Auteurs :

RICCI Cyril : Performance scientist, HNS Performance, cyril.ricci@orange.fr

BOUVEROT Zian : Master STAPS EOPS, Université Perpignan Via Domitia zbouverot@gmail.com

Effects of Respiratory Muscle Training and Ventilatory Strategies on the Performance of Professional Cyclists

A 48-Week Longitudinal Analysis in 10 Elite Endurance Athletes

Abstract

The aim of this study was to evaluate the effects of a combined respiratory muscle training (RMT) protocol and specific ventilatory strategies on ventilatory function and performance in professional cyclists. Ten athletes (177 ± 9 cm; 64,5 ± 6,1 kg; maximal oxygen consumption [VO_2max]: 90.6 ± 5.2 ml·min^{-1}·kg^{-1}) completed a 48-week intervention including progressive inspiratory muscle training (Powerbreathe® K4) and isocapnic exercises (Breathe Way Better®), structured into six phases focusing on coordination, endurance, carbon dioxide (CO_2) tolerance, and ventilatory muscle strengthening.

Inspiratory and expiratory spirometry, along with physiological performance markers (VO_2max, tidal volume [TV], respiratory frequency [Rf], ventilatory thresholds [VT1 and VT2], absolute and relative aerobic power), were assessed throughout the protocol.

Results demonstrated an increase in VO_2max (+5,6%), VT1 (+10.2 %) and VT2 (+9.7 %) power, along with substantial reductions in Rf at ventilatory thresholds. These improvements were accompanied by increases in TV, suggesting reduced ventilatory cost and enhanced CO_2 tolerance. No significant changes were observed in minute ventilation (VE), indicating improved ventilatory efficiency.

These findings support the integration of RMT and targeted ventilatory strategies as effective interventions to enhance ventilatory determinants and aerobic performance, notably by lowering the respiratory muscle metaboreflex and reducing perceived exertion (RPE).

Keywords: respiratory muscle training, ventilatory strategies, cycling, ventilation, VO_2max, metaboreflex

Introduction

Background

Performance in cycling, as in other endurance sports, relies on a complex interaction between mechanical, physiological, and environmental factors. Predictive models of cycling performance incorporate all variables that determine movement efficiency, including muscular power output, aerodynamic, gravitational, and rolling resistance, as well as the athlete's individual physiological characteristics. These approaches particularly highlight the central role of aerobic capacity, among which maximal oxygen uptake (VO_2max), cycling economy, and resistance to muscular fatigue play a prominent role.

In time-trial efforts, characterized by sustained intensity and heavy reliance on the aerobic metabolism, the power output at lactate threshold (LTw) emerges as a key determinant of performance in trained cyclists. This physiological variable serves as an integrated marker of muscular oxygenation capacity, as it simultaneously reflects maximal oxygen consumption (VO_2max) and cycling economy, i.e., the amount of oxygen required to produce a given mechanical power. A high LTw therefore indicates an athlete's ability to maintain an intensity close to VO_2max while optimizing the energetic cost of the effort, which is crucial for medium and long-duration time-trial events[1,2]. These findings underscore the need to simultaneously optimize both energy efficiency and aerobic potential to sustain high-intensity efforts.

However, by focusing primarily on cardiovascular and peripheral muscular components, these models tend to overlook a critical functional link in the oxygen supply chain: the ventilatory system.

However, some studies now highlight a striking disconnect between the physiological importance of the respiratory muscles and the limited attention they receive in training strategies. Paradoxically, the respiratory muscles of highly trained endurance athletes represent a remarkable example of a muscle group that exhibits structural under adaptation relative to the demands of their sport[3]. While the cardiovascular system and peripheral musculature of these athletes show profound training-induced adaptations, the ventilatory muscles, particularly the diaphragm, but also the internal and external intercostals, and the transversus abdominis in the context of active expiration, remain relatively "underdeveloped." This relative under adaptation may impair both their mechanical efficiency and fatigue resistance, especially during prolonged, high-intensity efforts where ventilatory demands are significantly increased.

Moreover, it has been demonstrated that during exercise performed at maximal oxygen consumption (VO_2max), respiratory muscles can account for up to 15 to 20% of total oxygen uptake and systemic blood flow in highly trained endurance athletes, whereas this proportion typically does not exceed 8 to 10% in untrained individuals[4–6]. This high metabolic demand reflects substantial recruitment of the ventilatory muscles during intense exercise. In the absence of targeted adaptations aimed at these muscles, such physiological strain may lead to significant respiratory muscle fatigue, which can impair exercise tolerance and constitute a major limiting factor for sustained aerobic performance.

Additionally, data from near-infrared spectroscopy (NIRS) have revealed a mismatch between oxygen delivery and the metabolic demands of respiratory muscles during high-intensity exercise, resulting in localized deoxygenation of these muscles[7]. This finding suggests that, in trained athletes, the metabolic requirements of the respiratory muscles may exceed their oxygen supply capacity under intense exercise conditions, leading to pronounced diaphragmatic fatigue, which may directly limit aerobic performance[8].

Moreover, numerous studies have highlighted the fundamental role of respiratory muscle function in endurance performance[9,10]. Scientific literature also indicates that traditional training programs specific to endurance disciplines do not appear to provide a sufficient stimulus to induce significant adaptations in respiratory muscles, whether in terms of strength or endurance[11,12]. Although early evidence supporting the ability to improve respiratory muscle strength and endurance in healthy individuals through targeted training dates back nearly fifty years[13], the effectiveness of Respiratory Muscle Training (RMT) has long been a subject of controversy[14,15].

This prolonged lack of scientific consensus regarding the effectiveness of RMT can be attributed to methodological discrepancies in the assessment of its effects, as well as to other factors such as inappropriate training prescriptions, the absence of placebo or sham control groups, small sample sizes, or insufficient rigor in the supervision of RMT implementation[16]. Another major obstacle lies in the difficulty of objectively identifying respiratory muscle fatigue, which often goes undetected during standard cardiopulmonary exercise tests that are typically too short and not intense enough to significantly challenge these muscles[17]. In contrast, longer protocols that are more specific to endurance better replicate the physiological demands of prolonged exercise, but are rarely used due to their methodological complexity and low reproducibility in laboratory settings.

As a result, the role of the respiratory muscles as a potentially limiting factor in endurance performance has long been underestimated. However, the most recent findings from the scientific literature highlight significant effects of respiratory muscle training (RMT) on performance, demonstrated across a range of experimental protocols including intermittent incremental tests, constant-load exercises, and time-trial efforts. RMT induces notable functional adaptations, such as improvements in respiratory muscle strength and endurance, a reduction in perceived dyspnea, and decreased ventilatory fatigue—even under hypoxic conditions[18–20]. These benefits primarily stem from enhanced mechanical ventilatory efficiency and increased resistance of the respiratory muscles to fatigue. These adaptations help delay or reduce the activation of the respiratory muscle metaboreflex, a sympathetic reflex mechanism that, in response to diaphragmatic fatigue, induces vasoconstriction in locomotor muscles to preserve perfusion of the respiratory muscles[21]. By limiting the onset of this phenomenon, RMT helps maintain peripheral blood flow, reducing the systemic impact of exercise-induced fatigue and thereby supporting aerobic performance. Despite these scientific advances and the documented benefits, the use of RMT remains marginal in current strength and conditioning coaching practices[22].

Building on the benefits associated with strengthening the ventilatory muscles through RMT, recent research has highlighted the significant impact of other respiratory strategies—particularly those involving voluntary modulation of breathing patterns—on key physiological parameters involved in performance regulation in sports contexts[23–25]. It is now well established that ventilation, when consciously controlled, can phasically modulate sympathetic vasoconstrictor activity throughout the respiratory cycle, thereby influencing systemic hemodynamic regulation[26]. This close interaction between the respiratory and cardiovascular systems underscores the ergogenic potential of certain breathing techniques aimed at performance optimization.

Among these approaches, slow-paced breathing (SPB) has garnered growing interest in the scientific literature. This technique promotes an increase in tidal volume along with a reduction in alveolar dead space, thereby improving the efficiency of gas exchange. Moreover, it fosters optimized synchronization between the ventilatory and cardiac systems, as reflected by increased heart rate variability (HRV) and enhanced baroreceptor sensitivity[27]. These effects indicate a beneficial modulation of autonomic activity, particularly a parasympathetic predominance, which may contribute to better regulation of the physiological stress induced by exertion[26], ultimately translating to improved performance during prolonged efforts[24].

