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Breathing Motion Pattern in Cyclists: Role of Inferior against Superior Thorax Compartment

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ABSTRACT

The thoracoabdominal breathing motion pattern is being considered in sports training because of its contribution, along with other physiological adaptations, to overall performance. We examined whether and how experience with cycling training modifies the thoracoabdominal motion patterns. We utilized optoelectronic plethysmography to monitor ten trained male cyclists and compared them to ten physically active male participants performing breathing maneuvers. Cyclists then participated in a self-paced time trial to explore the similarity between that observed during resting breathing. From the 3D coordinates of 32 markers positioned on each participant's trunk, we calculated the percentage of contribution of the superior thorax, inferior thorax, and abdomen and the correlation coefficient among these compartments. During the rest maneuvers, the cyclists showed a thoracoabdominal motion pattern characterized by an increased role of the inferior thorax relative to the superior thorax (26.69 ± 5.88 %, 34.93 ± 5.03 %; $p = 0.002$, respectively), in contrast to the control group (26.69 ± 5.88 %; 25.71 ± 6.04 %, $p = 0.4$, respectively). In addition, the inferior thorax showed higher coordination in phase with the abdomen. Furthermore, the results of the time trial test underscored the same pattern found in cyclists breathing at rest, suggesting that the development of a permanent modification in respiratory mechanics may be associated with cycling practice.

Introduction

Cycling is a demanding endurance sport that requires high physical fitness and stamina. Professional cyclists exhibit specific physiological responses such as considerable reliance on fat metabolism, even at high power outputs, and several neuromuscular adaptations [1–3]. Respiratory efficiency is also critical for cyclists [4–6]. Through training, they can improve oxygen uptake, which helps to improve endurance and delay the onset of fatigue during prolonged efforts [6–8]. In particular, they develop distinctive breathing patterns at high workloads that are distinguished by a lack of tachypnoeic shift, as they maintain increased pulmonary ventilation by increasing tidal volume rather than respiratory frequency of breathing [5, 9]. It is suggested that this breathing adaptation can enhance metabolic efficiency, partly accounting for the VO_2 kinetics [1].

While all such physiological adaptations are well documented, there is insufficient information regarding respiratory mechanics, described as thoracoabdominal (THA) motion patterns, i. e. displacement and coordination of the rib cage and abdomen [10]. Generally speaking, THA motion patterns modify according to the physical activity intensity, being dependent also on other factors such as gender, posture, and motion task [11–14]. Conversely, long-term sports training can permanently modify the THA motion patterns (evidenced by measurements taken during rest breathing maneuvers), to the advantage of better respiratory performance [15–17].

Especially, optimized lung and chest wall compliance, required to progressively suppress dyspnea and minimize the work of breathing, elicits respiratory mechanics adaptation [18, 19]. At rest and during exercise, there are distinct patterns of muscular recruitment. During rest, the rib cage muscles (as external intercostals, scalene, sternocleidomastoid) and the diaphragm act as pressure generators, and the abdominal muscle is not active. Instead, during exercise, the diaphragm behaves essentially as a flow generator because its shortening ability is greater than the inspiratory rib cage muscles, and the rib cage and abdominal muscles (such as transversus abdominis and internal and external oblique) are pressure generations [20, 21].

Among different non-invasive technologies to measure chest wall displacements, optoelectronic systems have been largely adopted, which record the 3D position of physical markers distributed homogeneously on the trunk surface [15, 16, 22–24]. Traditionally, the shape of the chest wall is partitioned into three functional compartments independent of each other [25]. This compartmental division provides information on respiratory muscles' action and assesses breathing movement patterns [18].

During pedaling, breathing muscles act as a crucial postural function, where optimal relation between the diaphragm, abdominal wall, parasternal, and pelvic floor provides production, transfer, and control of the active force [26]. In particular, the bike sitting posture may induce physical constraints to THA expansion and could affect respiratory mechanics. These differences in thoracoabdominal patterns become particularly prominent during moderate-intensity efforts, where there is an expected gradual increase in ventilation aligned with alveolar ventilation [27] and respiratory function [28, 29]. This phenomenon can be observed, for instance, during a time trial race that involves cyclists completing a predetermined distance as swiftly as possible. Such races have been utilized in laboratory settings to simulate endurance events and predict aerobic performance indicators like VO_2 and lactate threshold [30].

