The effect of exercise modality on respiratory muscle performance in triathletes

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ABSTRACT

BOUSSANA, A., S. MATECKI, O. GALY, O. HUE, M. RAMONATXO, and D. LE GALLAIS. The effect of exercise modality on respiratory muscle performance in triathletes. *Med. Sci. Sports Exerc.*, Vol. 33, No. 12, 2001, pp. 2036–2043. **Purpose:** The aim of this study was to examine the effects of the cycle-run and run-cycle successions of the triathlon and duathlon, respectively, on respiratory muscle strength and endurance. **Methods:** Respiratory muscle strength was assessed by measuring maximal inspiratory (P_{Imax}) and expiratory (P_{Emax}) pressures. Respiratory muscle endurance was assessed by measuring the time limit (T_{lim}). Twelve triathletes participated in a three-trial protocol. The first trial consisted of an incremental cycle test to assess the maximal oxygen uptake ($\dot{V}O_{2max}$) of triathletes. Trial 2 consisted of 20 min of cycling followed by 20 min of running (C-R), and trial 3 consisted of 20 min of running followed by 20 min of cycling (R-C). Trials 2 and 3 were performed at the same metabolic intensity (% $\dot{V}O_{2max}$). P_{Imax} and P_{Emax} were measured before and 10 min after C-R and R-C, and 1 min after the post-C-R and post-R-C T_{lim} measurements (P_{Imax} 1'). T_{lim} was measured 1 d before and 30 min after C-R and R-C. **Results:** The results showed a significant decrease in P_{Imax} after C-R (126.7 ± 4.3 cmH$_2$O, $P < 0.05$) and R-C (123.7 ± 4.9 cmH$_2$O, $P < 0.05$) compared with the baseline values (130 ± 3.8 and 129.6 ± 4.3 cmH$_2$O, respectively). P_{Imax} 1' showed a significantly greater decrease after R-C versus C-R (111.2 ± 5.5 cmH$_2$O vs 121.2 ± 3.9 cmH$_2$O, respectively, $P < 0.001$). T_{lim} after C-R (3.3 ± 0.3 min) and R-C (2.1 ± 0.3 min) decreased significantly compared with baseline values (4.19 ± 0.3 min and 4.02 ± 0.3 min, respectively). However, the T_{lim} decrease after R-C was significantly greater than after C-R ($P < 0.001$). **Conclusion:** We concluded that respiratory muscle strength and endurance were less decreased after the cycle-run succession and that cycling induced a greater decrease in respiratory muscle endurance than running. **Keys Words:** TRIATHLON, RESPIRATORY MUSCLE STRENGTH, RESPIRATORY MUSCLE ENDURANCE, MAXIMAL INSPIRATORY PRESSURE (P_{Imax}), TIME LIMIT (T_{lim})

Respiratory muscle strength and endurance are altered after both short exercise (3,31) and endurance events (18). Loke et al. (20) and Chevrolet et al. (8) indicated that the marathon race induces a decrease in inspiratory (P_{Imax}) and expiratory (P_{Emax}) muscle strength. This decrease in P_{Imax} was also reported after a triathlon (13) and after an incremental multistage shuttle run to volitional fatigue (26). These authors suggested that the alterations in pressure generated by the respiratory muscles indicated the development of exercise-induced respiratory muscle fatigue, secondary to the increase in ventilatory mechanical work. The decrease in respiratory muscle strength after exercise may be due to several pathophysiological factors: changes in pulmonary compliance, airway obstruction (22), bronchoconstriction, transient pulmonary edema, and small airway closure (23,30).

Respiratory muscle fatigue may limit human performance (7,16). To better understand this fatigue, respiratory muscle endurance, which is the property of respiratory muscle that affords resistance to fatigue, has been assessed by maximal voluntary ventilation (MVV) and the time limit (T_{lim}). T_{lim} corresponds to the length of time a subject can sustain a respiratory load before the process of fatigue develops sufficiently to cause task failure (11). MVV was found to be decreased after a marathon (20) and after long-term exhausting treadmill exercise (3). Similarly, T_{lim} was found to be still decreased 3 d after an ultramarathon (18) and after an exhaustive cycling endurance test (31). Thus, both laboratory and fields tests may decrease respiratory muscle strength and endurance. Moreover, other studies have shown that exercise modality may play a role in these changes. Hill et al. (13) reported that P_{Imax} decreased significantly after the cycle segment of a triathlon and then remained constant during the subsequent run of the race. The authors suggested that the drop in P_{Imax} observed after the cycling segment—which may be associated with the crouched position of cycling—was probably due to the increase of abdominal impedance and thus the respiratory work of breathing. Recently, Hue et al. (14) corroborated this result; they reported a significant increase in residual volume and functional residual capacity after 30 min of cycling and 5 km of running compared with 30 min of

TABLE 1. General physical characteristics, training regimen data, oxygen uptake, and heart rate assessed throughout the incremental cycle test for twelve male triathletes; training distances were averaged during the period of the study.

