Prolonged Intermittent Running Induces Inspiratory-Muscle Fatigue in Female Runners

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Abstract: Inspiratory-muscle fatigue (IMF) may occur after long-duration or continuous short-duration exercise and may limit exercise performance. Daily athletics training is often intermittent, but it is unclear if intermittent running induces IMF. We investigated IMF after a maximal anaerobic running test (MART) and maximal intermittent graded exercise test. Nine female middle-distance (400 or 800 m) runners performed MART and maximal intermittent graded exercise tests. Maximal inspiratory pressure (MIP) was measured before and after each test using a portable autospirometer. There was no significant difference in mean MIPs before (105 ± 24 cm H₂O) and after (104 ± 28 cm H₂O) the MART ($P = 0.95$, effect size [ES] as partial $\eta^2 = 0.01$). Mean MIP after the maximal intermittent graded exercise test (97 ± 26 cm H₂O) was lower than before exercise (105 ± 27 cm H₂O) ($P = 0.01$, $\eta^2 = 0.83$). Mean IMF was higher for the maximal intermittent graded exercise test (8.5 ± 4.2 cm H₂O) than for the MART (0.8 ± 4.1 cm H₂O) ($P = 0.01$, ES as Cohen's $d = 1.88$). IMF occurs after relatively long-duration intermittent running exercise. Coaches may consider recommending inspiratory-muscle training or warm-up to reduce IMF resulting from relatively long-duration intermittent running exercise.

Key words: Respiratory muscle, diaphragm, maximal inspiratory pressure, track and field, MART.

1. Introduction

Inspiratory-muscle fatigue (IMF) occurs after various types of long-duration continuous exercise [1-3]. However, a previous study found that short-duration continuous exercise to exhaustion did not alter stimulated transdiaphragmatic pressures [4], suggesting that the exercise duration ($> 90\%$ $\dot{V}O_{2\max}$ for only 4.3 min) was too short for the cumulative work of the diaphragm to reach levels that caused fatigue [4, 5]. It is therefore likely that both the intensity and duration of exercise are involved in the development of IMF [5].

We previously demonstrated that runners experience IMF, not only after long-duration continuous exercise sessions lasting more than 10 min [6-8], but also after short-duration continuous exercise [9]. Specifically, IMF occurred after 400-m and 800-m running tests in trained female middle-distance runners [9]. Running

requires additional work from the inspiratory muscles, and runners might thus be more susceptible to IMF than other athletes [10].

Although athletic track running events are continuous in nature, physical-fitness testing and daily training are often intermittent. It is unclear if intermittent running can induce IMF, and clarification of this issue could help to inform physical-fitness measurements and the development of training programs for runners in light of limitations on exercise performance due to IMF [5, 11].

In the present study, we determined if IMF was induced by both short-duration and relatively long-duration intermittent running. We hypothesized that short-duration intermittent running exercise would not induce IMF because it would be relieved during the rest periods, whilst relatively long-duration intermittent running exercise would induce IMF. We compared maximal inspiratory pressure (MIP) before and after a short-duration intermittent exercise test with

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the results of a relatively long-duration intermittent running test. We used the maximal anaerobic running test (MART), because the lengths of time spent running during this test were similar to those spent in short-duration continuous running exercise that induced IMF in previous studies [9]. We also used the maximal intermittent graded exercise test approximately more than 10 min.

2. Methods

2.1 Experimental Overview

Participants visited the laboratory on three occasions. During the first visit, they completed an assessment of dynamic pulmonary function and familiarization with tests for measuring MIP. During the second and third visits, a MART and a maximal intermittent graded exercise test were performed. These tests were performed in random order and were separated by at least 24 h. MIP was measured before and after each test. A 30-min whole-body warm-up was performed before each test consisting of 10 min of stretching exercises and 20 min of running exercise. The whole-body warm-up was the same for the MART and maximal intermittent graded exercise test. Participants were required to consume their last meal at least 3 h before and to refrain from drinking caffeinated beverages for at least 10 h before each test.