In this context, diaphragmatic breathing also emerges as a particularly promising complementary modality. By fully engaging the diaphragm, it enables deeper and more efficient ventilation, promoting better expansion of the lower lung regions and optimizing alveolar gas exchange. By increasing tidal volume while reducing respiratory frequency, this strategy supports enhanced tissue oxygenation by raising the partial pressure of CO_2 ($PpCO_2$) in a controlled manner to maximize the Bohr effect, thereby delaying the onset of ventilatory fatigue. These physiological adaptations serve to boost endurance capacity and tolerance to prolonged exertion, making diaphragmatic breathing a relevant ergogenic lever for improving aerobic performance in endurance athletes. Recent studies have demonstrated that diaphragmatic breathing can significantly enhance athletic endurance by reducing the metabolic demand of the respiratory muscles while improving their oxygen utilization efficiency, particularly during long-duration exercise[28,29]. This improvement in respiratory efficiency and effort management contributes to sustained aerobic performance by reducing perceived fatigue and allowing athletes to maintain higher levels of effort over extended periods.

Finally, it has been shown that a diaphragmatic breathing pattern is associated with better pulmonary function test outcomes. However, some studies have revealed the presence of dysfunctional breathing patterns in a significant proportion of athletes, suggesting that a systematic assessment of ventilatory patterns, combined with the integration of targeted breathing exercises, could be essential to promote efficient functional respiration and maximize the benefits of ventilation[25,29].

Over the past decades, the understanding of the physiological determinants of endurance performance, particularly in cycling, has advanced considerably. Current predictive models emphasize the central importance of maximal aerobic capacity (VO_2max), pedaling economy, and tolerance to muscular fatigue. However, these approaches primarily focus on cardiovascular and peripheral muscular adaptations, often overlooking a critical functional component : ventilation. Yet, in highly trained endurance athletes, respiratory muscles, especially the diaphragm, tend to show a relative under-adaptation when compared to the mechanical and metabolic demands they face during prolonged efforts. At high intensities, these muscles can account for up to 20% of total oxygen consumption, leading to respiratory fatigue that may trigger the ventilatory metaboreflex, a mechanism detrimental to performance.

Despite growing evidence supporting the effectiveness of respiratory training on ventilatory function and exercise tolerance, this optimization strategy remains underutilized in training programs, largely due to a lack of consensus regarding its application modalities and the translatability of its effects to actual performance. Moreover, ventilatory strategies applied in dynamic settings (such as awareness, coordination, or CO_2 tolerance) are rarely explored in a systematic way. In this context, it appears necessary to evaluate the impact of a protocol combining respiratory training and integrated ventilatory strategy on ventilatory determinants and performance markers in professional cyclists.

Research Problem

In this context, ventilation can no longer be considered merely an automatic support process during exercise, but rather as a specific physiological skill, trainable and adjustable according to performance demands. Yet, although the effects of Respiratory Muscle Training (RMT) on ventilatory function are increasingly well documented, their direct application to endurance disciplines, and particularly to professional cycling, remains relatively unexplored. The central question thus becomes : To what extent can a structured protocol combining inspiratory muscle strengthening and integrated ventilatory strategies during exercise help optimize aerobic performance in already highly trained athletes ?

Hypothesis

From this perspective, it is necessary to formulate specific hypotheses to assess the actual impact of a protocol combining inspiratory training and ventilatory strategies applied during exercise. This investigation is guided by three main areas. First, targeted respiratory training is expected to improve several key ventilatory parameters, such as Forced Expiratory Volume in 1 second (FEV_1), Forced Expiratory Volume in 6 seconds (FEV_6), the S-Index, Peak Inspiratory Flow (PIF), as well as overall lung volumes. Second, integrating dynamic ventilatory strategies during exercise is assumed to facilitate the functional transfer of these static adaptations to exercise contexts that mirror competitive demands. Finally, the combination of these two approaches, enhancing ventilatory function at rest and optimizing the breathing pattern during physical exertion, is expected to result in improved pedaling economy and, ultimately, a measurable increase in aerobic performance among elite cyclists.

Methodology

This study adopts a longitudinal intervention approach, using a quasi-experimental repeated-measures design conducted over a 48-week period. It aims to evaluate the effects of a protocol combining specific inspiratory training (using variable resistance), isocapnic training, and ventilatory strategies integrated into exercise, on the ventilatory and physiological performance of professional cyclists. The absence of a control group is offset by a rigorous within-subject design (pre/post intervention), based on monthly assessments of ventilatory and performance parameters. This design allows for the individual and collective monitoring of parameter evolution over time, while accounting for the specific constraints of high-level athletic practice and the ethical impracticality of removing potentially beneficial training components from professional athletes. The study follows a logic of applied ecological evaluation, with a strong emphasis on the direct transferability of findings to real-world training environments.

Participants

The study group consists of ten professional athletes specializing in endurance disciplines (cycling and triathlon), who chose to incorporate respiratory training into their training plans and develop ventilatory strategies during exercise to optimize performance. These individuals exhibit homogeneous anthropometric and physiological characteristics, consistent with high-level endurance sport performance standards.

The average height of the participants is 177 ± 9 cm, reflecting a morphology compatible with biomechanical efficiency in cyclical activities. The average body weight is 64.5 ± 6.1 kg, indicating a favorable height-to-weight ratio, often sought after in endurance sports to optimize the power-to-weight ratio.

Before the implementation of the respiratory training protocol, all participants underwent both inspiratory and expiratory spirometry, as well as an incremental exercise test to evaluate aerobic, ventilatory, and mechanical capacities. These baseline measurements served as reference points to quantify the effects of the intervention.

The ventilatory parameters measured at rest revealed a high-performing ventilatory profile, consistent with the status of highly trained endurance athletes. The average forced expiratory volume in one second (FEV_1) was 5.09 L, while the forced expiratory volume over six seconds (FEV_6) reached 6.12 L, indicating a strong ability to maintain high ventilatory flow during prolonged expiration. The FEV_1/FEV_6 ratio, estimated at 0.832, suggests efficient expiratory dynamics without signs of functional limitation.

On the inspiratory side, the athletes demonstrated a peak inspiratory flow (PIF) of 8.0 L/s, indicating high inspiratory power. The mobilizable inspiratory volume was 5.1 L, reflecting substantial usable lung capacity. Finally, the inspiratory strength index (S-index), which integrates the strength and coordination of inspiratory muscles during a resisted inhalation, showed an average value of 145 cmH_2O, indicating excellent inspiratory muscular performance even prior to the start of the protocol. For a clearer overview, these various parameters are summarized in Table 1.

Table 1: Ventilatory Parameters of Participants Before the Protocol (n = 10)

Parameters	**Mean Value**
FEV_1 (L)	5.09
FEV_6 (L)	6.12
FEV_1/FEV_6	0.832
S-Index (cmH_2O)	145
PIF (L/s)	8.00
Inspiratory Volume (L)	5.10

From a physiological standpoint, these athletes exhibit a particularly high VO_2max, with an average of 89.87 ± 3.2 $ml\cdot min^{-1}\cdot kg^{-1}$. This exceptional VO_2max level serves as an objective marker of their superior aerobic capacity, well above the values typically reported among amateur athletes or even elite performers in certain disciplines. Such a value reflects not only an excellent ability to absorb, transport, and utilize oxygen at the muscular level, but also remarkable cardiovascular and ventilatory efficiency, both essential conditions for optimal performance in long-duration endurance events. Ventilatory thresholds were also elevated, with a first ventilatory threshold (VT1) of 52.65 ± 2.99 $ml\cdot min^{-1}\cdot kg^{-1}$ and a second ventilatory threshold (VT2) of 78.82 ± 3.8 $ml\cdot min^{-1}\cdot kg^{-1}$. These values confirm a well-trained endurance profile, capable of sustaining a high percentage of VO_2max over extended periods.

Concerning ventilatory perspective, the data reveal a peak respiratory frequency (Rf) at VO_2max of 58.4 $breaths\cdot min^{-1}$, along with a tidal volume (Tv) of 3.31 L, indicating substantial recruitment of respiratory muscles during intense effort. Tidal volumes observed at the ventilatory thresholds were also high, with 2.65 L at VT1 and 3.65 L at VT2. Meanwhile, minute ventilation (VE) reached 193.3 $L\cdot min^{-1}$ at VO_2max, and was measured at 173.12 $L\cdot min^{-1}$ (VT2) and 65.61 $L\cdot min^{-1}$ (VT1), confirming effective ventilation proportional to the metabolic demand. As previously, these average values and their standard deviations are summarized in Table 2.

