Short communication R1

Title

Relationship between respiratory muscle endurance and dyspnea during high-intensity exercise in trained distance runners

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Abstract

We hypothesized that the trained distance runners, who have a relatively high respiratory muscle endurance, but not high respiratory muscle strength, have lower dyspneic sensations during submaximal running. Twenty-one male collegiate distance runners participated. Incremental respiratory endurance tests (IRET) and maximal inspiratory mouth pressure (PI_{max}) measurements were performed under resting conditions. A submaximal exercise test was also performed on a treadmill at two different speeds (16 and 18 km/h) for 4 min each, and the subjects reported the rate of dyspnea (range: 0–10). The time to endpoint during the IRET, an index of respiratory muscle endurance, ranged from 9.4 to 18.8 min, and PI_{max}, as an index of inspiratory muscle strength, ranged from 74.1 to 137.0 cmH_2O. The dyspnea rating during running at 16 and 18 km/h ranged from 1 to 6 and from 4 to 8, respectively. The relative exercise intensity was approximately 80% of peak oxygen uptake ($\dot{V}O_{2peak}$) at 16 km/h and 90%$\dot{V}O_{2peak}$ at 18 km/h. The time to endpoint during the IRET was significantly negatively correlated with dyspnea during running at 18 km/h ($r = -0.459$, $P = 0.040$), but not at 16 km/h ($r = -0.161$, $P = 0.470$). There was no significant correlation between PI_{max} and dyspnea during running at 16 km/h ($r = -0.003$, $P = 0.989$) or 18 km/h ($r = 0.070$, $P = 0.755$). These results suggest that dyspneic sensations during high-intensity running are related to respiratory muscle endurance, but not inspiratory muscle strength, in trained distance runners.

Keywords

respiratory muscles, breathing exercise, isocapnic hyperpnea, pulmonary function

1. Introduction

Dyspnea is defined as discomfort associated with breathing. Although the causal mechanisms of dyspnea during exercise are unclear, factors that impair the contractile properties of the respiratory muscles (e.g., alternations in the pattern of tension development, functional weakening of respiratory muscles, and respiratory muscle fatigue) could be related to the amount and perception of respiratory effort (McConnell and Romer, 2004a). Harms et al. (Harms et al., 2000) investigated the impact of manipulating the work of breathing during high-intensity exercise (90% maximal oxygen uptake [$\dot{V}O_{2max}$]) on the sensation of dyspnea, leg discomfort (rating of perceived exertion [RPE]), and exercise performance; the change in time to exhaustion was significantly negatively correlated with the changes in dyspnea and leg RPE. Accordingly, it is supposed that dyspneic sensations during high-intensity exercise are related to the whole-body exercise performance. What are the specific aspects of respiratory muscle function (i.e., respiratory muscle endurance or respiratory muscle strength) enhancement that are linked to ergogenic effects on dyspnea during exercise in endurance athletes? (McConnell and Romer, 2004b). For trained distance runners, respiratory muscle endurance seems more important because several studies reported that respiratory muscle endurance, but not strength (i.e., maximal inspiratory mouth pressure [PI_{max}]), is higher in distance runners than in sedentary individuals (Eastwood et al., 2001; Itoh et al., 2016; Martin and Stager, 1981). However, interindividual variability exists in respiratory muscle endurance and strength in distance runners with comparable levels of aerobic capacity (i.e., $\dot{V}O_{2max}$) (Eastwood et al., 2001; Itoh et al., 2016; Martin and Stager, 1981). To the best of our knowledge, there are no available data on the relationship between the degree of dyspnea during exercise and respiratory muscle endurance or strength in trained distance runners.

We hypothesized that the runners, who have a relatively high respiratory muscle endurance, would experience less dyspnea during exercise. To test this hypothesis, we examined the relationship between respiratory muscle endurance or strength and the degree of dyspnea during submaximal treadmill running in trained distance runners.

2. Methods

2. 1. Ethical approval

This study was approved by the Human Research Committee of the Research Center of Health, Physical Fitness and Sports, Nagoya University (25-14). All subjects were informed about the experimental procedures and potential risks involved, and written consent was obtained. All procedures were performed in accordance with the standards of the Declaration of Helsinki.