Since 2008, our group has been investigating factors affecting THA motion patterns, such as physical activities, exercise, long-term training, and more in general anamnestic data [15, 16, 22, 31]. Experienced swim training was shown to increase coordination of the THA volumes and the ribs motion [22], and the contribution of the abdominal compartment [15]. Experienced ballet dancers, both men and women, showed the predominant respiratory contribution of the upper thorax and abdomen [16]. Interestingly, age was found to be a weak predictive factor for changes in breathing motion patterns, contrary to what is commonly believed in the field of respiratory physiology [31].

Capitalizing on such previous studies, this work aimed to investigate the THA breathing motion pattern in experienced cyclists compared to non-cyclists. To provide further clarity, a secondary objective was to examine potential disparities in the THA motion pattern of experienced cyclists during periods of rest and exercise, with the intention of evaluating the consistency and stability of such patterns. To achieve these objectives, our study involved subjecting the cyclists to a targeted simulated 20-km time trial.

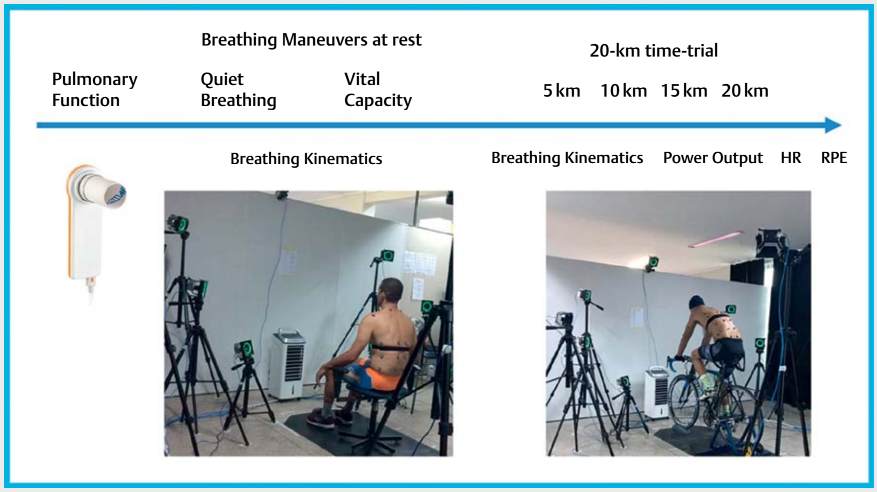
Material and Methods

Participants and experimental protocol

Twenty healthy and non-smoker participants were enrolled in this study. They were divided into two sets, respectively control and cyclist groups. The control group comprised ten males physically active in different recreational sports, none of whom had ever been involved in intensive cycling practice. Every participant in the control group engaged in physical exercise for more than 3 hours per week. The cyclist group was composed of ten trained cyclist males with at least five years of competitive experience on speed bikes, who regularly participate in regional cycling events. The acquisition protocol involved a pulmonary function test performed by both groups. Specifically, three maneuvers of forced vital capacity were monitored first throughout spirometry. Then breathing maneuvers at rest, namely quiet breathing, and vital capacity trials, were monitored by optoelectronic plethysmography (▶ **Fig. 1a**). The cyclist group performed a simulated 20-km time-trial test (▶ **Fig. 1b**). The study was approved by the University Ethics Committee (Number 59773616.0.0000.5153) in compliance with the Declaration of Helsinki, and all participants provided written informed consent.

Pulmonary function test

To compare the pulmonary function, a spirometer (Micro-medical, Rochester, Kent, England) was used. The control and cyclist groups performed three maneuvers of the forced vital capacity according to a standard protocol in a sitting posture [32]. Measurements were obtained for forced vital capacity (FVC), which is the greatest total amount of air expired, and for the forced expiratory volume in one second (FEV_1), which is the volume delivered in the first second of a forced vital capacity maneuver according to the guidelines estab-



▶ **Fig. 1** General protocol and tests performed.

lished by the American Thoracic Society/European Respiratory Society [33]. These data were expressed as mean and percentages of predicted values for the Brazilian population, according to [34].

