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Recent advancements in our understanding of the ergogenic effect of respiratory muscle training in healthy humans: a systematic review

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Abstract

Respiratory muscle training (RMT) has been shown to be an effective ergogenic aid for sport performance. RMT has been documented to improve performance in a wide range of exercise modalities including running, cycling, swimming, and rowing. The physiological effects of RMT that may explain the improvements in performance have been proposed to include diaphragm hypertrophy, muscle fiber type switching, improved neural control of the respiratory muscles, increased respiratory muscle economy, attenuation of the respiratory muscle metaboreflex, and decreases in perceived breathlessness and exertion. This review summarizes recent studies on the ergogenicity and mechanisms of RMT since 2013 when the topic was last systematically reviewed. Recent evidence confirms the ergogenic effects of RMT, and explores different loading protocols, such as concurrent exercise and respiratory muscle training (i.e., "functional" RMT). These studies suggest that adapting new training protocols may have an additive improvement effect, but evidence of the efficacy of such an approach is conflicting thus far. Other recent investigations have furthered our understanding of the mechanisms underpinning RMT-associated improvements in performance. Importantly, changes in ventilatory efficiency, oxygen delivery, cytokine release, motor recruitment patterns, and respiratory muscle fatigue resistance are highlighted as potential mechanistic factors linking RMT with performance improvements. It is suggested that future investigations focus on development of sport-specific RMT loading protocols, and that further work be undertaken to better understand the mechanistic basis of RMT-induced performance improvements.

Keywords

respiratory muscles; diaphragm fatigue; resistive breathing; performance; lung function

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R-J.S. declares no conflicts of interest.

INTRODUCTION

In recent years, the role of the respiratory muscles during exercise, and specifically their susceptibility to fatigue during and immediately after exercise, has garnered much attention (1, 12, 13, 53). Several seminal works over the last three decades have greatly advanced our knowledge in this area by documenting significant respiratory muscle fatigue during exercise (33), characterizing the respiratory muscle metaboreflex (25, 26), which may occur downstream of respiratory muscle fatigue, and identifying potential strategies to optimize respiratory muscle performance during exercise (9, 10). The hypothesis that training the respiratory muscles, and in particular the inspiratory muscles, can improve exercise capacity and performance has been thoroughly investigated over the past several decades (24, 32). While many studies have studies specific inspiratory muscle training (IMT), it is important to note that other studies utilizing both inspiratory and expiratory muscle training have similarly shown efficacy. Therefore, this review will consider all forms of respiratory muscle training (RMT), unless specifically referring to individual studies which utilized IMT as an RMT training modality. The majority of studies have found that training the respiratory muscles appears to be an effective ergogenic aid for exercise performance. Nevertheless, there has been some controversy regarding the efficacy of training the respiratory muscles to improve exercise tolerance (42, 55). This quagmire appears to be somewhat resolved by two systematic reviews and meta-analyses, both of which concluded that there is abundant evidence that RMT has an ergogenic effect on exercise performance (24, 32).

In addition to concluding that RMT improves endurance exercise performance and sport performance (24, 32), it is noted that matching the ventilatory demands of RMT to those required during athletic competition, combined with an aggressive progression of training intensity may produce greater improvements (24). The underlying mechanisms behind the improvements in exercise performance following a period of RMT are likely varied, and incompletely described. However, most training, regardless of modality, aims to increase the strength and endurance of the diaphragm and accessory muscles of inspiration (73). The mechanisms underpinning improvements in performance are still equivocal, although several putative mechanisms have been suggested.

Current evidence indicates that RMT may 1) decrease the inspiratory muscle motor drive while preserving pressure generation (31), 2) promote hypertrophy of the diaphragm and increase the proportion of type I fibers and the size of type II fibers in the external intercostal muscles (14, 16), 3) attenuate the respiratory muscle metaboreflex (83), which is a sympathetically-mediated vasoconstriction that may redirect blood flow away from the limb locomotor muscles (13, 25, 26, 68, 76), 4) decrease the rating of perceived breathlessness or rating of perceived exertion (41, 67), 5) improve respiratory muscle economy (79), 6) reduces the work of breathing (27) and 7) improves respiratory muscle endurance (65). These potential mechanisms are likely inter-related to each other. For example increasing the proportion of type I fibers may enhance respiratory muscle economy and help to delay respiratory muscle fatigue and the respiratory muscle metaboreflex. At present however, the complex interplay between these factors and how they impact exercise performance is not well understood.

Several recent reviews have discussed the use of RMT in a variety of clinical populations such as asthma, stroke patients, and chronic heart failure (45, 73, 74); however some time has passed since the efficacy of RMT on enhancing sport performance was last reviewed (24, 32). Thus, the aim of this review is to highlight recent investigations (since 2013) examining the ergogenic effect of RMT, and to discuss data from recent (since 2013) investigations that advances our understanding of the mechanistic basis by which RMT may improve exercise performance. This review provides an update on RMT-related investigations since the previous systematic reviews (24, 32).

