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Effect of respiratory muscle endurance training on respiratory sensations, respiratory control and exercise performance
A 15-year experience

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Abstract

Respiratory muscle endurance training (RMET) can improve respiratory muscle endurance as well as cycling and swimming endurance. Whether these improvements are caused by reduced perception of adverse respiratory sensations and/or a change in ventilatory output remains unclear. We re-analysed nine (five randomized controlled) RMET studies performed in our laboratory. One hundred and thirty-five healthy subjects completed either RMET [i.e. an average of 12.4 ± 4.9 h (median 10; range 10–25) of normocapnic hyperpnoea at 60–85% of maximal voluntary ventilation achieved during 27 ± 11 sessions (median 20; range 20–50) of 29 ± 4 min (median 30; range 15–30) duration over 6.5 ± 4.2 weeks (median 4; range 4–15), $n = 90$] or no RMET (CON, $n = 45$). Before and after RMET/CON, respiratory (≈70% MVV) and cycling (70–85% maximal power) endurance were tested. RMET increased both respiratory and cycling endurance, reduced perception of breathlessness and respiratory exertion during volitional and exercise-induced hyperpnoea, and slightly increased ventilation at identical workloads. Decreased respiratory sensations did not correlate with improved cycling endurance. Changes in ventilation correlated with changes in cycling endurance in both groups. We conclude that reduced adverse respiratory sensations after RMET are unlikely to cause the improvements in cycling endurance, that the level of ventilation seems to affect cycling endurance and that additional factors must contribute to the improvements in cycling endurance after RMET.

Keywords: Respiratory muscle training; Exercise; Endurance; Respiratory sensations; Ventilation

1. Introduction

Numerous studies have been performed to test the ability of respiratory muscle endurance or strength training to improve respiratory muscle performance (endurance and/or strength) and exercise performance (maximal and/or endurance cycling, running, rowing or swimming) in healthy subjects [for review, please see Sheel (2002)]. Although some degree of controversy exists regarding the effect of respiratory muscle training on exercise performance (Sonetti et al., 2001), several well controlled studies showed recently that respiratory muscle endurance training (RMET) (Markov et al., 2001; Stuessi et al., 2001; McMahon et al., 2002; Holm et al., 2004) as well as inspiratory muscle threshold training (Volianitis et al., 2001; Romer et al., 2002b) can improve cycling or rowing endurance (assessed during constant-load exercise or in a time trial) in healthy subjects. The physiological mechanisms underlying these improvements remain, however, unclear.

It has been proposed (Volianitis et al., 2001; Romer et al., 2002a) that a reduction in the perception of respiratory effort may contribute to the improvement in exercise performance after respiratory muscle training. An increase in maximal strength of respiratory muscles (Killian et al., 1982; Redline et al., 1991) and/or an improvement in fatigue resistance (Verges et al., 2008) may indeed reduce the perception of respiratory effort. However, studies having evaluated the effect of respiratory muscle training on respiratory sensations during exercise gave controversial results, with either reduced perception of respiratory effort after resistive inspiratory or expiratory training (Suzuki et al., 1995; Volianitis et al., 2001; Romer et al., 2002a), or unchanged respiratory sensations after resistive inspiratory or hyperpnoea training (Suzuki et al., 1993; Williams et al., 2002; Holm et al., 2004). Therefore, it remains to be clarified whether a reduction in the perception of adverse respiratory sensations

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may underlie the improvement in exercise performance after respiratory muscle training (Sheel, 2002).

Furthermore, some data suggests that RMET may increase minute ventilation ($\dot{V}_E$) at identical workloads in some (Boutellier et al., 1992; Kohl et al., 1997; Reed and Coates, 2001; Holm et al., 2004; Verges et al., 2008), but not all subjects (Stuessi et al., 2001; McMahon et al., 2002). Whether an increase in $\dot{V}_E$ may impair a potential positive effect of RMET on adverse respiratory sensations and/or on endurance performance remains to be clarified.