Table 2. Physiological characteristics of participants before intervention (n = 10, mean ± standard deviation)

Parameters	Pre-intervention (mean ± SD)
VO_2max (ml/min/kg)	90.6 ± 5.2
Ventilatory threshold 2 – VT2 (ml/min/kg)	78.82 ± 3.8
Ventilatory threshold 1 – VT1 (ml/min/kg)	52.65 ± 2.99
Respiratory rate at VO_2max (Rf/min)	58.4
Respiratory rate at VT2 (Rf/min)	47.43
Respiratory rate at VT1 (Rf/min)	24.76
Tidal volume at VO_2max (L)	3.31
Tidal volume at VT2 (L)	3.65
Tidal volume at VT1 (L)	2.65
Minute ventilation at VO_2max (L/min)	193.30
Minute ventilation at VT2 (L/min)	173.12
Minute ventilation at VT1 (L/min)	65.61

In terms of mechanical performance, the athletes demonstrated a maximal power output at VO_2max of 425.76 ± 24.11 W, which corresponds to a relative power of 6.50 $W \cdot kg^{-1}$, confirming excellent mechanical efficiency. The power levels recorded at ventilatory thresholds were also high, with 297.52 ± 24.54 W at VT1 (i.e., 4.54 $W \cdot kg^{-1}$) and 387.76 ± 28.51 W at VT2 (i.e., 5.92 $W \cdot kg^{-1}$), reflecting a strong ability to sustain high intensities before substantial lactate accumulation. These parameters are summarized below in Table 3.

Table 3. Performance Characteristics of the Participants Before the Intervention (n = 10, mean ± standard deviation)

Parameters	Pre-protocol (mean ± SD)
Power at VO_2max (W)	425.76 ± 24.11
Power at VT1 (W)	297.52 ± 24.54
Power at VT2 (W)	387.76 ± 28.51

Parameters	Pre-protocol (mean ± SD)
Relative power at VO_2max (W/kg)	6.50
Relative power at VT1 (W/kg)	4.54
Relative power at VT2 (W/kg)	5.92

Taken together, these data represent a particularly robust functional profile, providing a relevant baseline for evaluating the impact of a structured respiratory muscle training program on overall performance.

Protocol

The ventilatory training protocol implemented in this study is called " Ventilatory strategy and training" and is based on a systemic and hierarchical approach to the development of respiratory function. It can be summarized by the following figure.

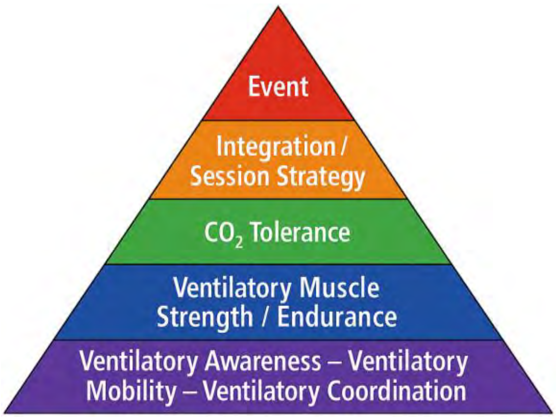

Figure 1 : Ventilatory Performance Pyramid, from *Cyril RICCI*

This pyramid presents a progressive organization of ventilatory levers contributing to performance, ranging from ventilatory awareness to practical integration in competition settings.

At the base of the pyramid lie awareness, mobility, and ventilatory coordination. These foundations are essential for enabling the athlete to voluntarily control their breathing, typically an automatic function, and to modulate tidal volume (TV) and respiratory frequency (Rf) according to the demands of the effort (duration, intensity, modality, environment). Such control allows for the optimization of total ventilation ($Ve = TV \times Rf$), a reduction in the energetic cost of breathing, and greater hemodynamic and neuromuscular stability during exertion.

The second level of the pyramid involves the development of strength and endurance in the ventilatory muscles. This entails maintaining both the contractile ability and relaxation capacity of the muscles involved in breathing, over 80 in total, including the diaphragm, intercostals, and deep abdominals, all of which play a critical role. Strengthening these muscles increases the pressure generated during each respiratory cycle, supports efficient ventilation at high intensities, and sustains effort over time. This is essential for minimizing activation of the respiratory metaboreflex, which is known to divert blood flow away from locomotor muscles toward the respiratory system.

The third pillar concerns CO_2 tolerance, a key determinant in the autonomic regulation of respiratory rate. The rise in the partial pressure of carbon dioxide ($PaCO_2$) is one of the main drivers of ventilation. However, improved CO_2 tolerance helps limit reflex hyperventilation and maintain a lower respiratory frequency for the same minute ventilation. This reduces the proportion of air lost in anatomical dead space and lowers the energetic cost of breathing. The aim is to sustain a high tidal volume despite increasing exercise intensity, thereby reducing ineffective alveolar ventilation and improving oxygen extraction at the muscular level through the Bohr and Haldane effects.

The top of the pyramid represents integration, defined as the strategic and conscious application of the ventilatory skills acquired, awareness, mobility, coordination, respiratory muscle strength and endurance, and CO_2 tolerance, into specific training and competition scenarios. This phase marks the culmination of the respiratory optimization process, requiring not only technical mastery of ventilatory mechanisms but also their contextual application, tailored to the demands of each effort (duration, intensity, continuous or intermittent format), environmental conditions (heat, hypoxia), or posture (particularly in time-trial positions). It is in this capacity to deploy an individualized ventilatory strategy that breathing becomes a true performance enhancer.

The ventilatory protocol presented in this study followed this framework, structured in successive cycles aimed at developing these various capacities synergistically, in order to enhance the overall respiratory function and maximize its transfer to endurance sport performance.

Tools

Three primary devices were employed throughout the protocol to address the different objectives of respiratory training, ranging from ventilatory awareness to the evaluation of respiratory muscle function.

Breathe Way Better® – Isocapnic Tool

All athletes began the protocol with isocapnic training using the Breathe Way Better® device. This tool represents a central component of the methodological approach, allowing for controlled breathing work without significantly altering the acid-base balance (capnia maintenance). Isocapnic training offers several major physiological advantages that make it a fundamental element of the ventilatory optimization protocol. Firstly, it promotes active awareness of ventilation, encouraging athletes to take voluntary control of respiratory variables such as tidal volume (TV) and respiratory frequency (Rf). This control forms the foundation of any effective breathing strategy during exertion.

Additionally, isocapnic exercises facilitate the functional activation of respiratory muscles, particularly the diaphragm, internal and external intercostals, and deep abdominal muscles. This targeted stimulation helps restore or improve ventilatory mechanics, both during inspiration and expiration.

This training also promotes better neuromuscular coordination of the respiratory chains by strengthening the synchronization of the muscle groups involved in the respiratory cycle. Such coordination is essential for maintaining effective high-frequency breathing without compromising tidal volume.

Finally, maintaining high tidal volumes over prolonged periods at a modulated frequency helps develop respiratory muscle endurance by progressively adapting them to the metabolic demands encountered during high-intensity endurance exercise.

This training modality was maintained throughout the protocol, with adjustments in intensity, frequency, and duration parameters depending on the goals of each training phase.

Powerbreathe® K4 – Variable Resistance Inspiratory Training

From the sixth week onward, athletes began using the Powerbreathe® K4 device, a portable tool enabling inspiratory training against variable resistance. This device was used to specifically target the strength, power, and endurance of the inspiratory muscles, with individualized load progression based on measured respiratory capacities.

Inspiratory resistance training was planned according to a progressive periodization strategy, including deload phases, high-intensity periods, and functional specialization stages. The Powerbreathe® K4 also provides real-time feedback on maximal inspiratory pressure (PImax), contraction speed, and inspired volume, thereby facilitating personalized programming.

Spirometer – Functional Assessment

To monitor the progression of ventilatory capacities throughout the intervention, regular assessments of respiratory function were carried out using portable digital spirometers. For each athlete, both expiratory and inspiratory spirometry tests were performed at regular intervals, each targeting specific functional dimensions of ventilation.

On one hand, expiratory spirometry allowed for the evaluation of volumes and flow rates during expiration through two main indicators: forced expiratory volume in one second (FEV_1) and the volume exhaled in six seconds (FEV_6). These parameters help detect possible obstructive or restrictive limitations and quantify adaptations of the expiratory system over the course of training.

On the other hand, inspiratory spirometry was used to characterize the mechanical capabilities of inspiration, particularly through peak inspiratory flow (PIF), inspired volume, and the inspiratory strength index (S-index), which reflects the power produced by the inspiratory muscles during a forced inhalation.

These assessments provided reliable quantification of the mechanical and functional adaptations induced by the ventilatory training, allowing for real-time adjustments to the protocol.

Protocol Description

The intervention was carried out over a 48-week period, following a progressive plan aimed at stimulating the various components of ventilatory function: breathing coordination, inspiratory muscle strength and endurance, CO_2 tolerance, and functional transfer under exertion conditions. Two main modalities were integrated in a complementary manner throughout the protocol: isocapnic exercises, performed using the *Breathe Way Better*® device, which targeted respiratory rate control, autonomous regulation, and the stability of gas exchange; and inspiratory resistance training using the *Powerbreathe® K4*, focused on the specific strengthening of ventilatory muscles such as the diaphragm, intercostals, and deep abdominal muscles.