Subjects (N = 12)	Age (yr)	Height (cm)	Weight (kg)	Mean Training Distances (km·wk^{-1})			$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})		HR (b·min^{-1})	
				Swim	Bike	Run	Max	Th$_{vent}$	Max	Th$_{vent}$
Mean	22.3	176.5	65.2	13.9	291.6	40.8	69.9	49.2	179.0	144.8
SE	0.9	2.0	1.6	0.7	29.3	3.1	0.9	1.8	2.3	1.8

$\dot{V}O_{2max}$, maximal oxygen uptake; HR, heart rate; Th$_{vent}$, ventilatory threshold. Values are expressed as mean ± SE.

running and 5 km of running at the same metabolic intensity. The authors concluded that the crouched position of cycling induced respiratory disturbance, leading to a greater respiratory recruitment and thus to respiratory muscle fatigue.

It therefore seems that cycling is more constraining and may induce a greater decrease in respiratory muscle function than running. We hypothesized that the decrease in respiratory muscle strength and endurance would be greater after a run-cycle trial than a cycle-run trial because alterations induced during cycling may be partially reversed during the subsequent run.

To test this hypothesis, we assessed respiratory muscle strength and endurance before and after a cycle-run trial similar to the succession of the triathlon and compared the results with a balanced run-cycle trial similar to the succession of the duathlon. In a previous study of endurance measurements, subjects were allowed to modify freely their tidal volume (Vt) or inspiratory (Ti) and expiratory (Te) times despite the finding that breathing pattern may influence the values of respiratory muscle endurance (25). Thus, in the present study, we used a method developed in our laboratory (24), and we tested the reproducibility of this method for quantifying respiratory muscle endurance by using control of breathing pattern in the triathletes.

METHODS

Approach to the problem and experimental design. This study utilized a pre- and post-test experimental design. Both pre- and post-tests were identical for the assessment of respiratory muscle force and endurance (dependent variables). The exercise modality performed between pre- and post-tests consisted of the succession of cycling and running or the reversed succession (independent variables). In addition, $\dot{V}O_2$ during exercise was fixed (controlled variable). Twelve triathletes performed two randomized trials at 1-wk interval at the same $\dot{V}O_2$. Cardiopulmonary data were measured during trials. Respiratory muscle force and endurance were measured before and after trials (pre- and post-tests). This protocol allowed us to study the effect of exercise modality (cycle-run versus run-cycle) on respiratory muscle force and endurance and simulated the successions in field events such as the triathlon and duathlon.

Subjects. Twelve nonsmoking male competitive triathletes participated in this study. All were students at the School of Physical Education at the University of Montpellier, France, and members of the university athletic team, which has been French national champion in the triathlon

for 5 consecutive years. All had been competing in the triathlon for 6.3 ± 2.7 yr and were in the competitive period at the time of the study. They were aged 22.3 ± 0.9 yr, with a weight of 65.2 ± 1.6 kg and a height of 176.5 ± 2.0 cm (Table 1). None had a prior history of respiratory or cardiovascular disease. All subjects had a forced vital capacity (FVC) >80% and forced expiratory volume in 1 s FEV$_1$/ FVC ratio >75% of predicted values (1). Subjects were informed of the purpose of the study and gave written consent before participating in the protocol, which was approved by the local Ethics Committee.

Spirometric tests. Forced expiratory volume in 1 s (FEV$_1$), forced vital capacity (FVC), residual volume (RV), functional residual capacity (FRC), and total lung capacity (TLC) were measured by plethysmography (Sensor Medics, Anaheim, CA) according to standard techniques and procedures. Lung volumes and expiratory flows were compared with reference values (1).

Respiratory muscle strength. Inspiratory (P$_{Imax}$) and expiratory (P$_{Emax}$) pressures at functional residual capacity (FRC) and the inspiratory load of the mouth pressure (p.m.) sustained were obtained with a Validyne MP 45 transducer (± 300 cmH$_2$O; model MP 45, Validyne Corp., Northridge, CA) and a CD 15 carrier demodulator. The athletes were asked to make a maximal inspiratory effort against an occluded airway according to the method described by Black and Hyatt (5). At least five repeated determinations were made until three reproducible measurements were obtained (variation in P$_{Imax}$<10%). The reported data represented the best value for each athlete.

Breathing pattern measurements during the respiratory load period. Breathing pattern was studied in a sitting position. The subjects breathed with a nose clip through a unidirectional low-resistance valve (0.9 cmH$_2$O L·s^{-1}, dead space 50 mL; Warren E. Collins, Inc., Braintree, MA) connected to a mouthpiece. Inspiratory flow was measured with a Fleish no. 2 pneumotachograph (Fleisch, Lausanne, Switzerland) placed on the inspiratory line, and a differential pressure transducer with a measuring range of ± 2 cmH$_2$O (model MP 45, Validyne Corp., Northridge, CA). Tidal volume (Vt), inspiratory time (Ti), and total duty cycle (Ttot) were obtained by integration of the flow signal.

