Relation between 1,500-m running performance and running economy during high-intensity running in well-trained distance runners

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Abstract  Running economy (RE), which is evaluated at an exercise intensity below the lactate threshold (LT), is recognized as the most important physiological variable for estimating running performance. However, middle- and long-distance athletes run above LT intensity during their competitive events. This study elucidates the relation between 1,500-m running performance and physiological variables, including RE measured at intensities below and above the LT. The study included 34 male distance runners (1,500-m velocity: 22.2 ± 0.8 km·h⁻¹, equivalent to race times of 4′03″2 ± 8″5). RE was calculated at four running velocities selected to provide intensities of 90%LT and 95%LT below LT (RE₈LT) and 105%LT and 110%LT above LT (RE₉LT). RE was determined from aerobic energy metabolism, calculated from oxygen uptake and the respiratory exchange ratio, combined with anaerobic energy metabolism, calculated from the change in blood lactate concentration. Results show that the 1,500-m velocity was not related to maximal oxygen uptake (V̇O₂max) or LT intensity (r = 0.19 and 0.10, respectively). This velocity correlated with both RE₈LT and RE₉LT, with the correlation coefficient being higher for RE₈LT (r = −0.65 and −0.71 vs −0.56 and −0.58). Furthermore, the coefficient of determination for 1,500-m velocity determined from V̇O₂max, LT intensity and RE₈LT was higher than that determined from V̇O₂max, LT intensity and RE₈LT (R² = 0.603 and 0.640 vs 0.415 and 0.543). These results suggest that RE measured at an intensity above LT intensity may be better than other physiological variables for estimating 1,500-m running performance.

Keywords : running, athletes, energy metabolism, lactic acid, oxygen

Introduction

More than 70% of long-distance performance between subjects is explained by three physiological variables: maximal oxygen uptake (V̇O₂max), lactate threshold (LT) intensity and running economy (RE)⁴. V̇O₂max is a measure of maximal aerobic energy metabolism capacity and shows a positive relation with middle- and long-distance running performance⁵,⁶. However, this relation is not observed in elite⁶ and highly trained runners⁵ because of the similarly high V̇O₂max levels exhibited by these two groups. In contrast, a relation has been shown between running performance and RE⁵,⁶, a measure of submaximal aerobic metabolism capacity. RE is a better predictor of running performance in athletes than V̇O₂max.

RE has been evaluated using several methods⁴⁻¹³, almost always using oxygen uptake (V̇O₂) measured with the subject running at an intensity below the LT¹⁴. This is for two reasons. VO₂ is not observed in a steady state and anaerobic metabolism increases at intensities above the LT, making the evaluation of RE more complex. However, except in marathons, middle- and long-distance athletes generally run above the LT intensity during their competitive events. For example, aerobic and anaerobic metabolisms contribute to 80% and 20%, respectively, of the overall energy expended during a 1,500-m running event⁵, suggesting RE measured during high-intensity running may provide more information than RE measured at a lower intensity.

V̇O₂ during high-intensity running does not reach a steady state, but increases slowly and continuously until exhaustion. This phenomenon is known as the slow component of V̇O₂¹⁶. However, in well-trained endurance runners, V̇O₂ attains a steady state faster and the slow component is smaller than that observed in sprinters¹⁷,¹⁸. This suggests that high-intensity RE could be evaluated in distance runners with superior aerobic capacity.