2. 2. Subjects

Twenty-one male distance runners participated in the present study. They belonged to a collegiate track team that had competed in the 2013–2018 Japanese intercollegiate road relays. Their physical characteristics were as follows: age 20.0 ± 0.9 years, height 170.5 ± 6.3 cm, and body mass 57.8 ± 6.0 kg (mean ± SD).

2. 3. Experimental procedures

During the preliminary visit, subjects were familiarized with the experimental apparatus. Subjects reported to the laboratory on three additional occasions, separated by at least 24 hrs. On the first day, pulmonary function and respiratory muscle strength were assessed. On the second day, an incremental respiratory endurance test (IRET) was conducted with subjects in the sitting position. On the third day, submaximal and maximal exercise tests were performed on a treadmill.

2. 4. Measurements

2. 4. 1. Pulmonary function and inspiratory muscle strength

Pulmonary function (forced vital capacity [FVC], forced expiratory volume in 1 sec [$FEV_{1.0}$, $FEV_{1.0}$/FVC%], and maximal voluntary ventilation for 12 s [MVV_{12}]) were determined using a computerized spirometry system (AS-507; Minato Medical Science, Osaka, Japan) (Itoh et al., 2016). The maximal inspiratory pressure (PI_{max}) was measured using a handheld mouth pressure meter (AAM 337, Minato Medical Science) connected to a computerized spirometry system. The PI_{max} was taken from the residual volume. We repeated the PI_{max} measurements three times and adopted the highest value.

2. 4. 2. Incremental respiratory endurance test

The IRET protocol was performed in a sitting position according to the 2002 American Thoracic Society/European Respiratory Society recommendations, as in our previous study (Itoh et al., 2016). Initially, baseline respiratory variables were measured for 5 min during spontaneous breathing. Next, the IRET was started. The target minute ventilation ($\dot{V}_E$) was set at 30% of MVV_{12} for the first 3 min and was increased by 10% of MVV_{12} every 3 min. The tidal volume (V_T) was fixed at 60% of the vital capacity (VC), and the breathing frequency (fb) was increased every 3 min to the set target $\dot{V}_E$. The ratio of inspiratory to expiratory time per breath cycle was set to 1:1 based on auditory feedback from a metronome. The end-tidal partial pressure of CO_2 (P_{ETCO_2}) was maintained at ± 5 torr of the spontaneous breathing level for the first minute, and the P_{ETCO_2} was maintained at ± 4 torr by adding CO_2 to the inspired air from the second minute to the end of testing. The IRET ended when the subject no longer maintained the target V_T (60% of the VC) or fb despite ‘warnings’ for three consecutive breaths. The time to endpoint during the IRET was used as an index of for respiratory muscle endurance and is expressed in minutes rounded to two decimal places (e.g., 10 min 30 sec is expressed as 10.5 min).

During the IRET, the subjects breathed through a mouthpiece attached to a hot-wire flowmeter (RF-H, Minato Medical Science), which was connected to a rebreathing bag of approximately 10 L. Sample gas was drawn through a sampling tube connected to the mouthpiece to measure the CO_2 fraction using a gas analyzer (MG-360, Minato Medical Science). Flow and CO_2 signals were sampled at a frequency of 200 Hz through an analog-to-digital converter (CSI-3204; Interface, Hiroshima, Japan) and saved to a computer (CSI-F8; Panasonic, Osaka, Japan).

2. 5. Exercise tests

2. 5. 1. Submaximal exercise test

The subjects ran at a speed of 12 km/h on a treadmill (Valiant, Lode BV, Groningen, Netherlands) for 5 min to warm up. Next, the subjects performed submaximal level running on the treadmill at two different speeds (16 and 18 km/h) for 4 min, separated by a 1-min rest period. The subjects were asked to report the degree of dyspnea at the end of each exercise using Borg’s modified scale (0-10) (Borg. Borg’s perceived exertion and pain scales. Human Kinetics 1998), where 0 represented "no breathing discomfort at all", and 10 represented "the most intense breathing discomfort ever experienced" (Welch et al., 2018). During exercise, $\dot{V}_E$, oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and respiratory exchange ratio (RER) were measured using an online system (AE300S, Minato Medical Science). Heart rate (HR) was also recorded during the test using a wireless HR monitor (Acculex Plus, Polar Electro Oy, Kempele, Finland).