As part of the isocapnic training, athletes performed five weekly sessions, structured in a twice-daily format. The first session, conducted before the main training session and lasting between 5 and 8 minutes, primarily aimed to raise breathing awareness, actively mobilize the diaphragm, and coordinate ventilatory muscles. The second session, shorter in duration (4 to 5 minutes), was systematically scheduled during the post-training recovery phase.

Inspiratory training was progressively introduced. During the first 60 days, athletes performed 2 sets of 30 daily inspirations, six days a week. This initial phase was designed to stimulate the contraction capacity of the inspiratory muscles through short but intense efforts. Starting from the third month, the training volume was stabilized to one set of 30 daily inspirations, still six days a week, combined with a gradual increase in resistance. This progression made it possible to simultaneously develop maximal inspiratory strength and fatigue resistance.

The protocol was structured into distinct phases, each defined by a specific functional objective and evaluated through expiratory and inspiratory spirometry tests, systematically conducted at the beginning and end of each cycle.

Table 4 : Structuration of the Different Phases of the Protocol

Weeks	Main Objectives	Tools Used	Evaluations
1 to 5	Ventilatory coordination and diaphragmatic mobilization	Isocapnia (*Breathe Way Better*®) – twice-daily sessions (5x/week)	Inspiratory and expiratory spirometry
6 to 11	Ventilatory endurance, maintenance of coordination	*Powerbreathe*® *K4* + isocapnia (twice-daily protocol)	Inspiratory and expiratory spirometry
12 to 13	Deload, consolidation of adaptations	1 session/week *Powerbreathe*® + 1 session/week isocapnia	Inspiratory and expiratory spirometry
14 to 26	Ventilatory integration under challenging conditions (hypoxia)	*Powerbreathe*® *K4* + continuous isocapnia + altitude simulation (*ALTITUDE 4W*)	Inspiratory and expiratory spirometry
27 to 38	Maximal inspiratory strength and CO_2 tolerance	*Powerbreathe*® *K4* (increased resistance) + isocapnia (prolonged expiratory times)	Inspiratory and expiratory spirometry
39 to 41	Active recovery (*REST 1*), maintenance of gains	1 session/week *Powerbreathe*® + 1 session/week isocapnia	Inspiratory and expiratory spirometry
42 to 48	Final consolidation of adaptations	*Powerbreathe*® *K4* + isocapnia (twice-daily protocol, 5x/week)	Final inspiratory and expiratory spirometry

This combined protocol thus enabled targeted action on all the key determinants of ventilatory function : diaphragmatic mobilization, inspiratory muscle strengthening, regulation of breathing frequency, CO_2 tolerance, and strategic integration during exertion. Ultimately, it aims to enhance ventilatory efficiency, manage respiratory fatigue, and improve overall aerobic performance in endurance athletes.

Results

Ventilatory Parameters

Evolution of Expiratory Ventilatory Parameters

The analysis of expiratory spirometry data throughout the intervention reveals a significant progression in expiratory ventilatory function among the athletes.

The initial mean FEV_1 measured in April was 5.09 L. A steady increase was observed over the months, with the FEV_1 reaching 5.50 L by April of the following year, an absolute gain of +0.41 L, corresponding to a relative improvement of approximately +8% compared to the baseline value.

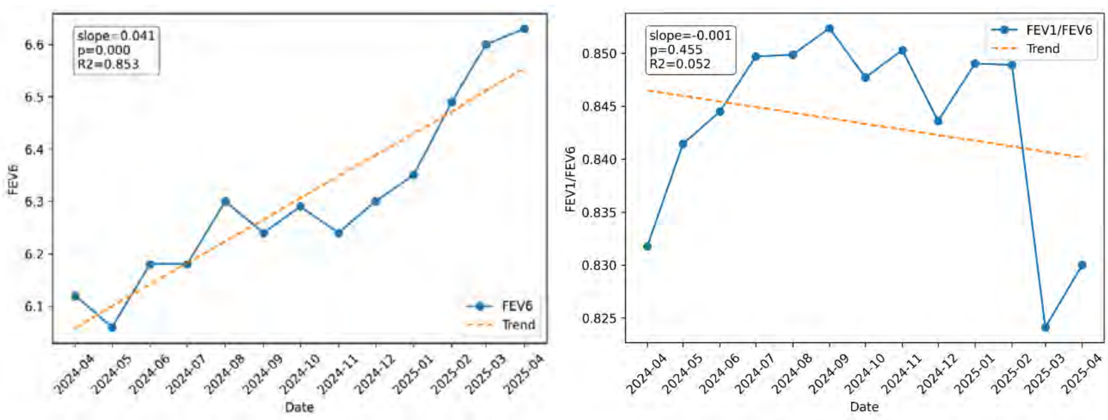

Figure 2 : Evolution of FEV_6 and FEV_1/FEV_6 ratio

For FEV_6, a continuous and significant progression was observed, with an increase of +0.041 L/month ($p < 0.001$, $R^2 = 0.85$). After 11 months of training, the average value rose from 6.12 L to 6.63 L, representing a gain of +0.51 L, which corresponds to a relative increase of approximately +8.3%.

The FEV_1/FEV_6 ratio, which reflects dynamic expiratory efficiency, remained stable throughout the protocol, changing from 0.831 to 0.830 ($p = 0.46$, $R^2 = 0.05$). This stability indicates that the increase in expiratory volumes occurred in a balanced manner, with no signs of ventilatory limitation or functional imbalance.

These results reflect a mechanical improvement in expiratory efficiency, consistent with enhanced alveolar ventilation, reduced relative dead space, and improved ventilatory flow during high-intensity efforts, critical parameters for sustained endurance performance.

Evolution of Inspiratory Ventilatory Parameters

The analysis of monthly inspiratory tests revealed a progressive and significant improvement in the participants' ventilatory capacities, both in terms of strength, peak inspiratory flow, and mobilizable volume.

The S-index, an indicator of the force generated during resistance-based inspiration, increased from 145 cmH_2O at the beginning of the protocol to 187.13 cmH_2O at the end of the intervention, an increase of +29.2%. This linear progression, particularly notable within the first three months (+15.7% by June), reflects a significant functional adaptation of the inspiratory muscles, primarily the diaphragm and external intercostals.

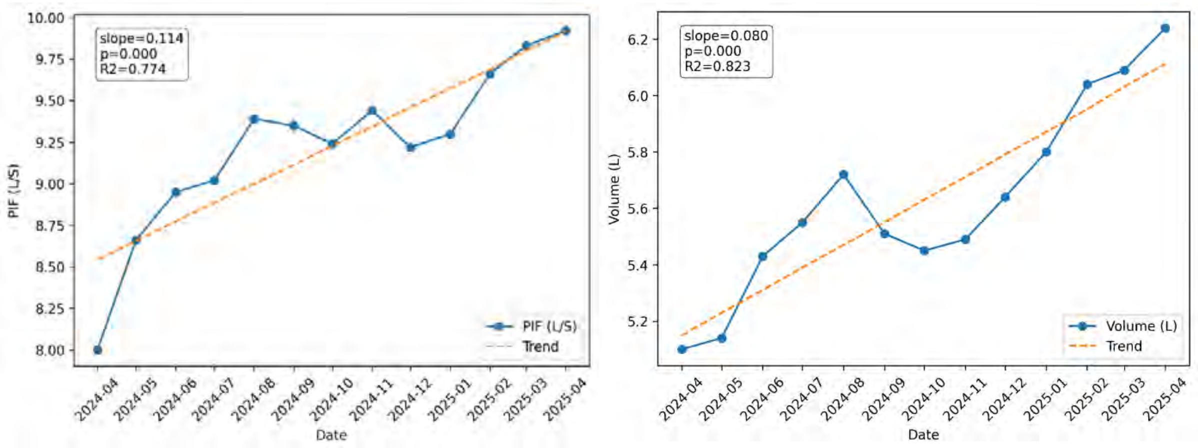

Figure 3 : Evolution of PIF and inspiratory volume

Peak Inspiratory Flow (PIF) showed a continuous and significant increase of +0.114 L/s per month ($p < 0.001$, $R^2 = 0.77$), rising from 8.00 L/s to 9.92 L/s by the end of the protocol. This represents a +24% improvement and reflects an enhanced ability to rapidly mobilize large volumes of air, an essential capacity to meet high ventilatory demands during intense physical exertion.

The mobilizable inspiratory volume also progressed steadily and significantly, with an increase of +0.080 L per month ($p < 0.001$, $R^2 = 0.82$), going from 5.10 L to 6.24 L, corresponding to a +22.4% improvement. This reflects a greater inspiratory ventilatory amplitude and improved thoraco-diaphragmatic flexibility. These volumetric adaptations are consistent with the improvements observed in ventilatory coordination and thoracic mobility across the phases of the protocol.