THA – movement patterns by three-dimensional kinematics of the trunk compartments

Thirty-two retro-reflective markers were placed on the trunk of the participants [25]. The markers were positioned as a grid, using anatomical references allowing trunk division into three compartments namely superior thorax (ST), from 2^{nd} rib to the xiphoid process, inferior thorax (IT), from this line to the 10^{th} rib, and abdomen (AB), from this line to transverse of the abdomen [16]. The 3D coordinates of the markers were acquired with eleven OptiTrack Prime 17 W cameras (NaturalPoint, Corvallis, OR, USA, 360 Hz), positioned around the participants. A low pass, cutoff frequency of 10 Hz, was used to filter the marker trajectories. From the filtered marker locations, the compartmental volumes were calculated frame by frame using a volumetric convex hull method in the software Visual 3D (C-Motion, USA) [23]. The variation of the compartmental volume was expressed as a function of the time, divided into breathing cycles, defined as the beginning of inspiration to the end of expiration. Considering *n* breathing cycles, the percentage of contribution of each compartment (*%ST*, *%IT*, *%AB*) was computed as:

$$\%ST = \frac{1}{n}\sum_{i=1}^{n}\left(\%\frac{ST_i}{Vtot_i}\right)$$
$$\%IT = \tfrac{1}{n}\textstyle\sum_{i=1}^{n}\left(\%\frac{IT_i}{Vtot_i}\right) \qquad (1)$$
$$\%AB = \frac{1}{n}\sum_{i=1}^{n}\left(\%\frac{AB_i}{Vtot_i}\right)$$

where V_{tot} is the total trunk volume in the i^{th} breathing cycle. We also calculated the relative ratio between percentage of contribution of superior thorax and abdomen, and inferior thorax and abdomen. In order to assess the coordination among the THA compartments, the correlation coefficient was computed by means of the cross-correlation between the pairs of the compartmental volume during the inspiration phase. Positive and negative correlations indicated coordinated and paradoxical movements, respectively.

Breathing maneuvers at rest

Participants (control group and cyclist group) were seated on a chair without back support, with shoulder abduction, forearms leaned on a rigid support, 90º of knee flexion, and feet on the ground (▶ **Fig. 1a**). Following an adaptation period (at least 2 min) to the experimental setup, they performed two quiet breathing trials (30 s, each). Then, they performed two trials of five cycles of vital capacity, characterized by five periods of maximum inspiration followed by maximum forced expiration. The participants were directed to perform this maneuver using a verbal cue.

Simulation of the 20-km time trial

The cyclists performed a self-paced time trial in laboratory settings (▶ **Fig. 1b**) using their bicycle coupled to a cycle trainer (Computrainer ProLab 3D, Racermate, Seattle, WA, USA). The rear wheel of the personal bike was changed to Powermeter equipment (PowerTap, Saris, Madison, USA). The 20-km time trial protocol was configured in the Computrainer software as a flat course and consisted of a 10-min warm-up, and a 20-km time trial simulated test performed in the shortest time possible. The participants received verbal encouragement stimulus when they were nearly to achieve a distance of 5, 10, 15 km, and at the end of the test (20 km). They were instructed to maintain their hands at brake hoods enabling trunk markers' tracking. The THA movement pattern was evaluated one minute earlier each step in 5, 10, 15, and 20 kilometers. Heart rate (HR) and ratings of perceived exertion (RPE) were acquired at the following distances, namely 5, 10, 15, and 20 km. HR was measured using a Polar Fitness tracker chest strap and the data was acquired by smartphone app (Elite HRV). The RPE was measured using Borg's CR-10 scale (1 to 10) [35], where 1 corresponds to 'no exertion' and 10 corresponds to 'extreme/maximal exertion'.

The participants received standardized instructions for each measure using this scale before the exercise session.