METHODS

Experimental Approach to the Problem

Given that this area has recently been the subject of two systematic reviews (24, 32), this systematic review aims to provide a summary of evidence published since 2013. The following electronic databases were searched (through 4 May 2018): PubMed/MEDLINE, CINAHL, Embase, Web of Science, Google Scholar, Scopus, and SPORTDiscus; using the search terms: ‘inspiratory muscle training’, ‘IMT’, ‘respiratory muscle training’ and ‘RMT’, which were combined with the terms ‘exercise performance’, ‘performance’, ‘exercise’, ‘sport’, and ‘mechanism’. Search equations are given in Appendix 1, and search terms were modified accordingly to fit the requirements of individual databases. Results were evaluated by title and abstract to determine whether they were relevant to the present review. Inclusion criteria comprised: 1) studies which utilized a clearly defined and structured respiratory muscle training intervention aimed at enhancing the strength and/or endurance of the respiratory muscles, 2) a healthy population was studied, 3) both observational and randomized controlled studies were included, 4) outcome measures included either an exercise or performance measure, or physiological data which supported a mechanistic insight into the effects of RMT, and 5) published in 2013 or later. Studies were excluded if 1) subject populations were clinically diagnosed with any pathological conditions, 2) if RMT was coupled with supplementary ventilatory muscle strengthening exercises, 3) if they were published in a language other than English, and 4) if they were published prior to 2013, which was when the last *systematic* review of RMT was conducted (24). The reference lists of each full text article were checked to avoid omission of potentially relevant articles. Figure 1 summarizes the search strategy and study selection.

The subject of inspiratory and respiratory muscle warm-up has received significant attention recently (20); however this area is beyond the scope of this review and studies investigating inspiratory and respiratory muscle warm-up were excluded from this review. Likewise, although respiratory muscle training has been extensively studied in a variety of disease states, this area is beyond the scope of this review. Thus, studies examining the effects of respiratory muscle training on various disease populations were excluded.

DISCUSSION

Ergogenicity of RMT for Exercise Performance

The efficacy of RMT for improving exercise performance is well studied in a wide range of exercise modes (24, 32). Thus far RMT has been documented to improve time trial performance in cycling (30, 34, 63, 75), swimming (36), running (37), and rowing (61, 81). Additionally, endurance time (or time to exhaustion) has been shown to be improved with RMT in cycling (21, 30, 44, 51, 75), running (37, 47), swimming (85), and intermittent sprint sports (4). For a complete review of the efficacy of RMT on performance, readers are referred to published reviews (24, 32). More contemporary evidence largely confirms these findings, with studies demonstrating improvements in core function (7), exercise tolerance assessed by a multistage fitness test (23), aerobic fitness in healthy volunteers (11, 50), peak running velocity and running time to exhaustion (15), and maximal cycling and running capacity in triathletes (6) following a period of RMT, although one recent study failed to document an ergogenic effect of RMT in rowing performance (5).

While the rowers in the latter study were able to improve both static maximal inspiratory and expiratory mouth pressures, these improvements in respiratory muscle strength did not translate to improved exercise performance. This may have been due to inadequate training load compared to other methods of pressure-threshold training. While the duration of 9 weeks is quite long in comparison to most RMT studies, the number of repetitions subjects completed was comparatively lower (8–10 breaths, 1×/day, progressing to 3×/day compared to a typical pressure-threshold protocol of 60 breaths daily). Therefore, it is possible that the loading protocol used was sufficient to improve respiratory muscle strength, but not endurance, which may could partially account for the findings in this study.

Team Sports—Interestingly, although RMT induced a significant improvement in inspiratory muscle strength (maximal inspiratory mouth pressure, P_{Imax}) in male soccer players, this improvement was only associated with improvements in a nonspecific multistage fitness test, but not a soccer-specific fitness test (23). Similarly, shuttle run performance was not improved in a separate study of soccer players after five weeks of voluntary hyperpnea RMT, despite an improvement in P_{Imax} (54); and university tennis players who undertook five weeks of pressure threshold IMT did not improve their static balance test or agility test performances (84). In contrast, however, Archiza et al. (3) found that six weeks of pressure-threshold IMT improved running time-to-exhaustion and repeated sprint ability in soccer players. These findings suggest the ergogenic effect of RMT may be primarily in endurance or cardiopulmonary fitness, and may not necessarily translate to different types of exercise. Previous investigations on the impact of RMT on intermittent sprint exercise have been inconclusive (4, 63), further supporting the conclusion that RMT may not be as effective beyond endurance sports.

Exercise in Hypoxia—Several recent studies have sought to investigate the application of RMT as a training aid to enhance performance in specific environmental and occupational settings that present unique demands to the cardiorespiratory system during exercise. For example, hypoxia is known to compromise exercise capacity and impair performance (2, 62). In a hypoxic environment, a compensatory hyperventilation typically occurs in order to offset the reduction in inspired oxygen. This increase in minute ventilation also increases the work of breathing and oxygen cost of breathing, thereby placing additional stress on the respiratory muscles. Therefore, RMT has been investigated as a strategy to minimize the deleterious effects of hypoxia on exercise capacity. Lomax et al (40) found that four weeks of pressure-threshold IMT significantly increased inspiratory muscle strength and arterial oxygen saturation, reduced minute ventilation ($\dot{V}_E$) and carbon dioxide output ($\dot{V}CO_2$) during fixed-intensity sub-maximal cycle ergometry tests. Interestingly, these observations occurred in the absence of inspiratory muscle fatigue, suggesting that inspiratory muscle fatigue is not required in order for RMT to be of benefit. Separately, Helfer et al (28) found that voluntary isocapnic hyperpnea RMT produced an improvement in exercise time to exhaustion in hypoxia. This study is of particular interest because the RMT modality chosen mimicked the increased ventilatory demand which is typically present in hypoxia. Thus, this matches the previous recommendations to match the training program to the ventilatory demands of the athletic activity (24).