Finally, the correlation matrix across all measurement series reveals very strong relationships ($r > 0.88$, $p < 0.001$) between FEV_1, FEV_6, the inspiratory strength index (S-INDEX), peak inspiratory flow (PIF), and inspiratory volume. The FEV_1/FEV_6 ratio showed weaker correlation, as expected for a specific efficiency ratio. These correlations suggest that several of these measurements are redundant, paving the way for a streamlined ventilatory monitoring approach based on a few key indicators.

Variable	FEV1	FEV6	FEV1/FEV6	S INDEX (CmH2O)	PIF (L/S)	Volume (L)
Variable						
FEV1	1.000	0.944***	-0.130	0.928***	0.932***	0.960***
FEV6	0.944***	1.000	-0.434	0.828***	0.843***	0.960***
FEV1/FEV6	-0.130	-0.434	1.000	0.024	-0.012	-0.258
S INDEX (CmH2O)	0.928***	0.828***	0.024	1.000	0.998***	0.885***
PIF (L/S)	0.932***	0.843***	-0.012	0.998***	1.000	0.889***
Volume (L)	0.960***	0.960***	-0.258	0.885***	0.889***	1.000

Figure 4 : Correlation matrix, * = (**r** > 0,88, p < 0,001)

Overall, these results demonstrate the effectiveness of the combined intervention, isocapnic training and inspiratory resistance training, in optimizing inspiratory function in already highly trained endurance athletes, thereby strengthening a commonly overlooked link in the aerobic performance chain. For a clearer overview, these various parameters are summarized below in Table 5.

Table 5 : Monthly Evolution of Ventilatory Parameters (Expiratory and Inspiratory) Throughout the Protocol (n = 10 athletes)

Month	FEV_1 (L)	FEV_6 (L)	FEV_1/FEV_6	S-Index (cmH_2O)	PIF (L/s)	Inspiratory Volume (L)
April 2024	5.09	6.12	0.8317	145.00	8.00	5.10
May 2024	5.10	6.06	0.8414	159.61	8.66	5.14
June 2024	5.22	6.18	0.8445	167.76	8.95	5.43
July 2024	5.25	6.18	0.8497	168.71	9.02	5.55
August 2024	5.36	6.30	0.8498	176.44	9.39	5.72
September 2024	5.31	6.24	0.8524	175.49	9.35	5.51
October 2024	5.33	6.29	0.8477	172.37	9.24	5.45
November 2024	5.31	6.24	0.8503	177.13	9.44	5.49

Month	FEV_1 (L)	FEV_6 (L)	FEV_1/FEV_6	S-Index (cmH_2O)	PIF (L/s)	Inspiratory Volume (L)
December 2024	5.31	6.30	0.8436	172.48	9.22	5.64
January 2025	5.39	6.35	0.8490	173.43	9.30	5.80
February 2025	5.51	6.49	0.8489	183.36	9.66	6.04
March 2025	5.51	6.60	0.8241	184.91	9.83	6.09
April 2025	5.50	6.63	0.8300	187.13	9.92	6.24

Physiological values

The evaluation of physiological data collected before and after the ventilatory protocol reveals significant adaptations, resulting in a marked improvement in ventilatory efficiency and aerobic capacity among professional cyclists.

Maximal oxygen consumption (VO_2max) increased from 90.6 ± 5.2 to 93.2 ± 4.0 ml/min/kg, representing an improvement of nearly 3%. While this gain may appear modest, it is highly significant for elite athletes, whose margins for improvement at such a level of performance are extremely narrow, and where the difference between winning and finishing second in competition is often less than 1%[30]. This development suggests enhanced peripheral oxygen extraction and utilization, possibly linked to increased ventilatory efficiency and a reduced energetic cost of breathing.

The increase in ventilatory thresholds represents a notable advancement. VT1 rose from 52.65 ± 2.99 to 57.78 ± 3.03 ml/min/kg, a gain of +9.7%, while VT2 increased from 78.82 ± 3.80 to 84.56 ± 3.67 ml/min/kg, representing a +7.3% improvement. These gains indicate a shift of intensity zones upward, allowing athletes to sustain higher workloads.

A marked reduction in respiratory rate was observed across all intensities: at VO_2max, it decreased from 58.40 to 51.54 cycles/min (−11.7%); at VT2, from 47.43 to 38.39 cycles/min (−19.1%); and at VT1, from 24.76 to 15.43 cycles/min (−37.7%). This reduction indicates a slower and more controlled breathing pattern, characteristic of an improved ventilatory rhythm. It also suggests a reduced ventilatory load, which decreases respiratory muscle fatigue and delays the onset of the metaboreflex.

This improvement in ventilatory efficiency is also reflected in the tidal volumes (VT), which showed a clear increase: +18% at VO_2max (from 3.31 to 3.91 L), +20% at VT2 (from 3.65 to 4.39 L), and +55% at VT1 (from 2.65 to 4.12 L). These increases reflect enhanced pulmonary mobilization, particularly at lower intensities. This suggests greater ventilatory amplitude, likely linked to diaphragm strengthening and improved thoracic compliance.

Regarding minute ventilation (VE), the results are more mixed. VE increased slightly at VO_2max (from 193.30 to 201.52 L/min), a gain of +4.2%, but decreased slightly at VT2 (from 173.12 to 168.53 L/min, −2.6%) and at VT1 (from 65.61 to 63.57 L/min, −3.1%). This evolution suggests improved ventilatory efficiency. The cyclists were able to maintain optimal gas exchange levels at a reduced ventilatory cost, thanks to increased tidal volume and lower respiratory frequency.

These adaptations demonstrate an optimization of the ventilatory system in terms of mechanics (increased volumes mobilized), neuromuscular function (reduced respiratory rate), and functionality (increased ventilatory thresholds and VO_2max). The protocol implemented appears to have promoted synergy between the respiratory muscles, central ventilatory control, and overall aerobic performance. The evolution of these different parameters is summarized below in Table 6.

Tableau 6 : Evolution of physiological parameters (n = 10, mean ± standard deviation)

Parameters	**Pre-Protocol**	**Post-Protocol**
VO_2max (ml/min/kg)	90.6 ± 5.2	93.2 ± 4.0
Ventilatory Threshold 2 – VT2 (ml/min/kg)	78.82 ± 3.80	84.56 ± 3.67
Ventilatory Threshold 1 – VT1 (ml/min/kg)	52.65 ± 2.99	57.78 ± 3.03
Respiratory Frequency at VO_2max (breaths/min)	58.4	51.54
Respiratory Frequency at VT2 (breaths/min)	47.43	38.39
Respiratory Frequency at VT1 (breaths/min)	24.76	15.43
Tidal Volume at VO_2max (L)	3.31	3.91
Tidal Volume at VT2 (L)	3.65	4.39
Tidal Volume at VT1 (L)	2.65	4.12
Minute Ventilation at VO_2max (L/min)	193.30	201.52
Minute Ventilation at VT2 (L/min)	173.12	168.53
Minute Ventilation at VT1 (L/min)	65.61	63.57

Performance

Analysis of performance parameters shows a significant improvement in power output, both in absolute terms and in relative power, after the training protocol.

Absolute Power

The maximum power achieved at VO_2max increased from 425.76 ± 24.11 W to 449.65 ± 21.76 W, representing an average gain of 23.89 W (+5.6%). This increase suggests an improvement in the participants' capacity, allowing for increased power output at maximum effort, possibly linked to improved muscle efficiency and tissue oxygenation capacity.

Power at ventilatory threshold 1 increased from 297.52 ± 24.54 W to 327.87 ± 21.25 W, representing an average increase of 30.35 W, or 10.2%. This improvement in VT1 is particularly relevant for prolonged moderate-intensity efforts. Higher power at VT1 means that athletes can maintain a higher intensity while remaining in a physiological zone that optimizes energy reserves and delays the onset of fatigue.

Similarly, power at ventilatory threshold 2, which is generally correlated with the maximum sustainable intensity before rapid lactate accumulation, increased from 387.76 ± 28.51 W to 425.36 ± 24.67 W, an improvement of 37.60 W, corresponding to an increase of 9.7%. This increase in VT2 indicates an increased ability to sustain high-intensity efforts without immediately falling into metabolic imbalance. In a competitive context, this allows cyclists to ride longer at intensities close to their critical threshold, which is a major advantage in time trial or mountain events.

Thus, the increase in power shows not only an improvement in maximum capacity, but also an optimization of submaximal zones, which are essential for endurance performance. The evolution of these different parameters is shown below in Table 7.

