Respiratory Muscle Training Effects on Performance in Hypo- and Hyperbaria

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INTRODUCTION: Performing at high altitude and scuba diving impose functional limitations to the respiratory system and impair exercise performance compared to normobaria. At altitude, the partial pressure of oxygen is reduced, which decreases arterial oxygen saturation and exercise performance. Falling arterial oxygen saturation results in hyperventilation and increased pulmonary ventilation. Diving poses unique effects on the respiratory system. The work of breathing is increased from marked increased airway resistance, static lung load, and hydrostatic pressure from the water on the thoracic wall. Both altitude and diving increase the work and energy cost of breathing, resulting in respiratory muscle fatigue. Respiratory muscle training (RMT) has been employed to target the deleterious effects on the respiratory system and exercise capacity. Although the literature is sparse, RMT has been reported to decrease the work and energy cost of breathing and improve pulmonary ventilation, respiratory muscle strength, pulmonary function, and exercise capacity. This narrative review summarizes what is currently known about RMT for exercise performance at altitude and in diving, including potential mechanisms and outlines gaps in the literature.

KEYWORDS: diving, altitude, respiratory muscle, respiratory physiology.

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Hyperventilation and increased work of breathing (WOB) during exercise in humans can lead to respiratory muscle fatigue and a decline in exercise performance.[19] Depending on exercise intensity and the fitness status of the individual, respiratory muscles can use up to 15% of total oxygen consumption and 14–16% of cardiac output during exercise.[6–8] The work of the respiratory muscles can compromise exercise performance through reflex vasoconstriction of the exercising limbs, causing a shift in cardiac output away from locomotor muscles.[6–8] It was later determined that respiratory muscle fatigue attenuated exercise performance through a metaboreflex (i.e., accumulation of blood lactate in the respiratory muscles) that triggered increased sympathetic nervous system activation, causing locomotor muscle vasoconstriction to increase blood flow to respiratory muscles ("blood stealing").[11,14,26] These combined responses cause early locomotor muscle fatigue and a rapid cessation of exercise.

The environment can increase the WOB, amplifying respiratory muscle fatigue. Both altitude and diving increase the work of breathing in two distinct ways. The lower partial pressure of oxygen (i.e., hypoxia) at altitude leads to decreased arterial oxygen saturation, or hypoxemia, which activates the carotid body chemoreflex to increase pulmonary ventilation.[24] While the decreased gas density at altitude reduces the air resistance, hypoxia leads to hyperventilation and subsequently increases the work of breathing at rest and during exercise.[24] In diving, the WOB is increased by hydrostatic pressure, static lung load, and airway resistance.[20]

Both environments lead to premature respiratory muscle fatigue during submaximal and maximal exercise and subsequently impair performance. Given the relative influence the respiratory muscles have on exercise performance, respiratory muscle training (RMT) has been reported to reduce the deleterious effects of respiratory muscle fatigue on exercise performance. The details of the ergogenic effects of RMT in normobaric conditions have been previously reviewed.[5,13] Therefore, the purpose of this qualitative review was to determine the effects of RMT on the respiratory responses, work of

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breathing, and exercise performance at altitude and in diving. In addition, this review will provide practical implications and identify avenues for future research.

METHODS

We searched PubMed, Medline via EBSCOhost, and Web of Science. The following keywords were used in various combinations: respiratory muscle training, inspiratory muscle training, altitude, diving, scuba diving, divers, exercise, performance, hypoxia, respiratory mechanics, work of breathing, respiration, respiratory muscles, ventilation, and respiratory function. All searches were limited to the English language. Review articles and reference sections were used to identify additional articles not found in the search. Additionally, the Web of Science "cited articles" function was used to further identify articles. Abstracts from articles were screened to eliminate studies that did not meet inclusion requirements.

Specific inclusion requirements were: 1) original research; 2) human subjects; 3) randomized design; 4) ≥2 wk of RMT; 5) pre- and post-RMT pulmonary function testing; and 6) performance outcome in hyperbaric, at altitude, or under normobaric, hypoxic conditions. We did not include review articles, case studies, or textbooks. Animal studies were not included. The original search yielded seven potential articles for RMT at altitude (or hypoxia) and eight potential articles for RMT in diving. Two articles for RMT at altitude and two articles for RMT in diving were excluded because they used RMT a single time instead of as a training device, and/or did not measure a performance outcome.