It has been reported that V̇O₂ does not increase linearly as running intensity increases¹⁶,¹⁹,²⁰. In particular, oxygen demand in endurance runners showed an upwardly cur-
A linear relation with increasing running intensity\(^{19}\), with \(\text{VO}_2\) attenuated above the LT intensity\(^{20}\). The difference between \(\text{VO}_2\) and the actual energy demand may therefore be greater at faster running velocities, and \(\text{RE}\) above the LT intensity may be overestimated if the conventional method is used. This difference is due to anaerobic energy metabolism, which suggests that evaluation during anaerobic energy metabolism may provide a valid estimate of \(\text{RE}\). The energy requirement while running at an intensity above the LT involves anaerobic energy metabolism, which leads to an accumulation of blood lactate\(^{21}\). From this, di Prampero et al.\(^{20,23}\) calculated anaerobic energy production as \(3.0 \text{mLO}_2\cdot\text{kg}^{-1}\cdot\text{per} 1 \text{mmolL}^{-1}\) blood lactate accumulation and used this value to evaluate \(\text{RE}\) at an intensity above LT intensity by adding it to \(\text{VO}_2\). Kyröläinen et al.\(^{20,23}\) evaluated \(\text{RE}\) by combining aerobic energy metabolism, calculated from \(\text{VO}_2\) and the respiratory exchange ratio (RER), with anaerobic energy metabolism, calculated from the change in blood lactate concentration (bLa). However, they did not examine the relation between \(\text{RE}\) and running performance, and no other study has evaluated \(\text{RE}\) using this method\(^{20,23}\).

The purpose of the present study was therefore to elucidate the relations between 1,500-m running performance and several physiological variables: \(\text{VO}_2\max\), LT intensity and \(\text{RE}\) at intensities measured below and above the LT in well-trained runners. We hypothesised that \(\text{RE}\) measured at high intensity would be more strongly related to 1,500-m running performance than \(\text{RE}\) measured at low intensity.

**Materials and Methods**

**Subjects.** The study included 34 male middle- and long-distance runners (age 20.0 ± 1.4 years, height 172.2 ± 4.5 cm, body weight 58.6 ± 4.0 kg, 1,500-m season best time 4′03″2 ± 8″5, equivalent to an average velocity over 1,500 m of 22.2 ± 0.8 km·h\(^{-1}\)). All were university students who belonged to the same track and field team. As an indication of their running performance, we took their 1,500-m running performance at the end of the stage was 12.6 or 13.8 km·h\(^{-1}\). The study was approved by the Research Ethics Committee at the University of Tsukuba Graduate School of Comprehensive Human Sciences (Issue Number: 23–131).

**Experimental protocol and calculated values.** The subjects ran on a treadmill (ORK-7000; Ohtake-Root Kogyo Co., Ltd, Iwate, Japan) at a 1% grade\(^{24}\). They performed two tests separated by a 5-min rest. The first test was an intermittent incremental load test, during which \(\text{VO}_2\), carbon dioxide production (\(\text{VCO}_2\)), \(\text{RE}\) and bLa were measured at each running velocity. The velocity for the initial stage was 12.6 or 13.8 km·h\(^{-1}\), depending on the subject's running performance, and was increased by 1.2 km·h\(^{-1}\) at each subsequent stage up to a total of five or six stages. Each stage consisted of 3-min running\(^{9,20,23}\) and 2-min rest. For each velocity, breath-by-breath \(\text{VO}_2\) was averaged over 30-s intervals. Steady state was defined as \(\text{VO}_2\) increasing by less than 100 mL·min\(^{-1}\) over the final 1 min of the trial. In the one case for which this steady state was not achieved, the stage was continued for another 30 s\(^{25}\). The end of the stage was decided when two of the following occurred: (1) the rate of perceived exertion exceeded 17, (2) \(\text{RE}\) exceeded 1.00, or (3) bLa exceeded 8.00 mmol·L\(^{-1}\).

Expired gas was analyzed breath-by-breath for \(\text{VO}_2\), \(\text{VCO}_2\), pulmonary ventilation and RER using the computerized standard open circuit technique with an expired gas analyzer (AE310-S Aero monitor; Minato Medical Science Co., Ltd, Osaka, Japan)\(^{26}\). The gas analyzer was calibrated using a calibration gas (air equivalent: 20.90% \(\text{O}_2\), 0.03% \(\text{CO}_2\), balance \(\text{N}_2\); exhalation equivalent: 15.00% \(\text{O}_2\), 5.00% \(\text{CO}_2\), balance \(\text{N}_2\)), and the flow sensor was calibrated with a flow calibrator (ACA105, 2L) before and after measurement. To measure bLa, a fingertip blood sample was taken from the subject before the first test, after each stage of running, and at 1, 3 and 5 min of exhaustion, and analyzed with a lactate analyzer (1500 SPORT lactate analyzer; Yellow Springs Inc., Yellow Springs, OH, USA). HR was measured with an HR monitor (Polar S610i; Polar Electro Japan, Tokyo, Japan). The measurement room was ventilated continually throughout the experiment.