Table 7 : Changes in absolute power (in watts, mean ± standard deviation, n = 10)

Parameter	Before Protocol	After Protocol
Power at VO_2max (W)	425.76 ± 24.11	449.65 ± 21.76
Power at VT1 (W)	297.52 ± 24.54	327.87 ± 21.25
Power at VT2 (W)	387.76 ± 28.51	425.36 ± 24.67

Relative power

Relative power (W/kg) is a fundamental indicator of performance in cycling, particularly when climbing, where the weight-to-power ratio is decisive. This measurement allows for a fair comparison of performance between athletes of different sizes.

The power relative to VO_2max increased from 6.50 W/kg to 6.95 W/kg, representing an increase of 0.45 W/kg (+6.9%). This gain is significant in terms of performance, particularly for competitions involving prolonged high-intensity efforts. Such an improvement suggests that the athlete is not only capable of producing more power in absolute terms, but also that they did so without significant weight gain, or with a favorable body adjustment.

At ventilatory threshold 1, relative power increased from 4.54 W/kg to 5.07 W/kg, a gain of 0.53 W/kg (+11.7%). This change indicates improved performance at moderate intensities, which translates into an ability to maintain a more sustained intensity while remaining within a ventilatory and metabolic comfort zone.

For the VT2, relative power increased from 5.92 W/kg to 6.57 W/kg, representing an improvement of 0.65 W/kg (+11%). This improvement reflects the ability to maintain high intensity while preserving optimized energy and ventilatory efficiency.

Overall, these improvements in relative power, both at VO_2max and ventilatory thresholds, confirm the positive effect of the intervention (including respiratory training and ventilatory strategies) on the specific performance of cyclists, enabling them to produce more power at each stage of relative intensity, without any negative impact on body composition.

Table 8 : Changes in relative power (in W/kg, average, n = 10)

Parameter	Before Protocol	After Protocol
Relative power at VO_2max (W/kg)	6.50	6.95
Relative power at VT1 (W/kg)	4.54	5.07
Relative power at VT2 (W/kg)	5.92	6.57

Discussion

The results of this study highlight a significant improvement in ventilatory capacity and physiological performance in professional cyclists following a protocol combining inspiratory training and ventilatory strategies. Several elements deserve to be discussed in detail here, including the dynamics of adaptations, their underlying mechanisms, and their concrete translation in terms of physiological efficiency and performance.

A central element of the protocol is based on the development and implementation of individualized ventilation strategies, which are the main vehicle for transferring adaptations achieved in static conditions to dynamic exercise contexts. Determining these strategies is therefore a key challenge in optimizing athletic performance, particularly in cycling. The main objective of these strategies is to reduce the energy cost associated with ventilation in order to maximize the fraction of energy expenditure available for mechanical power production.

However, there is no universal ventilation strategy, as each athlete must develop a specific approach based on their own ventilation capacities and functional discriminants. Nevertheless, the design process can be systematized: during incremental exercise testing, specific power outputs are associated with a given minute ventilation (VE), which can be broken down into respiratory rate (Rf) and tidal volume (Tv). This analysis forms the basis for developing an optimized ventilation strategy.

Based on this data, the objective is to identify an alternative combination of Rf and Tv that maintains the same VE for a given intensity while reducing the energy cost of ventilation. This new combination is based on ventilatory capacities measured at rest, particularly using spirometry, and will subsequently be refined by monitoring sessions in dynamic contexts. The use of forced expiratory volume in one second (FEV_1), multiplied by a coefficient specific to the modality (e.g., cycling, sitting), allows for the estimation of an ideal tidal volume (i Tv) up to ventilatory threshold 2 (VT2), generally associated with Rf values between 35 and 40.

Beyond this point, the inspiration time becomes strictly less than one second. In this case, Tv can no longer be estimated from FEV_1, but must instead be based on the maximum inspiratory volume achievable in a given time, which requires a more detailed dynamic analysis of inspiratory kinetics in order to define an ideal tidal volume. This intensity zone corresponds to the most decisive competitive situations, where the ability to maintain an efficient ventilatory pattern can make the difference in terms of performance. It is with this in mind that the concept of i Tv R (Ideal Tidal Volume for Racing) was defined, representing a specific inspiratory tidal volume for high intensities.

As for respiratory rate, it is modulated according to the intensity of the effort and evolves in a similar way to the kinetics of power increase, in order to preserve effective ventilation as much as possible without compromising respiratory economy.

For example, prior to the protocol, the average VE measured at ventilatory threshold 1 (VT1) for the group was 65.61 L/min, with an Rf of 24.76 and a Tv of 2.65 L. The average FEV_1 was 5.09 L. Applying a coefficient of 0.83 gives an ideal tidal volume (i Tv) of 4.22 L. In order to maintain the initial VE, this optimal Tv can be combined with an ideal target Rf (i Rf) of approximately 15.8 cycles/min. This type of ventilatory readjustment improves respiratory efficiency while respecting the physiological constraints of the target intensity.

Longitudinal analysis reveals that the most significant gains appear during the last three months of intervention, which seems to coincide with better individualization of inspiratory resistance and target power to be developed using the Powerbreathe K4.

The kinetics of respiratory rate reduction are particularly remarkable at VT1, reflecting improved CO_2 tolerance, better respiratory synchronization, and optimized ventilatory coordination. These adaptations are the result of increased awareness of ventilation, a central process in the appropriation of respiratory strategies during exercise[10]. At VT2, a parallel improvement is observed, also correlated with increased mechanical power. Although the ventilatory thresholds expressed as a percentage of VO_2max did not change, the power associated with VT1, VT2, and VO_2max increased. This reflects a reduction in the energy cost of ventilation, probably related to an increase in Tv and a decrease in respiratory rate.

Data relating to Rf reveal a particularly marked improvement at VT1, reflecting improved CO_2 tolerance. This phenomenon is attributable to the central pillar of the protocol, respiratory awareness, which enabled better voluntary management of ventilatory rate. A reduction in Rf was also observed at VT2, correlated with an increase in mechanical power achieved at this threshold, suggesting an improvement in the overall efficiency of ventilation/performance coupling.

Minute ventilation did not change significantly between the pre- and post-intervention phases, suggesting that the gains did not result from an increase in overall ventilatory flow, but rather from a qualitative improvement in ventilation, particularly in terms of oxygen extraction and reduction of ventilatory dead space. This finding is consistent with the observations of *HajGhanbari et al. (2013),* who demonstrated that respiratory training improves not only ventilatory functions but also exercise tolerance and perception of exertion, particularly a decrease in cardiac RPE (rating of perceived exertion), as reported by athletes during test sessions. This decrease in perceived physiological load at constant intensity reflects improved ventilatory efficiency and reduced cardiovascular stress at iso-intensity.

Although our study did not directly measure exercise time limits, the observed increases in power at VT1, VT2, and VO_2max, coupled with reduced RPE and improved ventilatory mechanics, strongly suggest a potential increase in time limits at equivalent relative intensities, as also observed by *Leddy et al. (2007)* in comparable contexts.

The results of this study are consistent with previous research highlighting the positive impact of respiratory training on endurance performance, particularly in disciplines such as rowing, running, and cycling. In rowers, research by *Klusiewicz et al. (2008), Volianitis et al. (2001), and Griffiths & McConnell (2007)* showed that a 4- to 6-week respiratory muscle training protocol improved muscle strength, but that the effect on performance became significant and more stable after 11 weeks of practice[31]. The gains observed include a reduction in the perception of dyspnea, an improvement in respiratory capacity, and an increase in performance during maximal or timed efforts[32,33], with a +3.5% improvement on a 6-minute test and a 3.1% reduction in time over 5000 meters. These results are consistent with those observed in the present study, which shows a marked reduction in respiratory rate and an improvement in power at ventilatory thresholds, indirect indicators of a decrease in ventilatory cost and improved respiratory efficiency.

In the context of running, studies by *Katayama et al. (2019) and Leddy et al. (2007)* reported substantial improvements in maximum voluntary ventilation (+10%), respiratory muscle endurance (+208%), and treadmill exercise time limit (+11 to +50%), accompanied by a significant reduction in ventilatory and metabolic parameters (Rf, VE, VO_2, blood lactate). These effects, in particular the decrease in respiratory rate and perception of dyspnea, are perfectly aligned with the adaptations observed in our study, reinforcing the hypothesis that ventilation is a lever for overall performance across endurance disciplines.

Among cyclists, several studies[10,13,34–36] have reported that a 4- to 6-week protocol was sufficient to induce an improvement in inspiratory strength and dynamic ventilatory functions, with increases in ventilatory capacity estimated at between +12 and +16%. The ergogenic effect also resulted in a decrease in time trial times of 2.1 to 4.75% [10,36,37]. These results confirm the value of incorporating inspiratory strengthening sessions into the planning of cyclic disciplines, which our protocol demonstrated over an extended period of 48 weeks, with a progressive structure combining isocapnic work, inspiratory resistance, and dynamic strategies during exercise.

