

RESEARCH ARTICLE

Effect of Regular Yoga Practice on Respiratory Regulation and Exercise Performance

Eveline Beutler¹, Fernando G. Beltrami¹, Urs Boutellier^{1,2}, Christina M. Spengler^{1,2*}

1 Exercise Physiology Lab, Institute of Human Movement Sciences, ETH Zurich, Winterthurerstrasse 190, 8057, Zurich, Switzerland, **2** Zurich Center for Integrative Human Physiology (ZIHP), University of Zurich, Winterthurerstrasse 190, 8057, Zurich, Switzerland

* christina.spengler@hest.ethz.ch

Abstract

Yoga alters spontaneous respiratory regulation and reduces hypoxic and hypercapnic ventilatory responses. Since a lower ventilatory response is associated with an improved endurance capacity during whole-body exercise, we tested whether yogic subjects (YOGA) show an increased endurance capacity compared to matched non-yogic individuals (CON) with similar physical activity levels. Resting ventilation, the ventilatory response to hypercapnia, passive leg movement and exercise, as well as endurance performance were assessed. YOGA (n = 9), compared to CONTROL (n = 6), had a higher tidal volume at rest (0.7 ± 0.2 vs. 0.5 ± 0.1 l, $p = 0.034$) and a reduced ventilatory response to hypercapnia (33 ± 15 vs. 47 ± 15 l·min⁻¹, $p = 0.048$). A YOGA subgroup (n = 6) with maximal performance similar to CONTROL showed a blunted ventilatory response to passive cycling (11 ± 2 vs. 14 ± 2 l·min⁻¹, $p = 0.039$) and a tendency towards lower exercise ventilation (33 ± 2 vs. 36 ± 3 l·min⁻¹, $p = 0.094$) while cycling endurance (YOGA: 17.3 ± 3.3 ; CON: 19.6 ± 8.5 min, $p = 0.276$) did not differ. Thus, yoga practice was not associated with improved exercise capacity nor with significant changes in exercise ventilation despite a significantly different respiratory regulation at rest and in response to hypercapnia and passive leg movement.



OPEN ACCESS

Citation: Beutler E, Beltrami FG, Boutellier U, Spengler CM (2016) Effect of Regular Yoga Practice on Respiratory Regulation and Exercise Performance. PLoS ONE 11(4): e0153159. doi:10.1371/journal.pone.0153159

Editor: Claudio Passino, Fondazione G. Monasterio, ITALY

Received: December 1, 2015

Accepted: March 24, 2016

Published: April 7, 2016

Copyright: © 2016 Beutler et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper.

Funding: The authors have no support or funding to report.

Competing Interests: The authors have declared that no competing interests exist.

Introduction

The scientific interest in yoga has increased substantially in recent years and a number of physiological effects of yoga, including physical postures (asanas; [1, 2]), controlled breathing (pranayama; [3, 4–6]) and meditation [7], have been explored.

Focusing on the respiratory aspect of yoga, Pranayama generally involves controlled breathing techniques affecting the respiratory rhythm, namely through prolongation and shortening of breaths, and sometimes breath-holding, all implying voluntary control of respiratory muscles. These voluntary acts influence the breathing pattern, which is normally determined by the autonomic respiratory control center in the brain. There is evidence that voluntary control of breathing (practiced for 6–10 weeks) induces persistent alteration of the breathing pattern at

rest, shown in a reduced breathing frequency (f_R) [2, 3, 8–10]. On the other hand, some degree of controversy exists concerning changes in lung function, as improvements following yoga training are often [2, 8–12] but not always [3, 13, 14] reported.