Respiratory muscle endurance. Respiratory muscle endurance was measured by assessing the time limit (T$_{lim}$). This parameter represents the maximal time a subject can breathe against a predetermined inspiratory submaximal load. During the experimental run, a threshold valve was connected to the inspiratory side of the respiratory system. This valve consisted of a Plexiglas cylinder containing a

spring-loaded poppet valve (Threshold Inspiratory Muscle Trainer, Healthscan Products, Cedar Grove, NJ). When the negative pressure inside the cylinder exceeds the predetermined pressure load, the inspiratory orifice situated at the bottom of the cylinder is opened, allowing inspiratory flow. The spring adjustment of this valve allowed us to impose 75% of the athlete's P_{Imax} at FRC at each inspiration (18). Mouth pressure, which represented this imposed inspiratory load, was constant for a given adjustment of the threshold valve and was nearly flow-independent once the orifice was opened (17). Thus, during inspiration through the valve, the athletes had to produce 75% of their P_{Imax} to initiate and maintain airflow. A volume signal was displayed as visual feedback to the subject on a storage oscilloscope to facilitate control of Vt during the required maneuver. A beep was produced with an electronic metronome as auditory feedback. The athlete was asked to inspire and expire at each beep. Two parallel lines were drawn on the oscilloscope screen, with their distance from each other corresponding to the Vt imposed during the test at 700 mL. The electronic metronome rate was $30 \cdot min^{-1}$, in order to reproduce the respiratory cycle at rest ($Ttot_{rest}$ = 4 s) with Ti/Ttot = 0.5. The athletes then breathed with a nose clip through the unloaded respiratory system while seated and at rest. Each athlete was asked to control his inspiratory volume in such a way as to maintain the corresponding curve between the two lines at each breath, at which time the electronic metronome was started and the subject began inspiration at the first beep and began expiration at the following beep to control inspiratory volume. When control of breathing pattern at rest was obtained for 10 consecutive respiratory cycles, loaded breathing was started by adding the threshold valve to the inspiratory side at a threshold pressure of 75% of the individually determined P_{Imax} (18). The athletes were asked to achieve a target inspiratory volume that corresponded to the Vt imposed at each inspiration (700 mL) (36) while following the beeps and receiving verbal encouragement. Each subject was free to use his diaphragm or intercostal and accessory respiratory muscles, or both, to develop the required p.m. The loaded breathing was continued until the subject reached task failure; this corresponded to the time when he could no longer maintain the target tidal volume for three consecutive breaths or when he could no longer tolerate the procedure and came off the mouthpiece.

At the end of the run, we assumed that all the inspiratory muscles, not just the diaphragm, were fatigued. The period of loaded breathing was defined as the duration of the run, or the endurance time (T_{lim}). P_{Imax} 1' was then measured 1 min after the end of T_{lim} measurements. All signals were displayed on a Gould ES1000 recorder (Gould, Inc., Cleveland, OH). From an average of 10 respiratory cycles, we measured the following parameters at rest and at the beginning and end of the T_{lim} measurement: Ti, Ttot, the ratio of inspiratory time to total inspiratory time (Ti/Ttot) of the respiratory cycle, and imposed p.m. The beginning of Ti was determined from the p.m. signal and the end from the flow signal. To test the reproducibility of T_{lim}, subjects repeated the measurements on two occasions before exercise.

Gas exchange measurements. Ventilatory data were measured every minute during the three trials of the protocol by using a mass spectrometer breath-by-breath automated system (MGA-1100, Marquette, NY): minute ventilation ($\dot{V}_E$: $L \cdot min^{-1}$), oxygen uptake ($\dot{V}O_2$: $mL \cdot min^{-1}$, $mL \cdot kg^{-1} \cdot min^{-1}$), carbon dioxide production ($\dot{V}CO_2$: $mL \cdot min^{-1}$), respiratory exchange ratio (R), respiratory equivalents for O_2 ($\dot{V}_E/\dot{V}O_2$) and CO_2 ($\dot{V}_E/\dot{V}CO_2$), breathing frequency (f: $breaths \cdot min^{-1}$), and tidal volume (V_T: mL). Heart rate (HR: $b \cdot min^{-1}$) was measured using a telemetric system (Polar Sport Tester, Polar Electro Oy, Kempele, Finland). Trial 1 was performed to assess maximal oxygen uptake ($\dot{V}O_{2max}$) and ventilatory threshold (Th_{vent}) of triathletes. $\dot{V}O_{2max}$ was determined according the following criteria: identification of a plateau in $\dot{V}O_2$ with a further increase in power output (W), HR equal to age-predicted maximal HR ($\pm$ 10 $b \cdot min^{-1}$), and respiratory exchange ratio (R) $\geq$ 1.10. Th_{vent} was automatically determined using the V-slope method of Beaver et al. (2). This method involves the analysis of $\dot{V}CO_2$ as a function of $\dot{V}O_2$ and assumes that the Th_{vent} corresponds to the breakpoint in the $\dot{V}CO_2$-$\dot{V}O_2$ relationship. $\dot{V}O_{2max}$ and Th_{vent} were used to determine the metabolic intensity of trials 2 and 3: 75% $\dot{V}O_{2max}$ and above Th_{vent}.