2. 5. 2. Maximal exercise test

Next, the subjects performed an incremental exercise test. The initial treadmill speed was set at 18.6 km/h for 2 min and increased by 0.6 km/h every minute until exhaustion. Respiratory parameters and HR were recorded with the same apparatus used in the submaximal exercise test and averaged every 30 sec afterward. The highest $\dot{V}_E$, $\dot{V}O_2$, and HR obtained during the maximal exercise test were used as the $\dot{V}_{Epeak}$, $\dot{V}O_{2peak}$, $\dot{V}CO_{2peak}$, and HR_{peak}, respectively.

2. 6. Statistical analysis

Values are expressed as means ± SD. The statistical analysis of cardiorespiratory variables during the IRET was limited to the first 9 min and the end, because one subject could not maintain the target by 10 min of hyperpnea. Changes in the variables during the IRET were evaluated by a one-way analysis of variance with repeated measures (ANOVA RM). Spearman's rank correlation coefficient was used to examine the correlations between variables. Statistical comparisons were performed with StatView (5.0; SAS Institute, Tokyo, Japan). Statistical significance was set at $P < 0.05$.

3. Results

3. 1. Pulmonary function and inspiratory muscle strength

The pulmonary function and inspiratory muscle strength values were as follows: FVC = 4.3 ± 1.0 L (% predicted 98.5 ± 8.3, range: 3.0–5.0, $FEV_{1.0}$ = 4.0 ± 0.4 L (% predicted 90.6 ± 8.2, range: 3.0–4.8), $FEV_{1.0}/FVC$ = 93.5 ± 4.3 % (% predicted 103.6 ± 4.7, range: 81.4–99.3), MVV_{12} = 173.0 ± 21.8 L/min (% predicted 127.1 ± 8.7, range: 142–219), and PI_{max} = 105.6 ± 16.3 cmH_2O (% predicted 95.4 ± 16.3, range: 74.1–137.0).

3. 2. Incremental respiratory endurance test

As expected, the $\dot{V}_E$ and fb increased progressively during the IRET ($P < 0.001$) ($\dot{V}_E$: endpoint 133.6 ± 21.5 L/min, $P < 0.001$, fb: endpoint 47.1 ± 8.6 breaths/min, $P < 0.001$). In contrast, the V_T and P_{ETCO_2} were unchanged throughout the IRET (V_T: endpoint 2.9 ± 0.3, $P = 0.182$, P_{ETCO_2}: endpoint 40.0 ± 1.9 torr, $P = 0.168$). The time to endpoint during the IRET was 14.4 ± 2.7 min (range: 9.4–18.8).

3. 3. Exercise tests

3. 3. 1. Submaximal exercise test

Table 1 indicates cardiorespiratory variables during the last minute of each 4-min treadmill run at 16 and 18 km/h. The rating of dyspnea was 3.1 ± 1.0 (range: 1–6) at 16 km/h and 5.0 ± 1.3 (4–8) at 18 km/h. The relative intensity of each run calculated using the $\dot{V}O_{2peak}$ which is indicated in next paragraph, was 79.4 ± 5.6%$\dot{V}O_{2peak}$ (68.9–91.1) at 16 km/h and 90.3 ± 5.1%$\dot{V}O_{2peak}$ (79.9–98.0) at 18 km/h, respectively.

3. 3. 2. Maximal exercise test

The highest cardiorespiratory variables during the maximal exercise test were as follows: $\dot{V}E_{peak}$ = 144.1 ± 12.7 L/min (range: 126.8–171.8), $\dot{V}O_{2peak}$ = 3.9 ± 0.4 L/min (3.3–4.8), 68.0 ± 3.4 mL/kg/min (61.3–72.9), $\dot{V}CO_{2peak}$ = 4.3 ± 0.4 L/min (3.6–5.1), RER = 1.10 ± 0.04 (1.02–1.21), and HR_{peak} = 190.7 ± 7.3 beats/min (182–210).

3. 4. Correlation between the time to endpoint during the IRET or PImax and dyspnea during submaximal exercise

There was no significant correlation between the time to endpoint during the IRET and dyspnea during treadmill running at 16 km/h (Figure 1A). By contrast, significant negative correlation was found between the time to endpoint during the IRET and dyspnea during treadmill running at 18 km/h (Figure 1B). No correlation was found between PI_{max} and dyspnea during treadmill running at 16 or 18 km/h (Figure 2).