Statistical analysis

The normality of the data was evaluated using the Shapiro-Wilk test. The percentage of contribution and correlation coefficient were not normally distributed and the arcsine transformation and Fisher's z-transformation were applied, respectively. Quiet breathing and vital capacity maneuvers were analyzed separately. To analyze breathing maneuvers at rest, the Mann-Whitney test was adopted to compare the descriptive participants' characteristics between groups. Repeated measure ANOVAs were then considered to evaluate the percentage of contribution and correlation coefficient both with one between factors (groups: control group and cyclist group) and one within factor (contribution of compartments: superior thorax, inferior thorax and abdomen or pairs compartments: superior thorax × inferior thorax, superior thorax × abdomen and inferior thorax × abdomen, respectively). The repeated measure ANOVA with one within factor (time) was applied to evaluate the power output and HR, and for the RPE the Friedman test was used. To analyze the breathing motion pattern during the 20-km time trial, the repeated measure ANOVA with two within factors (contribution of compartments: superior thorax, inferior thorax and abdomen or pairs compartments: superior thorax × inferior thorax, superior thorax × abdomen and inferior thorax × abdomen and time: quiet breathing, vital capacity, 5, 10, 15, 20 km) were employed, respectively. Mauchly's test of sphericity was performed and the Huynh-Feldt correction was exploited to correct the variability in experimental error. If significant F-ratios were detected, a Bonferroni post-hoc comparison was applied to determine where the differences occurred. Cohen's *d* standardized effect sizes and confidence intervals (set at 95 %) were reported when appropriate. Statistical significance was set at ($\alpha = 5\,\%$) for all analyses and was performed using SPSS version 18.0.

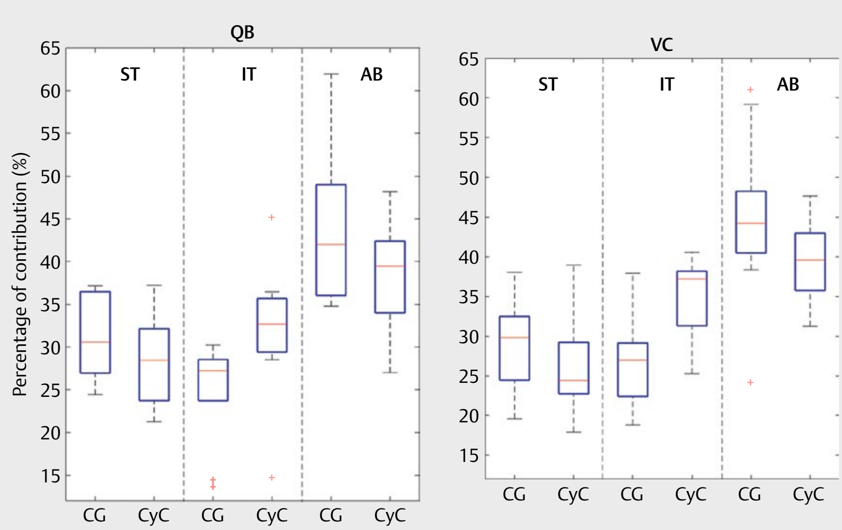
▶ **Table 1** Description of the study sample (mean ± SD) for the subjects' characteristics, pulmonary function, and training.

	Cyclists	**Control**
Subject characteristics		
Age (years)	42.7 ± 6.3	41.9 ± 8.7
Height (m)	1.75 ± 0.07	1.7 ± 0.08
Weight (kg)	75.9 ± 7.4	81.4 ± 10.2
Pulmonary function		
FEV_1 (l)	3.9 ± 0.6	3.6 ± 0.5
FEV_1 (% predict)	109.7 ± 19.3	105.2 ± 15.8
FVC (l)	4.3 ± 0.8	4.4 ± 0.7
FVC (% predict)	100.3 ± 20.6	104.8 ± 14.8
Training description		
Time per week (h)	11.2 ± 2.1	5.9 ± 2.7
Experience (years)	19.2 ± 10.9	22.6 ± 14*

Results

The two groups did not differ significantly in terms of age, height, and weight (▶ **Table 1**). All the participants showed pulmonary function results equal to or higher than predicted, and no significant differences between groups were found.

Regarding the relative ratio between inferior thorax and abdomen, the cyclist group exhibited values of 0.81 for quiet breathing and 0.89 for vital capacity, whereas the control group showed values of 0.56 for quiet breathing and 0.60 for vital capacity. The ANOVA analyses of the percentage of contribution in quiet breathing (▶ **Fig. 2a**) showed that the effect of the factor group was not significant ($p = 0.458$). The effect of the factor compartment was significant ($p < 0.001$) and inferior thorax and superior thorax had a similar contribution, while abdomen had a significantly higher contribution than both inferior thorax (AB: 41.6 ± 7.9 %, 95 %CI [37.8, 45.3]; IT: 28.3 ± 7.7 %, 95 %CI [24.7, 31.9]; $p = 0.002$. $d = 1.68$)



▶ **Fig. 2** Boxplot of the percentage of contribution of superior thorax (ST), inferior thorax(IT), and abdomen (AB) during quiet Breathing(QB) (**a**) and vital Capacity (VC) (**b**) for the control and cyclist group; + : outlier data.