Under hypoxic conditions, the work of Álvarez-Herms et al. (2019) showed that respiratory training increased maximum inspiratory force (+15 to +28%), minute ventilation (+21 to +25%), and pulmonary diffusion (+23%), while significantly improving oxygen saturation and reducing cardiac load at equivalent intensity. These physiological effects led to a +36.7% improvement in time to exhaustion at 80% VO_2max and a 7.3% reduction in time on an ergocycle time trial. These data confirm the benefits observed in our protocol, particularly in terms of ventilatory control during prolonged intense exercise, as well as relative power and tidal volume at VO_2max.

In summary, our study corroborates and extends previous work by providing new insights into the long-term periodization of a structured respiratory protocol combining inspiratory strengthening, isocapnic work, and strategic integration. It reinforces the idea that ventilatory optimization is a training component in its own right, on a par with muscular, cardiovascular, and nutritional preparation, with measurable benefits for aerobic performance, energy economy, and perception of intensity.

In addition, this study revealed significant differences between the tidal volumes observed in static conditions (spirometry) and those recorded in dynamic conditions during exercise, highlighting the value of incorporating exercise-based ventilatory analysis tools for more accurate functional assessment[14]. Taken together, these results suggest that ventilatory training and respiratory strategies applied to exercise have three major effects: (1) a decrease in the activation of the respiratory metaboreflex, preserving blood flow to the locomotor muscles; (2) a reduction in the energy cost of ventilation through increased mechanical efficiency; and (3) improved oxygen extraction by tissues via the Bohr and Haldane effects, thereby improving overall aerobic performance[21,38].

Finally, this study confirms that ventilation is a specific motor skill that must be trained and strategically integrated into performance planning. This involves not only physiological adaptations, but also significant mobilization of cognitive abilities to implement ventilation strategies effectively and contextually[23]. The development of these skills is a lever for performance optimization that is still underutilized in the training of endurance athletes.

Study limitations

Despite the encouraging results observed in this study, several methodological limitations must be considered in order to interpret the data with caution.

Firstly, the study is based on a descriptive approach, relying solely on monthly average values of the measured parameters. No in-depth statistical analysis (such as significance testing, confidence intervals, or effect size calculations) could be performed due to the confidential and protected nature of the individual data. This choice was driven by the need to safeguard the strategic and economic interests tied to the performance of the professional athletes involved. Consequently, it is not possible to formally establish the statistical significance of the observed changes, even though some of them exceed the thresholds of variation commonly considered significant in the literature (±5 to 10%)[30].

Secondly, the sample is small (n = 10) and homogeneous, consisting exclusively of high-level male professional athletes, which limits the generalizability of the results to other sporting populations (women, amateurs, other disciplines). Moreover, the absence of a control or placebo group, an essential element in interventional research, prevents a clear distinction between the adaptations attributable to the ventilatory protocol and those resulting from other components of training.

The analysis highlights significant interindividual variability in responses to the respiratory training protocol, with gains ranging from 5 to 10% depending on the evaluated parameters (tidal volume, respiratory rate, S-index, power at ventilatory thresholds). This heterogeneity indicates that the effectiveness of ventilatory interventions cannot be considered uniform and depends greatly on the individual profile of each athlete. Several explanatory factors can be considered: differences in adherence to the protocol, cognitive ability to integrate dynamic breathing instructions, level of experience with ventilatory control techniques, or neuromuscular characteristics influencing respiratory muscle recruitment.

These elements support the need for highly individualized respiratory training programs. Furthermore, the athletes' ability to apply these ventilatory strategies in real-world effort situations, particularly during competition, depends on specific perceptual and attentional skills, which were scarcely explored in the present study. The effectiveness of the integrated ventilatory approach thus relies not only on physiological adaptations but also on the conscious and contextual mastery of the taught techniques, an area that remains largely under-investigated. Future research integrating neurocognitive measurements and in-depth evaluations of practical application in ecological settings would help clarify the conditions that foster optimal responses to the ventilatory protocol.

Thirdly, although the protocol spans a duration of 48 weeks, the study does not assess the medium- or long-term maintenance of the adaptations, nor the effect of discontinuing the protocol. The impact of "ventilatory detraining" was therefore not examined, raising the question of the sustainability of the gains achieved without specific maintenance. The study by *Kowalski et al. (2024)* highlights that although significant benefits can be obtained after just a few weeks of RMT, a detraining period of 8 to 12 weeks is sufficient to cause a partial decline in functional adaptations, even if some improvements persist beyond the complete cessation of training[39]. Consequently, the absence of a follow-up phase in our study prevents any definitive conclusions regarding the long-term durability of the protocol's effects.

Moreover, certain key performance parameters, such as time to exhaustion or post-exercise recovery kinetics, were not directly measured, even though they are commonly used in reference studies as indicators of functional transfer[10,40].

Finally, the interindividual variability in the appropriation of ventilatory strategies, particularly their integration in dynamic contexts such as competition, was not explored. Yet, the effectiveness of these strategies largely depends on the athlete's ability to apply them consciously, which may be influenced by complex cognitive, emotional, and sensory factors[23,24].

Despite these limitations, the results obtained provide valuable insights into the potential ventilatory adaptations induced by targeted training and their impact on endurance performance. They warrant further studies, including rigorous statistical analyses, additional measurements (fatigue, perceived exertion, transfer to competition), and longitudinal follow-up after discontinuation of the protocol.

Conclusion

This study aimed to assess the effects of a combined protocol of respiratory training and exercise-based ventilatory strategies on ventilatory function, exercise physiology, and performance in professional cyclists. The results obtained over a 48-week period highlight adaptations at the mechanical, neuromuscular, and functional levels of the respiratory system.

From a ventilatory perspective, the intervention led to improvements in both inspiratory and expiratory capacities, reflected in increases in the S-index, PIF, inspiratory volumes, as well as FEV_1 and FEV_6. These changes indicate enhanced strength, coordination, and endurance capacity of the ventilatory muscles in a group of already highly trained athletes. The improvement in ventilatory pattern was confirmed by a reduction in respiratory rate at all intensities, compensated by a significant increase in tidal volume, an indicator of more efficient breathing.

At the physiological level, the slight increase in VO_2max and especially the elevation of ventilatory thresholds (VT1 and VT2) allow athletes to sustain higher intensities without quickly entering a zone of metabolic fatigue. The stabilization or reduction of minute ventilation, despite increased intensity, suggests a decreased energetic cost of breathing, likely related to better CO_2 tolerance and effective modulation of respiratory frequency.

In terms of performance, the observed gains in both absolute and relative power, at VO_2max and at the thresholds, demonstrate an effective transfer of ventilatory adaptations to mechanical output. The cyclists were able to produce more power at a constant body weight, which represents a decisive advantage in competition, particularly during prolonged efforts or climbs.

In conclusion, the combination of structured inspiratory training and integrated ventilatory strategies during exercise effectively optimized respiratory function in professional cyclists, simultaneously enhancing ventilatory mechanics, fatigue management, and respiratory efficiency. These results support the integration of ventilatory training as a complementary lever in the physical preparation of elite endurance athletes. A personalized approach, accounting for the specific demands of the sport, individual ventilatory profiles, and competitive constraints, appears essential to maximize the benefits of this approach.

References

1. Borszcz FK, Tramontin ,Artur F., de Souza ,Kristopher M., Carminatti ,Lorival J., and Costa VP. Physiological Correlations With Short, Medium, and Long Cycling Time-Trial Performance. *Res Q Exerc Sport*. 2018;89(1):120-125. doi:10.1080/02701367.2017.1411578

2. Støren Ø, Ulevåg K, Larsen MH, Støa EM, Helgerud J. Physiological Determinants of the Cycling Time Trial. *J Strength Cond Res*. 2013;27(9):2366-2373. doi:10.1519/JSC.0b013e31827f5427

3. Dempsey JA, La Gerche A, Hull JH. Is the healthy respiratory system built just right, overbuilt, or underbuilt to meet the demands imposed by exercise? *J Appl Physiol Bethesda Md 1985*. 2020;129(6):1235-1256. doi:10.1152/japplphysiol.00444.2020

4. Aaron EA, Seow KC, Johnson BD, Dempsey JA. Oxygen cost of exercise hyperpnea: implications for performance. *J Appl Physiol*. Published online May 1, 1992. doi:10.1152/jappl.1992.72.5.1818

5. Harms CA, Wetter TJ, McClaran SR, et al. Effects of respiratory muscle work on cardiac output and its distribution during maximal exercise. *J Appl Physiol Bethesda Md 1985*. 1998;85(2):609-618. doi:10.1152/jappl.1998.85.2.609

6. Marks DW, Robergs RA, Nelson J, Vella C, Bell-Wilson J, Apkarian M. Oxygen cost of ventilation and its effect on the VO2 plateau. *Respirology*. 2005;8(5):1-13.