**Data analysis.** \(\text{VO}_2\max\) was defined as the greatest oxygen uptake over a 1-min period during the test. The subject's velocity at \(\text{VO}_2\max\) (\(\text{vVO}_2\max\)) was calculated by substituting \(\text{VO}_2\max\) into the velocity-\(\text{VO}_2\) regression equation. The velocity at LT (\(\text{vLT}\)) was determined using the lactate threshold decision method (Lactate-E) of Newell et al.\(^{17}\). LT intensity (\(\text{LTI}\)) was determined from \(\text{vLT}\) and \(\text{vVO}_2\max\). \(\text{VO}_2\), \(\text{VCO}_2\) and \(\text{RE}\) were defined as the averages of the breath-by-breath data over the final 1 min at each running velocity. The running intensity (%\(\text{VO}_2\max\) and %\(\text{LT}\)) at a given velocity was determined from the ratio of \(\text{VO}_2\) to \(\text{VO}_2\max\). \(\text{RE}\) was calculated at four intensities, two below LT (\(\text{RE}_{\text{6LT}}\)) and two above LT (\(\text{RE}_{\text{11LT}}\)), with the running velocities set at intensities of 90%LT (\(\text{RE}_{\text{95LT}}\)), 105%LT (\(\text{RE}_{\text{105LT}}\)) and 110%LT (\(\text{RE}_{\text{110LT}}\)) respectively, using the method described by Kyröläinen et al.\(^{20,23}\). \(\text{VO}_2\), \(\text{RE}\), bLa at each inten-
High-intensity running economy related to 1,500-m running performance

Statistical analyses. The statistical analyses were performed using SPSS version 22 (IBM Corp., Armonk, NY, USA). The relations between 1,500-m velocity (used as the measure of running performance) and VO$_2$max, vVO$_2$max, vLT, LTI and RE were investigated using Pearson’s correlation coefficients. Multiple regression analysis was applied to 1,500-m velocity as the dependent variable and three physiological variables (VO$_2$max, LTI and either RE$_{LT}$ or RE$_{aLT}$) as independent variables. One-way analysis of variance was used to compare variables measured at intensities of 90%LT, 95%LT, 105%LT and 110%LT, including running velocity, VO$_2$, RER, bLa, %VO$_2$max, contribution ratio of anaerobic energy expenditure per RE (%RE$_{ana}$) and RE. When an interaction was observed, it was evaluated using the Bonferroni post hoc test. Data are expressed as mean ± SD. The level of significance was set at P < 0.05.

Results

VO$_2$max, vVO$_2$max, vLT and LTI were 71.1 ± 3.8 mL·kg$^{-1}$·min$^{-1}$, 19.8 ± 0.9 km·h$^{-1}$, 16.6 ± 1.0 km·h$^{-1}$ and 84.1 ± 4.5%, respectively (Table 1). The 1,500-m velocity showed a significant positive relation with vVO$_2$max and vLT (r = 0.65 and 0.61, respectively; P < 0.001), but no significant relation with VO$_2$max or LTI (r = 0.19 and 0.10; P = 0.28 and 0.58, respectively) (Fig. 1).