▶ **Table 2** Mean (±SD) values of the descriptive characteristics and thoracoabdominal movement pattern during TT20.

	5 km	**10 km**	**15 km**	**20 km**
RPE	3.6 ± 0.5	5.1 ± 0.67*	6.87 ± 0.76*◊	9.25 ± 0.31*◊†
HR (BPM)	171.5 ± 3.45	173.4 ± 3.34	176.4 ± 2.69	184 ± 3.18*◊†
Power Output (W)	245.76 ± 14.93	239.78 ± 14.16	237.41 ± 15.69	278.87 ± 20.81†
Percentage of contribution				
%ST	23.59 ± 3.06	23.60 ± 3.66	24.51 ± 3.23	23.59 ± 4.60
%IT	32.88 ± 2.33	32.94 ± 3.54	32.47 ± 2.84	33.01 ± 2.91
%AB	43.51 ± 3.28	43.45 ± 3.78	43.01 ± 4.20	43.38 ± 5.22
ST:AB	0.54	0.53	0.59	0.54
IT:AB	0.76	0.76	0.76	0.76
Correlation coefficient				
ST × IT	0.93 ± 0.03	0.92 ± 0.04	0.88 ± 0.07	0.89 ± 0.03
ST × AB	0.88 ± 0.06	0.87 ± 0.06	0.83 ± 0.09	0.84 ± 0.05
IT × AB	0.94 ± 0.04	0.94 ± 0.04	0.93 ± 0.03	0.92 ± 0.03

*significantly higher than 5 km; ◊significantly higher than 10 km; † significantly higher than 15 km. Significance level $p < 0.05$.

and superior thorax (30.1 ± 5.1 %, 95 %CI [27.6, 32.4]; $p = 0.001$, $d = 1.72$). Additionally, there was no significant interaction effect between the groups.