To address these issues based on a large group of subjects, we re-analysed nine RMET studies performed in our laboratory in a very similar setting over the past 15 years (Boutellier et al., 1992; Boutellier and Piwko, 1992; Kohl et al., 1997; Spengler et al., 1999; Stuessi et al., 2001; McMahon et al., 2002; Verges et al., 2007, 2008; unpublished data). By performing a meta-analysis of these data we aimed to test the following hypotheses: (i) RMET reduces the perception of adverse respiratory sensations during volitional and exercise-induced hyperpnoea, (ii) changes in the perception of adverse respiratory sensations are underlying the improved exercise performance after RMET, and (iii) RMET increases $\dot{V}_E$ during exercise, independent of changes in respiratory sensations and exercise performance.

2. Methods

Data of nine studies (five randomized controlled), performed between 1992 and 2006, were analysed. Results of eight of these studies were published as original articles (for details please see Table 1).

2.1. Subjects

One hundred and thirty-five healthy subjects (32 untrained, i.e. physical activity <1 h week^{-1}; 103 trained, i.e. physical activity ≥3 h week^{-1}) were investigated: 90 (9 female, 81 male) were assigned to an RMET group and 45 (7 female, 38 male) to a control group (CON) performing either no or sham training (see below). RMET subjects were 28 ± 4 years old, 183 ± 4 cm in height and 74 ± 7 kg in weight. CON subjects were 29 ± 5 years old, 176 ± 6 cm in height and 70 ± 8 kg in weight. Subjects had normal lung function [RMET: vital capacity (VC) 5.6 ± 0.9 l, forced expiratory volume in 1 s (FEV$_1$) 4.4 ± 0.7 l, peak expiratory flow (PEF) 10.3 ± 2.0 l s^{-1}, maximal voluntary ventilation (MVV) 190.0 ± 33.2 l min^{-1}; CON: VC 5.6 ± 1.0 l, FEV$_1$ 4.4 ± 0.7 l, PEF 9.8 ± 1.9 l s^{-1}, MVV 185.2 ± 37.2 l min^{-1}). The weekly amount of training was 6 ± 3 h week^{-1} in the RMET group and 7 ± 3 h week^{-1} in the CON group. All these variables did not differ between groups ($p > 0.05$). Subjects were requested to keep their individual physical training constant for at least the duration of the study.

2.2. Protocol

Before and after the RMET/CON-period, the following tests were performed (for details please see Table 1): lung function measurements, maximal inspiratory and expiratory pressure measurements, respiratory endurance test (RET), incremental cycling test and constant-load cycling endurance test (CET). To account for any task learning effect, subjects were familiarized with the different testing

Table 1
Number of subjects, training characteristics and tests performed before and after training (control) in the nine studies

Reference	Subjects (female/male)		Training		Tests				
	RMET	CON	RMET	CON	Lung function	Maximal pressures	RET	Incremental cycling	CET
Boutellier and Piwko (1992)	4 (1/3)	–	20 × 30 min over 4 weeks	–	Yes	No	Yes	No	Yes
Boutellier et al. (1992)	8 (1/7)	–	20 × 30 min over 4 weeks	–	Yes	No	Yes	Yes	Yes
Kohl et al. (1997)	8 (2/6)	–	20 × 30 min over 4 weeks	–	Yes	No	Yes	Yes	Yes
Spengler et al. (1999)	20 (0/20)	–	20 × 30 min over 4 weeks	–	Yes	No	Yes	Yes	Yes
Stuessi et al. (2001)	13 (5/8)	15 (7/8)	40 × 30 min over 15 weeks	No RMET	Yes	No	Yes	Yes	Yes
McMahon et al. (2002)	10 (0/10)	10 (0/10)	20 × 30 min over 4 weeks	No RMET	Yes	No	Yes	Yes	Yes
Verges et al. (2008)	8 (0/8)	6 (0/6)	40 × 15 min over 8 weeks	No RMET	Yes	Yes	Yes	Yes	Yes
Verges et al. (2007)	13 (0/13)	8 (0/8)	20 × 30 min over 4 weeks	Incentive spirometry	Yes	Yes	Yes	Yes	Yes
Unpublished data	6 (0/6)	6 (0/6)	50 × 30 min over 13 weeks	No RMET	Yes	Yes	Yes	No	No

RMET, respiratory muscle endurance training; CON, control; maximal pressures, maximal inspiratory and expiratory pressure measurement; RET, respiratory endurance test; incremental cycling, maximal incremental cycling test; CET, cycling endurance test; see Section 2 for more details.