RESULTS

Respiratory Muscle Training, Diving, and Altitude (or Hypoxia)

Four articles examining the effects of RMT on surface and underwater swim performance and pulmonary function in scuba divers were identified. These studies used RMT to attenuate the increased WOB in diving. We present aggregate data for surface and underwater swimming performance following RMT in **Table I**. Pulmonary function data is presented in **Table II**.

Five articles examining the effects of RMT [or inspiratory-only muscle training (IMT)] on exercise performance and pulmonary function were identified. RMT was employed to attenuate the functional limitations of the respiratory muscles and cardiopulmonary system at altitude (or in hypoxia). We will present aggregate data for exercise performance at altitude or in hypoxia. Pulmonary function data is presented in **Table III**.

Performance in Diving

All of the RMT in diving studies that included a performance outcome identified observed augmented performance following RMT. These studies used healthy, male recreational divers. Prior to beginning RMT, the subjects in these studies completed fin swim training 3 d/wk for 4 wk to limit between-subject

Table I. Respiratory Muscle Training and Diving: Performance.

ARTICLE	SUBJECTS	DESIGN	RMT PROTOCOL	EXERCISE MODE	FINDINGS
Lindholm et al. (2007)[17]	N = 20 recreational divers	Randomized, noncontrolled; Pre/post RRMT testing	RRMT-3 (3 d/wk); RRMT-5 (5 d/wk); 4 wk	Underwater endurance swim	Underwater swim endurance time was improved (RRMT-3: 25.48 ± 7.12 vs. 47.97 ± 31; RRMT-5: 19.01 ± 10.65 vs. 31.60 ± 11.69 min pre- and post-RRMT, respectively; $P < 0.05$).
Ray et al. (2008)[21]	N = 9 recreational divers	Pre/post RRMT testing	RRMT (5 d/wk; 4 wk)	Underwater endurance swim	RRMT increased underwater endurance swim time (31.3 ± 11.6 vs. 49.9 ± 16.0 min pre- and post-RRMT, respectively; $P < 0.05$).
Ray et al. (2010)[22]	N = 8 recreational divers	Pre- and two post-RRMT tests	RRMT (5 d/wk; 4 wk)	Underwater endurance swim	RRMT increased underwater endurance swim time (26.4 ± 9.7 vs. 49.4 ± 21.6 min pre- and post-RRMT, respectively; $P = 0.004$).
Wylegala et al. (2007)[30]	N = 30 swimmers	RCT; pre/post RMT testing	PRMT, RRMT, ERMT (5 d/wk; 4 wk)	Underwater endurance swim	Underwater endurance swim time was unchanged in PRMT and improved in the RRMT and ERMT groups (18.9 vs. 31.4 min pre- and post-RRMT; 20.3 vs. 25.7 min pre- and post-ERMT; $P < 0.05$).

RMT = respiratory muscle training; RRMT = resistive respiratory muscle training; RCT = randomized control trial; PRMT = placebo respiratory muscle training; ERMT = endurance respiratory muscle training.

technique or training status differences. The fin swim training protocol employed in all four studies consisted of three 10-min swimming sessions with 10 min recovery interspersed at 70–75% $\dot{V}O_{2max}$. The fin swim training program had been previously established and validated.[31]

Wylegala et al. were the first to use RMT for swimming endurance in divers.[30] There were 3 RMT protocols ($N = 10$ per RMT group) examined: 1) placebo RMT (PRMT); 2) endurance RMT (ERMT); and 3) resistive RMT (RRMT). All RMT was completed for 30 min/d, 5 d/wk, for 4 wk. The PRMT consisted of 10-s breaths once per minute and acted as a placebo-control, the ERMT used isocapnic hyperpnea, and the RRMT consisted of a vital capacity maneuver against 50 cmH_2O resistance every 30 s. Subjects completed two endurance swims (surface and underwater) to exhaustion at 70–75% $\dot{V}O_{2max}$ before and after RMT. Surface swim performance did not change in the control group (PRMT), while time to exhaustion (min) was augmented in both the ERMT and RRMT groups (~38% and ~33%, respectively) following RMT. However, there were no differences between those two groups. Interestingly, the underwater (1.2 msw) swim performance was greater in the RRMT group compared to the ERMT group (+66% vs. +26%). Underwater swimming endurance did not change in the PRMT group.[30]