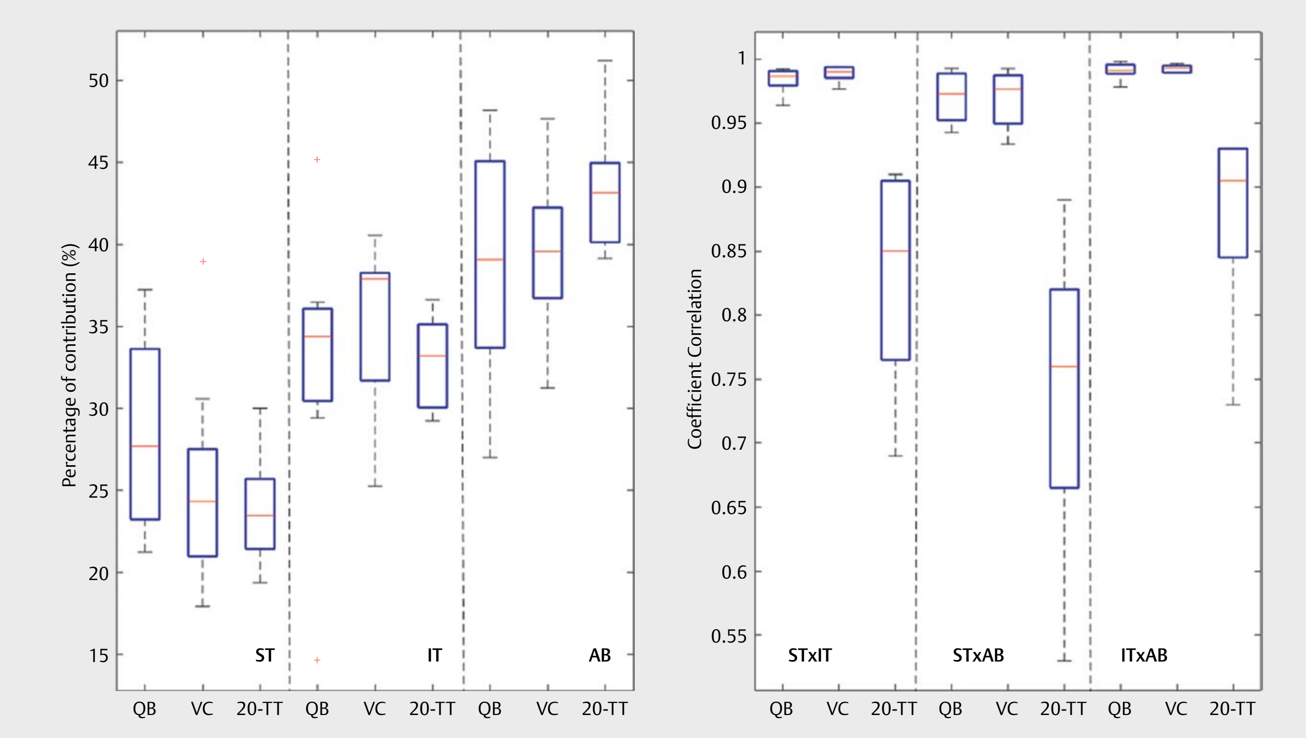
Again, in the vital capacity maneuver (▶ **Fig. 2b**), the ANOVA analyses showed that the effect of the factor group was not significant ($p = 0.336$), and the factor compartment was significant ($p < 0.001$), the abdomen contributing significantly more than inferior thorax (AB: 42.0 ± 8.4 %, 95 %CI [38.1, 45.9]; IT: 30.8 ± 6.8 %, 95 %CI [27.6, 34.0], $p = 0.003$, $d = 1.46$) and superior thorax (27.2 ± 5.9 %, 95 %CI [24.4, 29.9], $p < 0.001$, $d = 2.03$). In the cyclist group, the superior thorax had a lower contribution than the inferior thorax (ST: 25.7 ± 6.0 %, 95 %CI [21.4, 30.0]; IT: 34.9 ± 5.1 %, 95 %CI [22.5, 30.9], $p = 0.002$, $d = 1.65$) and abdomen (39.3 ± 4.8, 95 %CI [35.9, 42.8], $p = 0.004$, $d = 2.49$). In the control group, the abdomen had a higher contribution than the inferior (AB: 44.6 ± 10.5 %, 95 %CI [37.1, 52.1]; IT: 26.7 ± 5.8 %, 95 %CI [31.3, 38.5], p = 0.001, $d = 2.11$) and superior thorax (28.7 ± 5.6 %, 95 %CI [24.6, 32.7], p < 0.001, $d = 1.88$). Additionally, there was a significant interaction effect between the factors and the inferior thorax contribution of the cyclist group, which was significantly higher than the control group ($p = 0.004$, $d = 1.46$).

Both groups presented strong positive correlation coefficient values for quiet breathing and vital capacity (0.9 to 0.97). The cyclist group had correlation coefficient values significantly higher than the control group in quiet breathing ($p = 0.01$) and in vital capacity ($p = 0.034$). The inferior thorax × abdomen compartmental pair had significantly higher correlation coefficient values than superior thorax × inferior thorax and superior thorax × abdomen and superior thorax × inferior thorax was significantly higher than superior thorax × abdomen. In both maneuvers, Cohen's d values ranged from 0.22 to 0.99 ($p < 0.001$). Both groups presented this coordination pattern in quiet breathing. However, during vital capacity, this pattern changed. While the control group had similar coordination between abdomen × inferior thorax and superior thorax × inferior thorax, the abdomen × inferior thorax of the cyclist group was higher than the superior thorax × inferior thorax. Summarized statistical results are available in the supplementary material.

Due to missing data of some retro-reflective markers placed on the trunk of two cycling athletes during time trial, the results were reported only for eight participants (▶ **Table 2**). The RPE was different from each step of the time trial ($\chi^2 = 22.41$, $p < 0.001$; 5 > 10 > 15 > 20 km). In the last step of the time trial (20 km), HR was significantly higher than 5 km ($p = 0.001$), 10 km ($p = 0.011$), and 15 km ($p = 0.017$). Also, significant differences in power output were found ($p < 0.001$) and the 20 km was higher compared to 15 km ($p = 0.021$).