2.2 Participants

Nine female middle-distance runners (400 m, $n = 5$, best-time range 55.26–58.22 s; 800 m, $n = 4$, best time range 126.71–132.17 s) participated in this study (age 20.1 ± 1.2 years, height 163.2 ± 5.5 cm, weight 51.1 ± 4.6 kg, athletic career 8 ± 4 years). All participants were members of a collegiate athletic team and had participated in interscholastic and/or intercollegiate athletic competitions at least once. Participants had no history or clinical signs of cardiovascular or pulmonary disease. We informed participants of the purpose of the experiment, the procedure, and the possible risks, and each provided written consent to participate. This study

was approved by the Human Subjects Committee at the Japan Institute of Sports Sciences, in the spirit of the Declaration of Helsinki.

2.3 MART

The MART was introduced to determine the neuromuscular and metabolic components of maximal anaerobic performance [12] and to determine peak blood lactate concentration ($[La]_b$). It consists of a series of 20-s runs on a treadmill with the incline set at 4° with 100 s recovery between runs. The running velocity is 250 m/min in the first stage and is increased by 25 m/min in subsequent stages. The treadmill is stopped when the participant can no longer keep up with the treadmill. Strong, vigorous encouragement was given during the test. Fingertip blood samples (0.3 μ L) were collected to measure $[La]_b$ after a recovery period of 40 s and at 1, 3, 5, 7, and 10 min after the end of the test. Peak $[La]_b$ values were recorded as the highest value collected after the end of the test.

2.4 Maximal Intermittent Graded Exercise Test

A maximal intermittent graded exercise test was performed using the treadmill to determine $[La]_b$ curve and $\dot{V}O_{2peak}$. This is one of the most-used tests of aerobic energy-supply capacity for middle-distance runners at the Japan Institute of Sports Sciences. Participants performed a warm-up, and running speed was then adjusted to 180 m/min and increased by 30 m/min every 3 min until exhaustion. Participants were allowed to rest for 1 min between stages. If a participant completed the 330-m/min stage, running speed was adjusted constantly, without rest periods, until exhaustion. Participants were required to maintain running speed during the test. The test was terminated if a participant could not maintain the required running speed despite vigorous encouragement. Breath-by-breath respiratory-gas-exchange values were measured using an automated gas-analysis system (AE-310s; Minato Medical Science, Osaka, Japan) to determine minute ventilation ($\dot{V}E$), and oxygen uptake

($\dot{V}O_2$) during the test. Respiratory-gas-exchange values were averaged every 30 s. Heart rate (HR) was monitored (RS800; Polar Electro, Kempele, Finland) and averaged every 5 s during the test. The gas-analysis system was calibrated before each test using a gas mixture of known O_2 and CO_2 concentrations. The volume transducer was calibrated before each test using a 2-L syringe (Minato Medical Science). Maximal values were recorded for the maximal intermittent graded exercise test. $\dot{V}O_{2peak}$ was defined as the highest $\dot{V}O_2$ attained during the maximal intermittent graded exercise test. Fingertip blood samples (0.3 μ L) were collected to measure $[La]_b$ using the lactate oxidase enzyme electrode method (Lactate Pro 2 LT-1730; Arkray, Kyoto, Japan) at each rest period (between stages) and 1, 3, and 5 min after the end of the test. Peak $[La]_b$ value was recorded as the highest value collected after the end of the test.

2.5 MIP Procedure

MIP is commonly used to measure inspiratory-muscle strength and was assessed according to published guidelines [13]. MIP was measured before the whole-body warm-up, and within 2 min after completion of the MART and maximal intermittent graded exercise tests, using a portable autospirometer (AS-507; Minato Medical Science) with a handheld mouth-pressure meter (AAM377; Minato Medical Science) [14]. All measurements were made while the participant sat with her nose occluded. Participants were instructed to perform maximal exhalation and then inhale as hard and as quickly as possible to total lung capacity, and sustain this inspiration for at least 1 s. Measurements were repeated until a minimum of five and a maximum of seven technically satisfactory measurements were obtained, and the greatest of the three measurements with $< 10\%$ between-measurement variability was defined as the maximum [15]. The percentage decrease in MIP from pre-warm-up to post test was considered to represent the IMF associated with each test.

