Effects of Respiratory Muscle Training on Performance in Athletes: A Systematic Review With Meta-Analyses

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Abstract

HajGhanbari, B, Yamabayashi, C, Buna, TR, Coelho, JD, Freedman, KD, Morton, TA, Palmer, SA, Toy, MA, Walsh, C, Sheel, AW, and Reid, WD. Effects of respiratory muscle training on performance in athletes: A systematic review with meta-analysis. *J Strength Cond Res* 27(6): 1643–1663, 2013—The purpose of this study was to perform a systematic review to determine if respiratory muscle training (RMT) improves sport performance and respiratory muscle strength and endurance. Methodology followed the Cochrane Collaboration protocol. MEDLINE, CINAHL, SPORTDiscus, PEDro, EMBASE, EBM reviews, and COCHRANE electronic databases were searched until July 2011. Articles were included if: (a) participants were athletes; (b) RMT was compared with sham or control in a randomized controlled design and included outcomes of respiratory muscle and sport performance; and (d) published in English. Quality assessment using PEDro and data abstraction was performed by 2 authors. Outcomes evaluated were measures of sport performance, exercise capacity, spirometry, and respiratory muscle strength and endurance. Meta-analyses were performed on outcomes reported in 2 or more papers. Results of this systematic review revealed that of the 6,923 citations retrieved from the search strategy, 21 met the inclusion criteria. Meta-analyses demonstrated a significant positive effect of RMT on sport performance outcomes of time trials, exercise endurance time, and repetitions on Yo-Yo tests. Inspiratory muscle strength and endurance improved in most studies, which in part, was dependent on the type of RMT employed. Determination of the type of athlete that may benefit most from RMT was limited by small sample sizes, differing RMT protocols, and differences in outcome measures across studies. In conclusion, RMT can improve sport performance. Closer attention to matching the ventilatory demands of RMT to those required during athletic competition and more aggressive progression of training intensity may show greater improvements in future studies.

Key Words inspiratory muscles, expiratory muscles, sports performance, breathing exercises, muscle strength, muscle endurance

Introduction

Competition drives athletes to continually seek new ways to gain the edge over their fellow competitors. Historically, training for high performance has focused on rigorous peripheral muscle and cardiovascular training using partial or full-body exercises. In an attempt to surpass the plateau achieved by such training, respiratory muscle training (RMT) and particularly inspiratory muscle training (IMT) have been investigated as a method through which athletes could improve their performance.

Mechanisms postulated to explain improved sport performance from RMT are decreases in the rating of perceived breathlessness (RPB) or rating of perceived exertion (RPE) and attenuation of the metaboreflex phenomenon that may result in the redirection of blood flow from the locomotor muscles to the muscles of respiration (15,23,31,49). The details of these mechanisms are well beyond the scope of this study; however, the fact that inspiratory muscle fatigue occurs during sport performance provides further impetus to investigate the potential ergogenic effect of RMT.

Conflicting results have been reported on the effectiveness of RMT to improve sports performance (32). Failure of studies to elicit changes in maximal oxygen consumption ($\dot{V}O_2max$) (12,58) after RMT supports the premise that exercise is not limited by the respiratory system's ability to transport and deliver metabolic gases. However, $\dot{V}O_2max$ is not the single

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determinant of endurance exercise performance (31). Other factors such as endurance of the limb and respiratory muscles can play a major role. Inspiratory muscle fatigue (as defined by decreasing maximal inspiratory pressures over time), secondary to the physiological demands of mechanical work of breathing, occurs during sporting activities such as marathon running (48), triathlons (20), rowing (11), cycling (46), and swimming (27).

Respiratory muscle training research has examined two main outcomes–changes in respiratory muscle performance and athletic performance. Improved respiratory muscle strength and endurance after RMT is often demonstrated in athletes (3,17,33,56,58). However, the impact of RMT on sport performance is quite contentious. Some studies demonstrated minimal differences on performance (7,12,35), whereas other reports describe improved sport performance after RMT (3,9, 22,29,36, 46–48,56). Despite these findings, controversial issues remain concerning the optimal RMT protocol and type of sport that might gain the most benefit from different RMT protocols. Another consideration is that the vast majority of studies included very small samples, that is, average sample size of 10 per group, such that they were underpowered to detect small or moderate effect sizes of exercise performance.

To determine whether RMT can enhance sport performance in athletes, we performed a systematic review including meta-analyses to assess: (a) the impact of RMT on sport performance, (b) the impact of RMT on respiratory muscle strength and endurance in athletes who perform different sports, (c) the type of athletes or sports that demonstrate the most consistent gains from RMT and if recreational or elite athletes benefit more so from RMT, and (d) to determine the most efficacious mode of RMT.

Methods

Experimental Approach to the Problem

We performed a systematic review using the methodology outlined by the Cochrane Collaboration protocol (5). Electronic databases from 1946 to July 30, 2011 were searched including: Cochrane Central Register of Controlled Trials, MEDLINE, CINAHL (Cumulative Index to Nursing and Allied Health Literature), SPORTDiscus, EMBASE, PEDro (Physiotherapy Evidence Database), and EBM reviews.

Gray literature, including government reports, theses, and reference lists, were also searched for relevant articles. Search terms are exemplified by the MEDLINE search strategy (Appendix 1). Search terms were modified accordingly to fit the requirements of the other databases.

Study Criteria

Articles were eligible if (a) participants were healthy athletes, with no disability, between 15 and 40 years, inclusive; (b) the study was a randomized controlled trial (RCT) that compared an IMT or RMT group with a sham, control (a healthy group with no intervention), or placebo group; (c) the study included outcomes of sport performance and respiratory muscle strength or endurance; and (d) it was published in English. Articles

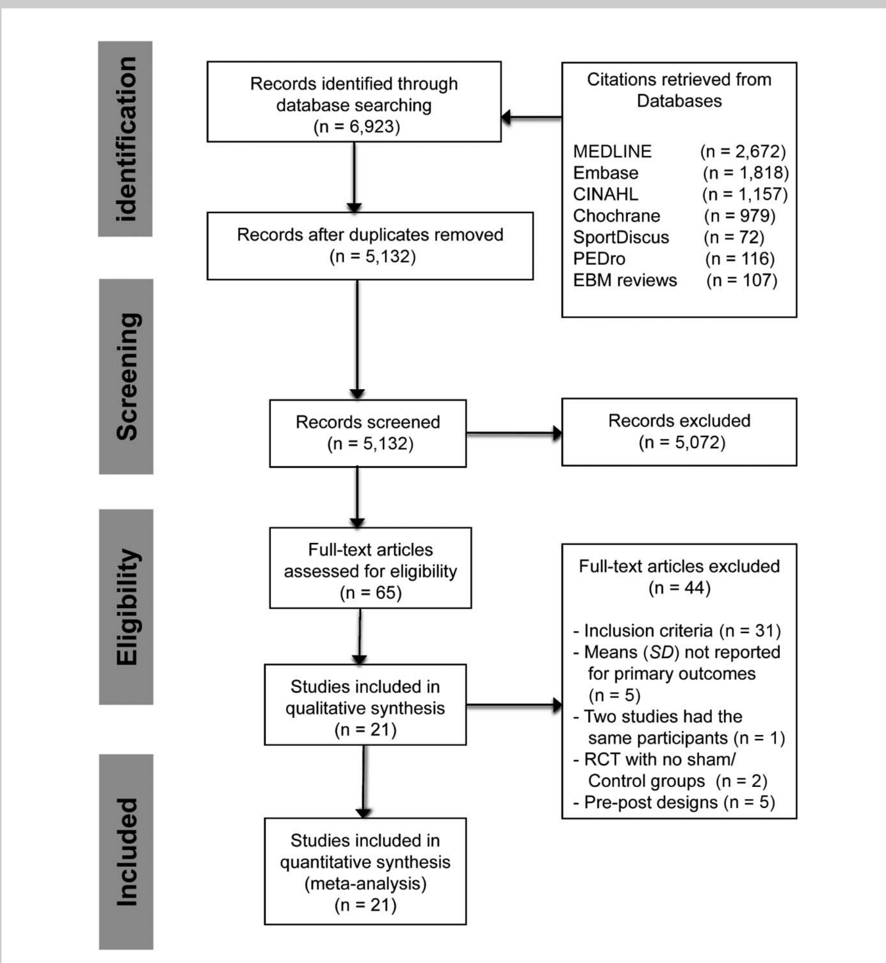

Figure 1. Flow chart of search strategy and retrieval of articles.

Table 1. Ratings of levels of evidence and PEDro quality assessment.*

First author, year	PEDro ratings 1	2	3	4	5	6	7	8	9	10	11	Total†	Evidence levels
Bailey, 2010 (1)	Yes	1		1	1			1	1	1	1	7	2b
Fairbarn, 1991 (7)	Yes	1		1				1	1	1	1	6	2b
Holm, 2004 (16)		1		1				1		1	1	5	2b
Inbar, 2000 (17)	Yes	1		1	1			1	1	1	1	7	1b
Johnson, 2007 (18)	Yes	1		1	1			1	1	1	1	7	1b
Kilding, 2010 (21)	Yes	1		1	1			1	1	1	1	7	2b
Leddy, 2007 (22)	Yes	1		1	1			1		1	1	6	2b
McMahon, 2002 (33)	Yes	1	1	1				1	1	1	1	7	1b
Mickleborough, 2010 (34)	Yes	1		1				1	1	1	1	6	2b
Morgan, 1987 (35)	Yes	1		1						1	1	4	2b
Nicks, 2009 (36)	Yes	1		1				1	1	1	1	6	1b
Riganas, 2008 (44)	Yes	1		1				1	1	1	1	6	2b
Romer, 2002 (46)	Yes	1	1	1	1		1	1	1	1	1	9	2b
Romer, 2002 (45)	Yes	1	1	1	1		1	1	1	1	1	9	1b
Sonetti, 2001 (51)	Yes	1		1				1	1	1	1	6	2b
Sperlich, 2009 (52)		1		1				1	1	1	1	6	2b
Tong, 2008 (54)	Yes	1		1	1			1	1	1	1	7	1b
Tong, 2010 (55)	Yes	1		1				1	1	1	1	6	1b
Volianttis, 2001 (56)	Yes	1		1	1			1	1	1	1	7	2b
Wells, 2005 (57)	Yes	1		1	1			1	1	1	1	7	1b
Wylegala, 2007 (61)	Yes	1		1	1				1	1	1	6	1b

*Description of PEDro Categories: 1 = eligibility criteria were specified; 2 = subjects were randomly allocated to groups; 3 = allocation was concealed; 4 = the groups were similar at baseline regarding the most important prognostic indicators; 5 = blinding of all subjects; 6 = blinding of all therapists who administered the therapy; 7 = blinding of all assessors who measured at least 1 key outcome; 8 = measures of 1 key outcome were obtained from >85% of subjects initially allocated to groups; 9 = all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least 1 key outcome was analysed by "intention to treat"; 10 = the results of between-group statistical comparisons are reported for at least 1 key outcome; 11 = the study provides both point measures and measures of variability for at least 1 key outcome.