| VO$_2$max (mL·kg$^{-1}$·min$^{-1}$) | vVO$_2$max (km·h$^{-1}$) | vLT (km·h$^{-1}$) | LT intensity (%) |
|----------------------------------|------------------------|------------------|-----------------|
| Mean ± SD                        | 71.1 ± 3.8             | 19.8 ± 0.9       | 16.6 ± 1.0      | 84.1 ± 4.5     |
| r                                | 0.19                   | 0.65             | 0.61            | 0.10           |
| p value                          | 0.28                   | <0.001           | <0.001          | 0.58           |

Fig. 1 The relationships between 1,500-m velocity and maximal oxygen uptake (open triangles) and lactate threshold intensity (filled triangles) (n = 34).
bLa at rest was 1.1 ± 0.3 mmol·L⁻¹. Even when the subjects were running at velocities above LTI, VO₂ was stable (changing by <100 mL·O₂·min⁻¹). Values for running velocity, VO₂, RER, bLa, %VO₂max and %REA measured below and above LTI intensity are shown in Table 2. RE₉₀, RE₉₅, RE₁₀₅ and RE₁₁₀ were 4.45 ± 0.19, 4.51 ± 0.20, 4.67 ± 0.17 and 4.71 ± 0.18 J·kg⁻¹·m⁻¹, respectively; they were significantly and negatively correlated with a 1,500-m velocity (r = −0.56, −0.58, −0.65 and −0.71, respectively) (Table 3). Notably, RE₉₀ (RE₁₀₅ and RE₁₁₀) showed a stronger correlation with a 1,500-m velocity than RE₉₅ (RE₉₀ and RE₉₅) (Fig. 2).

Multiple regression analysis with 1,500-m velocity as the dependent variable and VO₂max, LTI and either RE₉₀, RE₉₅, RE₁₀₅ or RE₁₁₀ as the independent variables showed significant relations (R² = 0.415, 0.543, 0.603 and 0.640; P < 0.01, 0.001, 0.001 and 0.001). The relation was stronger when using VO₂max, LTI, and RE₁₁₀ (VIF = 1.163, 1.168 and 1.044, respectively) (Table 4).

**Discussion**

This study aimed to elucidate the relations between 1,500-m running performance and VO₂max, LTI and RE measured at intensities below and above the LT in well-trained runners. The main finding was that RE measured at an intensity above the LT was more strongly related to 1,500-m velocity, in agreement with our hypothesis.

The 1,500-m running performance of our subjects was slightly lower than that in previous studies⁹,¹⁰,²⁸); however, VO₂max was approximately 70 mL·kg⁻¹·min⁻¹, similar to values found in previous studies⁹,¹⁰,²⁸-³⁰). It may have been the case that the subjects in this study had nearly elite-level physiological capacities, but slightly lower running performance than elite 1,500-m runners.

Many researchers have reported that VO₂max can explain most of the difference in distance running performance¹,²,⁹). Nevertheless, a relation between VO₂max and 1,500-m running performance has not been observed in

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**Table 2.** Running velocity, Oxygen uptake, respiratory exchange ratio, blood lactate concentration, %maximal oxygen uptake intensity, ratio of anaerobic energy expenditure per RE and running economy at below and above lactate threshold intensity (n = 34).

| LT intensity | Running velocity (km·h⁻¹) | VO₂ (mL·kg⁻¹·min⁻¹) | RER | bLa (mmol·L⁻¹) | %VO₂max | %REA | RE (J·kg⁻¹·m⁻¹) |
|--------------|---------------------------|----------------------|-----|---------------|---------|------|----------------|
| at below LT  | 90%LT                     | 15.2 ± 1.1           | 53.7 ± 3.3 | 0.95 ± 0.04   | 1.3 ± 0.04 | 76.7 ± 3.7 | 0.3 ± 0.06 | 4.45 ± 0.19   |
|              | 95%LT                     | 15.9 ± 1.0           | 56.7 ± 3.5 | 0.96 ± 0.04   | 1.7 ± 0.04 | 80.3 ± 3.7 | 0.7 ± 0.06 | 4.51 ± 0.20   |
| at above LT  | 105%LT                    | 17.6 ± 1.1           | 62.7 ± 3.9 | 1.02 ± 0.04   | 3.5 ± 0.04 | 89.2 ± 3.7 | 3.8 ± 0.06 | 4.67 ± 0.21   |
|              | 110%LT                    | 18.3 ± 0.9           | 65.3 ± 3.5 | 1.04 ± 0.04   | 4.0 ± 0.05 | 92.7 ± 3.7 | 4.2 ± 0.06 | 4.71 ± 0.22   |