Exercise in Occupational Settings—Despite the finding that inspiratory muscle fatigue may not need to be present in order for RMT to be of benefit, many sport and occupational settings do induce significant inspiratory muscle fatigue, suggesting that these activities may benefit from RMT as well. One such occupational scenario is during load carriage exercise, when an external load such as a backpack or protective vest is worn over the thorax for the transportation of gear and supplies and/or for protection (70). Thoracic load carriage has been shown to induce global respiratory muscle fatigue (17, 18). Moreover, load carriage has been shown to lower the critical threshold at which diaphragm fatigue occurs (71), making subjects exercising with LC more susceptible to diaphragm fatigue and diaphragm-fatigue-related decrements in exercise capacity. Two recent studies have demonstrated that RMT improves running time trial performance with load carriage (19) as well as submaximal constant-load running to exhaustion capacity (71). The former study (19) found that pressure-threshold IMT attenuated the severity of global respiratory muscle fatigue (assessed by voluntary mouth pressures) immediately following the loaded time trial. In contrast however, the latter study (71) demonstrated no change in the severity of diaphragmatic fatigue (assessed by non-volitional transdiaphragmatic twitch pressure in response to bilateral phrenic nerve stimulation) at the point of volitional exhaustion following a six week flow-resistive IMT training period. It is possible that the difference between the criterion tasks (time trial vs run to exhaustion) may partially explain this discrepancy, given that the constant-load exercise task required subjects to reach volitional exhaustion prior to the cessation of exercise. Although the subjects in this study ran significantly longer post-IMT, they exhibited the same severity of diaphragm fatigue pre- and post-training following the exercise task suggesting that the severity of diaphragm fatigue may be a factor in reaching volitional exhaustion during exercise with load carriage.

Concurrent RMT and Exercise—Given that the efficacy of RMT as an ergogenic aid is becoming widely accepted, more recent studies have focused on modifications to RMT training protocols, with several studies focusing on whether there is an additive effect of performing RMT during exercise (22, 29, 56), rather than at rest as it has traditionally been done (24, 32, 70, 73). Two recent studies found that performing RMT while simultaneously undertaking cycling exercise resulted in greater EMG activity in the diaphragm (29), improved both the ventilatory threshold and respiratory compensation threshold, and power output at ventilatory threshold and the respiratory compensation threshold (56). It is noted however, that the latter study utilized an “elevation” training mask which purportedly simulates altitude training, but in fact, does not alter the partial pressure of oxygen to induce a hypoxic state during exercise. Rather, this device acts as a resistive breathing device, mimicking other commercially available RMT devices, but not simulating altitude. A separate investigation using the same device demonstrated only mild hypoxemia, which was attributed to inadequate hyperventilation, rather than a decrease in inspired oxygen tension (22). Taken together, these data suggest that the combination of RMT and cycling performed simultaneously may provide an additive training effect. Furthermore, another study demonstrated that performing “functional” RMT concurrent to core muscle exercises improved both running performance and running economy (77).

Interestingly, a recent investigation found no difference between exercise training alone and exercise training completed with an additional inspiratory load (15% of P_{Imax}) (43) after three weeks of training. However after six weeks of training, the additional inspiratory load produced an ~8% improvement in a five mile cycling time trial. The inspiratory load in this study was much smaller in magnitude compared to others, which utilized an inspiratory load of roughly 40–50% of P_{Imax}. Therefore, the stimulus in this study may have required a longer training time to induce appreciable adaptations in the respiratory muscles.