†Total score was tally of categories 2–11.

were excluded if subjects (a) had a physical impairment that interfered with exercise involving large muscle groups and (b) were healthy adults but were not elite or recreational athletes.

Two individuals independently reviewed titles and abstracts and then compared results. Full-text screening was performed on potential relevant articles by two reviewers independently and then compared to determine inclusion in the systematic review. In the event of disagreement, a third person was consulted to determine inclusion. The flow chart of the search strategy and study selection is summarized in Figure 1.

Operational Definitions

Inspiratory muscle training referred to training methods that only applied loads during inspiration, whereas RMT referred to methods when both inspiration and expiration were loaded, that is, hyperpnea or threshold loads added to both phases of respiration. An athlete was classified as elite or recreational based on the author's description and if the $\dot{V}O_2max$ was above or below, respectively, the minimum requirements for being considered an athlete by standards set by Wilmore and Costill (59); however, $\dot{V}O_2max$ was not always reported. Healthy was defined as able-bodied noninjured subjects without chronic disease. Sham was defined as IMT at less than 15% of the maximal inspiratory pressure (MIP), with minimal or no training load that was not sufficient to activate important placebo factors such as expectations (37). Low-intensity sham was performed at 15% MIP or higher (≤30% MIP). Placebo was defined as having no inherent physiologic influence while generating expectations of potential improvement that is meaningful to the subjects (37). In studies that included a comparison of a placebo group, the training device contained loosely packed aquarium gravel, and subjects were told that the gravel reduced the oxygen content of each breath, mimicking the effects of high altitude.

Quality Assessment

Methodological quality was independently assessed by two reviewers using Oxford's level of evidence (25) and the PEDro Scale (28,38). Studies were assigned a 1b if they were higher quality RCTs, had smaller confidence intervals (CIs), and had a minimum sample size of 9 people in each comparison group (55).

The PEDro scale (28,38) consists of 11 items related to scientific rigor including the following: eligibility criteria, random allocation, concealed allocation, follow-up, baseline comparability, blinded subjects, blinded therapists, blinded assessors, intention to treat, between-group analysis, and both point and variability measures. The maximum final score of 10 points did not include item 1 (eligibility criteria) as it affects the external validity rather than internal validity (28,38).

Data Extraction

Data were extracted by two independent reviewers using standardized forms that included information about the study citation, study purpose, description of participants

TABLE 2. Characteristics of participants.*

First author, year	M/F	Age in years (*SD*)	$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)†	Sport	Fitness/ competitive level
Bailey, 2010 (1)	12/4	IMT = 20 (2.0) Sham = 22.0 (4.0)	IMT = 47.0 (5.0) Sham = 48.0 (8.0)	Intermittent sprint sports	Recreational
Fairbarn, 1991 (7)	10/0	RMT = 22 (2.7) C = 23.0 (4.0)	RMT = 64.2 (1.9) C = 68.0 (6.6)	Cyclists	Elite; highly trained
Holm, 2004 (16)	16/4	Both = 28.5 (7.0)	RMT = 54.0 (4.7) C/placebo = 56.8 (3.0)	Cyclists and/or triathletes	Recreational
Inbar, 2000 (17)	20 (Gender not reported)	Both = 28.9 (8.9)	IMT = 58.0 (4.6) Placebo = 61.2 (4.7)	Endurance athletes	Elite; national track events
Johnson, 2007 (18)	18/0	IMT = 31.6 (7.5) Placebo = 29.9 (8.9)		Cyclists	Elite; competitive
Kilding, 2010 (21)	10/6	IMT = 19.1 (2.6) Sham = 19.0 (2.1)		Swimmers	Elite; club level
Leddy, 2007 (22)	22/0	RMT = 29.0 (8.0) Placebo = 34.0 (6.0)	RMT = 56.4 (6.7) Sham = 52.0 (2.7)	Distance runners	Elite
McMahon, 2002 (33)	20/0	RMT = 26.0 (4.0) C = 28.0 (6.0)	RMT = 73.6 (15.0) C = 70.1 (12.6)	Cyclists	Elite††; experienced
Mickleborough, 2010 (34)	12/12	IMT/C/sham = 21.5 (1.9)		Road runners	Recreational
Morgan, 1987 (35)	9/0	RMT = 24.0 (2.0) C = 25.0 (2.24)	RMT = 3.89 (0.52) $L \cdot min^{-1}$ C = 3.9 (0.16) $L \cdot min^{-1}$	Cyclists	Recreational; moderately trained
Nicks, 2009 (36)	22/7	IMT = 19.8 (0.9) C = 19.9 (1.3)		Soccer	Elite; mid-level NCAA Division 1 collegiate soccer players
Riganas, 2008 (44)	12/7	IMT = 21.7 (18.2) C = 19.7 (4.2)	IMT = 51.8 (6.5) C = 51.0 (6.4)	Rowers	Elite; Greek National rowing
Romer, 2002 (46)	16/0	IMT = 29.5 (9.3) Sham = 30.3 (7.3)	IMT = 4.6 (0.48) $L \cdot min^{-1}$ Sham = 4.7 (0.23) $L \cdot min^{-1}$	Road cyclists (5 triathletes)	Elite
Romer, 2002 (45)	24/0	IMT = 21.3 (3.8) Sham = 20.2 (2.4)	IMT = 56.3 (3.1) Sham = 55.8 (5.9)	Repetitive sprint sport players	Elite; at least amateur club level
Sonetti, 2001 (51)	17/0	IMT/placebo = 24.2 (4.9)	IMT = 55.0 (5.0) Placebo = 54.2 (2.5)	Cyclists	Elite; local races
Sperlich, 2009† (52)	12/5	IMT/C = 24.9 (2.5)	IMT = 53.5 (8.1) C = 55.8 (8.5)	Special forces police squad	Recreational
Tong, 2008 (54)	30/0	IMT = 21.3 (0.9) C = 22.0 (1.9) Sham = 21.5 (2.1)	IMT = 60.8 (4.7) C = 59.1 (5.2) Sham = 55.8 (7.9)	Soccer or rugby	Recreational

Tong, 2010 (55)	18/0	IMT = 21.1 (1.1) C = 22.3 (1.0)	IMT = 59.0 (6.3) C = 58.1 (4.5)	Soccer or rugby	Recreational; nonprofessional athletes
Volianitis, 2001 (56)	0/14	IMT/Sham = 23.8 (3.8)	IMT/sham = 3.56 (0.17) $L\cdot min^{-1}$	Rowers	Elite
Wells, 2005 (57)	14/20	RMT/placebo = 15.6 (1.3)		Swimmers	Elite; national level
Wylegala, 2007 (61)	30/0	RMT/placebo = 23.4 (4.3)		Swimmers	Recreational experienced

*The data are reported as mean (*SD*). M/F = male/female; C = control group; IMT = inspiratory muscle training group; NCAA = National Collegiate Athletic Association of the USA; RMT = respiratory muscle training.

†Unless specified as 1/min.

‡Based on $\dot{V}O_2$max levels defined as "athletes" by Wilmore and Costill[59].

(demographics, inclusion criteria, and type of sport), description of intervention including group comparisons, outcomes of sport performance and respiratory muscle performance, and the units of the measures, their timing, and statistical significance of the data. Authors' conclusions and proposed mechanisms were also noted. Disagreements regarding data abstraction were discussed by the 2 reviewers until consensus was achieved; in the event of an irresolvable disagreement, a third person was included in the discussion until consensus was achieved. Several authors were contacted to gain further data or to clarify information.

Statistical Analyses

Meta-analyses were performed on similar outcomes from RCTs that compared IMT or RMT with a control, sham, or placebo group. Using RevMan 5.0.25 software (43), meta-analyses were performed using the randomized effects model with continuous data to calculate the weighted mean difference (WMD) and 95% CI of the following: (a) sport performance outcomes–time trial performance, exercise time to exhaustion (ET_{lim}), maximal speed, maximal repetitions for Yo-Yo test (36,55), $\dot{V}O_2$max, peak work, maximal minute ventilation (VE_{max}), RPB, and RPE; (b) respiratory muscle outcomes–MIP, maximal expiratory pressure (MEP), maximum voluntary ventilation (MVV), respiratory endurance time (RET); and (c) spirometry–forced expiratory volume in 1 second (FEV_1) and forced vital capacity (FVC). For the definition of above terms, refer to Appendix 2. When units differed among included studies, meta-analyses were performed using the fixed effects model for the outcomes: FEV_1 and FVC. The presence of heterogeneity was investigated using the I-squared test. When an improved experimental effect resulted in a negative change, the data were multiplied by −1, so all improvements were reflected as a positive change. This was performed on data from time trials, RPE, and RPB.

A WMD calculated by using data from some studies provides a greater contribution than others based on preassigned factors. In this case, the inverse variance method in RevMan calculates the weight for study data based on the assumption that variance is inversely proportional to importance, that is, those studies with a smaller variance contribute more to the WMD. We also chose the random effects model, which is based on the assumption that the true treatment effects in the individual studies may be different from each other (unlike the fixed model). This means that rather than a single number, there is a distribution of numbers to estimate in the meta-analysis and that these different true effects are normally distributed.