Additionally, Spicuzza et al., [15] and Stanescu et al., [13] found that long-term yoga practice reduced chemoreflex sensitivity to hypoxia and hypercapnia, while blunted hypoxic ventilatory response (HVR) has also been shown both while breathing a modified gas mixture and at high altitude (hypobaric hypoxic conditions) in subjects with a broad experience in yoga practice [16]. Interestingly, a similarly reduced HVR and hypercapnic ventilatory response (HCVR) was described in athletes compared to sedentary controls [17] and in untrained subjects who have completed a 5-week period of cycling endurance training [18]. Therefore, a connection between changes in chemoreceptor sensitivity induced by practicing breathing exercises and physical performance seems plausible. Since the magnitude of the ventilatory response during exercise influences endurance capacity [19], this mechanism could be postulated for subjects practicing yoga, suggesting a lower ventilation during exercise, ultimately resulting in larger endurance capacity.

In fact, several studies indicate that regular yoga training could influence exercise performance in healthy subjects, shown in increased maximal tolerable workload (W_{max}) and decreased oxygen consumption during equal workload [20–23] or a higher maximal oxygen consumption ($\dot{V}O_{2peak}$) after varying periods of yoga training [1, 14, 24, 25]. These results raise the question of whether the improvements in exercise performance are associated with an altered ventilatory response during exercise in subjects practicing yoga.

Therefore, the present study combined different assessments to determine whether long-term yoga practice is associated with (i) a modified breathing pattern at rest, (ii) a reduced ventilatory response to CO_2 , (iii) an extended breath-hold duration, (iv) a reduced ventilatory response to passive leg movement and (v) to exercise, and finally (vi) whether these changes are associated with increased endurance capacity. For this purpose, ventilation and breathing pattern at rest, lung function, respiratory muscle strength, breath-hold duration, HCVR (to investigate chemoreceptor sensitivity), the ventilatory response to passive leg movement and to exercise, in addition to exercise endurance capacity, were assessed.

Methods

Subjects

Fifteen healthy female subjects were enrolled in the study, either in the YOGA group ($n = 9$) or in the age-, height-, weight- and fitness level-matched control (CON) group ($n = 6$). Physical activity levels was matched based on modality, duration and intensity, excluding the time spent practicing yoga in the YOGA group. The YOGA group participants were all yoga instructors, practicing yoga for an average of 7.1 ± 3.5 h·wk⁻¹, including pranayama for 3.0 ± 1.6 h·wk⁻¹ for the past 8.1 ± 6.6 years. All participants were between 18–45 years of age, had a body mass index (BMI) of 18–25 kg·m⁻², normal lung function, did not smoke or take any medications and were recreationally physically active. None of the participants suffered from acute or chronic diseases (assessed by questionnaire), had acute injuries, nor did participants take part in any activities that could possibly influence respiration such as singing or playing a wind instrument on a regular basis (i.e. ≥ 30 min·wk⁻¹). For CON subjects, additional exclusion criteria were performing yoga or any kind of respiratory exercise or respiratory training.

After detailed oral and written information regarding all procedures and possible risks, each subject signed a written consent prior to participation. The study was approved by the ethics committee of ETH Zurich and was performed according to the Declaration of Helsinki (2008 Revision).

Subjects were advised to keep their physical activity level constant throughout the entire testing period and were instructed to arrive at the laboratory in a rested state, with a minimum of 7 h sleep during two preceding nights of each testing day. In addition all subjects had to avoid strenuous exercise 48 h prior to each testing session and avoid any exercise the day before and on test days. Each subject was also asked to consume a high-carbohydrate meal for dinner the day before test days and to refrain from caffeine and alcohol intake on test days prior to testing.

Study protocol

Subjects attended the laboratory on 3 different occasions, separated by at least 48 h. Since the effect of the menstrual cycle on exercise performance is still debated in the current literature [26] and effects of progesterone on the pulmonary system, including hyperventilation and an increase in resting chemosensitivity to CO₂ and O₂, have been established [27], all measurements were conducted between the 7th and 14th day after ovulation, the longest period with little change in hormone concentrations.

All measurements were performed at the same time of day within each subject, but were spread over the day between subjects to distribute assessments over the potentially influencing endogenous circadian rhythm [28].