P value <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001

Data are presented as mean (± SD). There are observed a significant difference in 90%LT vs 95%LT, 90%LT vs 105%LT, 90%LT vs 110%LT, 95%LT vs 105%LT, 95%LT vs 110%LT and 105%LT vs 110%LT.

**Table 3.** Correlation coefficients for the relationships between 1,500-m velocity and running economy measured below and above the lactate threshold intensity (n = 34).

| LT intensity | r      | R²   |
|--------------|--------|------|
| at below LT  |        |      |
| 90%LT        | −0.56* | 0.31*|
| 95%LT        | −0.58**| 0.33**|
| at above LT  |        |      |
| 105%LT       | −0.65**| 0.42**|
| 110%LT       | −0.71**| 0.51**|

*: P < 0.01 **: P < 0.001
elite runners\textsuperscript{10,28}, except in the study of Ingham et al.\textsuperscript{9}, which to the best of our knowledge, is the only study to report such a relation in top-level runners (season best times 3’44”\pm 6”5, n = 15). In this study involving well-trained runners, the relation between 1,500-m velocity and VO\textsubscript{2max} was weak (r = 0.19). LTI has also been used to attempt to explain differences in distance running performance\textsuperscript{31}; however, no study has reported a significant relation with 1,500-m running performance in male trained runners. This study showed similar results to those of previous studies that LTI was not related to 1,500-m running performance (r = 0.10). These results suggest that high-level runners share similar high levels of VO\textsubscript{2max} and LTI capacity as the assumption, and that they must possess a different form of superior aerobic capacity.

In previous studies, RE has been evaluated using VO\textsubscript{2} measured at intensities below the LT and was shown to have a significant relation with distance running performance\textsuperscript{53}; however, RE measured at high-intensity running has not been well investigated for two reasons: VO\textsubscript{2} is not observed to reach a steady state (due to the slow component of VO\textsubscript{2}), and the anaerobic energy metabolism increases. However, the slow component of VO\textsubscript{2} is smaller in well-trained endurance runners and their VO\textsubscript{2} reaches a steady state faster than that in sprinters\textsuperscript{17,18}. Indeed, in the present study, the subjects’ VO\textsubscript{2} reached a steady state (changing by less than 100 mLO\textsubscript{2}·min\textsuperscript{-1})\textsuperscript{25} even at an intensity above the LT. Using prior exercise, Burnley et al.\textsuperscript{32} showed greater motor unit recruitment in the early minutes of exercise, which may reduce the metabolic disturbance on each individual muscle fibre and thereby induce a lower rate of fatigue development for each fibre\textsuperscript{33}, resulting in stabilization of VO\textsubscript{2} during running. The relation between bLa and anaerobic energy metabolism can be observed since bLa is increased when an anaerobic energy metabolism is recruited.\textsuperscript{34} di Prampero et al.\textsuperscript{22} and other researchers\textsuperscript{20,23,35,36} have calculated anaerobic energy production as 3.0 mLO\textsubscript{2}·kg\textsuperscript{-1} per 1 mmol·L\textsuperscript{-1} blood lactate accumulation; this method of calculation was used in the present study.

\textbf{Fig. 2} The relationships between 1,500-m velocity and running economy measured at two exercise intensities: below lactate threshold (LT) (90\%LT; open circles) and above LT (110\%LT; filled circles) (n = 34).