Related to the percentage of contribution, compartments were different from each other ($p < 0.001$, ▶ **Table 2**), the abdomen was significantly higher than inferior thorax (AB: 43.34 ± 3.98, 95 %CI [41.9, 44.78]; IF: 32.82 ± 2.8, 95 %CI [31.81, 33.83], $p = 0.004$, $d = 3.08$) and superior thorax (23.82 ± 3.52, 95 %CI [22.55, 25.10]; $p < 0.001$, $d = 5.31$), and inferior thorax was significantly higher compared to the superior thorax ($p = 0.004$, $d = 2.87$). The percentage of contribution of each compartment was the same in all the steps of the 20-km time trial (5, 10, 15, 20 km, $p = 0.879$). While the ratio superior thorax and abdomen oscillated between the steps, inferior thorax and abdomen was stable during all of the 20-km time trial (▶ **Table 2**). All compartment pairs presented strong correlation coefficient values. The superior thorax × abdomen was significantly lower than superior thorax × inferior thorax and inferior thorax × abdomen ($p = 0.004$, $p = 0.001$, respectively). In addition, the correlation coefficient was statistically different between steps of the 20-km time trial ($p < 0.001$). Step 5 km was higher than 20 km ($p = 0.039$, $d = 0.72$), and 10 km presented higher values compared to 15 km ($p = 0.012$, $d = 0.38$) and 20 km ($p = 0.036$, $d = 0.55$).

Since no significant differences were observed among the distances of 5 km, 10 km, 15 km, and 20 km, we employed the mean value for comparison with the rest maneuvers. No statistical difference was found when the percentage of contribution of cyclists at rest were compared with the 20-km time trial ($p = 0.19$, ▶ **Fig. 3a**). The relative ratios between superior thorax and abdomen, likewise inferior thorax and abdomen, were higher in the quiet breathing



▶ **Fig. 3** Boxplot of the percentage of contribution of each compartment superior thorax (ST), inferior thorax(IT), and abdomen (AB) (**a**). Boxplot of the correlation coefficients of superior thorax × Inferior thorax(ST × IT), superior thorax × abdomen (ST × AB), and inferior thorax × abdomen (IT × AB) (**b**) during the quiet breathing (QB) and vital capacity (VC) and during the 20-km time trial (20-TT).

▶ **Table 3** Summarized statistical results of quiet breathing, vital capacity and 20-km time trial for both groups and variables.

Summarized Statistical Results – Rest Maneuvers		
	Control Group	**Cyclist Group**
Percentage of Contribution		
Quiet Breathing	AB > ST > IT	AB > IT = ST
Vital Capacity	AB > ST = IT	AB = IT > ST
20-km Time Trial	n. a.	AB > IT > ST
Correlation Coefficient		
Quiet Breathing	AB × IT = ST × IT = ST × AB	AB × IT > ST × IT = ST × AB
Vital Capacity	AB × IT = ST × IT > ST × AB	AB × IT = ST × IT > ST × AB
20-km Time Trial	n. a.	AB × IT = ST × IT > ST × AB

Legend: AB: abdomen; IT: inferior thorax; ST: superior thorax; n. a.: not applicable.

and vital capacity than in the last step of the test. The 20-km time trial correlation coefficients of all compartmental pairs, superior thorax × inferior thorax, superior thorax × abdomen, and inferior thorax × abdomen, were significantly lower than quiet breathing and vital capacity ($p < 0.001$, ▶ **Fig. 3b**), and the Cohen's *d* values ranged from 2.32 to 2.78. Concise summary of the statistical outcomes was reported (▶ **Table 3**).

Discussion

Globally, as verified in rest breathing maneuvers, the abdomen contribution was greater than superior thorax and inferior thorax contributions individually in both groups. Specifically, cyclists demonstrated a specific THA motion pattern characterized by an increased role of the inferior thorax compartment with respect to the superior thorax (▶ **Fig. 1**), in opposition to the control group. In addition, inferior thorax contribution showed higher coordination with abdomen. The 20-km time trial test results highlighted the same THA motion pattern, which was kept stable throughout the trial, thus confirming the development of a permanent modification of the breathing mechanics in the cyclist group (▶ **Table 2**). Since no significant differences in anthropometric and pulmonary function values (▶ **Table 1**) were found between control group and cyclist group groups, this suggests that the differences in THA motion pattern may be attributed to cycling training.

While the statistical analysis supported the conclusions, the small cohort reduced the generalization of the results. We did not calculate post hoc power analyses given current statistical recommendations, but we do report confidence intervals for our primary results, which may be a superior means of interpreting the null and positive effects. In addition, the trained cyclists involved were not professionals; however, differences in the THA motion pattern with non-cyclists were detected.