On the first day, lung function and respiratory muscle strength were measured for familiarization. On the second day, subjects performed lung function and respiratory muscle strength measurements again. After a 15-min resting period, subjects performed an incremental cycling test (ICT) to exhaustion. On the third day, subjects performed breath-hold testing followed, after a 10-min break, by 2 HCVR-tests that were separated by a 15-min break. Finally, after a 30 min break, the test including passive leg movement and a subsequent all-out constant load cycling endurance test (CET) was conducted. Tests are described in detail below.

Lung function and respiratory muscle strength

An ergospirometric device (Oxycon Pro, Jaeger, Höchberg, Germany) was used to assess lung function with precise volume measurements by means of a lightweight bi-directional digital volume transducer, attached directly to the mouthpiece and calibrated before each test, using a 3L syringe (Hans Rudolph, Kansas City, MO, USA).

Forced vital capacity (FVC), forced expired volume in one second (FEV₁), forced inspiratory volume in one second (FIV₁), peak expiratory flow rate (PEF), peak inspiratory flow rate (PIF) and maximal voluntary ventilation (MVV) were measured adhering to ATS/ERS standard procedures [29].

Respiratory muscle strength was determined using a hand-held mouth pressure meter, equipped with piezo resistive pressure sensing technology (Micro Medical, Kent, UK). Maneuvers were performed according to the ATS/ERS statement [30] on respiratory muscle testing. Maximal inspiratory mouth pressure (MIP) measurements were initiated at residual volume (RV), maximal expiratory mouth pressure (MEP) measurements at total lung capacity (TLC) using a flanged mouthpiece [31], with the subject seated in an upright position. Sniff nasal inspiratory pressure (SNIP) was measured by means of a plug occluding one nostril, initiated at functional residual capacity (FRC). A minimum of 5 well-executed measurements was conducted and the largest of the 3 values that varied less than 5% was defined as the maximum. For lung function [32] and respiratory muscle strength [33, 34], percent predicted values were calculated.

Breath-hold duration

Maximal voluntary breath-hold duration trials were performed at total lung capacity (TLC), in a sitting position and with nose clip in place. To prevent hyperventilation prior to breath-holding measurements, the experimenter controlled the subjects' breathing patterns visually. Subjects were instructed to continue breath-holding and to withstand any unpleasant feelings as long as possible. Maneuvers were continued until breath-hold duration did not increase any further, with a minimum of 3 trials per participant, always performed with 2-min breaks in-between. The largest breath-hold duration was used for further analysis.

Hypercapnic ventilatory response

The assessment of HCVR was performed according to the rebreathing method of Read [35]. The rebreathing circuit consisted of a mouthpiece connected to the ergospirometric device (Oxycon Pro, Jaeger, Höchberg, Germany; for calibration see incremental exercise test) and a 3-way valve which allowed to switch, at the end of a normal expiration, from breathing room air (for 5 min) to breathing in and out of the spirometer (starting volume: FVC+1L), containing an initial gas mixture of 7% CO₂ and 93% O₂. The test was continued until end-tidal CO₂ partial pressure (P_{ET}CO₂) reached 65 mmHg or the subjects stopped themselves.

Minute pulmonary ventilation (\dot{V}_E), f_R , tidal volume (V_T) and pressure of end-tidal CO₂ (P_{ET}CO₂) were recorded breath-by-breath. Oxygen saturation (SpO₂) and heart rate (HR) were monitored continuously on the forehead by means of a pulse oximeter (OxiMax™ N-600x™, Nellcor, Boulder, USA). The slope of the HCVR was calculated using a linear regression model, as described by Lorinc [36].

Incremental exercise test

ICT was performed on an electromagnetically braked bicycle ergometer (Ergoline 800, Bitz, Germany) and the subjects were connected via mouthpiece and turbine to the Oxycon Pro, which was calibrated before each test.