4. Discussion

The major novel findings of this study are that: 1) the time to endpoint during the IRET correlated negatively with dyspnea during running at 18 km/h, but not at 16 km/h, and 2) PI_{max} did not correlate with dyspnea during treadmill running at 16 or 18 km/h. These results suggest that dyspneic sensations during high-intensity running are related to respiratory muscle endurance, but not inspiratory muscle strength, in trained distance runners.

4. 1. Relationship between respiratory muscle endurance or strength and the rating of dyspnea during submaximal exercise

In this study, we recorded the time to endpoint during the IRET and PI_{max} under resting conditions as indexes of respiratory muscle endurance and inspiratory muscle strength, and the rating of dyspnea during submaximal treadmill exercise in trained distance runners. Next, we estimated the relationships among those variables. As shown in Figure 2, there were no significant correlations between PI_{max} and dyspnea during treadmill running at 16 and 18 km/h. In contrast, there was a significant negative correlation between the time to endpoint during IRET and dyspnea during running at 18 km/h, but not at 16 km/h. The relative exercise intensities during submaximal exercise at 16 and 18 km/h were approximately 80% and 90% of the $\dot{V}O_{2peak}$, respectively. These results indicate that runners, who have a higher respiratory muscle endurance, had lower dyspneic sensations during high-intensity running.

We need to consider the possible reasons for the significant correlation between respiratory muscle endurance, but not inspiratory muscle strength, and dyspnea at higher exercise intensity. Alternations in the pattern of tension development and functional weakening of respiratory muscles are candidates (Romer and Polkey, 2008). Endurance-trained athletes are susceptible to expiratory flow limitation, and the high ventilatory flows achieved by such individuals during high-intensity exercise exacerbate functional weakening (McConnell and Romer, 2004a). Therefore, it is conceivable that a greater inspiratory muscle strength reduces the rating of dyspnea. However, there was no significant correlation between PImax and dyspnea during treadmill running (Figure 2). Trained endurance athletes have less fatigable respiratory muscles than untrained individuals, yet even endurance athletes are sensitive to respiratory muscle fatigue during high-intensity exercise (McConnell and Romer, 2004a). Therefore, improvement of respiratory muscle endurance might be to prevent or delay exercise-induced respiratory muscle fatigue and consequent amelioration of dyspnea. (McConnell and Romer, 2004b). Indeed, there was a significant negative correlation appeared between the time to endpoint during IRET and dyspnea during running at 18 km/h (Figure 1). What is the reason for the lack of a significant correlation between the time to endpoint during the IRET and dyspnea during running at 16 km/h? Significant respiratory muscle fatigue occurs at exercise intensity > 85%$\dot{V}O_{2max}$ (Johnson et al., 1993). Additionally, Harms et al. (Harms et al., 2000) reported that the work of breathing normally incurred during sustained, high-intensity exercise (90%$\dot{V}O_{2max}$) has a significant influence on exercise performance. Taking these observations and our results into consideration, as for distance runners, it is likely that respiratory muscle endurance is more important for reducing the severity of dyspnea during high-intensity running than is respiratory muscle strength.

4. 2. Limitations

This study has several limitations. First, only young male runners were included. Guenette et al. (Guenette et al., 2010) found that exercise-induced inspiratory muscle fatigue and the level of breathing discomfort were lower in endurance-trained female athletes than in male athletes. Second, the estimation of respiratory muscle strength should be considered. We measured PI_{max} as an index of inspiratory muscle strength, but not maximal expiratory mouth pressure (PE_{max}) as an index of expiratory muscle strength. Third, in the present study, a number of subjects was twenty-one. A larger sample would have enabled evaluation of the strength of the relationship between dyspnea during high-tensity exercise and respiratory muscle endurance. Fourth, we did not assess actual running performance. Additional studies are needed to determine whether differences in respiratory muscle endurance are related to distance running performance among trained distance runners.