2.6 Pulmonary-Function Testing

Pulmonary function was assessed using a portable autospirometer (AS-507; Minato Medical Science) [14] to determine forced vital capacity (FVC) and forced expiratory volume in 1 s (FEV_1). All measurements were performed according to published guidelines [16]. Specifically, the participant inhaled rapidly and completely from functional residual volume with the breathing tube inserted into the mouth, making sure the lips were sealed around the mouthpiece. The participant was then prompted to blast the air from her lungs and was encouraged to exhale fully. The test was repeated at least three times.

2.7 Statistical Analysis

Values are expressed as mean $\pm$ standard deviation. Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 19.0 (IBM Corp., Armonk, NY, USA). Analysis of MIP (at baseline and after each test) was conducted using two-way repeated measures analysis of variance. Significant interactions were then assessed using Bonferroni *post hoc* tests. Paired *t*-tests were used to assess the differences in IMF values before and after the tests. Correlations between the IMF value and running time were determined and tested for significance using Pearson's product-moment test. Significance was set at $P < 0.05$.

3. Results

3.1 MART

Mean peak $[La]_b$ value after the MART was 13.8 ± 2.6 mmol/L. Mean exercise duration, excluding the recovery period between stages, was 2.6 ± 0.2 min.

3.2 Maximal Intermittent Graded Exercise Test

Mean values for the maximal intermittent graded exercise test were $\dot{V}O_{2peak}$ 48.6 ± 8.3 mL/kg/min, $\dot{V}E_{max}$ 113.9 ± 9.8 L/min, HR_{max} 197 ± 12 beats/min, respiratory exchange ratio 1.27 ± 0.11 , and $[La]_b$ 15.0 ± 2.7 mmol/L. Mean exercise duration, excluding the rest

period between stages, was 16.4 ± 2.6 min.

3.3 MIP and Pulmonary Function

Fig. 1 shows the individual and mean MIP values before and after the MART and maximal intermittent graded exercise tests. There was no significant difference in mean MIP values before and after the MART ($P = 0.95$, effect size [ES] as partial $\eta^2 = 0.01$). Mean MIP after the maximal intermittent graded exercise test was significantly lower than before exercise ($P = 0.01$, $\eta^2 = 0.83$). Mean IMF for the maximal intermittent graded exercise test was significantly higher than that of the MART ($P = 0.01$,

Fig. 1 Maximal inspiratory pressure before and after the MART ($\circ$ = individual, $\bullet$ = mean, $n = 9$) and maximal intermittent graded exercise test (Δ = individual, $\blacktriangle$ = mean, $n = 9$). *Significant difference vs. before test ($P < 0.05$). †Significant difference vs. MART ($P < 0.05$). MART, maximal anaerobic running test.

Fig. 2 Inspiratory-muscle fatigue values after the MART and maximal intermittent graded exercise test. Values are expressed as mean $\pm$ standard deviation ($n = 9$). MART, maximal anaerobic running test. *Significant difference ($P < 0.05$).

ES as Cohen's $d = 1.88$) (Fig. 2). There was no correlation between IMF and running time ($r = 0.16$, $P = 0.69$ and $r = -0.06$, $P = 0.88$ for the MART and maximal intermittent graded exercise test, respectively). Mean FVC and FEV₁ were 3.56 ± 0.52 L and 3.23 ± 0.36 L, respectively.

4. Discussion

The results of this study demonstrated that IMF occurred after maximal intermittent graded exercise testing, but not after MART. Fatigue may be defined as the failure of a muscle to maintain or develop its previous force of contraction [17], and the reduction in MIP observed after running in the present study represented the IMF associated with the maximal intermittent graded exercise test, but not the MART.