Swimming May Mimic RMT—A related area of inquiry has been whether certain exercise modes can mimic the effects of RMT. In particular, swimming exercise has been suggested to strengthen the respiratory muscle in a similar manner to RMT because when swimmers are immersed in water, the hydrostatic pressure surrounding the thorax increases the required respiratory muscle force to generate a given amount of pressure. Mickleborough et al. (46) showed that pulmonary and respiratory muscle function was not improved when RMT was combined with swim training, compared to swim training alone. In contrast however, a subsequent investigation using a near-identical study design in sub-elite swimmers found that respiratory muscle function did improve when RMT was combined with swim training, compared to swim training alone (72). The disparity between these studies is likely a result of the different study populations, who completed significantly different volume of swim training. The elite swimmers completed between 10 and 12 swim sessions per week, averaging 40–60 km of swimming per week compared to the sub-elite swimmers who completed 6–8 swim training sessions per week, averaging 18–25 km of swimming per week. Therefore, the latter group may not have performed sufficient swim training to induce respiratory muscle adaptations similar to those produced by RMT. These findings were recently confirmed by Lomax et al (39), who demonstrated that youth swimmers who completed ≤ 31 $\mathrm{km \cdot wk^{-1}}$ of swim training benefitted from the addition of RMT (performance in 100m and 200m swims improved by +3% and +7%, respectively); however those who completed >41 $\mathrm{km \cdot wk^{-1}}$ of swim training did not receive any performance benefit from RMT. Other findings in youth swimmers demonstrate a potential ergogenic effect of RMT (35, 38), however these studies did not report training volume in km·wk^{-1}, therefore it is unclear whether their training volume was sufficient to mimic the effects of RMT. Respiratory muscle adaptations to swim training are therefore likely to be dose dependent, and a significant volume of swim training is required to induce training adaptations in the respiratory muscles. Swimmers who perform a high volume of swim training are not likely to receive additional benefit from supplementing their swim training with RMT, or the training load for the RMT training regimen would need to be raised in order to induce respiratory muscle adaptations in these swimmers; however those who perform more modest volumes are likely to benefit from the combination of RMT and swim training.

Another recent study involving swimming exercise demonstrated that one month of respiratory muscle training, utilizing both a threshold inspiratory muscle trainer and a positive expiratory pressure device, improved performance in an apnea-max swim test in youth fin-swimmers (80). These findings are particularly interesting given that the apnea-max swim test that was used as a criterion measure, measured the maximal length of underwater swimming that swimmers could complete during a single inspiration. Therefore, the respiratory demands, rather than being for sustained hyperpnea as with most endurance tasks, actually consisted of a single sustained breath hold, presumably at or near total lung capacity, while swimming underwater. These swimmers demonstrated an increase in respiratory muscle strength as measured by an increase in P_{Imax}, which may have allowed the respiratory muscles to function during the breath hold at a lower intensity relative to their maximal capacity, since that maximal capacity was increased following RMT. Separately, given that RMT has been shown to improve respiratory muscle economy (79), it is possible that the oxygen demand of the respiratory muscles during the sustained breath hold was lower, which may have contributed to the observed improvement in performance (69).

In summary, recent studies for the most part have confirmed the efficacy of RMT for enhancing performance in a variety of endurance-based sports (Table 1). Moreover, the application of RMT as an ergogenic aid in novel areas such as hypoxia and load carriage increases the versatility and value of this training tool. Finally, innovative new training protocols, such as “functional” RMT and performing RMT concurrently with endurance exercise may have an additive effect, further enhancing performance outcomes after a regimen of RMT.

New Insights on IMT/RMT Mechanisms

Presently, although numerous putative mechanisms underpinning the improvements induced by RMT have been suggested, the relationship between these mechanisms is not well described. Recent investigations on the physiological adaptation induced by RMT have both confirmed some previous mechanistic suggestions, and introduced new avenues by which RMT exerts its positive effects. First, the findings of Turner et al (79) reporting improved respiratory muscle economy following a period of RMT have been replicated during sea-level submaximal cycle ergometry (78) and separately during simulated diving conditions in a hyperbaric chamber in both dry and submersed conditions (27). Turner et al (78) found that whole-body oxygen consumption ($\dot{V}O_2$) was reduced during submaximal cycling following a six week pressure-threshold IMT training period, with a concomitant reduction in both limb locomotor and respiratory muscle oxygen extraction. Similarly, with the use of esophageal balloon-tipped catheters, Held and Pendergast (27) were able to calculate respiratory muscle efficiency, which was improved following four weeks of resistance respiratory muscle training. This training protocol is unique in that it required subjects to complete vital capacity maneuvers against a spring-loaded resistance valve at 60% of P_{Imax} and P_{Emax} every 30s for 30 min, five days per week, with resistance increased by 10 cmH_2O weekly during the training period. Taken together, these studies support the hypothesis that RMT may improve the efficiency of the respiratory muscles, and thereby may partially account for improvements in performance.

RMT Improves Respiratory Muscle Efficiency and Dyspnea—Similar findings of improved respiratory muscle efficiency following in RMT have been observed in hypoxia as well (40, 64). Salazar-Martinez (64) found that six weeks of pressure-threshold IMT improved ventilatory efficiency in both normobaric normoxia and normobaric hypoxia, measured by the slope of the ratio of $\dot{V}_E$ and $\dot{V}CO_2$ ($\dot{V}_E/\dot{V}CO_2$ slope) from the beginning of exercise until the second ventilatory threshold. The authors also found that oxygen uptake efficiency slope (OUES) was not modified by RMT in their healthy sample. Importantly, although time trial performance was improved in both normoxia and hypoxia following RMT, TT performance was only correlated with OUES, and not $\dot{V}_E/\dot{V}CO_2$ slope, suggesting that, in the context of the influence of IMT on performance in hypoxia, OUES may be a better index of ventilatory efficiency than $\dot{V}_E/\dot{V}CO_2$ slope. Lomax et al. (40) confirmed that ventilatory efficiency, estimated by the ratio of peripheral capillary oxygen saturation (S_pO_2), measured by pulse oximetry, to $\dot{V}_E$ ($S_pO_2/\dot{V}_E$) was improved following RMT in hypoxia, but observed no differences in $S_pO_2/\dot{V}_E$ in normoxia following RMT. The authors speculated that an increase in lung diffusion capacity could be a potential mechanism, similar to the findings of Downey et al (14), although this hypothesis needs to be further investigated. Taken together however, in combination with those of Held and Pendergast (27), these studies suggest that RMT improves ventilatory efficiency, which may partially account for improvements in performance. Further, it is possible that improved ventilatory efficiency may contribute to enhanced resistance to respiratory muscle fatigue following RMT, as documented by recently by Segizbaeva et al. (66).