7. Legrand R, Marles A, Prieur F, Lazzari S, Blondel N, Mucci P. Related Trends in Locomotor and Respiratory Muscle Oxygenation during Exercise. *Med Sci Sports Exerc*. 2007;39(1):91-100. doi:10.1249/01.mss.0000241638.90348.67

8. Turner L, Tecklenburg-Lund S, Chapman R, Shei RJ, Wilhite D, Mickleborough T. The Effect of Inspiratory Muscle Training on Respiratory and Limb Locomotor Muscle Deoxygenation During Exercise with Resistive Inspiratory Loading. *Int J Sports Med*. 2016;37(08):598-606. doi:10.1055/s-0042-104198

9. Boutellier U, Büchel R, Kundert A, Spengler C. The respiratory system as an exercise limiting factor in normal trained subjects. *Eur J Appl Physiol Occup Physiol*. 1992;65:347-353. doi:10.1007/BF00868139

10. Romer LM, Mcconnell AK, Jones DA. Inspiratory muscle fatigue in trained cyclists: effects of inspiratory muscle training. *Med Sci Sports Exerc*. 2002;34(5):785.

11. Coast JR, Clifford PS, Henrich TW, Stray-Gundersen J, Johnson RLJ. Maximal inspiratory pressure following maximal exercise in trained and untrained subjects. *Med Sci Sports Exerc*. 1990;22(6):811.

12. Eastwood PR, Hillman DR, Finucane KE. Inspiratory muscle performance in endurance athletes and sedentary subjects. *Respirology*. 2001;6(2):95-104. doi:10.1046/j.1440-1843.2001.00314.x

13. Leith DE, Bradley M. Ventilatory muscle strength and endurance training. *J Appl Physiol*. Published online October 1, 1976. doi:10.1152/jappl.1976.41.4.508

14. McConnell AK. CrossTalk opposing view: Respiratory muscle training does improve exercise tolerance. *J Physiol*. 2012;590(15):3397-3398. doi:10.1113/jphysiol.2012.235572

15. Patel MS, Hart N, Polkey MI. CrossTalk proposal: Training the respiratory muscles does not improve exercise tolerance. *J Physiol*. 2012;590(15):3393-3395. doi:10.1113/jphysiol.2012.235408

16. McConnell AK, Romer LM. Respiratory Muscle Training in Healthy Humans: Resolving the Controversy. *Int J Sports Med*. 2004;25(4):284-293. doi:10.1055/s-2004-815827

17. Romer LM, Miller JD, Haverkamp HC, Pegelow DF, Dempsey JA. Inspiratory Muscles do not Limit Maximal Incremental Exercise Performance in Healthy Subjects. *Respir Physiol Neurobiol*. 2007;156(3):353-361. doi:10.1016/j.resp.2006.10.008

18. Álvarez-Herms J, Julià-Sánchez S, Corbi F, Odriozola-Martínez A, Burtscher M. Putative Role of Respiratory Muscle Training to Improve Endurance Performance in Hypoxia: A Review. *Front Physiol*. 2019;9:1970. doi:10.3389/fphys.2018.01970

19. Hajghanbari B, Yamabayashi C, Buna TR, et al. EFFECTS OF RESPIRATORY MUSCLE TRAINING ON PERFORMANCE IN ATHLETES: A SYSTEMATIC REVIEW WITH META-ANALYSES. *J Strength Cond Res*.

20. Sk I, U H, I F, Cm S. Effect of respiratory muscle training on exercise performance in healthy individuals: a systematic review and meta-analysis. *Sports Med Auckl NZ*. 2012;42(8). doi:10.1007/BF03262290

21. Illidi CR, Romer LM, Johnson MA, et al. Distinguishing science from pseudoscience in commercial respiratory interventions: an evidence-based guide for health and exercise professionals. *Eur J Appl Physiol*. 2023;123(8):1599-1625. doi:10.1007/s00421-023-05166-8

22. Weldon A, Duncan MJ, Turner A, LaPlaca D, Sampaio J, Christie CJ. Practices of Strength and Conditioning Coaches: A Snapshot From Different Sports, Countries, and Expertise Levels. *J Strength Cond Res*. 2022;36(5):1335. doi:10.1519/JSC.0000000000003773

23. Cruz LBVD, Pupin CDF, Verri ED. The influence of respiratory techniques on sports performance: Literature review. *Res Soc Dev*. 2024;13(9):e0813946759. doi:10.33448/rsd-v13i9.46759

24. Laborde S, Zammit N, Iskra M, et al. The influence of breathing techniques on physical sport performance: a systematic review and meta-analysis. *Int Rev Sport Exerc Psychol*. 2024;17(2):1222-1277. doi:10.1080/1750984X.2022.2145573

25. Migliaccio GM, Russo L, Maric M, Padulo J. Sports Performance and Breathing Rate: What Is the Connection? A Narrative Review on Breathing Strategies. *Sports*. 2023;11(5):103. doi:10.3390/sports11050103

26. Russo MA, Santarelli DM, O'Rourke D. The physiological effects of slow breathing in the healthy human. *Breathe*. 2017;13(4):298-309. doi:10.1183/20734735.009817

27. Guyenet PG. Regulation of Breathing and Autonomic Outflows by Chemoreceptors. *Compr Physiol*. 2014;4(4):1511-1562. doi:10.1002/cphy.c140004

28. Hamasaki H. Effects of Diaphragmatic Breathing on Health: A Narrative Review. *Medicines*. 2020;7(10):65. doi:10.3390/medicines7100065

29. Sikora M, Mikołajczyk R, Łakomy O, et al. Influence of the breathing pattern on the pulmonary function of endurance-trained athletes. *Sci Rep*. 2024;14(1):1113. doi:10.1038/s41598-024-51758-5

30. Currell K, Jeukendrup AE. Validity, Reliability and Sensitivity of Measures of Sporting Performance. *Sports Med*. 2008;38(4):297-316. doi:10.2165/00007256-200838040-00003

31. Klusiewicz A, Borkowski L, Zdanowicz R, Boros P, Wesołowski S. The inspiratory muscle training in elite rowers. *J Sports Med Phys Fitness*. 2008;48(3):279-284.

32. Griffiths LA, McConnell AK. The influence of inspiratory and expiratory muscle training upon rowing performance. *Eur J Appl Physiol*. 2007;99(5):457-466. doi:10.1007/s00421-006-0367-6

33. Volianitis S, Mcconnell AK, Koutedakis Y, Mcnaughton L, Backx K, Jones DA. Inspiratory muscle training improves rowing performance: *Med Sci Sports Exerc*. 2001;33(5):803-809. doi:10.1097/00005768-200105000-00020

34. Fairbarn M, Coutts K, Pardy R, McKenzie D. Improved Respiratory Muscle Endurance of Highly Trained Cyclists and the Effects on Maximal Exercise Performance. *Int J Sports Med*. 1991;12(01):66-70. doi:10.1055/s-2007-1024658

35. Hopper SI, Murray SL, Ferrara LR, Singleton JK. Effectiveness of diaphragmatic breathing for reducing physiological and psychological stress in adults: a quantitative systematic review. *JBI Database Syst Rev Implement Rep*. 2019;17(9):1855-1876. doi:10.11124/JBISRIR-2017-003848

36. Sonetti DA, Wetter TJ, Pegelow DF, Dempsey JA. Effects of respiratory muscle training versus placebo on endurance exercise performance. *Respir Physiol*. 2001;127(2-3):185-199. doi:10.1016/S0034-5687(01)00250-X

37. Holm P, Sattler A, Fregosi RF. Endurance training of respiratory muscles improves cycling performance in fit young cyclists. *BMC Physiol*. 2004;4:9. doi:10.1186/1472-6793-4-9

38. Katayama K, Goto K, Ohya T, et al. Effects of Respiratory Muscle Endurance Training in Hypoxia on Running Performance. *Med Sci Sports Exerc*. 2019;51(7):1477-1486. doi:10.1249/MSS.0000000000001929

39. Kowalski T, Granda D, Klusiewicz A. Practical Application of Respiratory Muscle Training in Endurance Sports. *Strength Cond J*. Published online April 2, 2024. doi:10.1519/SSC.0000000000000842

40. Leddy JJ, Limprasertkul A, Patel S, et al. Isocapnic hyperpnea training improves performance in competitive male runners. *Eur J Appl Physiol*. 2007;99(6):665-676. doi:10.1007/s00421-006-0390-7