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procedures several days before the beginning of the protocol.

Resting lung function (RMET, $n=90$; CON, $n=45$) as well as maximal inspiratory pressure (PI_{max}) and maximal expiratory pressure (PE_{max}; RMET, $n=27$; CON, $n=20$) were measured according to standard procedures (ATS, 1991; ATS/ERS, 2002).

In the RET, subjects were requested to breathe at a given target ventilation to exhaustion. This test was performed under normocapnic conditions either by adding CO_2 to the inspirate or by using a partial rebreathing device (see RMET below). Mean target ventilation was 73 ± 9% MVV for the RMET group and 71 ± 8% MVV for the CON group. The test was stopped when the subjects were not able to sustain the target V_T or f_R anymore or after a maximum of 40 or 60 min (while a 40 min maximum was taken for all analyses). Ventilation (RMET, $n=72$; CON, $n=39$) and HR (RMET, $n=37$; CON, $n=37$) were recorded continuously. Every 2 min, subjects rated breathlessness (i.e. the perception of “not getting enough air”) and respiratory exertion (i.e. the perception of respiratory work/effort) (RMET, $n=37$; CON, $n=30$) either on a modified Borg scale or a visual analog scale (VAS), and a sample of arterialised capillary blood (RMET, $n=50$; CON, $n=45$) was drawn from an earlobe or fingertip for blood lactate analysis. Subjects were interviewed extensively prior to the beginning of the study regarding their experience and understanding of the different respiratory sensations. The definitions of the particular sensations were then read to the subjects before each test.

The incremental cycling test (RMET, $n=80$; CON, $n=39$) to exhaustion was performed in order to determine the maximal work capacity ($\dot{W}_{max}$) and the maximal oxygen consumption ($\dot{V}_{O_2\,max}$). Subjects started cycling at 50–100 W for 2 min and subsequently the load was increased by 20–30 W every 2 min until voluntary exhaustion. At the beginning of the test, subjects chose their preferred pedaling frequency (between 60 and 100 rpm) which they then held constant for the remainder of the test. Ventilation, gas exchange and HR were recorded continuously. Breathlessness, respiratory exertion and leg exertion (RMET, $n=31$; CON, $n=24$), as well as blood lactate concentration (RMET, $n=72$; CON, $n=39$) were measured as described for the RET. The workload corresponding to the last stage sustained for at least 1.5 min was defined as $\dot{W}_{max}$.

During the CET (RMET, $n=84$; CON, $n=39$), subjects cycled at 70% $\dot{W}_{max}$ (untrained) −85% $\dot{W}_{max}$ (trained) to volitional exhaustion or until they were no longer able to sustain their individually chosen target pedalling frequency. Ventilation, gas exchange (RMET, $n=72$; CON, $n=39$) and HR (RMET, $n=31$; CON, $n=31$) were recorded continuously. Breathlessness (RMET, $n=31$; CON, $n=24$), respiratory exertion and leg exertion (RMET, $n=44$; CON, $n=39$), as well as blood lactate concentration (RMET, $n=72$; CON, $n=39$) were measured as described for the RET.

The RMET group performed 20 sessions of normocapnic hyperpnoea over 4–5 weeks, each training session lasting for 30 min (exceptions: 8 subjects trained 40 × 15 min over 8 weeks, 13 trained 40 × 30 min over 15 weeks and 6 subjects trained 50 × 30 min over 13 weeks), while the CON group performed no RMET ($n=37$) or sham training ($n=8$) using an incentive spirometer (Table 1). RMET was performed at a given tidal volume (V_T) and breathing frequency (f_R, paced by a metronome) with a duty cycle of 0.5. The target training ventilation was initially set at 60% MVV and was steadily increased throughout the training period. At least one training session per week was supervised in the laboratory where the training device was connected to the metabolic cart to control for the training technique and to ensure normocapnia was maintained.