\textbf{Table 4.} Multiple regression analysis for 1,500-m velocity, with maximal oxygen uptake, lactate threshold, and running economy measured below and above the lactate threshold intensity as the independent variables (n = 34).

| LT intensity | R\textsuperscript{2} | V\textsubscript{O2max} LT intensity | RE |
|--------------|----------------------|------------------------------------|-----|
| at below LT  |                      |                                    |     |
| 90\%LT       | 0.415**              | 1.142                              | 1.101|
| 95\%LT       | 0.543**              | 1.231                              | 1.170|
| at above LT  |                      |                                    |     |
| 105\%LT      | 0.603**              | 1.176                              | 1.110|
| 110\%LT      | 0.640**              | 1.163                              | 1.044|

**: P < 0.001
It has been pointed out that RE is the most important variable for estimating running performance in high- or top-level runners\(^6,5\). However, a significant relation with 1,500-m running performance was not observed. For example, Ingham et al.\(^9\) reported that, in top-level runners, 93.8% of 1,500-m running performance could be explained by V\(_{O2}\max\) and RE, but RE was not related to 1,500-m running performance (r = −0.01). In contrast, the present study showed a significant negative relation between RE and 1,500-m velocity; furthermore, this relation was stronger when measured at an intensity above the LT (r = −0.65 or −0.71) than at an intensity below the LT (r = −0.56 or −0.58). This is therefore the first study to claim the importance of RE measured at an intensity above the LT for estimating 1,500-m running performance.

Aerobic and anaerobic metabolisms contribute 80% and 20%, respectively, of the overall energy expended during a 1,500-m race\(^15\). At its highest, V\(_{O2}\) reaches 94% of V\(_{O2}\max\)\(^29\), with the remaining energy contributed by anaerobic energy metabolism. Thus, a 1,500-m race requires running with contributions from anaerobic energy metabolism. Running velocity tends to increase in the final phase of a 1,500-m race\(^29\). This suggests that race success may be decided by how well the runner conserves energy while running at a higher velocity. It can be seen from these characteristics that 1,500-m running is more closely related to RE at an intensity above the LT rather than below it. The intensity of RE\(_{110}\) was 4.2 ± 1.4% of V\(_{O2}\max\). This intensity was lower than the running intensity achieved in an actual 1,500-m race, but it may be more similar to V\(_{O2}\) attained during 1,500-m running than when measured at the intensity below the LT.

RE\(_{aLT}\) was significantly greater than RE\(_{bLT}\) (4.67 ± 0.17 or 4.71 ± 0.18 vs 4.45 ± 0.19 or 4.51 ± 0.20 J kg\(^{-1}\) m\(^{-1}\)), showing poorer economy when running at high intensity than at low intensity. The main reason for this poor economy at high running intensity is thought to be the reduction of mechanical efficiency with the increasing recruitment of type II muscle fibers. Both type I and type II muscle fibers are recruited during high intensity running; type II fibers tend to be less efficient than type I fibers and have higher oxidative capacity\(^4\). Type II fibers therefore have a higher energy cost for producing energy, and lower recruitment of type II fibers can lead to superior RE for a given running velocity. This suggests that RE at intensities above the LT, at which type II fibers are recruited, includes anaerobic energy metabolism and is related more strongly to 1,500-m running performance than is RE at intensities below the LT. The increased internal work\(^7\) and heat accumulation in active muscles\(^30\) at intensities above the LT also negatively affect RE. In particular, over 50% of the individual variation in RE is explained by biomechanical variables\(^30\). The biomechanical variables change with increasing running intensity, and RE deteriorates. This suggests that having superior RE at high intensity is important for 1,500-m running performance, despite RE deterioration.