RMT and Respiratory Muscle Recruitment—A recent study by Raux et al. (59) provides further insight into the mechanisms underpinning this improvement in respiratory muscle efficiency. The authors found that sustained inspiratory loading may support motor reorganization such that phrenic motoneuron recruitment was reduced. This “diaphragm sparing” may be part of an adaptive strategy to optimize respiratory muscle recruitment during sustained inspiratory loading, thus improving the efficiency of the respiratory muscles during inspiration. These findings are compatible with the previously discussed findings of improved respiratory muscle economy during voluntary hyperpnea following RMT (79). Further, an earlier study by the same group demonstrated by functional magnetic resonance imaging (fMRI) that sustained inspiratory muscle loading reduced cortical activation in premotor, motor, and sensory cortical areas (60). These findings suggest significant reorganization of the central respiratory drive following inspiratory loading, which may partially explain the alterations observed by others in respiratory muscle efficiency.

In contrast, however, Ramsook et al (58) demonstrated that following five weeks of pressure-threshold IMT, respiratory muscle activity, measured by electromyography (EMG), was unchanged compared with either pre-training or sham-control. The authors did find however, that exertional dyspnea was reduced in the RMT group, but not the control, suggesting that RMT provides some degree of dyspnea relief during exercise. These findings are compatible with others, which demonstrated reduced rating of perceived exertion and dyspnea during fixed-workload load carriage (10 kg) exercise following six weeks of flow-resistive IMT (71); and reduced breathing discomfort and leg discomfort during time trial exercise (2.4 km) with load carriage (25 kg) following six weeks of pressure-threshold IMT (19). Although inspiratory EMG was not altered by RMT in the study by Ramsook et al. (58), their finding of reduced dyspnea corroborate the earlier findings of Raux et al. (60) which demonstrated reduced sensory cortical activation during sustained inspiratory loading. Importantly, different modalities of RMT have been shown to differ in their activation of inspiratory respiratory muscles (82). Voluntary isocapnic hyperpnea and inspiratory pressure threshold loading both lead to higher EMG activity of the inspiratory muscles, and in particular the accessory inspiratory muscles, compared to inspiratory flow-resistive loading. Diaphragm activation was shown to be highest in inspiratory pressure-threshold loading. It is noted however, that the most important factors influencing respiratory muscle activation were: 1) maintaining specific target mouth pressure (or volume for voluntary hyperpnea) during training; and 2) the instructions on how to perform RMT (82). Together, these findings further support the recommendation to match RMT training as closely as possible with the specific ventilatory demands of the athletic activity participants are undertaking (24).

Reductions in dyspnea may be of particular interest given that perturbations to effort perception may have downstream effects in central motor command (52). Motor commands from the motor cortex may be concurrently transmitted to the sensory cortex, leading to a sensation of muscle activation (8), contributing to a feedforward/feedback process to continually adjust muscle contraction and motor performance. Therefore, alterations in the perception of dyspnea may impact respiratory muscle performance. If RMT indeed can reduce the perception of dyspnea, the respiratory muscle performance may be optimized partially by reduction of corollary discharge between the motor and sensory cortices.

An important consideration, which has only recently come to light, is whether how individuals are instructed to perform RMT may influence muscle recruitment patterns. When subjects are not given any specific instructions on how to recruit inspiratory muscles during IMT, the diaphragm, sternocleidomastoid, and scalenes are all activated to a similar degree during IMT (57). However, when subjects are instructed to specifically engage the diaphragm, diaphragmatic EMG activity and pressure production are significantly increased, suggesting that the manner in which subjects perform the inspiratory maneuvers during IMT has a meaningful effect on motor recruitment patterns (57).

RMT Attenuates Cytokine Response to Exercise—Finally, in a pair of elegant studies examining the effects of RMT on the systemic cytokine response to exercise, Mills et al. (48, 49) demonstrated the plasma interleukin-6 (IL-6) levels were decreased during maximal sustainable voluntary ventilation following 6 weeks of pressure-threshold IMT. During volitional hyperpnea, plasma IL-6 concentrations become elevated, even in the absence of diaphragm fatigue (48). This is partially ameliorated during exercise following a period of RMT, however interestingly this protective effects is only observed during exercise and not voluntary hyperpnea alone (48). However, at higher ventilation levels, such as the maximal sustainable voluntary ventilation, RMT does appear to have a protective effect by reducing plasma IL-6 (49), suggesting that the plasma IL-6 response is dependent upon the level of respiratory muscle work and $\dot{V}_E$. These findings indicate that RMT may exert an effect on the pro- or anti-inflammatory response during exercise and volitional hyperpnea, which may partially explain the positive effects of RMT on performance.