After the RMET/CON-period, subjects performed the same tests in the same order with the same resting days between tests as before the RMET/CON-period except for the incremental cycling test that was performed at the very end in some studies (RMET, $n=69$; CON, $n=30$). Furthermore, for every subject, all test sessions were performed at the same time of day before and after the RMET/CON-period.

2.3. Data analysis

For incremental cycling tests, ventilation and HR were averaged during the last minute while for [La] and sensations the values at the point of exhaustion were taken for comparisons. For variables assessed during RET and CET, averages over the duration of the shorter of the two tests were calculated, i.e. during identical durations.

For within-group comparisons, individual data of the available studies were pooled and compared using two-tailed paired *t*-tests. The Pearson product-moment correlation was applied for assessing correlations between before-to-after RMET/CON changes within groups. A multiple stepwise regression analysis was conducted to identify the determinants for changes in cycling endurance. For between-group comparisons of before-to-after RMET/CON changes (calculated as percentages of before values), individual data of the available RMET and CON studies (i.e. controlled studies only) were pooled and compared using two-tailed unpaired *t*-tests. Statistical power calculations demonstrated power ranges from 0.78 to 0.93. Analyses were performed using standard software (Statview 5.0, SAS Institute, Cary, NC, USA). All results are presented as means ± S.D. and $p < 0.05$ was considered to be statistically significant.

3. Results

3.1. Lung function and maximal pressures

After RMET compared to CON, a significant increase in VC (RMET: +2.0 ± 7.9% *vs.* CON: −1.4 ± 3.7%; $p=0.008$), FVC (RMET: +1.5 ± 4.3% *vs.* CON: −0.8 ± 4.3%; $p=0.033$), PEF (+4.0 ± 11.3% *vs.* −1.1 ± 11.8%; $p=0.021$) and MVV (+184.6 ± 190.1% *vs.* +40.6 ± 180.9%; $p<0.001$) was observed. No change was observed for FEV_1 (+0.2 ± 5.6% *vs.* −1.6 ± 5.7%; $p=0.058$), PI_{max} (+5.5 ± 12.3% *vs.* +7.1 ± 15.3%; $p=0.696$) and PE_{max} (+0.9 ± 16.5% *vs.* +1.3 ± 22.2%; $p=0.946$).

3.2. Respiratory endurance test

Mean $\dot{V}_E$ during the RET was 134.2 ± 19.9 $l\,min^{-1}$ in the RMET group and 135.5 ± 21.6 $l\,min^{-1}$ in the CON group. Mean

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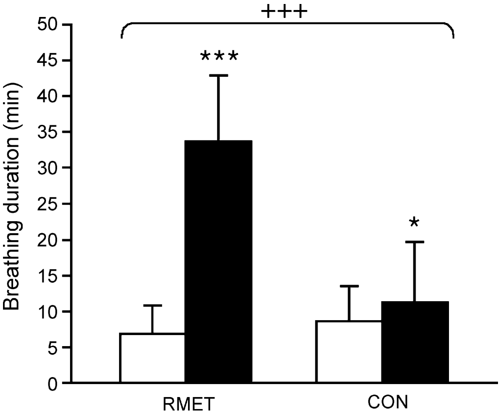

Fig. 1. Breathing duration during the respiratory endurance test in the respiratory muscle endurance training group (RMET) and the control group (CON) before (empty bars) and after (filled bars) training (control). Significant difference compared to before (*$p < 0.05$, ***$p < 0.001$); before-to-after change significantly different between groups ($^{+++}p < 0.001$).