The work of Wylegala et al. provided the groundwork for RMT in diving.[30] Lindholm et al. examined the effects of RRMT at two training frequencies (3 or 5 d/wk) on swim performance in divers.[17] Additionally, Lindholm et al. evaluated whether improvements following RRMT could be maintained over 3 mo by completing RRMT 2 d/wk. The RRMT protocol was consistent with that of Wylegala et al.[30] Time to exhaustion (min) during a surface endurance swim was increased in both the RRMT-3 and RRMT-5 groups (~50% and ~33%, respectively). In agreement with Wylegala et al., time to exhaustion improvements were greater during the underwater (1.2 msw) endurance swim compared to the surface endurance swim following RRMT (+88% and +66% after RRMT-3 and RRMT-5, respectively).[17,30] Furthermore, following 3 mo of maintenance RRMT, underwater endurance swim time remained elevated.

Two studies employing RRMT in diving investigated the effects of various depths on underwater swim performance.[21,22] Following a similar RRMT protocol as Wylegala et al., subjects completed underwater endurance swims to exhaustion at 17 msw and in a follow-up study examining the effects of RMT on the WOB at 37 msw. In agreement with previous studies, underwater swim performance increased by 59 ± 51% (31.3 ± 11.6 min vs. 49.9 ± 16.0 min) at 16.8 msw and 87% (26.4 ± 9.7 min vs. 49.4 ± 21.6 min) at 37 msw following RRMT. Collectively, these studies indicate that both ERMT and RRMT improve surface and underwater swimming endurance in recreational divers; however, RRMT appears to be superior in augmenting performance.

Performance at Altitude (or Hypoxia)

Of the five studies examining the effects of RMT or IMT on exercise performance at altitude (**Table IV**), only one

Table II. Respiratory Muscle Training and Diving: Pulmonary Function.

ARTICLE	SUBJECTS	DESIGN	RMT PROTOCOL	SVC	FVC	FEV_1	MVV	P_{IMAX}	P_{EMAX}	RET
Lindholm et al. (2007)[17]	$N = 20$ recreational divers	Randomized, noncontrolled; Pre/post RRMT testing	RRMT (3 d /wk); (RRMT (5 d/wk); 4 wk	RRMT-3 NC; RRMT-5 NC	RRMT-3 NC; RRMT-5 NR	RRMT-3 NC; RRMT-5 NC	RRMT-3 ↑; RRMT-5 NR	RRMT-3 ↑; RRMT-5 ↑	RRMT-3 ↑; RRMT-5 ↑	RRMT-3 ↑; RRMT-5 NR
Ray et al. (2008)[21]	$N = 9$ recreational divers	Pre/post RRMT testing	RRMT (5 d/wks; 4 wk)	NC	NC	NC	↑	↑	↑	↑
Ray et al. (2010)[22]	$N = 8$ recreational divers	Pre- and two post-RRMT tests	RRMT (5 d/wks; 4 wk)	↑	NC	NC	↑	↑	↑	↑
Wylegala et al. (2007)[30]	$N = 30$ swimmers	RCT; pre/post RMT testing	PRMT, RRMT, ERMT (5 d/wk; 4 wk)	PRMT NC; ERMT ↑; RRMT NC	PRMT NC; ERMT ↑; RRMT NC	PRMT NC; ERMT ↑; RRMT NC	PRMT NC; ERMT ↑; RRMT NC	PRMT NC; ERMT NC; RRMT ↑	PRMT NC; ERMT NC; RRMT ↑	PRMT NC; ERMT ↑; RRMT ↑

RMT = respiratory muscle training; SVC = slow vital capacity; FVC = forced vital capacity; FEV_1 = forced expiratory volume in 1 s; MVV = maximal voluntary ventilation; P_{Imax} = maximal inspiratory mouth pressure; P_{Emax} = maximal expiratory mouth pressure; RET = respiratory endurance test; RRMT = resistive respiratory muscle training; NC = no change; ↑ = significant increase; NR = not reported; RCT = randomized control trial; PRMT = placebo respiratory muscle training; ERMT = endurance respiratory muscle training.