In summary, these recent studies have greatly advanced our understanding of the mechanisms underpinning the physiological adaptations induced by RMT (Figure 2). Firstly, several independent studies have confirmed that RMT likely improves ventilatory efficiency, which supports the previous finding that RMT improved respiratory muscle economy during voluntary hyperpnea. Second, contemporary evidence suggests that motor recruitment patterns are altered following RMT, which may contribute to the improved ventilatory efficiency. Subjects may adopt a “diaphragm-sparing” recruitment pattern following a period of RMT which, in part, may alleviate the perception of dyspnea. This reduction in dyspnea in turn, may have downstream effects on the descending commands from the motor cortex and could help facilitate improvements in performance. Finally, RMT may modulate the release of cytokines such as IL-6 from the respiratory muscles during exercise and voluntary hyperpnea, thus altering the systemic pro- or anti-inflammatory environment. Taken together, these mechanistic insights further explain other findings that support the ergogenic effect of RMT on exercise performance. Future investigations should aim to link these mechanisms to improvements in performance.

Conclusion and Future Directions

Recent investigations have confirmed the ergogenic effect of RMT and highlighted the importance of developing a standardized protocol that adequately mimics the ventilatory demands of the specific competition exercise modality. Past evidence demonstrating an improvement in endurance exercise following RMT is affirmed by recent investigations, although it is noted that the effect of RMT on performance in other exercise modes such as short-duration or intermittent exercise is presently unclear. In particular, new evidence provides insight on the ergogenic effect of RMT in specific environmental and occupational situations, such as hypoxia and load carriage, which provide unique challenges to the cardiorespiratory system during exercise. Additional insights into the physiological mechanisms underpinning the ergogenic effects of RMT have come to light and suggest that RMT may exert additional benefits that were previously uncharacterized.

Future studies which standardize a RMT protocol should greatly aid in the interpretation of data linking RMT with improvements in exercise performance. Furthermore, it is recommended that a standardized protocol be developed for evaluating the ventilatory demands of sport- and activity-specific modalities, which can then be integrated into an RMT training prescription in order to allow RMT to be matched to the demands of specific activities. Further studies characterizing the numerous physiological effects of RMT and their relationship to improvements in exercise performance will also aid in enhancing our understanding of how RMT aids in optimizing exercise performance.

PRACTICAL APPLICATIONS

The evidence presented here solidifies the utility of RMT for enhancing sport and exercise performance, particularly in endurance exercise. The utility of RMT for intermittent and short-duration exercise remains unclear and warrants further investigation. Separately, the advancement in our understanding of the mechanisms underpinning the ergogenic effects of RMT help the coach and practitioner determine whether and how to incorporate RMT into a client’s training regimen. Specifically, it is recommended that the 1) ventilatory demands of the athletic competition be considered, 2) the unique exercise modality and other physical training program is accounted for when incorporating RMT into a comprehensive training plan, and 3) that any RMT protocol that is undertaken be uniquely designed to challenge those demands through the RMT program. The previous recommendation of HajGhanbari et al (24) that an aggressive progression of training intensity will likely produce the greatest improvements, and that care be taken to regularly assess respiratory muscle strength throughout the training period, is reiterated here.

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Appendix 1. Summary of search equations

“respiratory muscle training performance” *
“respiratory muscle training exercise performance” *
“respiratory muscle training sport performance” *
“respiratory muscle training mechanism” *
“respiratory muscle training sport” *
“respiratory muscle training exercise” *
“respiratory muscle training performance” *
*above searches repeated with “RMT” in place of “respiratory muscle training”

“inspiratory muscle training performance” ^
“inspiratory muscle training exercise performance” ^
“inspiratory muscle training sport performance” ^
“inspiratory muscle training mechanism” ^
“inspiratory muscle training sport” ^
“inspiratory muscle training exercise” ^
“inspiratory muscle training performance” ^
^above searches repeated with “IMT” in place of “inspiratory muscle training”