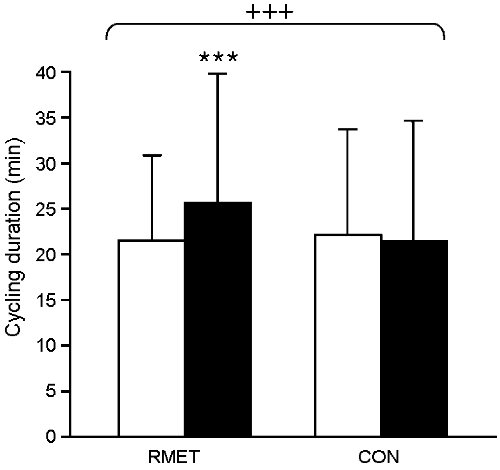

Fig. 2. Cycling duration during the constant-load cycling endurance test in the respiratory muscle endurance training group (RMET) and the control group (CON) before (empty bars) and after (filled bars) training (control). Significant difference compared to before (***$p < 0.001$); before-to-after change significantly different between groups ($^{++}p < 0.01$).

breathing durations in the RET are shown in Fig. 1. RMET increased breathing endurance by at least +590 ± 428% compared to CON (+53 ± 428%; $p < 0.001$). Sixty-nine subjects (77%) reached the 40 min time limit after RMET, while only one subject reached this limit after CON. RMET significantly reduced HR, [La], breathlessness and respiratory exertion during RET (Table 2).

3.3. Incremental cycling test

$\dot{V}_{O_2\,max}$ and $\dot{W}_{max}$ neither changed after RMET (before: 4025 ± 1026 ml min^{-1} and 322 ± 80 W; after: 4036 ± 1011 ml min^{-1} and 319 ± 81 W) nor after the CON-period (before: 3592 ± 1174 ml min^{-1} and 278 ± 96 W; after: 3483 ± 1178 ml min^{-1} and 268 ± 95 W). However, RMET significantly increased maximal $\dot{V}_E$ (+3.3 ± 14.1%) compared to CON (−4.9 ± 10.1%; $p = 0.002$), V_T (RMET: +3.8 ± 10.1% *vs.* CON: −1.6 ± 9.9%; $p = 0.009$) and reduced maximal breathlessness (−41.4 ± 63.2% *vs.* −1.3 ± 67.5%; $p = 0.010$). In addition, RMET significantly reduced maximal end-tidal CO2 partial pressure ($P_{ET_{CO_2}}$, −2.3 ± 8.0%; $p = 0.016$) and respiratory exertion (−8.6 ± 22.5%; $p = 0.015$), but these changes did not differ significantly from variations in CON ($P_{ET_{CO_2}}$, +0.6 ± 9.1%; $p = 0.093$; respiratory exertion: −2.5 ± 16.1%; $p = 0.264$). No other variable was changed significantly at the end of the incremental cycling test.

3.4. Constant-load cycling test

RMET significantly increased cycling duration by +19 ± 38% compared to CON (−3 ± 27%; $p = 0.002$; Fig. 2). Mean values of ventilation, gas exchange, HR, [La] and subjective measures are given in Table 3. RMET significantly increased average $\dot{V}_E$ and V_T and reduced the perception of breathlessness and respiratory exertion compared to CON. In addition, RMET significantly reduced $P_{ET_{CO_2}}$, [La] and leg exertion, but these changes did not differ significantly from variations of CON. No change was observed for f_R, $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$ and HR.

3.5. Relationships between before-to-after RMET/CON changes

In both the RMET and CON groups, changes in CET duration were negatively correlated with changes in average $\dot{V}_E$ (Fig. 3), f_R (RMET: $r^2 = 0.19$, $p < 0.001$; CON: $r^2 = 0.29$, $p < 0.001$) and leg exertion ($r^2 = 0.21$, $p = 0.002$; $r^2 = 0.19$, $p = 0.007$). This relation was the only to be significant ($r^2 = 0.42$, $p < 0.001$) with

Table 2
Heart rate, blood lactate concentration and respiratory sensations during the respiratory endurance test performed before and after respiratory muscle endurance training and control