4. 3. Perspective

Respiratory muscle training has been extensively studied and can the improve sports performance. Most respiratory muscle training studies have employed two models of training: 1) voluntary isocapnic hyperpnea to improve respiratory muscle endurance, and 2) inspiratory resistive loading to improve respiratory muscle strength. Here, it is necessary to consider which model of respiratory muscle training is appropriate for distance runners. Voluntary isocapnic hyperpnea seems to be appropriate because this model requires relatively low-resistance, high-speed inspiratory and expiratory muscle contractions, and these demands mimic ventilatory requirements during whole-body endurance running. Additionally, we found that the runners, who had higher respiratory muscle endurance, had lower dyspneic sensations during high-intensity running (Figure 2B). Based on these considerations and findings, as for distance runners, it is conceivable that voluntary isocapnic hyperpnea to improve respiratory muscle endurance could attenuate a rating of dyspnea and a delay of respiratory muscle fatigue during high-intensity running, thereby improving endurance running performance.

5. Conclusion

The time to endpoint during the IRET was significantly negatively correlated to dyspnea during treadmill running at 18 km/h (~90%$\dot{V}_{O2peak}$ intensity), but not at 16 km/h (~80%$\dot{V}_{O2peak}$ intensity). There was no significant correlation between PI_{max} and dyspnea during running at 16 or 18 km/h. These results suggest that dyspneic sensations during high-intensity running are related to respiratory muscle endurance, but not inspiratory muscle strength, in trained distance runners.

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Declaration of competing interest

The authors declare no conflict of interest related to this study.

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References

Eastwood, P.R., Hillman, D.R., Finucane, K.E., 2001. Inspiratory muscle performance in endurance athletes and sedentary subjects. Respirology 6, 95-104.

Guenette, J.A., Romer, L.M., Querido, J.S., Chua, R., Eves, N.D., Road, J.D., McKenzie, D.C., Sheel, A.W., 2010. Sex differences in exercise-induced diaphragmatic fatigue in endurance-trained athletes. J Appl Physiol 109, 35-46.

Harms, C.A., Wetter, T.J., Croix, C.M.S., Pegelow, D.F., Dempsey, J.A., 2000. Effects of respiratory muscle work on exercise performance. J Appl Physiol 89, 131-138.

Itoh, Y., Katayama, K., Iwamoto, E., Goto, K., Suzuki, Y., Ohya, T., Takao, K., Ishida, K., 2016. Blunted blood pressure response during hyperpnoea in endurance runners. Respir Physiol Neurobiol 230, 22-28.

Johnson, B.D., Babcock, M.A., Suman, O.E., Dempsey, J.A., 1993. Exercise-induced diaphragmatic fatigue in healthy humans. J Physiol 460, 385-405.

Martin, B.J., Stager, J.M., 1981. Ventilatory endurance in athletes and non-athletes. Med Sci Sports Exerc 13, 21-26.

McConnell, A.K., Romer, L.M., 2004a. Dyspnoea in health and obstructive pulmonary disease : the role of respiratory muscle function and training. Sports Med 34, 117-132.

McConnell, A.K., Romer, L.M., 2004b. Respiratory muscle training in healthy humans: resolving the controversy. Int J Sports Med 25, 284-293.

Romer, L.M., Polkey, M.I., 2008. Exercise-induced respiratory muscle fatigue: implications for performance. J Appl Physiol 104, 879-888.

Welch, J.F., Archiza, B., Guenette, J.A., West, C.R., Sheel, A.W., 2018. Effect of diaphragm fatigue on subsequent exercise tolerance in healthy men and women. J Appl Physiol (1985) 125, 1987-1996.

Figure legends

Figure 1. Relationship between dyspnea during treadmill running at 16 km/h (A) and 18 km/h (B) and the time to endpoint during the IRET.

Figure 2. Relationship between dyspnea during treadmill running at 16 km/h (A) and 18 km/h (B) and PI_{max}.