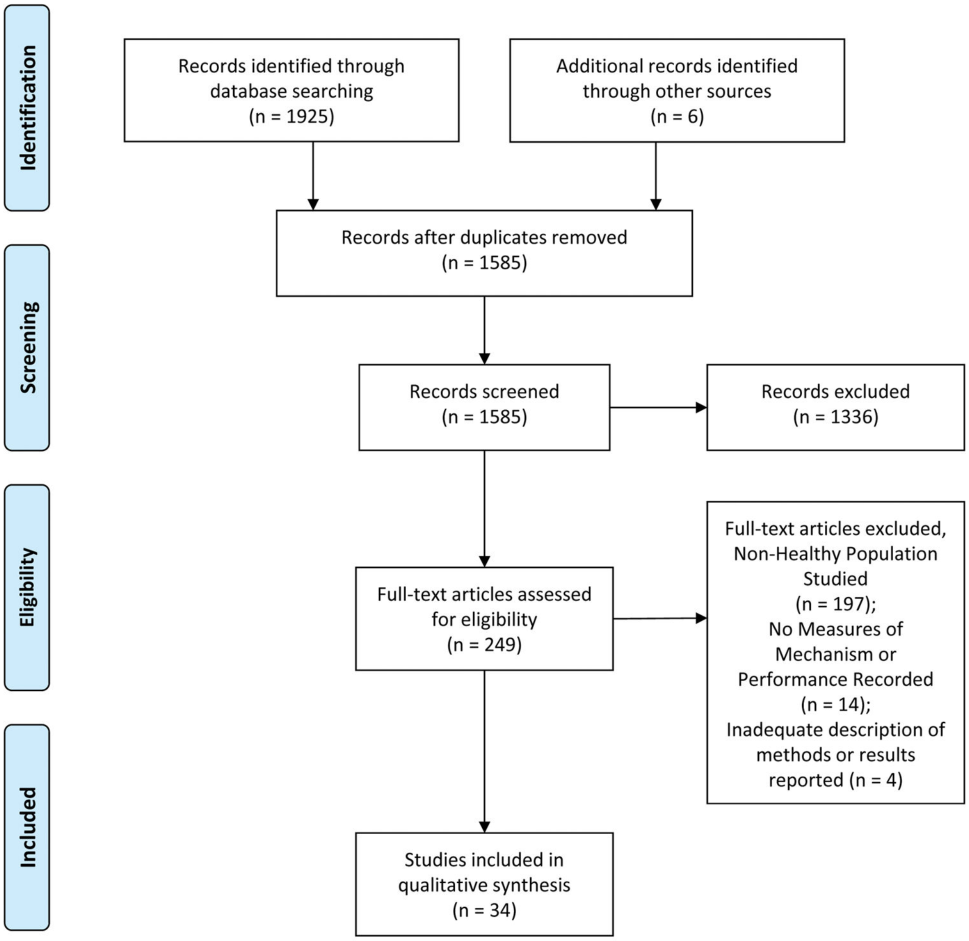

Figure 1.

Flow chart of search strategy and retrieval of articles.

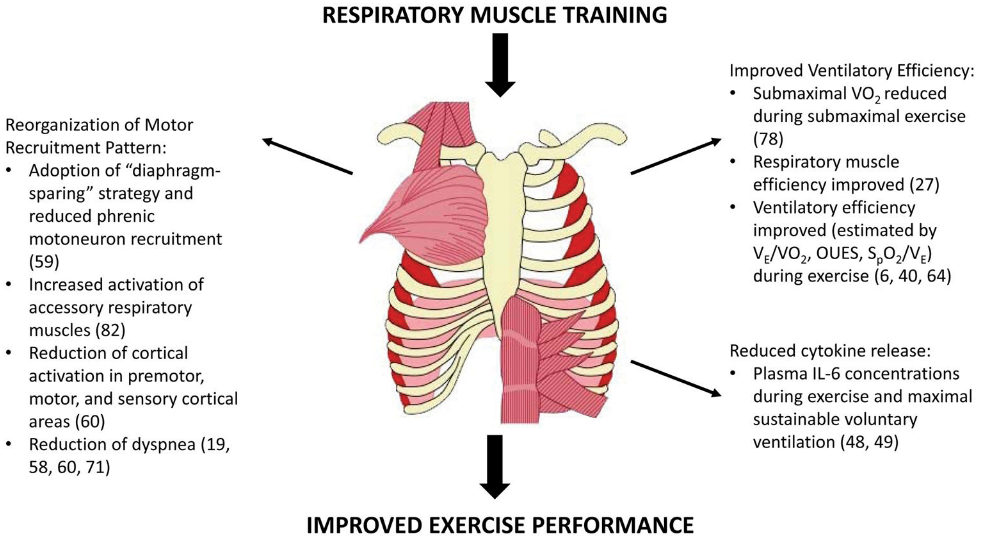

Figure 2.

Illustration of new insights from recent investigations into physiological adaptations induced by IMT that may enhance exercise performance.

