased in association with a decrease in the ECC/CON ratio.

The present study also showed that the average C_r value significantly increased during 90-min prolonged running, as previously reported (Brueckner et al. 1991; Guezennec et al. 1996; Xu and Montgomery 1995; Candau et al. 1998). It is of interest to note that the previous studies reported a 5% or 10% increase in the C_r value during prolonged running. In contrast, our results showed around a 15% increase in the average C_r value during 90-min prolonged running. Previous studies employed well or highly trained athletes, while our study used novice runners. Thus, such an inconsistency could be dependent on the subjects' suitability to prolonged running. The present study confirmed that the average *R* value during prolonged running was less than 1.0 at both sampling sessions, demonstrating that the physiological mechanisms behind the increase in the C_r in our study could be different from the cardiovascular $\dot{V}O_2$ drift reported by Poole et al. (1988). Thus, it is currently assumed that the prolonged exercise-induced muscle fatigue rather than the cardiovascular $\dot{V}O_2$ drift would predominantly induce an increase in C_r during prolonged running.

4-5. Conclusion

The ECC/CON ratio obtained from the VL significantly decreased during 90-min prolonged running in novice distance runners, which was caused by an increase in iEMG of the CON phase. Meanwhile, C_r increased throughout the prolonged running. These results suggest that an increase in C_r during 90-min prolonged running would be associated with a decrease in the ECC/CON ratio.