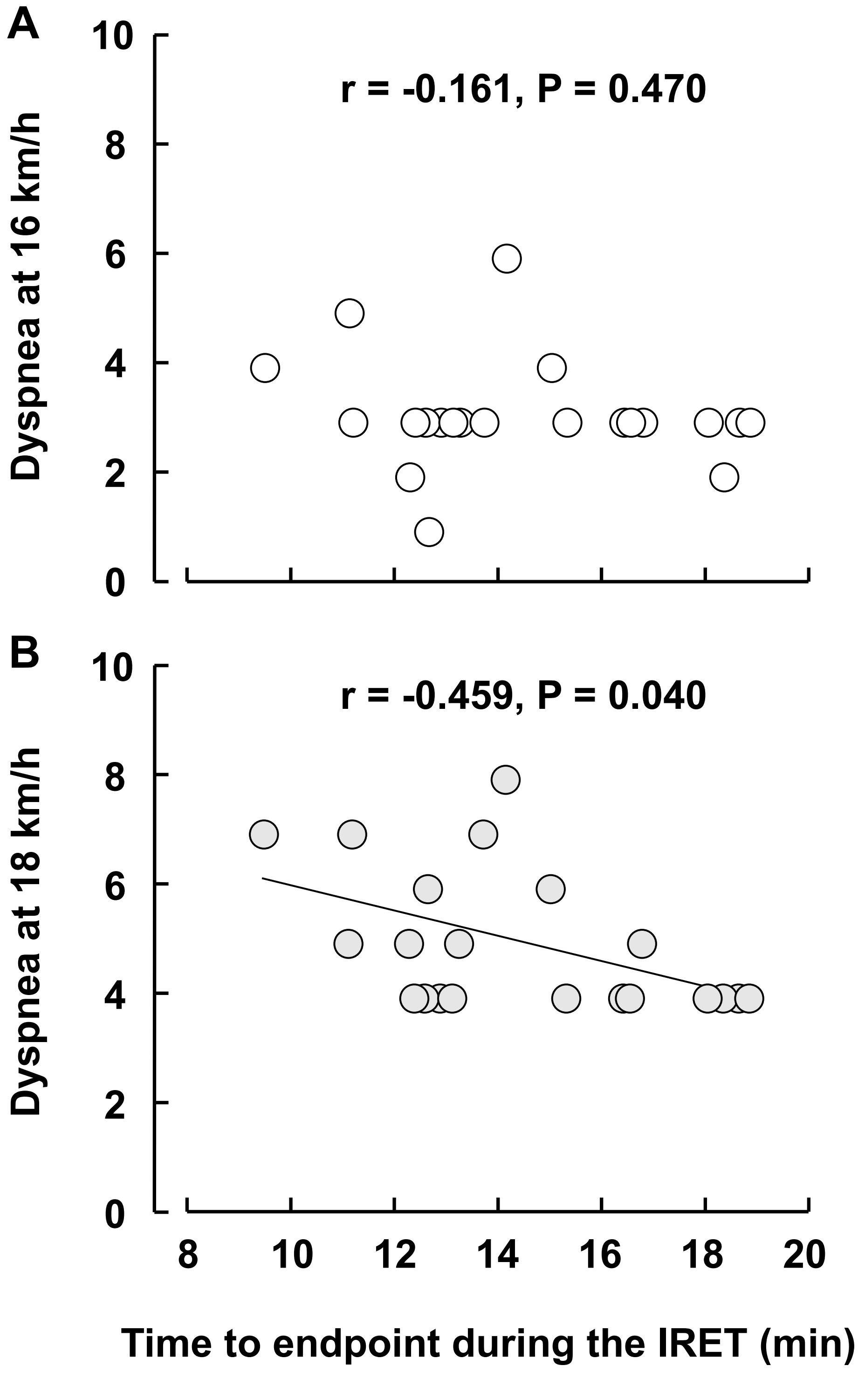
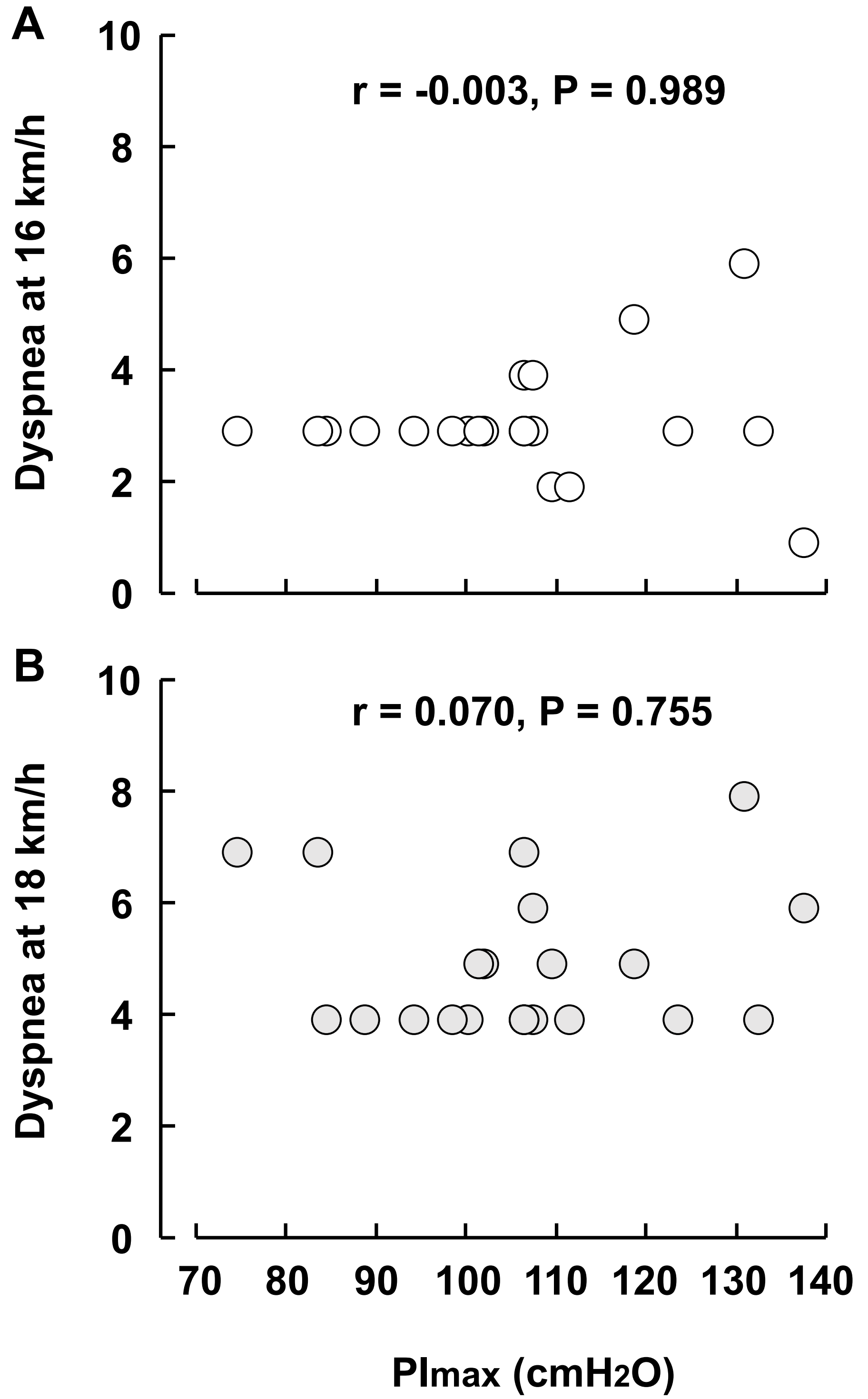