Table III. Respiratory Muscle Training and Altitude (or Hypoxia): Pulmonary Function.

ARTICLE	SUBJECTS	DESIGN	RMT PROTOCOL	SVC	FVC	FEV_1	MVV	P_{IMAX}	P_{EMAX}	RET
Downey et al. (2007)[3]	*N* = 12 (5 control; 7 IMT); moderately active	Pre/post IMT testing	IMT (2×/d; 5 d/wk; 4 wk); 40 inspirations at 55% PI_{max}	—	—	—	—	↑	—	—
Esposito et al. (2010)[4]	*N* = 9; moderately active	Pre/post RMT testing	RMT (5 d/wk; 8 wk); 10–20 min isocapnic hyperpnea	—	↑	↑	—	↑	—	—
Helfer et al. (2016)[10]	*N* = 15 (5 VIHTp; 10 VIHT); moderately active	Pre/post VIHT testing	VIHT (5 d/wk; 4 wk); 30 min per session	—	—	—	—	—	—	—
Keramidas et al. (2010)[15]	*N* = 18 (9 control; 9 recreationally active)	Pre- and mid two post-RMT tests	VIHT (5 d/wk; 4 wk); 30 min per session + 1 h cycling at 50% PPO or 1 h cycling alone (control)	—	NC	NC	NC	—	—	—
Salazar-Martinez et al. (2017)[23]	*N* = 16 (7 control; 9 IMT); physically active	Pre/post IMT testing	IMT (2×/d; 5 d/wk; 6 wk); 30 inspirations at 55% P_{Imax}	—	NC	NC	—	↑	—	—

RMT = respiratory muscle training; SVC = slow vital capacity; FEV_1 = forced expiratory volume in 1 s; FVC = forced vital capacity; FVC = forced vital capacity; FEV_1 = forced expiratory volume in 1 s; MVV = maximal voluntary ventilation; P_{Imax} = maximal inspiratory mouth pressure; P_{Emax} = maximal expiratory mouth pressure; RET = respiratory endurance test; IMT = inspiratory muscle training; — = not tested; ↑ = significant increase; VIHTp = placebo-control voluntary isocapnic hyperpnea training; VIHT = voluntary isocapnic hyperpnea training; PPO = peak power output; NC = no change.

was conducted in a hypobaric environment.[10] The four other studies used a normobaric hypoxic environment (F_IO_2 = 0.16–0.11).

Downey et al.[3] was the first to examine the effects of IMT on running in hypoxic conditions. Subjects completed IMT two times per day, five sessions per week, for 4 wk. The IMT consisted of 40 inspiratory breaths at 50% of their individual maximal inspiratory pressure (P_{Imax}). Subjects completed a treadmill run to exhaustion at 85% $\dot{V}O_{2max}$ pre- and post-IMT in normobaric normoxia ($F_IO_2 = 0.21$) and normobaric hypoxia ($F_IO_2 = 0.14$). There was no change in time to exhaustion following IMT in either the normoxic or hypoxic conditions.[3] Esposito et al.[4] also failed to show improvements in $\dot{V}O_{2max}$ during an incremental maximal cycle test in normobaric normoxia and normobaric hypoxia (F_IO_2 = 0.21 or 0.11, respectively) following 8 wk of RMT.

In contrast to Downey et al. and Esposito et al., other studies have shown performance improvements following 4 wk of voluntary isocapnic hyperpnea training (VIHT).[10,15] Helfer et al.[10] observed a 44% increased cycle time to exhaustion at 70–75% $\dot{V}O_{2max}$ at a simulated altitude of 3000 m (9842.5 ft) and 3600 m (11,811 ft). However, Keramidas et al.[15] reported VIHT improved cycle time to exhaustion at 85% $\dot{V}O_{2max}$ in normoxia ($F_IO_2 = 0.21$), but not in hypoxia ($F_IO_2 = 0.12$). Salazar-Martinez et al.[23] employed a similar IMT protocol as Downey et al.; however, subjects completed 30 breaths per training session. Subjects completed two 10-min time trials (TT) at 85% peak power output before and after IMT. Following 4 wk of IMT, subjects increased mean power output during the 10-min TT in both normoxic ($F_IO_2 = 0.21$) and hypoxic ($F_IO_2 = 0.1645$) conditions by 11.33% and 7.33%, respectively.