Early studies showed that intense engagement in sports may easily elicit long-lasting THA patterns, with the greatest contribution to ventilation provided by the abdomen compartment [18, 36, 37], and our results agree with these findings. It is well known that physical activity recruits the abdominal muscles, featuring a higher magnitude than rib cage muscles, leading to a rise in diaphragmatic oxidative capacity [38]. Nonetheless, it was clearly documented that exercise training improves diaphragm antioxidant capacity and endurance [39]. More recent studies have shown that sport specificity is responsible for developing diverse changes in THA patterns [15–17], triggering specific improvements in breathing mechanics efficiency [40]. Nonetheless, it was argued that postural constraints may further contribute to the development of custom THA patterns [1]. In Silvatti and coauthors [15], the authors argued that long-term swimming training contributed to the development of very specific THA motion patterns. Likewise, professional ballet dancers were able to keep unchanged breathing mechanics in quiet breathing and vital capacity maneuvers [16]. The effect of training in Pilates practitioners was documented to modify the thoracoabdominal motion pattern by increasing the contribution of the abdomen [17]. A raise in the force, in both appositional and insertional of the diaphragm, related to the inferior thorax compartment, was already found in cyclists [12, 41].

The 20-km time trial simulation allowed us to use an ecological methodology to understand the THA pattern of cyclists, with a major contribution of inferior thorax than superior thorax, along with different coordination with abdomen. As a matter of fact, all the cyclists showed a U power-output strategy, with higher values at the beginning and end of the test. Nonetheless, as shown, the THA pattern was not different during the steps evaluated, highlighting their capacity to maintain the breathing motion pattern during the whole test. The reduced coordination between superior thorax and abdomen can be motivated by the limited mechanical linkage between them, which is intentional to minimize elastic work when moving the chest wall [42]. We may argue that another possible explanation is the difference in the inspiratory and expiratory reserve volumes, which are relatively greater in the rib cage and abdominal compartment [18], respectively, and prevent paradoxical motion of any chest wall compartment during exercise [21]. The greater percentage of contribution of the inferior thorax found in our results, and the long-lasting pattern due to training, was further supported by literature outcomes about untrained individuals performing cycling [12, 18, 43]. All studies pointed out the major contribution of superior thorax to the breathing pattern. In trained cyclists, it can be hypothesized that the inferior thorax mechanics have a greater role in intra-abdominal pressure regulation, contributing the most to spinal and pelvic floor stabilization [44, 45], respiratory function, and power output [41, 45, 46]. As a result, we argue that the planning of specific inspiratory muscle training is to be considered to further improve the performance of competitive cyclists, in agreement with [5] who suggested that inspiratory muscle training attenuates the perceptual response to maximal incremental exercise.

While our findings provide valuable insights into the differences between cyclists and non-cyclists, it is essential to acknowledge the inherent limitations of our approach. As our study employed a cross-sectional design, we lacked information about cyclists' breathing patterns from the inception of their training journey. Additionally, we did not track cyclists over the course of their progression from novice to experienced cyclists or monitor changes in their breathing patterns over time. To gain a more comprehensive understanding of the impact of cycling training on the thoracoabdominal motion pattern, future research should incorporate longitudinal designs. Longitudinal studies would allow for tracking the trajectory of individuals' thoracoabdominal motion patterns from the beginning of cycling training, potentially capturing the magnitude of its influence and uncovering causal relationships. Additionally, differentiating patterns between novice and experienced cyclists warrants investigation. Such studies would significantly contribute to a more in-depth exploration of the dynamic nature of thoracoabdominal motion in the context of cycling training.

In summary, cyclists demonstrated a specific thoracoabdominal motion pattern characterized by an increased role of the inferior thorax compartment with respect to the superior thorax. In addition, the inferior thorax contribution showed higher coordination with the abdomen. During the simulated 20-km time trial, the significant participation of the abdomen and inferior thorax was retained during all the tests, which can be associated with the cyclists' capacity to maintain during the effort imposed. Finally, the breathing mechanics outlined in this study can assist in designing specific programs aimed at improving the performance of competitive cyclists by enhancing the functionality of their inspiratory muscles, mainly the diaphragm.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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