Testing protocol. All subjects performed a three-trial protocol. The tests were conducted in an air-conditioned laboratory with a mean room temperature of 21 $\pm$ 0.2°C and a barometric pressure of 777.5 $\pm$ 4.5 mm Hg. Testing was at the same time of the day and during the same day of the week to minimize the influences of circadian rhythm and personal training on the study. The triathletes were asked to maintain their training schedule for the duration of the study, but they were not allowed to compete in a triathlon during the testing period. In addition, they were asked to refrain from training on experimental days. All athletes were familiarized with treadmill running and with the use of the cycle ergometer before testing. Trial 1 consisted of an incremental cycle test performed on an electromagnetic cycle ergometer (Monark 864, Monark-Crescent AB, Varberg, Sweden). After a 3-min warm-up at 30 W, the power was then increased by 30 W every minute until the subject reached volitional fatigue. Trial 2 consisted of 20 min of cycling followed by 20 min of running (C-R), and trial 3 consisted of 20 min of running followed by 20 min of cycling (R-C). Trials 2 and 3 were performed at the same metabolic intensity (% $\dot{V}O_{2max}$) at a 1-wk interval.

Plethysmography was measured at rest before beginning the testing protocol; respiratory muscle strength was measured before and 10 min after trials 2 and 3, and endurance was measured on the day before and 30 min after trials 2 and 3. Trials 2 and 3 were performed at the same O_2 consumption ($\dot{V}O_2$). These two trials were performed in random order to minimize the effect of order. As reported in a previous study (14), the cycling and running $\dot{V}O_{2max}$ values of the present group of triathletes were similar. Thus, the cycling $\dot{V}O_{2max}$ value measured in trial 1 was used to monitor both the running and cycling intensities during the C-R and R-C trials. During trials 2 and 3, cycling was

performed on each triathlete's personal cycle equipped with a handlebar and placed on a home trainer (Pro Trainer, P.T., Milan, Italy). The intensity (and gear ratio) was close to the triathlete's performance level and above the Th_{vent} calculated in trial 1 (nearly 75% of $\dot{V}O_{2max}$). The cycling speed was reached in less than 1 min and the $\dot{V}O_2$ level was reached approximately at the 3rd minute. Triathletes then adjusted their cycling speed by 1 $km \cdot h^{-1}$ each minute to optimize their cycling time performance. Distances were measured with a bike odometer (Top Bike, Tokyo, Japan). At the end of the 20 min of cycling in trial 2, the subjects had 1 min to change their shoes and get on the treadmill (Gymroll 1800, Gymroll, Roche la Molière, France). Intensity was calculated to be close to the athlete's performance level and above the Th_{vent} calculated in trial 1 (nearly 75% of $\dot{V}O_{2max}$). The run speed was reached in less than 1 min, and the $\dot{V}O_2$ level was reached approximately at the 3rd minute. Triathletes then adjusted their run speed by 0.5 $km \cdot h^{-1}$ each minute to optimize their running time performance. Running distances were measured with the treadmill odometer. During trial 3, running and cycling were performed for the same amount of time and at the same metabolic intensity, but in the opposite order, as in trial 2.

Statistical analysis. The results are expressed as means ± SE. Cycling and running distances of C-R and R-C were compared using the Student paired t-test. $\dot{V}O_2$ values throughout C-R versus R-C were compared using a two-way analysis of variance (ANOVA) for repeated measures. Respiratory muscle function (P_{Imax}, P_{Emax}, and T_{Lim}) before and after C-R and R-C (and after T_{lim} for P_{Imax} 1') was compared using a two-way ANOVA for repeated measures. When significant results were obtained with ANOVA, the Scheffé *post hoc* test was carried out. The reproducibility of T_{lim} was assessed by plotting the difference between the first and second sets of measurement against the mean T_{lim}, as described by Bland and Altman (6). The comparison of the breathing pattern at preload, begin-load, and end-load, after C-R and R-C, was done using a two-way ANOVA. When significant results were obtained with ANOVA, the Scheffé *post hoc* test was carried out. Statistical analysis was performed using a statistical software package (SYSTAT). Statistical significance was accepted at the $P < 0.05$ level.

RESULTS

Exercise intensities. The incremental exercise test produced the following values: 69.9 ± 0.9 $mL \cdot kg^{-1} \cdot min^{-1}$ $\dot{V}O_{2max}$, 179.6 ± 1.8 $b \cdot min^{-1}$ HR max, 49.2 ± 1.8 $mL \cdot kg^{-1} \cdot min^{-1}$ $\dot{V}O_2$, and 144.8 ± 1.8 $b \cdot min^{-1}$ HR at Th_{vent} (Table 1).