ICT started with a 5 min resting period, during which subjects were sitting quietly on the bicycle. Thereafter, subjects were instructed to pedal with their self-selected pedaling rate of 60–80 rpm, starting at an initial workload of 60 W. The workload was then increased by 30 W every 2 min until exhaustion or until the subject could not keep the pedaling rate within ± 3 rpm of their preferred cadence. The experimenter did not encourage the subjects at any time.

Breath-by-breath pulmonary gas-exchange data, \dot{V}_E , f_R , V_T and HR were collected continuously during the test. For the determination of blood lactate concentrations, 20 μ l blood samples from the earlobe were taken at rest and at the end of each work and analyzed enzymatically (Biosen 5040, EKF Diagnostic, Barleben, Germany).

In addition, the subjects had to rate their perception of breathlessness, respiratory exertion and leg exertion every 2 min, using a visual analogue scale (VAS), which was post-hoc split into values between 0 and 10. The extremes of the scale were defined as “none” up to “maximal” leading to an immediate termination of the test due to these particular sensations. To ensure that subjects could distinguish between breathlessness and respiratory exertion [37, 38], subjects' personal experience with these sensations were discussed comprehensively in advance. Hence, breathlessness was defined as “not getting enough air for a required effort”, respiratory exertion as “sensation of work and effort of respiratory muscles” or “how difficult it is to breathe” and leg exertion as “sensation of work and effort related to leg muscles”.

$\dot{V}O_{2peak}$ was taken as the highest 15 s average value of oxygen consumption ($\dot{V}O_2$) attained before the subject's volitional exhaustion in the test and W_{max} was extrapolated proportionally according to time spent at the final workload.

ICT data, i.e. ventilation, gas exchange and HR, were analyzed (at submaximal exercise) by means of 15 s averages over the first 8 min, the longest available period completed by all subjects, whereas for lactate concentration and ratings of perceived sensations, values taken at 2, 4, 6 and 8 min were averaged. The slope of the ventilatory equivalent for CO₂ ($\dot{V}E/\dot{V}CO_2$) was calculated from all breath-by-breath data during cycling [39].

ICT was accepted as a maximal test if at least two of the following criteria were met: respiratory exchange ratio > 1.1, HR_{max} > 90% of the age-predicted HR_{max}, i.e. 220- age, ratings on the VAS > 8, maximal lactate concentration > 8 mmol·L⁻¹.

Passive exercise and constant-load exercise test

The same experimental setting as described above was used for CET, including passive leg cycling movements, using the following protocol: after 5 min of rest, the subjects passively (without active muscle contractions) followed the cycling movements for 2 min while their feet were strapped to the pedals of the ergometer and the experimenter manually turned the pedals with the previously selected pedaling rate (ICT) which subjects subsequently maintained throughout the test. After the 2 min of passive pedalling, the workload was increased to 40% W_{max} for 2 min, subsequently to 60% W_{max} for 2 min, followed by 85% W_{max} until exhaustion or until subjects could no longer maintain the self-selected pedaling rate within ± 3 rpm. Subjects received no encouragement from the experimenter at any time.

Breath-by-breath data of ventilation, gas exchange and HR were collected during the test. Blood samples from the earlobe were taken at the beginning and at the end of each 2-min interval. Subjects marked VAS according to their perception of breathlessness, respiratory exertion and leg exertion every 2 min as described above. The time to task failure was used as a measure of exercise capacity and was recorded when the pedaling rate fell more than 3 rpm below the required pedaling rate.

To enable data comparison of the 2-min passive leg movement at steady-state, a 15-s average (from 1:30 to 1:45 min) was calculated and lactate concentration at the end of the 2-min period was used for analysis. Ventilation, gas exchange and HR data of the CET were analyzed by means of 15-s averages during the first 8 min (the longest period completed by all subjects), whereas for lactate concentration and rating of sensations, values taken at 4, 6 and 8 min were averaged.