DISCUSSION

Respiratory muscle training is a well-recognized approach for augmenting exercise and sport performance by increasing respiratory muscle strength and endurance.[5,13] In addition to the WOB during exercise, the exercising environment can have additive effects on respiratory muscles. Thus, the purpose of this review was to examine the effects of respiratory muscle training on exercise performance at altitude (or during hypoxia) and in scuba diving. The primary finding of this review is that RMT improves both surface and underwater swimming performance in recreational divers. An additional finding is that the specificity of RMT (RRMT over ERMT) is critical for maximizing performance in the two environments.

All four of the RMT in diving studies showed significant improvements up to 88% in underwater endurance swimming performance. This large improvement was observed following 4 wk of RRMT, which reduced the energy cost of swimming via a reduction in the WOB.[9,22,27] The WOB underwater is augmented by a negative static lung load, which increases the effort required from the inspiratory muscles.[18,28] Additionally, the translocation of blood to the thorax from the limbs during immersion may reduce total lung volume and residual volume and decrease lung compliance. These factors combine to increase the WOB by reducing the elastic component of the lung and chest wall. Increased hydrostatic pressure with depth provides an additional stimulus that increases the WOB.[22,27] Combined, these effects increase minute ventilation and breathing frequency while decreasing ventilatory threshold during underwater endurance swimming. If similar to other forms of resistance training, RRMT may increase contractile protein quantity in the skeletal muscle or enhance recruitment of high threshold motor units to counter the hydrostatic effects of the underwater environment. This would be in contrast to ERMT, which presumably would increase capillarity and mitochondrial number.

Unlike the RMT in diving studies, the studies employing RMT to enhance exercise performance at altitude fail to reach a consensus. RMT was designed to reduce the WOB during exercise by either increasing respiratory muscle strength or endurance. Similar to other physical training modalities, specificity is important. The studies that observed improved performance during exercise at altitude or hypoxia likely employed the most specific RMT protocol for those conditions.[10,15,23] Helfer et al.[10] used VIHT (i.e., ERMT), which has been shown to increase

Table IV. Respiratory Muscle Training and Altitude (or Hypoxia): Performance.

ARTICLE	SUBJECTS	DESIGN	RMT PROTOCOL	EXPERIMENTAL CONDITIONS	PERFORMANCE OUTCOME
Downey et al. (2007)[3]	*N* = 12 (5 control; 7 IMT) moderately active	Pre/post IMT testing	IMT (2×/d; 5 d/wk; 4 wk); 40 inspirations at 55% P_{Imax}	Run to exhaustion (min) at 85% $\dot{V}O_{2max}$; normobaric normoxia or hypoxia (F_IO_2 = 0.21 or 0.14, respectively)	NC in normoxia or hypoxia
Esposito et al. (2010)[4]	*N* = 9 moderately active	Pre/post RMT testing	RMT (5 d/wk; 8 wk); 10–20 min isocapnic hyperpnea	Cycling $\dot{V}O_{2max}$ test; normobaric normoxia or hypoxia (F_IO_2 = 0.21 or 0.11, respectively)	NC in normoxia or hypoxia
Helfer et al. (2016)[10]	*N* = 15 (5 VIHTp; 10 VIHT) moderately active	Pre/post VIHT testing	VIHT (3 d/wk; 4 wk); 30 min per session	Cycle to exhaustion (min) at 70–75% $\dot{V}O_{2max}$ at 3000 or 3600 m (9842.5 or 11,811 ft)	VIHTp: NC; VIHT: 44% increase in time to exhaustion at altitude
Keramidas et al. (2010)[15]	*N* = 18 (9 control; 9 recreationally active	Pre- and mid two post-RMT tests	VIHT (5 d/wk; 4 wk); 30 min per session + 1 h cycling at 50% PPO or 1 h cycling alone (control)	Cycle to exhaustion (min) at 80% $\dot{V}O_{2max}$; normobaric normoxia or hypoxia (F_IO_2 = 0.21 or 0.12, respectively)	VIHT and Control: ↑ in normoxia; NC in hypoxia
Salazar-Martinez et al. (2017)[23]	*N* = 16 (7 control; 9 IMT) physically active	Pre/post IMT testing	IMT (2×/d; 5d/week; 6 wk) 30 inspirations @ 55% P_{Imax}	Cycling TT (10 min) at 85% PPO; normobaric normoxia or hypoxia (F_IO_2 = 0.21 or 0.1645, respectively)	IMT: ↑ in MPO, PTF in normoxia and hypoxia; control NC