TABLE 2. Mean oxygen uptake and distances measured during the cycle-run (C-R) and run-cycle (R-C) trials; values are expressed as mean ± SE.

Parameters	Trial 2		Trial 3	
	Cycle	Run	Run	Cycle
Distance (km)	12.61 ± 0.2	6.57 ± 0.1	6.53 ± 0.1	11.95 ± 0.3
$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	53.8 ± 1.2	51.1 ± 1.6	52.2 ± 1.5	53.2 ± 1.4
$\dot{V}O_{2max}$ (%)	75.5 ± 1.0	72.8 ± 1.4	74.2 ± 1.2	75.7 ± 1.2

No significant difference was noted between the two trials.

TABLE 3. Mean spirometric absolute values and percentage (%) predicted before cycle-run (C-R) and run-cycle (R-C); values are expressed as mean ± SE.

Parameters	Trial 2 Cycle-Run	Trial 3 Run-Cycle
FVC (L)	5.62 ± 0.1	5.77 ± 0.1
FVC (% predicted)	108.5 ± 2.4	109.0 ± 2.2
FEV_1 ($L \cdot s^{-1}$)	4.64 ± 0.2	4.79 ± 0.1
FEV_1 (% predicted)	103.9 ± 2.1	107.3 ± 1.5
FEV_1/FVC (%)	80.4 ± 2.0	80.6 ± 2.0

No significant difference was noted between the two trials.

No significant difference was noted in the cycling and running distances during C-R and R-C: 12.6 ± 0.2 km and 6.5 ± 0.1 km versus 11.9 ± 0.3 km and 6.5 ± 0.1 km, respectively. Similarly, no significant difference was noted in cycling and running $\dot{V}O_2$ during C-R and R-C: 53.8 ± 1.2 $mL \cdot kg^{-1} min^{-1}$ and 51.1 ± 1.6 $mL \cdot kg^{-1} \cdot min^{-1}$ versus 52.2 ± 1.5 $mL \cdot kg^{-1} \cdot min^{-1}$ and 53.2 ± 1.4 $mL \cdot kg^{-1} \cdot min^{-1}$ (Table 2).

Spirometry. The absolute values and percentages (%) of predicted values for FVC, FEV_1, and FEV_1/FVC were within normal ranges before trials 2 and 3 (Table 3).

Respiratory muscle strength. No significant difference in P_{Emax} was noted pre- versus post-tests or between the two trials (Fig. 1). A significant decrease in P_{Imax} was noted pre- versus post-tests ($P < 0.05$), but no difference was noted between the two trials (Fig. 2). Moreover, a significant decrease in P_{Imax} was noted post-tests versus post-T_{lim} measurements. Lastly, a significant difference in P_{Imax} was noted between trials at post-T_{lim} measurements (Fig. 3).

Respiratory muscle endurance. The reproducibility of T_{lim} as tested by the Bland and Altman (6) method showed variations below 10% between the pre-test measurements (Fig. 4). A significant decrease in T_{lim} was noted pre-versus post-tests. Moreover, a significant difference was noted between trials (Fig. 5). The breathing pattern (Vt, Ti,
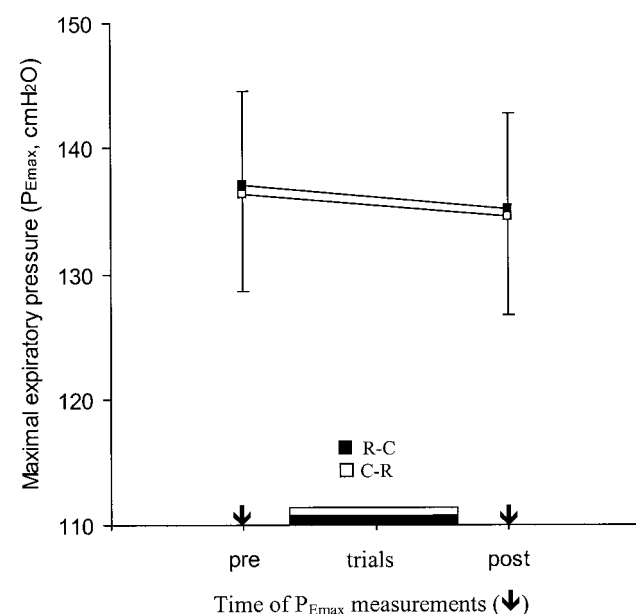