Of the variation in 1,500-m velocity between individuals, 41.5% (P < 0.01) is explained by V\(_{O2}\max\), LT and RE\(_{aLT}\); this is lower than the coefficient of determination for marathon performance (R\(^2\) > 70%)\(^9\). This difference could be explained by the overall energy contribution of distance running. Thus, aerobic metabolism contributes 80% and 100% to 1,500-m and marathon running, respectively\(^15\). 1,500-m running performance is affected by both aerobic and anaerobic energy metabolism capacity (i.e. maximal accumulated oxygen deficit and maximal lactate accumulation). Nevertheless, when RE\(_{aLT}\) was replaced by RE\(_{bLT}\), the coefficient of determination of the multiple regression analysis was above 60%. This result shows RE\(_{aLT}\) to be a useful variable for estimating 1,500-m running performance.

We did not treat v\(_{V\(_{O2}\)max}\) and v\(_{LT}\) as physiological variables in this study. Previously, strong relations have been observed between running performance and v\(_{V\(_{O2}\)max}\)\(^6,40\) or v\(_{LT}\)\(^6,41\). Indeed, Noakes et al.\(^38\) suggested that v\(_{V\(_{O2}\)max}\) showed the strongest relation with running performance. However, we regard these variables as physiological performance variables. Finding a relation between physiological performance variables (km h\(^{-1}\)) and running performance (km h\(^{-1}\)) is inevitable. Nevertheless, the variable showing the strongest relation with running performance in the present study was RE\(_{aLT}\) rather than v\(_{V\(_{O2}\)max}\) or v\(_{LT}\). This result also suggests that RE at an intensity above the LT is a useful variable. V\(_{O2}\max\) was used as a relative value (mL kg\(^{-1}\) min\(^{-1}\)) rather than an absolute value (L min\(^{-1}\)) in this study. The reason underlying this is that other researchers\(^1-5,9,10,28-30\) who investigated distance running performance often used a relative V\(_{O2}\max\) value; therefore, we can compare our values with the values from their studies. When a relative V\(_{O2}\max\) value is replaced by an absolute V\(_{O2}\max\) value, the correlation between V\(_{O2}\max\) and a 1,500-m running velocity is observed to be slightly stronger, but it is still not a significant relationship (r = 0.25, P = 0.15).

This study has some limitations. The subjects in this study ran at the same five or six running velocities (12.6 to 19.8 km h\(^{-1}\)), with physiological parameters (i.e. V\(_{O2}\), RER and bLa) at each intensity calculated for each subject using the interpolation method. However, these parameters had a strong relation with running velocity in each subject, suggesting it was not possible to control each individual running intensity well. A pre-test should be carried out in order to better control the running intensity, but that was difficult for this study due to the participation of many competitive runners. However, RE\(_{aLT}\) and RE\(_{bLT}\) for all the subjects were measured at intensities below and above the LT, and so the overall result of this study is not inaccurate. It could be claimed that RE measured at an intensity above the LT is more closely related to 1,500-m running performance than is RE at an intensity below the LT. This result represents a new finding about
the relation between running performance and physiological variables. Although this study has clarified the relation between 1,500-m running performance and REaLT, further research is needed to establish whether there is a similar relation with 800-m and 5,000-m running performance, race distances that both involve a contribution (at 40% and 5%, respectively) from anaerobic energy metabolism to the overall energy expenditure during running\textsuperscript{15,42). The findings of this study could become widely useful. In addition, modifying the running form improves the RE\textsuperscript{43), making it possible to improve running performance. The ground reaction force and muscle activity increase with the running velocity\textsuperscript{20}, economical running form at high-intensity running is different compared to low-intensity running. The correlation between REaLT at absolute running velocity and biomechanical variables should be clarified in the future.

**Conclusion**

Both VO\textsubscript{2max} and LTI were not observed to exhibit a significant relation to 1,500-m running performance in well-trained runners, whereas there was a significant negative relation observed with RE, particularly at an intensity above the LT. Of the variation in 1,500-m velocity between the subjects, over 60% was explained by VO\textsubscript{2max}, LTI and RE measured at an intensity above the LT. These results suggest that RE measured at an intensity above the LT is an important physiological variable for estimating 1,500-m running performance.

**Conflict of Interests**

The authors declare that they have no conflict of interests in the authorship and publication of this study.

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