Subgroup analysis of outcomes was performed according to the following categorization: (a) type of sport (intermittent sprint sports, swimming, cycling, rowing, endurance track sports, and diving); (b) type of IMT and

TABLE 3. Description of interventions.*

First author, year	Type of training	Starting intensity	Progression of training intensity	Sessions/ day or week	No of weeks	Duration of session	Supervision	Control/sham
Bailey, 2010 (1)	POWERbreathe (threshold)	50% of MIP	Periodically increased load so that only 30 maneuvers could be completed	2 sessions daily	4 wk	30 inspirations	Twice weekly in laboratory	Sham: similar protocol except at 15% MIP daily
Fairbarn, 1991 (7)	Isocapnic hyperpnea	Baseline MSVC	Initially at baseline MSVC and then progressed to maximum tolerated in 8 min bout. After 8 sessions, the duration of bouts increased to 10 min.	3–4 sessions per wk (16 sessions)	4 wk	Three times 8 min for 8 sessions; 3 times 10 min for 8 sessions	Supervised	Control: no intervention
Holm, 2004 (16)	Isocapnic hyperpnea	max V_T and f_B from cycling test	V_T or f_B increased every 1–2 days. Targeted 19 on a 20-point respiratory effort scale	5 sessions per wk	4 wk	30 min	Supervised	Control: no intervention Sham: trained for 5 min at 65% of max V_T and f_B
Inbar (17)	Threshold	30% of MIP	Increased 5% each session to 80% of MIP by 4 wk. Thereafter trained at 80% of their MIP adjusting for weekly increase in MIP	6 sessions per wk	10 wk	30 min	Supervised	Sham: training with same device at no load
Johnson (18)	POWERbreathe (threshold trainer)	50% of MIP	Periodically increased load so that only 30 maneuvers could be completed	2 sessions daily	6 wk	30 inspirations	Completed a training diary to record training	Sham: 15 min × 5 $d \cdot wk^{-1}$ with no load
Kilding (21)	POWERbreathe (threshold)	50% of MIP	Attempt to set MIP at value that participant could only achieve 30 breaths	Twice daily	6 wk	30 inspirations 2 times a day	Supervised once weekly and completed daily training diary	Sham: 60 slow protracted breaths once daily for 6 wk at 15% MIP, with no periodic increase
Leddy (22)	Isocapnic hypercapnea	30 breaths/ min ~50% of MVV	Increase by 1–2 breaths/min per session	5 $d \cdot wk^{-1}$	4 wk	30 min	Home training	Sham: inhaled to TLC followed by 10 s breath hold

McMahon (33)	Normocapnic hyperpnea	~60% of 15 s MVV	Increased V_E (primary by increasing f_B) till subject could hold the training-V_E constant for at least 30 min but not 35 min	20 sessions in 4–6 wks	4–6 wk	30 min	Home training. Supervised every 5th session	Control: no training
Mickleborough (34)	RT2 training device (targeted resistive)	80% of the SMIP	At each session the SMIP was reassessed and the training template for that day set at 80% SMIP	3 sessions per wk	6 wk	36 inspirations	Supervised	Control: no training Sham: 30% of the SMIP.
Morgan (35)	Normocapnic hyperpnea	85% of 15 s MVV	When 85% MVV performed for 2, 5, 9 min, and 12 min (4 bouts), intensity was increased by 5% MVV the next day.	4× daily, 5 $d \cdot wk^{-1}$	3 wk	28 min	Supervised	Control: not specified
Nicks (36)	PowerLung (threshold)	50% MIP	Gradually increased the % MIP of the device 1–2 times per week	2× daily, 5 times per wk	5 wk	30 inspirations	Mostly supervised and participants submitted training logs	Control: no training
Riganas (44)	Threshold	30% MIP	Increased by 5% at each exercise session to reach 80% of their MIP at the end of the second week. Continued at 80% of MIP, adjusted weekly to the new MIP	5 sessions per wk	6 wk	30 min	Supervised	Control: no training
Romer (46)	POWERbreathe (threshold)	50% of MIP	Periodically increased load so that only 30 maneuvers could be completed	Twice daily	6 wk	30 inspirations 2 times a day	Supervised	Sham: similar protocol except at 15% MIP
Romer (45)	POWERbreathe (threshold)	50% of MIP	Periodically increased load so that only 30 maneuvers could be completed	Twice daily	6 wk	30 inspirations 2 times a day	Supervised	Sham: similar protocol except at 15% MIP
Sonetti (51)	POWERbreathe (threshold), or hyperpnea	Threshold: 50% of MIP; Hyperpnea training: 50–60% of MVV	Threshold: increased f_B every 1–2 d and increased load once a week Hyperpnea: increased f_B once a week.	5 times per wk	5 wk	Threshold: ~ 40 inspirations; 3–5 min Hyperpnea: 30 min session	1 supervised and 4 home sessions per wk	Sham: 30 min with no load
Sperlich (52)	Ultrabreathe (resistive with no target)	90% of MIP	Increased weekly to adjust to 90% inspiratory pressure to near maximum fatigue	Twice daily	6 wk	30 inspirations 2 times a day	Participants logged training	Sham: same training protocol with no resistance

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Tong (54)	POWERbreathe (threshold)	50% of MIP	Increased by 10–15 cmH_2O when subjects performed 30 uninterrupted breaths	Twice daily, 6 $d \cdot wk^{-1}$	6 wk	30 inspirations 2 times a day	Trained in laboratory	Control: no training Sham: 15% of MIP
Tong (55)	POWERbreathe (threshold)	50% of MIP	Increased by 10–15 cmH_2O when subjects performed 30 uninterrupted breaths	Twice daily, 6 $d \cdot wk^{-1}$	4 wk	30 inspirations 2 times a day	Not reported	Control: no training
Volianttis (56)	POWERbreathe (threshold)	50% MIP	Not described	Once daily	11 wk	30 inspirations 2 times a day	Home training (diary recording)	Sham: 60 breaths once daily, at 15% MIP
Wells (57)	PowerLung (threshold)	50% MIP and MEP	1st to 3rd wk: 50% MIP/MEP, 4th to 6th wk: 60% MIP/MEP, 7th to 9th wk: 70% MIP/MEP, and 10th to 12th wk: 80% MIP/MEP	Around 10 sessions per week	12 wk	30 inspirations	Supervised	Sham: training devices with no loads
Wylegala (61)	Isocapnic hyperpnea or threshold	Threshold: ±50 cmH_2O on inspiration and expiration Hyperpnea: 55% of SVC and variable f_B	Threshold group: none reported Hyperpnea group: initially increased f_B by 1–2 per min after 20 min of training until f_B = 50. Thereafter V_T increased by 0.1 L and f_B adjusted to achieve same V_E. The cycle was then repeated	5 $d \cdot wk^{-1}$	4 wk	30 $min \cdot day^{-1}$ for all groups	Supervised 1 session per week and laptop logged home sessions	Sham: inhaled to total lung capacity for 10 s breath hold on modified apparatus

*CON = control group; f_B = breathing frequency; IMT = inspiratory muscle training; max = maximal; MEP = maximal expiratory pressure; MIP = maximal inspiratory pressure; MVV = maximum voluntary ventilation; MSVC = maximum sustained ventilatory capacity; SVC = sustained vital capacity; SMIP = sustained maximal inspiratory pressure; TLC = total lung capacity; V_E = minute ventilation; V_T = tidal volume.

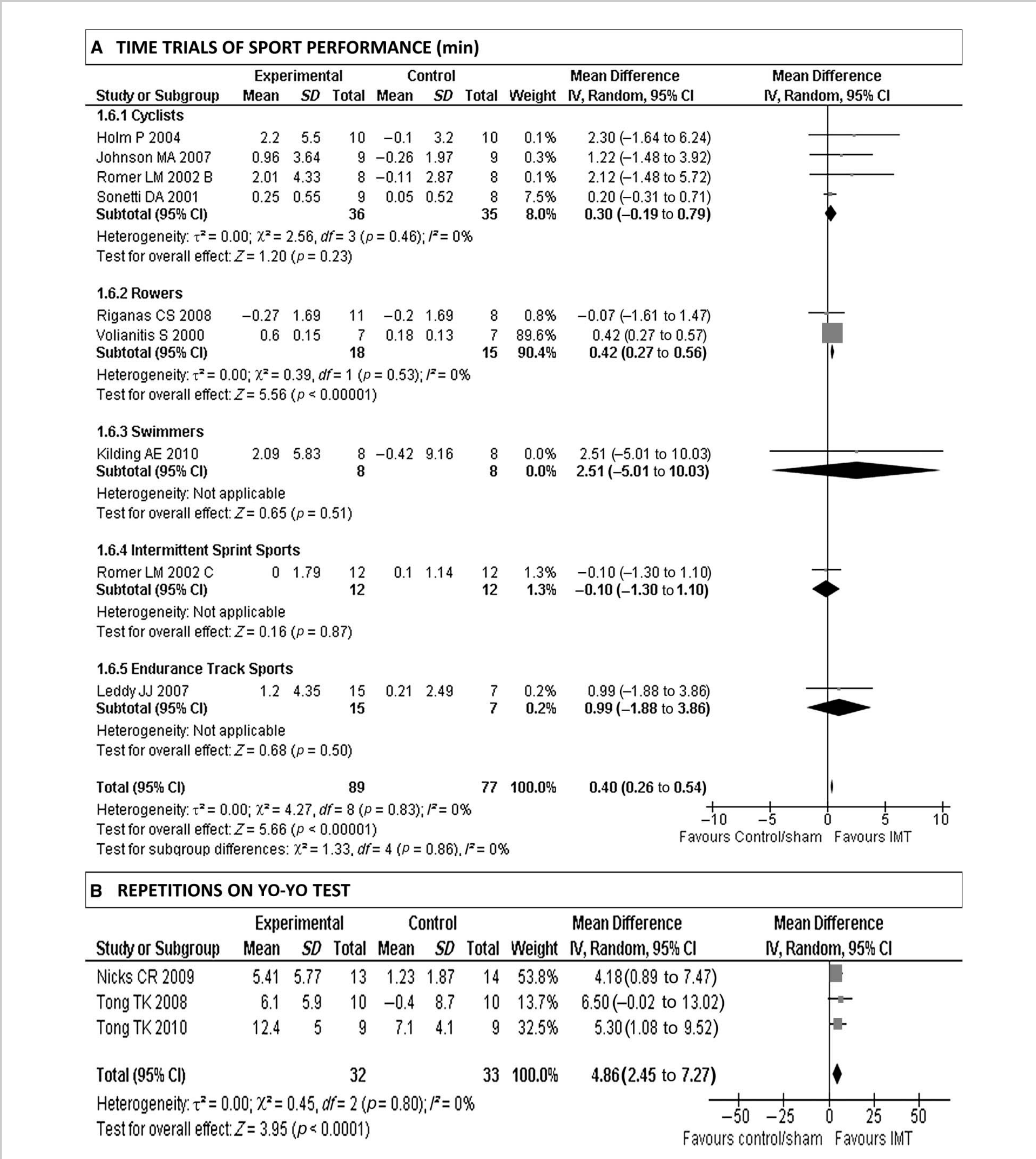

Figure 2. Forest plots of sports performance: time trials and Yo-Yo test. Subgroup and overall totals are provided for time trial data. Horizontal lines indicate confidence intervals for each study. Horizontal diamonds show overall confidence intervals and the midline indicates the mean difference for subgroups or all trials in the meta-analysis.