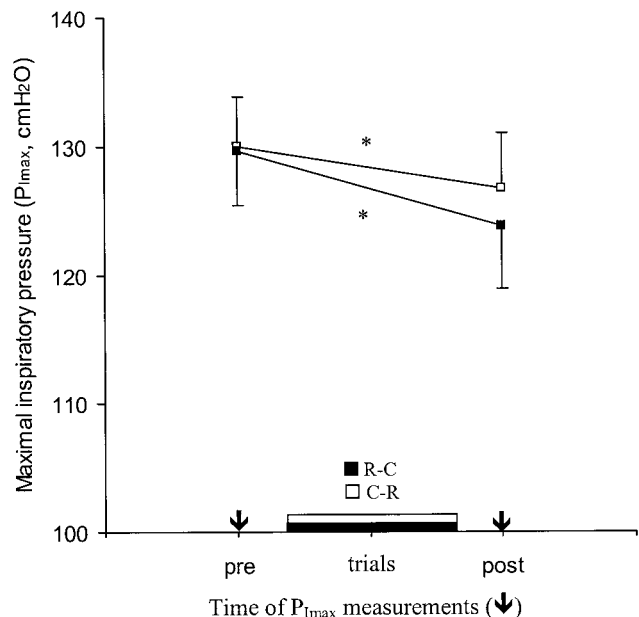FIGURE 1—Maximal expiratory pressure (P_{Emax}) at pre- and post-C-R (□) and R-C (■). No significant differences.

FIGURE 2—Maximal inspiratory pressure (P_{Imax}) at pre- and post-C-R ($\square$) and R-C ($\blacksquare$). * Significant differences ($P < 0.05$) between pre- versus post-values.

Ttot) showed no significant difference between the resting values versus those recorded at the beginning and end of the T_{lim} measurements after the two trials (Table 4).

DISCUSSION

The present study showed that after a cycle-run succession and an inverse run-cycle succession, both of the same duration (run = cycle = 20 min) and at the same metabolic
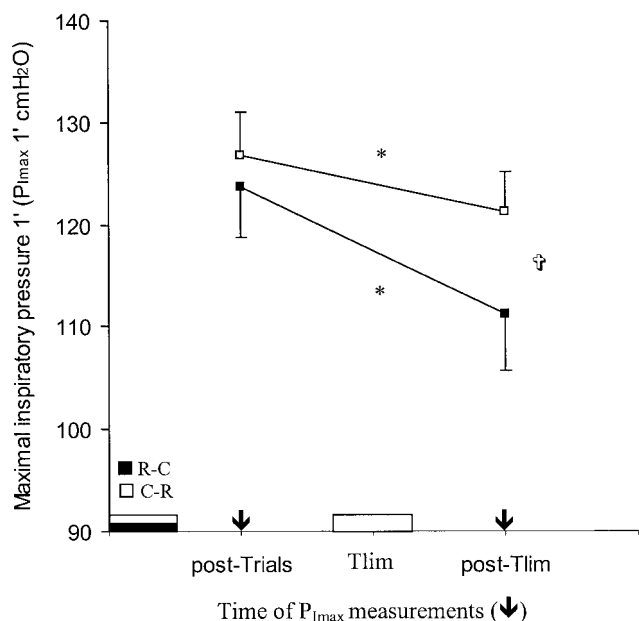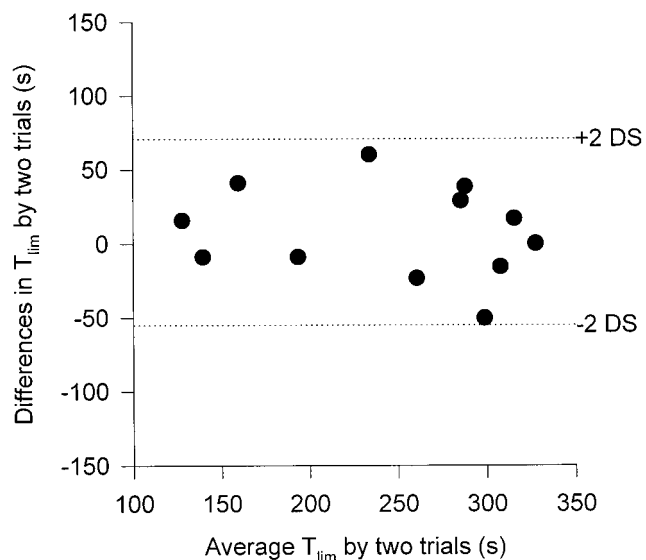

FIGURE 4—Plot of the differences between T_{lim} values obtained from the analysis of all athletes in the two different trials at rest before C-R and R-C, against their means. The dashed lines represent mean ± two standard deviations (2 SD).

intensity (75% $\dot{V}O_{2max}$), inspiratory muscle strength and endurance were significantly decreased. In addition, the run-cycle exercise induced a significantly greater decrease in respiratory muscle endurance than the cycle-run exercise.

Respiratory muscle strength. The effect of exercise on expiratory muscle strength and fatigue remains controversial. Chevrolet et al. (8) suggested that the use of expiratory muscles during exercise and hyperventilation differs among subjects and that abdominal muscles can sustain part of the expiratory work during heavy breathing. Suzuki et al.