Table 1

Summary of Select Recent Studies Examining RMT and Performance

Study	Reference	Population	Intervention	RMT Outcomes
Archiza et al. 2018	(1)	Experienced female football (soccer) players (n=18)	Pressure threshold: 50% P_{Imax} 30 breaths, 2×/day, 5 day/week, 6 week	Improved running time-to-exhaustion (+42.1%) and repeated sprint ability (RSA; +3.9% best time, +6.1% mean RSA times, −30.4% percentage of performance decrement)
Bell et al. 2013	(5)	Experienced rowers (n=27), 12M/15F	Pressure threshold: Resistance set so inspiration/expiration took 3–4s and 8–10 repetitions could be completed; 8–10 breaths, 1×/day progressive to 3× 8–10 breaths, 2×/day, 7 day/week, 9 week	No significant improvements in 2000m rowing performance or cardiorespiratory fitness
Bernardi et al 2014	(6)	Amateur male triathletes (n=20)	Respiratory muscle endurance training: 60% VC, ~50% MVV, 20 min/day 7 day/week, 5 week	Improved peak power output (+10.3%) and speed (+6.0%) in cycling and running maximal incremental exercise tests, respectively
Brilla and Kaufman 2014	(7)	Healthy, recreationally active individuals (n=32), 8M/24F	Pressure threshold: 80% P_{Imax} 5×12 breaths, 1×/day, 5 day/week, 6 week	Improved core muscle function (+44.9% in Stabilizer test of transversus abdominis)
Cybulska and Drobnik 2015	(11)	Healthy women aged 20–25 yr (n=33)	Pressure threshold: 60 breaths daily ¼ of adjustment on unit (%P_{Imax} not reported) OR elastic bands	Improved peak power output (+14.1% RMT, +14.4% elastic bands) and $\dot{V}O_{2max}$ (+11.9% RMT, +10.8% elastic bands) with both interventions
Edwards 2013	(15)	Healthy adult males (n=36)	Pressure threshold: 55% P_{Imax}, 30 breaths, 1×/day, 7 day/week, 4 week	Higher running velocity during incremental exercise testing (~ +2.0%) and longer time to volitional exhaustion in response to incremental exercise testing (+5.3%)
Faghy and Brown 2016	(19)	Healthy physically active males (n=19)	Pressure threshold: 50% P_{Imax}, 30 breaths, 2×/day, 7 day/week, 6 week	Improved running time-trial performance with 25 kg backpack load carriage (+8%)
Guy et al. 2014	(23)	Recreational male soccer players (n=31)	Pressure threshold: 50% P_{Imax}, 30 breaths, 2×/day, 7 day/week, 6 week	Improved performance in multi-stage fitness test (+12%), but no change in soccer-specific fitness test
Helfer et al. 2016	(28)	Healthy active males (n=15)	Voluntary isocapnic hyperpnea, 60% MVV 30 min/day, 3 day/week, 4 week	Improved exercise endurance at simulated altitude (+44%)
Kapus 2013	(35)	Young trained swimmers (n=12), 5M/7F	Pressure threshold: 50% P_{Imax}, 30 breaths, 2×/day, 7 day/week, 6 week	Improved 50m butterfly (+2%) and 100m front crawl (+2%) performance, but no change in 50m front crawl or 50m breaststroke performance
Lemaitre et al. 2013	(38)	Young well-trained swimmers (13–18 yr), (n=20); 13M/7F	Voluntary normocapnic hyperpnea, 60% MVV 30 min/day, 5 day/week, 8week	Improved performance in 50m (+3%) and 200m (+4%) swimming time trials
Lomax et al. (In Press)	(39)	Well-trained youth swimmers (n=33), 18M/15F	Pressure threshold: 50% P_{Imax}, 30 breaths, 2×/day, 7 day/week, 6 week	Improved 100m (+3%) and 200m (+7%) swim performance (only in group that performed ≤31 km·wk^{-1} swim training)
McEntire et al. 2016	(43)	Active, healthy subjects (n=15), 10M/5F	Inspiratory load during exercise training of 15% P_{Imax}	Improved performance in 5-mile cycling time trial (+18%)
Mishchenko et al. 2017	(50)	Healthy female university students (n=26)	Elastic belts applied to lower part of chest to force of 2.5 kg at FRC	Increased performance at ventilatory threshold (+61%) maximal power output (+14.4%), power output at ventilatory threshold (+20.7%), and $\dot{V}O_{2max}$ (+10.8%) on cycle ergometer during incremental exercise test

Study	Reference	Population	Intervention	RMT Outcomes
Ozmen et al. 2017	(54)	Male soccer players (n=18)	Voluntary hyperpnea, 60%MVV 15 min/day, 2 day/week, 5 week	No change in 20-meter shuttle-run test
Porcari et al. 2016	(56)	Moderately trained university students (n=24), 16M/8F	“Elevation Training Mask 2.0” worn during exercise training; resistance not reported	Improved power output at ventilatory threshold (+19.3%) and improved power output at respiratory compensation threshold (+16.4%)
Shei et al. 2018	(71)	Recreationally active males (n=12)	Flow-resistive: 80% SMIP TIRE regimen, up to 36 breaths 1×/day, 3 day/week, 6 week	Running time to exhaustion with 10 kg backpack load carriage improved (+29.3%)
Tong et al. 2016	(77)	Recreational runners (n=16), 12M/4F	Pressure threshold: 50% P_{Imax} 30 breaths, 2×/day, 6 day/week, 4 week; or “Functional” RMT of 50% P_{Imax} performed concurrently with functional core muscle training	Improved performance in one-hour treadmill run distance covered (+3.04%)
Vašíčová et al. 2017	(80)	Youth swimmers (n=28), M/F distribution not reported	Pressure threshold inspiratory and positive expiratory pressure: 30% $P_{\text{Imax a}}$nd 30% P_{Emax}; 10 breaths, 1×/day, 7day/week, 4 week	Improved performance in apnea-max swim test (+27.4%)
Wu et al. 2017	(84)	Healthy university tennis players (n=10), M/F distribution not reported	Pressure threshold: resistance not reported; 30 breaths, 2×/day, 5 day/week, 6 week	No change in performance on static balance test or agility test