RMT (threshold-type trainer or targeted resistive, resistive trainer, normocapnic hyperpnea trainer); (c) athletic level (elite vs. recreational athletes); (d) training duration (4–11 weeks of IMT or RMT); and (e) sham, control, or placebo and low-intensity sham groups.

Significance for an overall effect was set at $p < 0.05$, and significance for heterogeneity was set at $p < 0.1$. If heterogeneity was significant, then sensitivity analyses were performed to determine the potential sources of variance and the strength of findings.

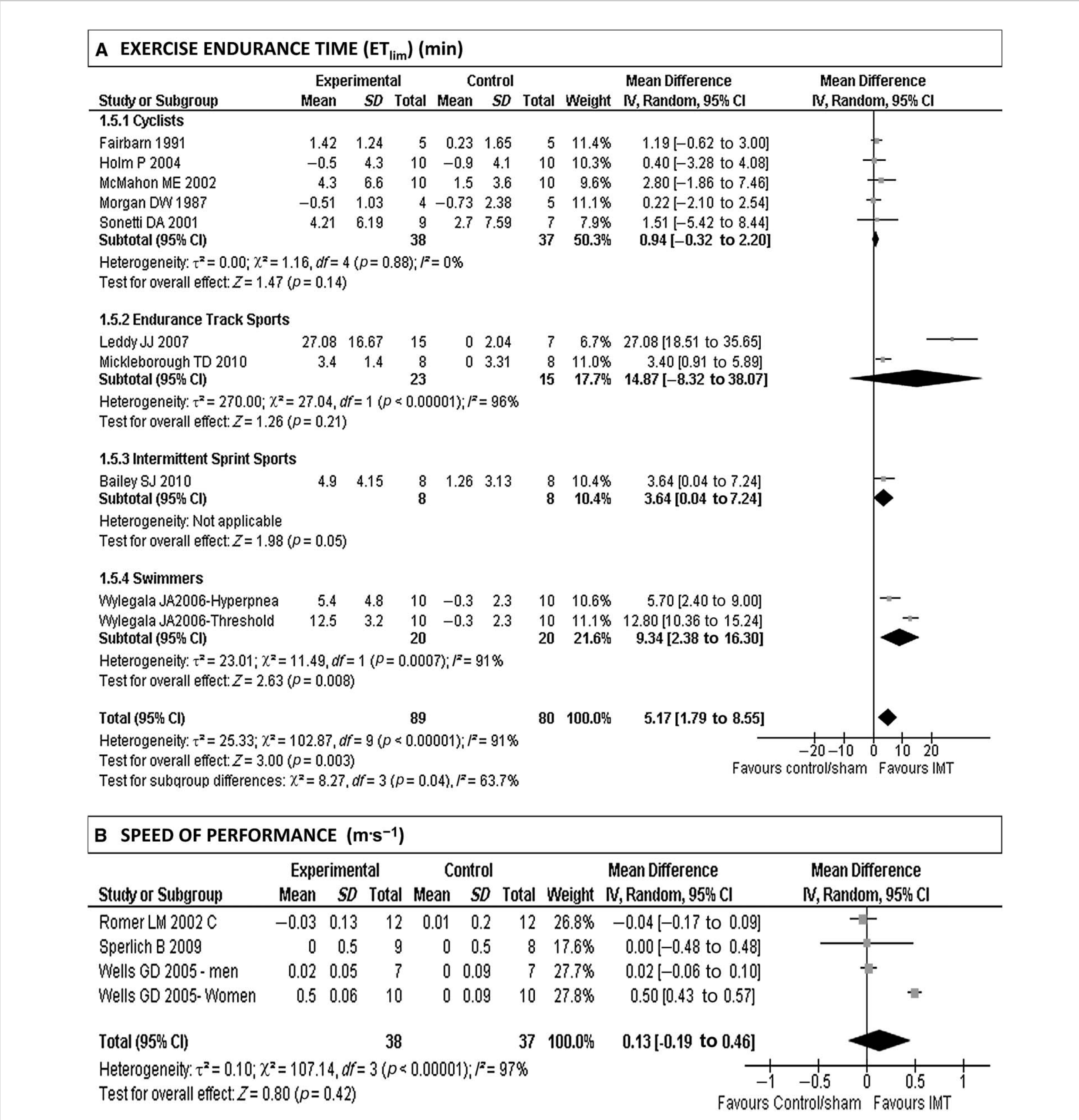

Figure 3. Forest plots of sports performance: endurance time and speed of performance subgroup and overall totals are provided for endurance time data. Horizontal lines indicate confidence intervals for each study. Horizontal diamonds show overall confidence intervals and the midline indicates the mean difference for subgroups or all trials in the meta-analysis.

Data for outcomes were not included in the meta-analyses if mean and *SD*s were not reported in the article and could not be obtained after attempting to contact the authors.

Results

Study Selection

The search strategies of databases yielded 6,923 citations (Figure 1). After review of full-text articles, 21 met the inclusion criteria. The main reasons for excluding articles were: (a) participants were not healthy athletes (e.g., healthy nonathletes or people with disabilities such as spinal cord injury); (b) RMT or IMT was not performed; (c) outcomes of sports performance or respiratory muscle function were not measured; (d) the study design was not an RCT; (e) data from the same study appeared in two different articles; and (f) the RCT did not include a comparison to a control, sham, or placebo group (Figure 1).

Levels of Evidence

Regarding Oxford's levels of evidence, 9 studies were rated level 1b and 12 studies were rated at level 2b (Table 1). Agreement between 2 raters was achieved without requiring input from a third person.

Methodological Quality of Studies

The mean PEDro score for the RCT studies, as described in Table 1, was 6.5 and ranged from 4 to 9. The most frequent omissions in the study design or its reporting were the following: the randomization process was not concealed (18 studies), testers were not blinded (19 studies), therapists applying treatment were not blinded (all 21 studies), or subjects were not blinded (10 studies). See Tables 2 and 3 for details on each study. Agreement between 2 raters was achieved on quality assessment.

Characteristics of Participants

The characteristics of subjects are presented in Table 2. The total number of participants was 426, who ranged from 15 to 40 years old. Eighty percent of participants were men; 11 studies only included men (Table 2) and 1 study only included women (56). The group sizes of participants were often less than 10 and ranged from 4–14 athletes per group.

Athletic level of participants ranged from nonprofessional recreational to highly trained athletes competing at the international level. Participants in the article by Sperlich et al. (52) were members of a German Special Force Squad that seemed to have undergone comparable levels of training to subjects in other studies and thus were included in our systematic review.

Characteristics of the Interventions

The characteristics the RMT interventions applied are summarized in Table 3. Regarding the type of training load, 1 study used a resistive trainer with a target (34), 1 study used a resistive trainer with no target (Ultrabreathe; Tangent Healthcare Ltd., Basingstoke, United Kingdom) (52), 7 studies used hyperpnea (Table 3), 12 used threshold training applied to inspiration only (Table 3), and 2 studies used threshold training applied to inspiration and expiration (57,61). Threshold devices included POWERbreathe (POWERbreathe; HaB International Ltd., Warwickshire,