	RMET		CON		RMET *vs.* CON
	Before	After	Before	After	
HR (beats min^{-1})	114 (16)	103 (17)***	106 (19)	102 (16)	0.048
[La] (mmol l^{-1})	2.92 (0.89)	2.45 (1.01)***	2.59 (1.19)	2.46 (1.13)	0.032
BR (points)	3.0 (2.5)	1.4 (2.1)***	2.5 (2.4)	2.4 (2.2)	0.013
RE (points)	6.3 (2.0)	3.5 (2.1)***	5.5 (1.6)	4.8 (1.9)*	0.002

Values are mean (S.D.) of average values corresponding to the duration of the shorter test, see Section 2; RMET, respiratory muscle endurance training; CON, control; HR, heart rate; [La], blood lactate concentration; BR, breathlessness; RE, respiratory exertion; significantly different from before (*$p < 0.05$, ***$p < 0.001$).

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Table 3
Ventilation, gas exchange, heart rate, blood lactate concentration and subjective measures during the constant-load cycling endurance test performed before and after respiratory muscle endurance training and control

	RMET		CON		RMET *vs.* CON
	Before	After	Before	After	
$\dot{V}_E$ (l min^{-1})	102.7 (27.8)	107.4 (29.2)***	90.8 (31.6)	90.8 (29.4)	0.007
V_T (l)	2.92 (0.67)	3.00 (0.72)**	2.65 (0.67)	2.65 (0.68)	0.028
f_R (cycles min^{-1})	35.7 (7.2)	36.3 (8.0)	34.3 (8.8)	34.6 (8.1)	0.341
$\dot{V}_{O_2}$ (ml min^{-1})	3469 (1017)	3474 (1009)	3019 (1166)	3054 (1135)	0.650
$\dot{V}_{CO_2}$ (ml min^{-1})	3411 (1165)	3428 (1163)	3158 (1299)	3185 (1240)	0.548
$P_{ET_{CO_2}}$ (mmHg)	39.6 (5.5)	38.5 (5.0)*	38.4 (4.7)	38.1 (4.6)	0.127
HR (beats min^{-1})	167 (12)	166 (13)	162 (15)	161 (15)	0.697
[La] (mmol l^{-1})	8.10 (2.39)	7.64 (2.21)*	6.42 (2.36)	6.59 (2.26)	0.131
BR (points)	3.6 (2.9)	2.4 (2.9)***	3.5 (2.6)	3.6 (3.0)	0.022
RE (points)	6.6 (1.4)	5.1 (1.8)***	6.0 (1.5)	5.7 (2.0)	0.026
LE (points)	7.3 (1.2)	6.6 (1.4)*	7.1 (1.3)	6.9 (1.5)	0.452

Values are mean (S.D.) of average values corresponding to the duration of the shorter test, see Section 2; $\dot{V}_E$, minute ventilation; V_T, tidal volume; f_R, respiratory frequency; $\dot{V}_{O_2}$, oxygen consumption; $\dot{V}_{CO_2}$, carbon dioxide production; $P_{ET_{CO_2}}$, end-tidal CO$_2$ partial pressure; LE, leg exertion; for other abbreviations see Table 2. Significantly different from before (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

stepwise multiple regression, i.e. changes in CET duration being the dependent variable and changes in average $\dot{V}_E$ and leg exertion during CET being independent variables. Changes in CET duration were positively correlated with changes in average $P_{ET_{CO_2}}$ ($r^2 = 0.24$, $p < 0.001$; $r^2 = 0.12$, $p = 0.036$) during CET.

Within the RMET group, changes in CET duration were also negatively correlated with changes in average [La] ($r^2 = 0.10$, $p = 0.006$) and respiratory exertion ($r^2 = 0.12$, $p = 0.022$) during CET, the latter correlation was, however, not present anymore when removing one outlier.