FIGURE 3—Maximal inspiratory pressure at post-trials (C-R $\square$ and R-C $\blacksquare$), and 1-min post-T_{lim} (P_{Imax} 1'). * Significant differences ($P < 0.05$) between post-trials versus post-T_{lim}. † Significant difference ($P < 0.02$) between post-T_{lim} measurements.
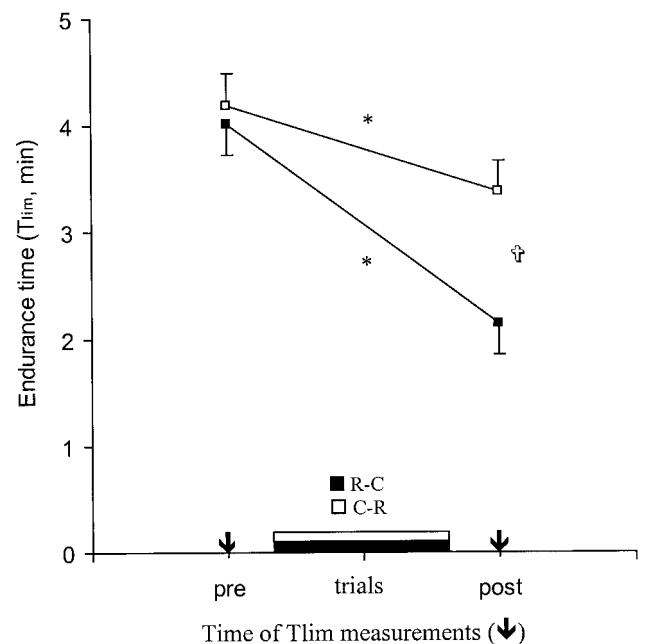
FIGURE 5—Respiratory muscle endurance time (T_{lim}) at pre- and post-C-R ($\square$) and R-C ($\blacksquare$). * Significant difference ($P < 0.05$) between pre- and post-trials. † Significant difference ($P < 0.001$) between post-trial measurements.

TABLE 4. Controlled breathing pattern in triathletes during measurement of respiratory muscle endurance after cycle-run (C-R) and run-cycle (R-C); values are expressed as mean ± SE.

Parameters	Pre-Load		Begin-Load		End-Load	
	C-R	R-C	C-R	R-C	C-R	R-C
Vt (mL)	740 ± 14	739 ± 14	737 ± 14	741 ± 14	738 ± 10	736 ± 14
Ttot (s)	3.98 ± 0.06	3.98 ± 0.05	3.97 ± 0.07	3.95 ± 0.08	3.96 ± 0.01	3.94 ± 0.09
Ti (s)	1.98 ± 0.02	1.98 ± 0.06	1.97 ± 0.09	1.96 ± 0.06	1.95 ± 0.07	1.93 ± 0.04
fr (br·min⁻¹)	15.0 ± 0.0	15.07 ± 0.0	15.1 ± 0.0	15.1 ± 0.0	15.1 ± 0.0	15.2 ± 0.0
Ti/Ttot	0.49 ± 0.05	0.49 ± 0.01	0.49 ± 0.01	0.49 ± 0.07	0.49 ± 0.07	0.48 ± 0.07

Pre-load, measurement without resistive valve; begin-load, measurement at the beginning of the run; end-load, measurement at the end of the run; Vt, tidal volume; Ttot, total time of respiratory cycle; Ti, inspiratory time; fr, breathing frequency; Ti/Ttot, inspiratory time/total time. Comparison between pre-load, begin-load, and end-load showed no significant difference.

(35) measured P_{Emax} at different loads and reported a significant decrease in P_{Emax} after high loads only. The authors concluded that in normal subjects, expiratory muscle fatigue was rather difficult to induce and that very high resistance must be applied to promote expiratory muscle fatigue. The similar P_{Emax} noted before and after C-R and R-C in the present study was in agreement with the post-exercise results reported in other studies (8,13). However, others (20,30) have reported a decrease after similar endurance or incremental exercises. We thus assume that our exercise task was insufficient to induce expiratory muscle fatigue in well-trained competitive triathletes.

The significant decrease in P_{Imax} supported the findings after strenuous exercise noted in previous studies (8,26). The differing responses of P_{Imax} and P_{Emax} to the same exercise suggest that inspiratory muscles may be more susceptible to fatigue than expiratory muscles (13). Several pathophysiological mechanisms are involved in the decrease in respiratory muscle strength after exercise. Mizuno and Secher (27) reported a larger fiber area and more capillaries per fiber in expiratory muscles compared with inspiratory muscles in a study of the histochemical characteristics of inspiratory and expiratory internal intercostals. Chevrolet et al. (8) reported a similar decrease in P_{Imax} and triceps surae force after a marathon, and they suggested that these results were due to local fuel shortage in individual muscles.

One might have expected that the decrease in P_{Imax} measured in the present study would be different after C-R and R-C because of the specific use of these muscles during cycling and running. Indeed, inspiratory muscles are not involved similarly during the two activities. Pulmonary function is known to be easier during running, in contrast with the crouched position of cycling, during which abdominal impedance may rise, thus increasing diaphragmatic work (13). The absence of difference in P_{Imax} after C-R and R-C could be explained by the fact that maximal inspiratory strength is not the main function of respiratory muscles. We therefore tested respiratory muscle endurance.