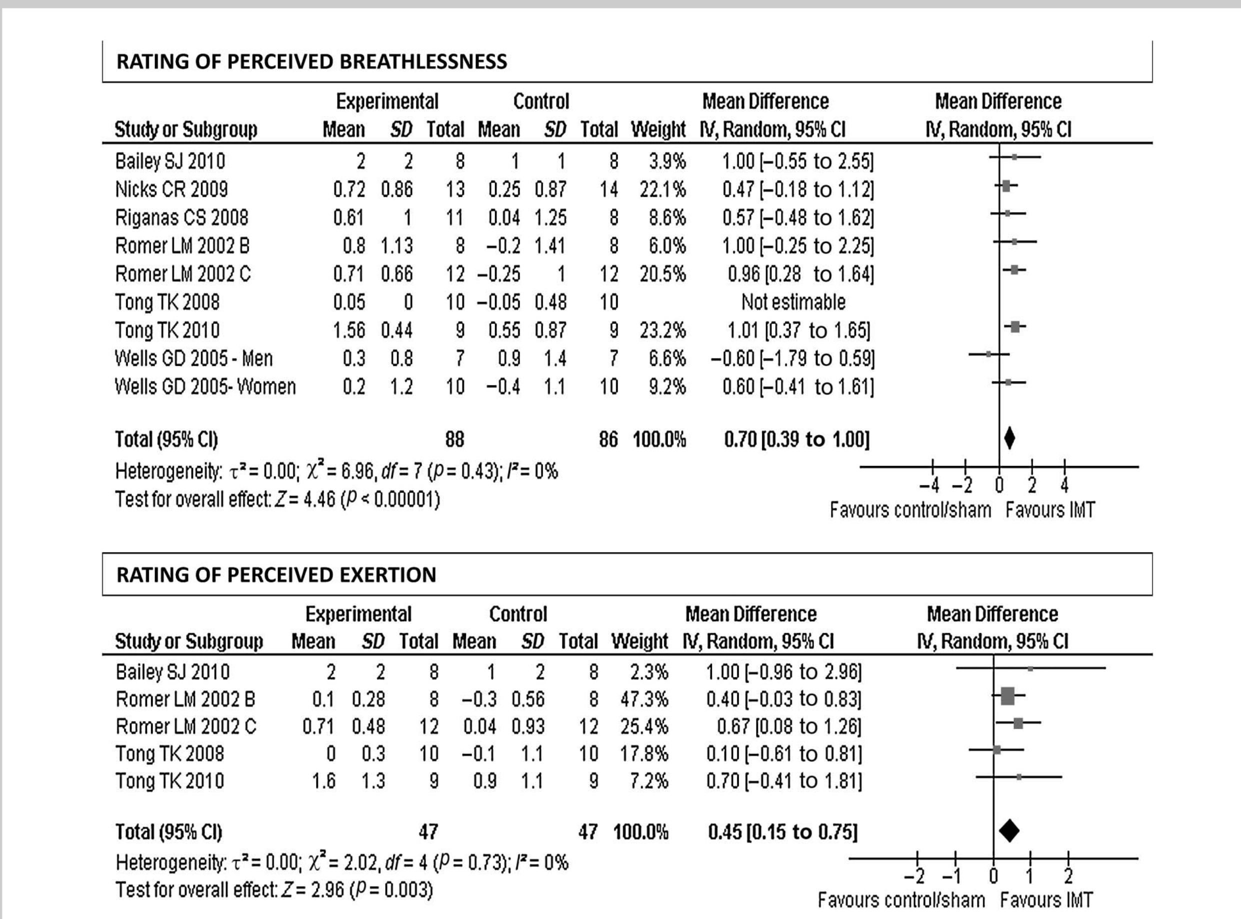

Figure 4. Forest plots of rating of perceived breathlessness and rating of perceived exertion.

MAXIMAL INSPIRATORY PRESSURES - Sport type (cmH_2O)

Study or Subgroup	Experimental Mean	Experimental *SD*	Experimental Total	Control Mean	Control *SD*	Control Total	Weight	Mean Difference IV, Random, 95% CI
3.2.1 Cycling								
Holm P 2004	10.4	8.3	10	2.3	7.4	10	8.3%	8.10 [1.21 to 14.99]
Johnson MA 2007	25.65	29	9	0	32	9	4.4%	25.65 [−2.56 to 53.86]
Romer LM 2002 B	24	16.97	8	−1	16.97	8	6.5%	25.00 [8.37 to 41.63]
Sonetti DA 2001	12.9	39.8	9	4.8	31.5	8	3.6%	8.10 [−25.85 to 42.05]
Subtotal (95% CI)			**36**			**35**	**22.8%**	**14.41 [3.98 to 24.84]**
Heterogeneity: $\tau^2 = 39.34$; $\chi^2 = 4.46$, $df = 3$ ($p = 0.22$); $I^2 = 33\%$								
Test for overall effect: $Z = 2.71$ ($p = 0.007$)								
3.2.2 Endurance Track Sports								
Inbar O 2000	35	24.8	10	1.3	22.2	10	5.7%	33.70 [13.07 to 54.33]
Mickleborough TD 2010	56.5	17.9	8	−0.1	23.9	8	5.7%	56.60 [35.91 to 77.29]
Subtotal (95% CI)			**18**			**18**	**11.5%**	**45.14 [22.69 to 67.58]**
Heterogeneity: $\tau^2 = 151.08$; $\chi^2 = 2.36$, $df = 1$ ($p = 0.12$); $I^2 = 58\%$								
Test for overall effect: $Z = 3.94$ ($p < 0.0001$)								
3.2.3 Intermittent Sprint Sports								
Bailey SJ 2010	26	22	8	6	34	8	4.4%	20.00 [−8.06 to 48.06]
Nicks CR 2009	27.2	18.2	13	2.6	5.9	14	7.8%	24.60 [14.24 to 34.96]
Romer LM 2002 C	43.5	12.81	12	0.9	12.47	12	7.8%	42.60 [32.49 to 52.71]
Tong TK 2008	46.2	19.6	10	1.2	19.4	10	6.4%	45.00 [27.91 to 62.09]
Tong TK 2010	32.9	29.8	9	−0.2	16.4	9	5.4%	33.10 [10.88 to 55.32]
Subtotal (95% CI)			**52**			**53**	**31.8%**	**34.38 [24.31 to 44.45]**
Heterogeneity: $\tau^2 = 64.25$; $\chi^2 = 8.46$, $df = 4$ ($p = 0.08$); $I^2 = 53\%$								
Test for overall effect: $Z = 6.69$ ($p < 0.00001$)								
3.2.4 Swimming and diving								
Kilding AE 2010	10.46	26	8	0.34	30	8	4.5%	10.12 [−17.39 to 37.63]
Wells GD 2005 - Men	5.33	23.2	7	4.5	21.4	7	5.2%	0.83 [−22.55 to 24.21]
Wells GD 2005- Women	14.9	22.2	10	14.4	20.7	10	6.1%	0.50 [−18.31 to 19.31]
Wylegala JA2006-Hyperpnea	5	35.4	10	−1	43.1	10	3.5%	6.00 [−28.57 to 40.57]
Wylegala JA2006-Threshold	12.6	23.7	10	−1	43.1	10	4.1%	13.60 [−16.89 to 44.09]
Subtotal (95% CI)			**45**			**45**	**23.4%**	**4.56 [−6.70 to 15.82]**
Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 0.78$, $df = 4$ ($p = 0.94$); $I^2 = 0\%$								
Test for overall effect: $Z = 0.79$ ($p = 0.43$)								
3.2.5 Rowing								
Riganas CS 2008	36.09	146.06	11	−3.13	86.72	8	0.6%	39.22 [−65.95 to 144.39]
Volianitis S 2000	40	25	7	5	6	7	6.0%	35.00 [15.95 to 54.05]
Subtotal (95% CI)			**18**			**15**	**6.6%**	**35.13 [16.39 to 53.88]**
Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 0.01$, $df = 1$ ($p = 0.94$); $I^2 = 0\%$								
Test for overall effect: $Z = 3.67$ ($p = 0.0002$)								
3.2.6 Special Forces								
Sperlich B 2009	10.34	24.14	9	1.53	40.72	8	3.8%	8.81 [−23.52 to 41.14]
Subtotal (95% CI)			**9**			**8**	**3.8%**	**8.81 [−23.52 to 41.14]**
Heterogeneity: Not applicable								
Test for overall effect: $Z = 0.53$ ($p = 0.59$)								
Total (95% CI)			**178**			**174**	**100.0%**	**23.69 [15.31 to 32.06]**
Heterogeneity: $\tau^2 = 207.73$; $\chi^2 = 65.02$, $df = 18$ ($p < 0.00001$); $I^2 = 72\%$								
Test for overall effect: $Z = 5.54$ ($p < 0.00001$)								
Test for subgroup differences: $\chi^2 = 23.64$, $df = 5$ ($p = 0.0003$), $I^2 = 78.9\%$								

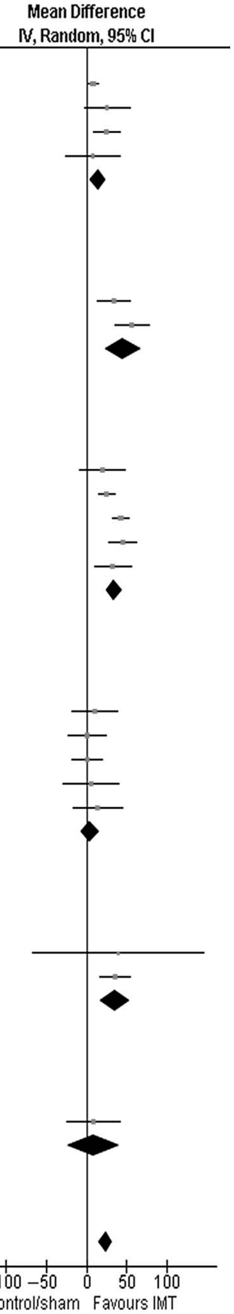

Figure 5. Forest plot of maximal inspiratory pressure: sport type.

United Kingdom), PowerLung (PowerLung, Inc., Burlington, Ontario, Canada), and the Respiratory Threshold Model 2 (threshold trainer; Philips Respironics, Murrysville, PA, USA). For all the studies, the intensity of training was increased gradually during the training time. Noteworthy, 13 studies (1,18,21,34,36,45,46,51,52,54–57,61) had subjects performing 1 or 2 sets of 30–40 vital capacity inspirations against inspiratory loads for the daily training

MAXIMAL INSPIRATORY PRESSURES - Type of IMT/RMT (cmH_2O)