We recently demonstrated that IMF occurred after short-duration continuous running exercise, with mean IMF values of $10.0 \pm 8.8\%$ and $15.1 \pm 10.1\%$ after 400-m and 800-m tests, respectively [9]. However, although the lengths of time spent running were approximately the same as the duration of the 800-m exercise (continuous running) that induced IMF in our previous study [9], IMF did not occur after the MART in the present study. Running requires additional work from the inspiratory muscles, and runners might thus be more susceptible to IMF than other athletes [10].

Although the diaphragm is the principal muscle of inspiration, the human diaphragm also performs postural functions [18, 19]. The recovery period during short-duration continuous running exercise, such as the MART in the present study, might attenuate IMF.

However, relatively long-duration intermittent running exercise can induce IMF despite the potential attenuation of IMF during recovery periods. It is difficult to compare directly the magnitude of the IMF observed during the maximal intermittent graded exercise test in the present study with previously reported results, because no previous study has quantified IMF after relatively long-duration intermittent running exercise. McConnell et al. [20] reported that MIP decreased significantly after a multi-stage shuttle-running test (relatively long-duration continuous running exercise test), with a mean IMF of 10.5%. The magnitude of the IMF seen in the maximal intermittent graded exercise test in the present study tended to be less than that reported after a relatively long-duration continuous running exercise test. Although relatively long-duration intermittent running exercise might attenuate the magnitude of the IMF compared with continuous running exercise, MIP might decrease after the exercise if the total time spent running is relatively long.

There was no correlation between IMF and running time in the maximal intermittent graded exercise test ($r = -0.06$, $P = 0.88$). However, although this study included a relatively small sample size, the results clearly demonstrated a consistent IMF response across all participants in the maximal intermittent graded exercise test and a weak relationship between IMF and running time, suggesting that these findings would likely be applicable to a larger group of individuals. Further studies are required to clarify the relationship between the magnitude of IMF and exercise performance.

Regarding practical applications, we demonstrated that IMF occurs after relatively-long duration intermittent running exercise. Although we found no

correlation between IMF and running time, coaches might choose to recommend inspiratory-muscle training or warm-up in an effort to reduce the IMF that inevitably accompanies relatively long-duration intermittent running exercise. Inspiratory-muscle warm-up, in addition to whole-body warm-up, can improve exercise performance by improving inspiratory-muscle function [21-23], reducing the perception of breathlessness [23], and reducing lactate concentrations during exercise [21]. An inspiratory-muscle warm-up protocol performed at 40% of MIP was shown to improve badminton footwork performance [21] and intermittent running performance [22].

This study had several limitations. First, all the participants were female, and the female diaphragm is more resistant to fatigue than the male diaphragm [1]. Although VE in males increases progressively and linearly with increased time spent at a fixed work rate, VE in females plateaus despite continuing to perform the same muscular task, meaning that females use a smaller proportion of their maximal exercise ventilatory capacity [1]. We therefore speculate that IMF might occur after the MART in males, but further research is needed to confirm this. Second, the inspiratory muscle-strength measurements were volitional. Although non-invasive techniques are subject to more variation than invasive techniques, such as the use of a balloon-catheter system, they are better tolerated by participants and have been shown to be reliable and valid [24, 25]. Finally, the test protocol was limited to the MART and maximal intermittent graded exercise test because that is the protocol most often used to determine the physical fitness of middle-distance runners at the Japan Institute of Sports Sciences. Furthermore, two participants in this study completed the 330-m/min stage of the maximal intermittent graded exercise test, after which the test was not truly intermittent. Further studies are required to clarify if other intermittent running protocols can induce IMF.

5. Conclusions

IMF occurred in trained female middle-distance runners after the maximal intermittent graded exercise test but not after the MART. These results demonstrate that IMF is not induced by short-duration intermittent running exercise, but is induced by relatively long-duration intermittent running exercise. Further studies are required to determine if other intermittent running protocols can induce IMF.

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