Respiratory muscle endurance. The measurement of respiratory muscle endurance has been widely reported in the literature by using MVV (20), inspiratory increased-load (10), and inspiratory constant-load (29). Previous authors showed a decrease in respiratory muscle endurance as measured by MVV 60 min after completion of a marathon and suggested respiratory muscle fatigue. Bender and Martin (3) proposed that the reduction in MVV was due to the deple-

tion of stored glycogen in the ventilatory muscles. MVV is influenced by subject coordination, volition, and pulmonary function (34). Moreover, the role of respiratory muscle is to generate pressure. Thus, techniques relying on resistive valves have been developed. Recently, Perret et al. (31) indicated that the constant-load resistive breathing test to task failure was an ideal test for global inspiratory muscle fatigue measurement. The most widely used device is the weighted inspiratory plunger valve (29). The pressure imposed at each breath is flow-independent and thus more constant than a linear inspiratory resistance. In the present study, we chose to use a Threshold Inspiratory Muscle Trainer valve, which has been validated by Johnson et al. (17). The load for respiratory muscle endurance measurement was 75% of P_{Imax}, similar to that used by Ker and Schultz (18). A meta-analysis of respiratory muscle training (34) suggested that endurance may be improved if resistance training is undertaken with control of breathing pattern. Clanton et al. (9), Mador et al. (21), and McCool et al. (25) showed that change in the breathing pattern induces change in the time limit. Therefore, to control breathing pattern, Vt was fixed at the comfortable value of 700 mL, according to Zocchi et al. (36), and breathing frequency (f) was fixed at 15 breaths·min⁻¹. Ti/Ttot was fixed at the duty cycle of 0.5 (18), with Ti = 2 s and Ttot = 4 s. This breathing pattern, similar to that of basal state, was easily maintained by the athletes throughout testing, as indicated by measurements at the beginning and end of the tests (Table 3). Lastly, the reproducibility of the method was tested at basal state on two occasions separated by 1 wk using the Bland and Altman (6) test, and the result showed variations below 10% of the average value. This method thus appears more reproducible than other methods for assessing ventilatory muscle endurance reported in the literature (29).

The significant decrease in T_{lim} in our triathletes after cycling followed by running or running followed by cycling may be defined as a failure of the respiratory muscles to develop and maintain a previous inspiratory threshold load due to fatigue. Thus, we can assume that we obtained a true respiratory muscle fatigue in all triathletes for three reasons. First, the imposed tension-time index was 0.375, and this corresponded to a work of breathing that may induce fatigue (32). Second, we noted a significant decrease in mean P_{Imax} 1 min after the end of respiratory muscle endurance measurement, confirming that fatigue was obtained (19,33). Third, the subjects received the same verbal encouragement,

and all seemed to be highly motivated to achieve the best score possible.

Finally, the aim of the present study was to examine the effects of cycle-run and run-cycle successions, as performed in triathlons and duathlons, on respiratory muscle strength and endurance. The greater significant decrease in P_{Imax} noted 1 min after the end of R-C versus C-R T_{lim} measurements suggested that cycling was more constraining for respiratory muscle than running. This was confirmed by the significantly lower T_{lim} noted after R-C than after C-R. As respiratory muscle fatigue is reversible (28), the alteration induced during cycling may be partially reversed during running. The higher inspiratory muscle fatigue induced by cycling versus running cannot be related to the specific $\dot{V}_E$ and breathing pattern reported during these two activities. Effectively, cycling is characterized by a lower $\dot{V}_E$, a lower breathing frequency and a higher Vt, and it appears to be more economical than running (4). The lower inspiratory muscle endurance induced by cycling could be due to a greater use of rib cage muscles instead of the diaphragm, which would lead to earlier inspiratory muscle fatigue. Hill et al. (13) suggested that the crouched position of cycling generated higher abdominal impedance, which is unfavorable to diaphragmatic work. This could explain the recruit-ment of rib cage muscles, which are thought to reach fatigue to a similar or larger extent than the diaphragm (15). In the present study, rib cage muscle fatigue during cycling in C-R may have been partially reversed during the subsequent running, which would not occur in R-C. In addition, the relative contribution of the diaphragm to total respiratory motor output has been found to be progressively reduced with exercise endurance (31), and this may indicate an increased contribution of the rib cage muscles. Lastly, Hershenson et al. (12) suggested that breathing against a threshold load preferentially fatigued rib cage muscles rather than the diaphragm.

In summary, the present study used a well-calibrated inspiratory constant-load test during successive cycle-run and run-cycle trials common to triathlons and duathlons. We detected a higher inspiratory muscle fatigue after cycling than after running. This result may be due to the crouched position of cycling, which increases the recruitment of rib cage muscle, or to the inspiratory load method, which preferentially measures rib cage muscle fatigue.

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