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
3.5.1 Threshold-type Trainer								
Bailey SJ 2010	26	22	8	6	34	8	4.4%	20.00 [−8.06 to 48.06]
Inbar O 2000	35	24.8	10	1.3	22.2	10	5.7%	33.70 [13.07 to 54.33]
Johnson MA 2007	25.65	29	9	0	32	9	4.4%	25.65 [−2.56 to 53.86]
Kilding AE 2010	10.46	26	8	0.34	30	8	4.5%	10.12 [−17.39 to 37.63]
Nicks CR 2009	27.2	18.2	13	2.6	5.9	14	7.6%	24.60 [14.24 to 34.96]
Riganas CS 2008	36.09	44.01	11	−3.13	30.66	8	3.6%	39.22 [5.64 to 72.80]
Romer LM 2002 B	24	16.97	8	−1	16.97	8	6.4%	25.00 [8.37 to 41.63]
Romer LM 2002 C	43.5	12.81	12	0.9	12.47	12	7.7%	42.60 [32.49 to 52.71]
Tong TK 2008	46.2	19.6	10	1.2	19.4	10	6.3%	45.00 [27.91 to 62.09]
Tong TK 2010	32.9	29.8	9	−0.2	16.4	9	5.4%	33.10 [10.88 to 55.32]
Volianitis S 2000	44	21.2	7	6	31.75	7	4.3%	38.00 [9.72 to 66.28]
Wells GD 2005 - Men	5.33	23.2	7	4.5	21.4	7	5.2%	0.83 [−22.55 to 24.21]
Wells GD 2005- Women	14.9	22.2	10	14.4	20.7	10	6.0%	0.50 [−18.31 to 19.31]
Wylegala JA2006-Threshold	12.6	23.7	10	−1	43.1	10	4.0%	13.60 [−16.89 to 44.09]
Subtotal (95% CI)			**132**			**130**	**75.4%**	**26.10 [17.98 to 34.22]**
Heterogeneity: $\tau^2 = 120.19$; $\chi^2 = 29.90$, $df = 13$ ($p = 0.005$); $I^2 = 57\%$								
Test for overall effect: $Z = 6.30$ ($p < 0.00001$)								
3.5.2 Targeted Resistive Trainer								
Mickleborough TD 2010	56.5	17.9	8	−0.1	23.9	8	5.6%	56.60 [35.91 to 77.29]
Subtotal (95% CI)			**8**			**8**	**5.6%**	**56.60 [35.91 to 77.29]**
Heterogeneity: Not applicable								
Test for overall effect: $Z = 5.36$ ($p < 0.00001$)								
3.5.3 Resistive-type Trainer								
Sperlich B 2009	10.34	24.14	9	1.53	40.72	8	3.8%	8.81 [−23.52 to 41.14]
Subtotal (95% CI)			**9**			**8**	**3.8%**	**8.81 [−23.52 to 41.14]**
Heterogeneity: Not applicable								
Test for overall effect: $Z = 0.53$ ($p = 0.59$)								
3.5.4 Normocapnic Hyperpnea Trainer								
Holm P 2004	10.4	8.3	10	2.3	7.4	10	8.1%	8.10 [1.21 to 14.99]
Sonetti DA 2001	12.9	39.8	9	4.8	31.5	8	3.6%	8.10 [−25.85 to 42.05]
Wylegala JA2006-Hyperpnea	5	35.4	10	−1	43.1	10	3.5%	6.00 [−28.57 to 40.57]
Subtotal (95% CI)			**29**			**28**	**15.2%**	**8.02 [1.39 to 14.65]**
Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 0.01$, $df = 2$ ($p = 0.99$); $I^2 = 0\%$								
Test for overall effect: $Z = 2.37$ ($p = 0.02$)								
Total (95% CI)			**178**			**174**	**100.0%**	**24.09 [15.72 to 32.47]**
Heterogeneity: $\tau^2 = 211.94$; $\chi^2 = 65.38$, $df = 18$ ($p < 0.00001$); $I^2 = 72\%$								
Test for overall effect: $Z = 5.64$ ($p < 0.00001$)								
Test for subgroup differences: $\chi^2 = 26.15$, $df = 3$ ($p < 0.00001$), $I^2 = 88.5\%$								

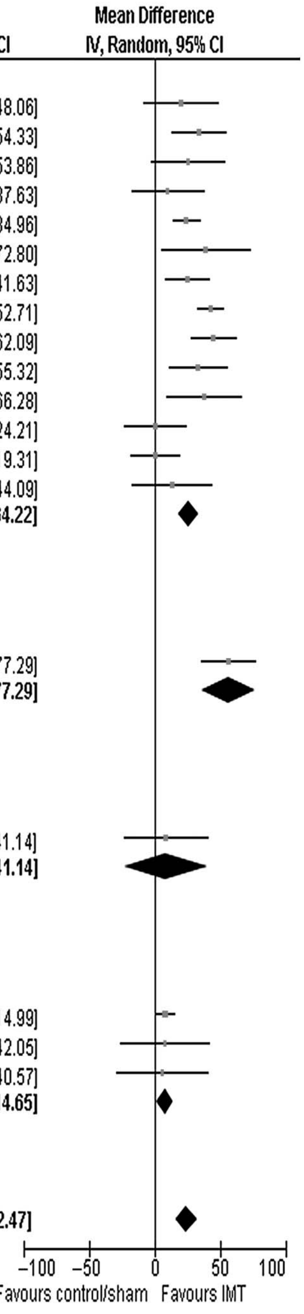

Figure 6. Forest plot of maximal inspiratory pressure: type of inspiratory muscle training (IMT)/RMT.

sessions rather than continuous ventilation against loaded inspiration for 15–30 minutes. The number of training sessions varied from 3 to 4 sessions per week to twice daily. Most frequently, the duration of RMT training was 6 weeks; however, this ranged from 3–12 weeks.

Regarding the comparison group, 2 had a placebo group (18,51), 4 had sham (17,22,57,61), 5 had low-intensity sham (1,21,45,46,56), 7 had a control group (7,33,35,36,44,52,56), and 3 included both sham and control groups (16,34,54). No differences were found from meta-analyses of

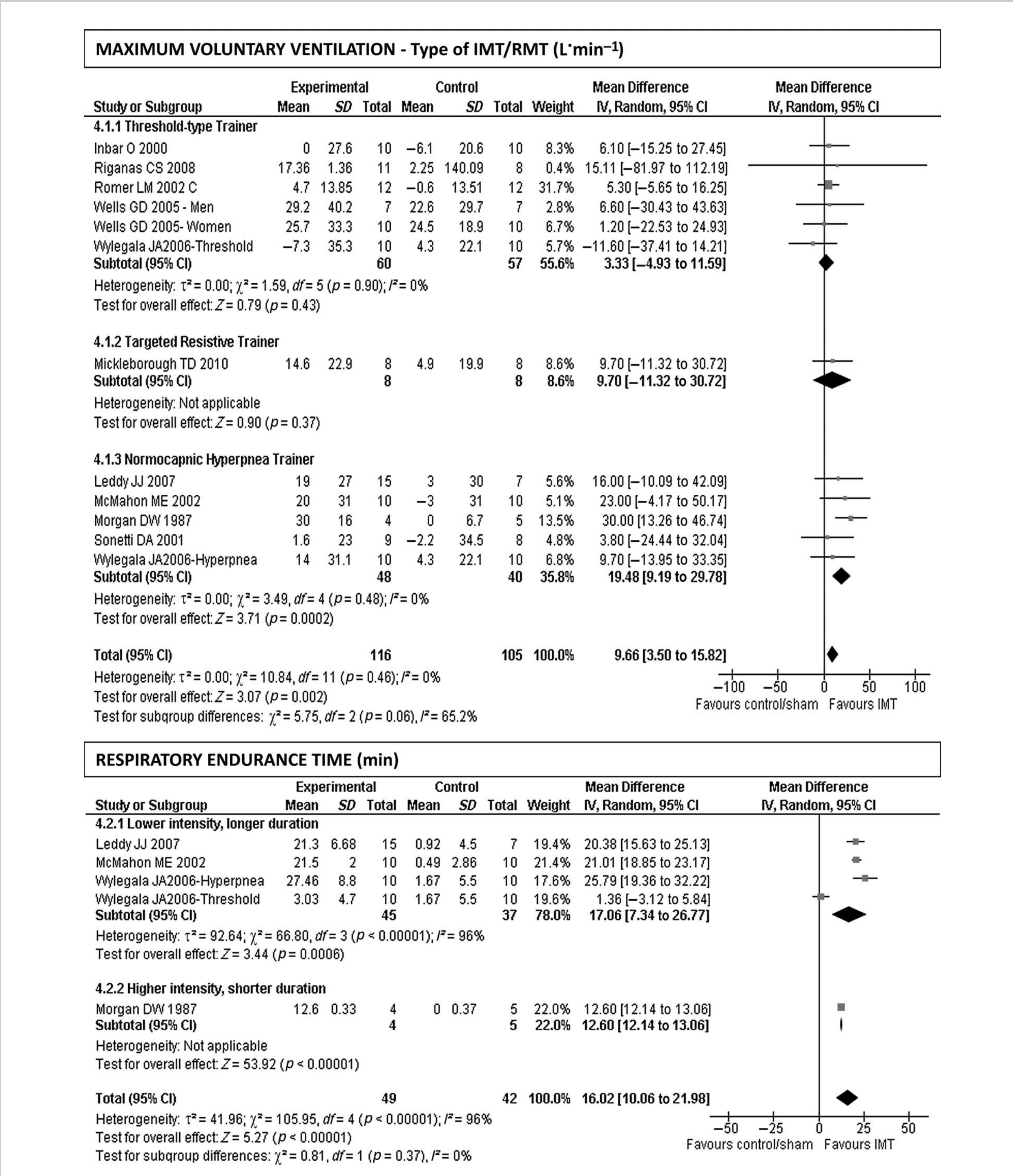

Figure 7. Forest plots of measures of respiratory muscle endurance: maximum voluntary ventilation, and respiratory endurance time.

outcomes comparing sham, placebo, and control and low-intensity sham groups (data not shown), so all subsequent descriptions of the comparison group of sham, control, or placebo will be termed control.

Sport Performance and Exercise Capacity

Meta-analyses of several measures of sports performance showed a greater improvement after IMT/RMT compared with regular training. Meta-analyses of 9 studies that evaluated sport performance as "fixed distance time trials" showed an overall effect in favor of the IMT/RMT group across all sports ($p < 0.0000$; Figure 2). Among these studies, the one by Volianitis demonstrated the largest benefit toward RMT and was assigned the highest overall weight of studies. Subgroup analysis showed that rowers who performed RMT had a decreased performance time compared with the control group ($p < 0.0000$) (44,56); none of the other sport subgroups showed greater improvement in the IMT/RMT compared with control group, although group size was 5–7 participants in all except the subgroup of cyclists. Repetitions of the Yo-Yo test (Figure 2) showed a greater improvement after IMT than control group ($p < 0.0001$), whereas speed of performance (cycling, running, and swimming) did not show a difference between IMT/RMT and control group ($p = 0.42$). An overall effect in favor of IMT/RMT was shown for ET_{lim} in 9 studies ($p = 0.003$; Figure 3). Subgroup analysis showed that IMT/RMT increased ET_{lim} more so in athletes who performed intermittent sprint sports and swimming than cyclists or endurance track sports ($p < 0.0000$; Figure 3).