RMT = respiratory muscle training; IMT = inspiratory muscle training; P_{Imax} = maximal inspiratory mouth pressure; F_IO_2 = fraction of inspired oxygen; NC = no change; $\dot{V}O_{2max}$ = maximal oxygen consumption; VIHTp = placebo-control voluntary isocapnic hyperpnea training; VIHT = voluntary isocapnic hyperpnea training; TT = time trial; PPO = peak power output; MPO = mean power output; PTF = peak torque force; ↑ = significant increase.

respiratory muscle endurance in both runners and cyclists.[12,16,31] This modality trains the primary response to hypoxia—hyperventilation.[24,25] The acute effects of hypoxia exposure have been shown to cause diaphragmatic fatigue during exercise and rest.[1,29] Helfer et al. successfully improved endurance performance at a simulated altitude [3000 m and 3600 m (9842.5 ft and 11,811 ft)] by 44%. Specificity of RMT likely produced this result. Other studies employed IMT consisting of 30–40 inspirations against an inspiratory resistance (50–60% P_{Imax}). This type of IMT does not appear to mirror the respiratory demands associated with exercise or altitude (hypoxia). Utilization of VIHT or a different ERMT protocol is warranted for augmenting exercise performance at altitude (or in hypoxia).

Gaps in the Literature

The implications for RMT in endurance performance at altitude remain inconclusive. The results from the studies outlined in this review are inconsistent and that may be due to methodological differences. Two studies employed IMT, which is programmed similarly to RRMT (e.g., 30 breaths at 55% P_{Imax}). However, IMT only trains the inspiratory phase of the ventilatory cycle.[3,23] The primary ventilatory response to acute altitude (or hypoxia) is a rise in ventilation. It is likely that this increase in ventilation occurs by subjects breathing above and below functional reserve capacity (i.e., increase in tidal volume) and increased respiratory rate. As observed during exercise, expiration is no longer a passive movement. Thus, training the complete ventilatory cycle is likely important. Additionally, airway resistance is reduced at altitude, so implementing RRMT is counterproductive.

Another methodological inconsistency was the use of a hypoxic gas mixture to simulate altitude vs. true hypobaria. The only study that showed performance augmentation at altitude used a hypobaric chamber and was able to test subjects at altitude.[10] The other studies used a hypoxic gas (F_IO_2 0.165–0.11). If using this model, investigators should target a specific altitude and match the Po_2 of the hypoxic gas and desired altitude. This may limit the differences in the reduction of S_aO_2. However, simply matching the P_IO_2 of normobaric hypoxia and hypobaric hypoxia fails to account for potential differences in physiological responses. Conkin[2] concludes in his recent review that investigators must consider the potential physiological differences between normobaric and hypobaric hypoxia. Small variances in gas density cause ventilatory mechanics and the work of breathing to differ between the two experimental conditions. Additionally, the increases in $\dot{V}_E$ are typically greater in normobaric hypoxia.[2]

Also unknown is the role of RMT in individuals who must perform in both hypo- and hyperbaria (e.g., diving at altitude). No study has employed concurrent RMT (i.e., ERMT + RRMT), which may be necessary for these special populations. Our review, and others, have identified that RMT must match the ventilatory demands of the activity or environment for augmented performance.[5] Additional studies are required to elucidate the role of RMT for performance at altitude.

Conclusions

Respiratory muscle training improves swimming performance in recreational divers and can improve exercise performance at altitude (or in hypoxia). When considering the literature available for respiratory muscle training in divers, resistive respiratory muscle training appears to be superior to other respiratory muscle training methods given the factors associated with the WOB underwater. In contrast, voluntary isocapnic hyperpnea training or endurance respiratory muscle training emerges as the better option for improving performance at altitude. However, there are mixed results in the respiratory muscle training and altitude literature. In conclusion, when performing respiratory muscle training, it is important to match the ventilatory demands of the exercise or sport and the environment.

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