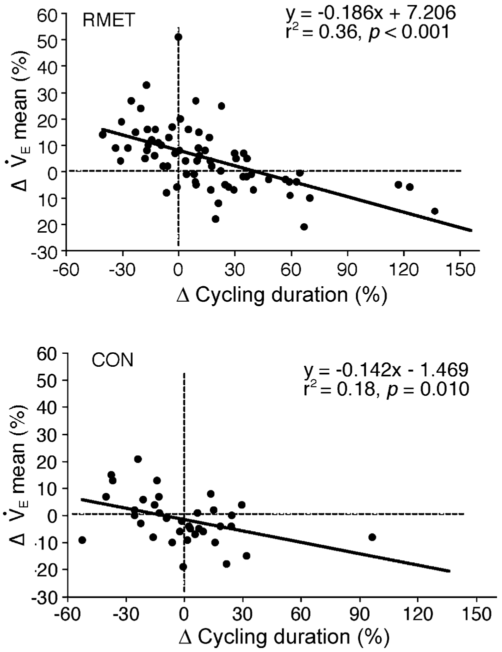

Fig. 3. Correlations between the change in minute ventilation ($\dot{V}_E$) and the change in cycling duration during the constant-load cycling endurance test from before to after respiratory muscle endurance training (RMET) or control (CON). Changes are given as percentage of before RMET (CON) values.

Also, changes in CET duration did not correlate with changes in breathlessness ($r^2 = 0.01$, $p = 0.551$) and relative workload (%$\dot{W}_{max}$: $r^2 = 0.04$, $p = 0.061$) during CET nor with subjects, $\dot{V}_{O_2\,max}$ ($r^2 = 0.02$, $p = 0.229$). Changes in average $\dot{V}_E$ during CET did not correlate with average changes in breathlessness ($r^2 = 0.01$, $p = 0.829$) and respiratory exertion ($r^2 = 0.09$, $p = 0.052$) during CET either but they correlated positively with changes in leg exertion ($r^2 = 0.13$, $p = 0.017$). Average changes in breathlessness correlated between RET and CET ($r^2 = 0.53$, $p < 0.001$) and so did changes in respiratory exertion ($r^2 = 0.42$, $p < 0.001$).

4. Discussion

The present analysis showed that RMET reduced the perception of adverse respiratory sensations, i.e. breathlessness and respiratory exertion, during volitional and exercise-induced hyperpnoea, independent of changes in RET- and CET-performance or changes in $\dot{V}_E$. RMET-induced changes were not related to the total RMET volume. Changes in cycling endurance correlated with changes in average $\dot{V}_E$ during CET in both the RMET and the CON groups, suggesting a link between spontaneous variations in ventilation and changes in cycling endurance at a given workload.

4.1. *Effect of RMET on respiratory sensations*

Previous results regarding changes in perception of adverse respiratory sensations during exercise after respiratory muscle training were ambiguous (Suzuki et al., 1993, 1995; Volianitis et al., 2001; Romer et al., 2002a; Williams et al., 2002; Holm et al., 2004). The diversity in type, duration and intensity of respiratory muscle training, type of respiratory sensations assessed (Scano et al., 2005), type of exercise testing and the small number of subjects in each training group (median: 7, range: 6–12 subjects) may account for these discrepancies. This diversity also makes a comparison among previous studies as well as with present

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findings difficult. In the current analysis, we observed a consistent reduction in breathlessness and respiratory exertion during volitional as well as during exercise-induced hyperpnoea after RMET, even in the face of an increased ventilatory output during cycling. The latter contrasts with the finding of Holm et al. (2004) who reported unchanged perception of respiratory effort in face of increased ventilation during constant-load cycling. The changes in perception of breathing in the present study did, however, not correlate with changes in cycling endurance. Thus, these results clearly show that RMET reduces the perception of adverse respiratory sensations during hyperpnoea and suggest that factors other than changes in respiratory sensations account for the improvement in exercise performance after RMET.

Which potential mechanism could underlie this change in perception of adverse respiratory sensations? Changes in respiratory sensations resulting from altered ventilatory impedance were shown to correspond to the force generated by the contracting respiratory muscles relative to their maximal strength (Killian et al., 1982; Redline et al., 1991). In the present analysis, however, RMET did not improve maximal respiratory muscle strength, i.e. PI_{max} and PE_{max}, but resulted in similar task-specific changes, e.g. significant improvements in MVV and respiratory endurance, as previously shown by Leith and Bradley (1976). Thus, the perception of adverse respiratory sensations during volitional as well as exercise-induced hyperpnoea seems to decrease with the increased ventilatory capacity. In addition, increased fatigue resistance of respiratory muscles during exercise after RMET (Verges et al., 2008) may contribute to reduce the perception of adverse respiratory sensations as respiratory muscle fatigue was previously shown to increase the perception of respiratory effort (Gandevia et al., 1981; Mador and Acevedo, 1991).