Meta-analyses of 13 studies that evaluated $\dot{V}O_2max$ on an incremental exercise test showed no effect in favor of the IMT/RMT group across all sports and within subgroup analyses ($p = 0.27$). Other outcomes of the incremental exercise test, maximal work, and maximal minute ventilation, did not show a difference between IMT/RMT and control group ($p = 0.78$ and $p = 0.41$, respectively).

Of particular interest, meta-analyses of RPB and RPE at the maximum level of an incremental exercise test showed an overall effect in favor of IMT/RMT compared with usual training ($p < 0.0000$ and $p = 0.003$, respectively; Figure 4).

Respiratory Muscle Strength–Maximal Inspiratory Pressure and Maximal Expiratory Pressure

Meta-analyses of MIP showed that IMT/RMT participants had greater improvements in MIP than control ($p < 0.0000$), and this effect differed among sports ($p < 0.0000$; Figure 5). Subgroup analysis of the type of sport demonstrated greater improvement in MIP after IMT/RMT than control group for cycling, endurance track sports, intermittent sprint-type sports, and rowing, whereas swimmers, divers, and special forces athletes showed no significant differences (Figure 5). Subgroup analyses of the level of athlete demonstrated that both elite and recreational athletes who performed RMT had greater improvements in MIP than the control group ($p < 0.0000$ and $p = 0.002$, respectively).

Meta-analysis of the type of trainers showed significant subgroup differences in improvements of MIP ($p < 0.00001$; Figure 6). Subgroup analyses demonstrated that threshold type ($p < 0.0000$), targeted resistive ($p < 0.0000$), and normocapnic hyperpnea ($p = 0.02$) showed improvements in MIP in favor of IMT/RMT, albeit the latter trainer results in smaller differences. The resistive-type trainer, however, did not improve MIP compared with control values (52). Regarding the length of training, improvements in MIP in favor of IMT/RMT vs. control group were shown at 4, 5, 6, 10, and 11 weeks ($p < 0.006$) but not for 12 weeks. However, only 1 study (57) reported data at 12 weeks. Subgroup analysis showed effects in favor of IMT/RMT regardless of whether the comparison group was control or a low-intensity sham ($p < 0.0001$). Five studies (16,45,52,57,61) included in a meta-analysis of MEP showed no effect in favor of IMT/RMT compared with control group ($p = 0.23$).

Maximum Voluntary Ventilation and Respiratory Endurance Time

Meta-analyses demonstrated an overall effect of greater improvement in the MVV after IMT/RMT than control group ($p = 0.002$; Figure 7). Subgroup analyses showed that only normocapnic hyperpnea showed an effect in favor of IMT/RMT, whereas threshold type and targeted resistive training did not. Meta-analyses demonstrated an overall effect of greater improvement in the respiratory muscle endurance time after RMT than control group ($p < 0.0000$; Figure 7).

Spirometry

Meta-analyses demonstrated a small difference in the effect size of FEV_1 (standardized mean difference and CIs: 0.30 [0.04, 0.56]; $p = 0.02$) and FVC ($p = 0.06$) in favor of IMT/RMT compared with control. Sensitivity analyses by removal of data by Wells et al. (57) that showed a mean difference four-fold greater than the standardized mean difference for the group resulted in a nonsignificant difference.

Discussion

This systematic review, through examination of 21 RCTs and 426 participants, demonstrated that IMT/RMT can increase athletic performance and respiratory muscle strength and endurance. Sports performance, as reflected by time trials, ET_{lim}, and the Yo-Yo test showed highly significant improvements ($p < 0.003$) in response to IMT/RMT compared with control group. In addition, athletes at the recreational or elite level showed comparable benefit from IMT/RMT. However, different protocols of IMT/RMT and the diverse methods used to evaluate sports performance complicate determination of the sports that respond most favorably and secondly, identification of the most sensitive outcomes to evaluate the benefit of RMT in improving sports performance. Similar to the previous literature, IMT/RMT consistently improved measures of respiratory muscle strength and/or endurance in different groups of athletes, with the exception of swimmers and divers.

The average PEDro score of 6.5 is well above the most common median PEDro scores of 4 and 5 that were reported in a review of 615 sports physiotherapy trials and another 11,503 trials (not sports related), respectively (50). The commonly missed items in the RCTs of our systematic review were similar to those reported in the review by Sherrington et al. (50). These included blinding, concealed allocation, and intention-to-treat analysis. Although participants were blinded to treatment in about half the trials, blinding of therapists or assessors was rare. The influence of these factors on RCT outcomes is well described (6,38). Thus, the inclusion of these key features of study design and the reporting of the respective details in the methodology is essential (6) in the performance of future RCTs that examine IMT/RMT in athletes.

Similar to endurance training of limb muscles, RMT increases oxidative enzymes and changes in fiber-type proportions and sizes in the respiratory muscles of animal models (2,19) and people with chronic respiratory disease (40). In many of the athletes reported in this systematic review, an improved aerobic capacity of primary and accessory muscles of respiration likely occurred during IMT/RMT because of enhanced aerobic metabolism and oxygen delivery. This in turn may have delayed the onset of fatigue and reduced competitive blood flow (14,60) between the exercising respiratory and limb muscles during sport performance. There is some evidence that specific training of the respiratory muscles can attenuate the respiratory muscle metaboreflex (60). However, this has yet to be demonstrated during conditions of dynamic exercise.

A major finding of our systematic review was that both the RPB and RPE were decreased after IMT/RMT compared with regular training, which is consistent with the previous findings (31,45,56). The precise etiology of dyspnea falls beyond the scope of this discussion and is well described elsewhere (31). However, dyspnea may in part be diminished because of desensitization to loading and the greater strength of the inspiratory muscles such that ventilation requires a lower proportion of maximum inspiratory strength (31). The fact that both RPE and RPB diminished after RMT lends further credence to the postulate that the trained respiratory muscles contributed to lesser sensations of fatigue in the inspiratory muscles (31,45,46,56) and in the peripheral muscles. The lesser fatigue of the respiratory muscles may in turn result in the metaboreflex occurring at a higher exercise intensity (31,60) and resultant decrease in RPE. The reduction in RPE and RPB, secondary to improvements in respiratory function, may be important mechanisms through which RMT can enhance sport performance (31,36,45).

Inspiratory muscle training/RMT improved MIP among all types of athletes with the exception of divers and swimmers. The lack of greater improvement after RMT in swimmers might be attributed to the postulate that the demands of swimming train the inspiratory muscles by the chest wall loading imposed by water pressure (21,31). Therefore, highly trained swimmers may be near plateau in regards to their respiratory muscle function and thus unable to make further gains in MIP after addition of RMT. Closer examination of whether baselines MIPs exceed normative values (13) would shed further light on this postulate. We were not able to examine this more closely because none of the studies reported MIP as a percentage of predicted, so we could not determine if swimmers had MIP values that were much greater than the average normative values. Alternatively, the RMT protocols used for the swimmers may not have imposed sufficient overloads to induce further increases in MIP beyond improvements resulting from swim training.

Noteworthy, the type of training seemed to influence within and across subgroup comparisons of threshold, normocapnic hyperpnea (maintaining CO_2 homeostasis during hyperpnea or increased ventilation), and resistive-type training, consistent with the specificity of training. Threshold and targeted resistive training resulted in the greatest improvements in MIP compared with usual training. Threshold training requires participants to achieve a threshold pressure to open the valve to provide an inflow of air, regardless of the pattern of breathing (10,41). Thus, a major element of strength is needed to achieve and maintain the target threshold pressure, which ranged between 50 and 80% of MIP in the included studies. Targeted resistive training also results in high levels of MIP being maintained if subjects are able to maintain the targeted loads (41). In contrast, normocapnic hyperpnea demands increased flow rates and higher velocities of respiratory muscle contraction. The increased airways resistance at these higher flows in healthy individuals, however, would be minimal (24). The resistive-type breather with no target used in 1 study (52) has the potential of a large resistance load but only if adequate inspiratory flows are maintained. The flow dependence of resistive loads is well known (26,42), and it has long been reported that the inspiratory force required to train on this device will fall dramatically if inspiratory flow rates fall. The lack of consistent training using this device has been clearly demonstrated in people with chronic obstructive pulmonary disease (8). For this reason, the inclusion of a target flow device is required during resistive training, otherwise participants may breathe more slowly during the RMT rendering the overload to be negligible.

The type of RMT influenced outcomes of respiratory muscle performance that demanded elements of high contraction velocities, namely the MVV, which can be described as a 15-second sprint of respiratory muscle contraction. In peripheral muscles, high-velocity training is usually velocity dependent such that greater improvements in outcomes occur when the velocity of training matches the test velocity of contraction (30). Consistent with findings in limb muscles, subgroup comparisons demonstrated that only normocapnic hyperpnea training showed greater improvement in the MVV in contrast to threshold and targeted resistive RMT. Specificity of training was again reflected in the meta-analysis of respiratory endurance time (Figure 7). All participants who performed normocapnic hyperpnea training had an improved respiratory endurance time with the exception of the threshold training group of 1 study (61) that did not demonstrate a significant effect size in favor of RMT.

The different sports studied in this systematic review demonstrated an improvement in at least 1 outcome of sports performance, with the exception of cyclists that showed modest trends in favor of IMT/RMT and special forces training that showed no difference (52). Clear patterns of the sport that shows the most gains or the most efficacious training protocol of IMT/RMT are more difficult to discern. However, some patterns emerged that merit discussion.

Possible explanations for the benefit of RMT on rowing may be because of its related physiological and mechanical demands. During rowing, the accessory and primary inspiratory muscles are not only recruited for ventilation but also contribute significantly to stabilization of the thorax for more efficient transmission of force during the pulling movement of the oars. Thus, the dual demands placed on the respiratory muscles may lead to breathing becoming entrained to the pattern of movement to maintain performance (53,56).

Swimmers (21,36) and divers (61) showed the least consistent trends in meta-analyses of sports performance with only ET_{lim} in 1 study (61) showing significant improvements after RMT. As discussed above, the meta-analysis showed no overall improvement in measures of respiratory muscle strength and endurance in swimmers. This might be because of the fact that water pressure on their thorax during regular swim training already induces RMT. Another consideration is that sample sizes were small, limited to 10 or less per group in each of the 3 studies that examined swimmers (21,57,61). Future studies with larger sample size and subgroup analysis of responders and nonresponders might reveal the characteristics of athletic swimmers who might benefit from this type of training. Lastly, more aggressive progression of training intensity may yield a more positive outcome.