A
r = -0.161, P = 0.470
Dyspnea at 16 km/h
0
2
4
6
8
10
B
r = -0.459, P = 0.040
Dyspnea at 18 km/h
0
2
4
6
8
10
8
10
12
14
16
18
20
Time to endpoint during the IRET (min)

Figure 1 R1



A
10
r = -0.003, P = 0.989
8
6
4
2
0
Dyspnea at 16 km/h
B
10
r = 0.070, P = 0.755
8
6
4
2
0
Dyspnea at 18 km/h
70
80
90
100
110
120
130
140
PImax (cmH2O)

Figure 2 R1

Table 1. Cardiorespiratory variables during submaximal exercise test.

Variables	Treadmill speed 16 km/h	Treadmill speed 18 km/h
$\dot{V}_E$ (L/min)	83.9 ± 11.0	109.8 ± 13.1
$\dot{V}O_2$ (L/min)	3.1 ± 0.3	3.5 ± 0.3
$\dot{V}O_2$ (mL//kg/min)	53.9 ± 3.4	61.4 ± 3.7
$\dot{V}CO_2$ (L/min)	2.8 ± 0.3	3.5 ± 0.3
RER	0.90 ± 0.03	0.99 ± 0.04
HR (beats/min)	173.2 ± 8.7	184.0 ± 6.4

$\dot{V}_E$, expired minute ventilation; $\dot{V}O_2$, oxygen uptake; $\dot{V}CO_2$, carbon dioxide output; RER, respiratory exchange ratio; HR, heart rate. Values are expressed mean ± SD.