4.2. *Effect of RMET on cycling endurance*

The present analysis showed a clear ergogenic effect of RMET, i.e. an average 19% increase in cycling duration at a constant load to exhaustion. As the change in perception of adverse respiratory sensations cannot explain this improvement, a more likely explanation is a reduced development of respiratory muscle fatigue observed after RMET (Verges et al., 2007). This would, in turn, reduce the impairment of leg blood flow related to the development of respiratory muscle fatigue, by means of the respiratory muscle metaboreflex suggested by Dempsey et al. (2006). A reduced impairment of leg blood flow would consequently reduce the development of leg muscle fatigue during exercise and improve cycling endurance.

This mechanism is supported by the observed reduction in [La] during volitional hyperpnoea and constant-load cycling after RMET. Increased [La] in the diaphragm was recently identified as one possible mediator of the respiratory muscle metaboreflex (Rodman et al., 2003). In the present analysis, the reduction in [La] during CET after RMET even correlated – although weakly ($r^2 = 0.10$) – with the improvement in cycling endurance.

When looking at individual data, however, we observed that 66% of subjects improved cycling endurance after RMET (+37 ± 34% *vs.* 55% of CON +19 ± 14%) while 33% did not reach pre-training cycling duration (−16 ± 11% *vs.* 45% of CON −19 ± 14%). This observation could possibly be explained by our recent finding that only those subjects with a significant amount of respiratory muscle fatigue (>10% fall in transdiaphragmatic twitch pressure at the point of exhaustion) in the CET prior to RMET improve cycling endurance after RMET significantly (Verges et al., 2007). Similarly, the lack of improvement in maximal incremental cycling performance after RMET can be explained by this mechanism as it was recently shown that this type of exercise fails to induce respiratory muscle fatigue (Romer et al., 2006b).

What caused, however, the rather large variation in cycling endurance after the 1–3-month period? Knowing that respiratory muscle work can influence cycling endurance (Harms et al., 2000; Dempsey et al., 2006), changes in $\dot{V}_E$ *per se* that correlated with changes in cycling endurance might be responsible for this variation. The weak but significant correlation between ventilatory changes and changes in perception of leg exertion are in agreement with the suggested link between respiratory muscle work and locomotor muscle fatigue (Romer et al., 2006a).

However, while the regression line of ventilatory changes and changes in cycling endurance after CON passes close to the origin, the line is shifted 'upwards' (towards increased $\dot{V}_E$) for changes after RMET. Long-term modification of the respiratory motor control (potentially associated with the changes in respiratory sensations) induced by repeated voluntary normocapnic hyperpnoea might be one possible mechanism underlying this increased ventilatory drive during exercise after RMET (present analysis; Reed and Coates, 2001; Holm et al., 2004). Several experimental results have emphasised the plasticity of the exercise ventilatory response in the past (Martin and Mitchell, 1993; Helbling et al., 1997; Reed and Coates, 2001). However, as the increase in $\dot{V}_E$ during cycling after RMET in the present analysis was accompanied by a significant increase in V_T, which, interestingly, was of a similar magnitude as the increase in VC (+100 ml), it may be suggested that subjects increased $\dot{V}_E$ only due to their increased ability to expand and/or compress their lungs after RMET.

In conclusion, RMET reduced the perception of adverse respiratory sensations during volitional and exercise-induced hyperpnoea, even in the presence of increased ventilation during exercise. These changes in the perception of adverse respiratory sensations are, however, unlikely to be the main factor responsible for the improved endurance performance after RMET in healthy subjects. Changes in the spontaneous level of ventilation seem to be more directly related to changes in cycling endurance although additional factors must contribute to the improvement in endurance after RMET.

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