Cyclists, examined by 7 reports (7,16,18,33,35,46,51) showed consistent trends favoring IMT/RMT across outcomes of sports performance including time trials, ET_{lim}, and $\dot{V}O_2max$. However, no significant subgroup analyses favored IMT/RMT. Five of the 8 studies used normocapnic hyperpnea (7,16,35,46,51), which requires high-velocity repetitive contractions of the respiratory muscles sustained over 30 minutes. Demands imposed on the respiratory muscles during this type of RMT seem to closely match those required during competitive cycling. This might have contributed to the positive trend in favor of RMT in the trials that investigated cyclist athletes. Studies imposing more aggressive progression and those selecting responders to IMT might reveal a greater benefit from IMT/RMT.

Noteworthy, 13 studies (1,18,21,34,36,45,46,51,52,54–57,61) had subjects perform 1 or 2 sets of 30–40 vital capacity inspirations against inspiratory loads for the daily training sessions. This IMT protocol does not seem to match the ventilatory demands of any of the sports performed by athletes in these studies. Several articles stated that the selection of this IMT protocol was rationalized by the fact that it had induced training of the respiratory muscles in the previous studies, which was supported by our meta-analyses of MIP as well. Despite the improvement in MIP, it is highly likely that the neuromuscular attributes taxed during 30–40 vital capacity inspirations against inspiratory loads did not closely match the ventilatory demands of sports performance. Utilization of hyperpnea or loaded hyperpnea sustained over several minutes may prove to be a more effective training modality for RMT applied to athletes in several of the sports examined. As discussed in the previous paragraphs, 5 of the other studies used normocapnic hyperpnea in cyclists. These studies showed a trend toward improved sports performance i.e. time trials and endurance time, although not significant changes. The high-velocity training required by normocapnic hyperpnea seems to more closely parallel the demands during cycling because both require high levels of high-velocity repetitive contractions.

Study design may also have played a role in lack of positive findings within previously mentioned reports or particular sports (6,11,16,46,50). Included studies in this systematic review had very small sample sizes, which would have made it difficult to detect small improvements in performance and other measures. For example, for training interventions that show moderate and large effect sizes (f = 0.25 and 0.40, respectively), sample size calculations indicate that a minimum n of 64 and 26 subjects per group, respectively, are required in an RCT design for a power of 0.80 and an alpha of 0.05 (4,39). Thus, only large effect sizes (f = 0.8) that require consistent improvement among study participants performing RMT would show a significant benefit from IMT/RMT when small sample sizes of about 10 per group are compared using an RCT design.

Another consideration that may have contributed to lack of significance for a particular sport is that athletes within the RMT subgroup may have included responders and nonresponders to the treatment in question. The underlying premise of a quantitative RCT design is that statistical significance is based on substantial benefit of the entire group of participants. Clinical or sport performance, however, is optimized on an individual basis. Although most participants were highly trained in a particular discipline, there remains considerable individual differences between athletes, each being performance limited by variable physiological or psychological factors. Consequently, within a particular athletic discipline, there might be a subgroup of individuals that respond favorably to RMT and another subgroup whereby RMT improves respiratory muscle function but does not affect overall athletic performance. The mix of responders and nonresponders within a small sample could easily influence the effect size of the study. This highlights the need to properly identify the limiting factors among athletes when deciding on a particular training regime and, in the case of RMT, identify those that may respond positively. Until these factors are identified, a trial of RMT might be warranted with special attention to use a protocol similar to the ventilatory demands of the sport.

Respiratory muscle training resulted in an increased FEV_1, which is a reflection of lesser airflow limitation;

however, sensitivity analysis by removal of an apparent outlier (57) resulted in no significant difference. The most obvious explanations for the several fold higher standardized mean difference in this study (57) compared with others could be inspiration to a higher total lung capacity and improved test performance. Given that FEV_1 was not accompanied by other lung volume measures such as total lung capacity, this improvement in favor of IMT/RMT is difficult to explain.

This systematic review was limited by the analysis of outcomes that were common among the included studies. Thus, we were not able to perform comparative meta-analyses that were specific to particular sports when they were not reported in 2 or more studies. A second challenge was differentiating between elite and recreational athletes because of the diverse manner of reporting such details. Our meta-analyses were limited to those studies in English. A notable limitation of the included studies is the consistently small sample sizes. Taken together, the results of this meta-analysis related to sports performance need to be applied with a degree of caution. However, the ability of threshold training to improve strength of the inspiratory muscles and the impact of normocapnic hyperpnea on hyperventilation outcomes are clearly demonstrated.

Practical Applications

Respiratory muscle training can improve sport performance for some athletes and clearly increases respiratory muscle strength and endurance. According to the specificity of training, benefits might be greatest when the muscle contraction parameters such as range of motion and speed of contraction match the demands of the sports. Thus, closer correspondence of the ventilatory demands during RMT to those required during sport performance might ensure that the most efficacious intensity, flow rates (velocity of inspiratory muscle contraction), and volume changes (range of motion of respiratory muscle contraction) are imposed during training. Secondly, an aggressive progression of RMT intensity to ensure a training overload is essential for optimal benefit. Given that the characteristics of athletes that benefit from RMT are not known, a trial of RMT for select athletes that require high ventilatory demands during those sports is warranted. Measures of inspiratory muscle strength and endurance will reflect the effectiveness of RMT. Using bigger sample sizes, future research needs to investigate the effect of progressive RMT methods, matched for individual athlete training level on sports performance while ensuring a sufficient training overload is imposed. This systematic review provides several examples of tests that can be used to determine the influence of RMT on optimizing sports performance.

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Appendix 1. Medline search strategy.

1. exp Breathing Exercises/
2. exp Respiration/ or exp Respiratory Muscles/
3. exp Lung/
4. exp Intercostal Muscles/ or exp Pharynx/ or exp Respiratory Mechanics/ or Neck Muscles/ or exp "Work of Breathing"/
5. exp Tidal Volume/ or exp Pulmonary Ventilation/ or exp Hyperventilation/
6. exp Inspiratory Capacity/ or exp Lung Volume Measurements/ or exp Diaphragm/
7. exp Total Lung Capacity/
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. (breath* adj exercis*).ti,ab.
10. (threshold adj (device or load*)).ti,ab.
11. ((inspiratory or expiratory or respiratory or ventilatory) adj resist*).ti,ab.
12. (isocapn* adj (hyperpn* or hyperventila*)).ti,ab.
13. (normocapn* or normocapn* train*).ti,ab.
14. (PFlex or Powerlung).ti,ab.
15. pulmonary ventilat*.ti,ab.
16. inspiratory capacity.ti,ab.
17. total lung capacity.ti,ab.
18. (PImax or MIP or Maximal Inspiratory Pressure).ti,ab.
19. Maximal expiratory Pressure.ti,ab.
20. respira* muscle*.ti,ab.
21. "work of breathing".ti,ab.
22. 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21
23. 8 or 22
24. exp "Physical Education and Training"/ or exp Sports/ or exp Athletes/
25. (professional or elite or colleg* or universit* or varsity or competitive or recreation* or national or olympi* or train* or "high level").ti,ab.
26. exp Athletic Performance/ or exp Running/
27. (((baseball or basketball or bicycl* or box* or football or golf or Gymnastic* or Hockey or Mountaineer* or mountain climb* or martial arts or Racquet Sport* or run* or skat* or Snow Sport* or ski* or soccer or swim* or Track) adj Field) or Volleyball or walk* or weight lift* or wrest*).ti,ab.
28. 24 or 25 or 26 or 27
29. 23 and 28
30. Resistance Training/ or "Physical Education and Training"/
31. train*.ti,ab.
32. 30 or 31
33. 29 and 32
34. limit 33 to (english language and humans and "all adult (19 plus years)" and english)

*MIP = maximal inspiratory pressure.

APPENDIX 2. Terms, abbreviations, and definitions.

Full term (abbreviation)	Definition
Weighted mean difference (WMD)	Is the difference between start and finish values in an experiment. In a meta-analysis, it is usually calculated as the sum of the differences in the individual studies, weighted by the individual variances for each study
Endurance time limit (ET_{lim})	Is defined as the ability to persist in an activity or task. The time duration one can persist or sustain on the task before fatigue makes him stop from continuing further is referred to as the endurance time limit
Yo-Yo endurance test	Consists of repeated 40m laps run back and forth on a 20 m length of track. Audio beeps from a tape recorder are used to assist the participant to run at increasingly greater speeds and he/she must complete each 40 m by the designated time for that lap. The endpoint of the test is determined when the participant fails to reach the finishing line in time. The total distance covered is recorded as the test measure
Maximal minute ventilation (VE_{max})	Is the greatest volume of gas that can be breathed per minute by voluntary effort
Rating of perceived breathlessness (RPB)	Is a measure of the amount of self-perceived shortness of breath or severity of dyspnea
Rating of perceived exertion (RPE)	Is a subjective measure of self-reported perception of exertion during exercise or physical activity
Maximum inspiratory pressure (MIP)	Is a measure of inspiratory muscle strength, and is defined as the highest level of negative pressure a person can produce against an occluded airway during inspiration. The maximum value of MIP is near the residual volume
Maximum expiratory pressure (MEP)	Is a measure of expiratory muscle strength, and is defined as the highest level of positive pressure a person can produce during an expiration. Its maximum value is close to total lung capacity
Maximum voluntary ventilation (MVV)	Is defined as the maximum amount of air that is ventilated during a short period of time i.e. usually 12–15 seconds
Respiratory muscle endurance test (RET)	Is an endurance measure of the inspiratory and expiratory muscles. The subject performs sustained ventilation at a percentage of the person's highest MVV. The time that the subject is able to sustain the target ventilation will be recorded. The test will be repeated on a different day at a higher percentage of MVV if the subject is able to sustain the ventilation for longer than 15 minutes
Forced expiratory volume in one second (FEV_1)	Is the volume of air that can forcibly be expired during the first one second after full inspiration
Forced vital capacity (FVC)	Is the total volume of air that can forcibly be blown out after full inspiration