Data analysis

Data are expressed as means ± standard deviations. Differences between groups were assessed by performing one-tailed student's t-tests for independent samples, except for anthropometric data and lung function where a two-tailed test was applied. For resting V.E, steady state data of relaxed quiet breathing (4th and 5th min) during ICT and CET were averaged and then compared to passive cycling or exercise, using one-tailed paired t-tests. Statistical significance was accepted at $p < 0.05$. Statistical evaluation was processed in IBM SPSS Statistics version 19.0 (SPSS, Chicago, IL, USA).

Results

Between the YOGA and the CON group, no differences were found with regard to age, height, body mass, body mass index (BMI) (Table 1) and recreational exercise activities (mean 2.7 ± 1.7 vs. 3.4 ± 1.0 h wk⁻¹, respectively; $p = 0.343$).

Table 1. Anthropometric data of yoga and control groups.

	YOGA	YOGA	CON
N	9	6	6
Age (years)	36 ± 6	35 ± 6	31 ± 5
Height (cm)	170 ± 4	171 ± 4	169 ± 5
Body mass (kg)	58 ± 4	59 ± 2	60 ± 4
BMI (kg·m ⁻²)	20 ± 1	20 ± 1	21 ± 2

Data is given as mean ± standard deviation. No significant differences were found between both yoga (YOGA) and control (CON) groups. BMI, body mass index.

doi:10.1371/journal.pone.0153159.t001

Lung function and respiratory muscle strength

Lung function and respiratory muscle strength of the YOGA and the CON group are shown in [Table 2](#). Lung function did not differ between the 2 groups. MIP and SNIP did not differ between the 2 groups while MEP was significantly lower in the YOGA compared to the CON group.

Breath-hold duration

Breath-hold duration did not differ ($p = 0.205$) between groups ([Table 2](#)).

Resting ventilation

Breathing pattern differed between groups, i.e. the YOGA group showed significantly higher V_T ($p = 0.034$) and lower f_R ($p = 0.058$), although the latter exhibited great variability and did

Table 2. Lung function, respiratory muscle strength and breath-hold duration.

	YOGA		CON	
	absolute	% pred.	absolute	% pred.
Lung function				
FVC (l)	4.6 ± 0.6	124 ± 15	4.3 ± 0.3	115 ± 8
FEV ₁ (l)	3.6 ± 0.5	112 ± 13	3.6 ± 0.3	109 ± 9
FIV ₁ (l)	4.1 ± 0.5	113 ± 14	4.0 ± 0.3	113 ± 8
PEF (l s ⁻¹)	7.8 ± 0.9	109 ± 12	8.0 ± 0.6	110 ± 10
PIF (l s ⁻¹)	5.8 ± 0.9	na	6.5 ± 0.7	na
MVV (l min ⁻¹)	132.8 ± 15.8	117 ± 14	144.2 ± 6.9	125 ± 7
Respiratory muscle strength				
MIP (cm H ₂ O)	100 ± 12	128 ± 17	111 ± 21	144 ± 26
MEP (cm H ₂ O)	140 ± 15*	144 ± 17*	161 ± 24	167 ± 24
SNIP (cm H ₂ O)	93 ± 17	107 ± 19	107 ± 19	121 ± 22
Breath-hold duration				
Time (s)	70 ± 29	na	83 ± 30	na

Data is given as mean ± standard deviation. FVC, forced vital capacity; FEV₁, forced expiratory volume in 1s; FIV₁, forced inspiratory volume in 1s; PEF, peak expiratory flow rate; PIF, peak inspiratory flow rate; MVV, maximal voluntary ventilation; MIP, maximal inspiratory mouth pressure; MEP, maximal expiratory mouth pressure; SNIP, sniff nasal inspiratory pressure; na, not available. Significant differences between yoga (YOGA, n = 9) and control (CON, n = 6) groups are indicated.

* $p < 0.05$.

doi:10.1371/journal.pone.0153159.t002

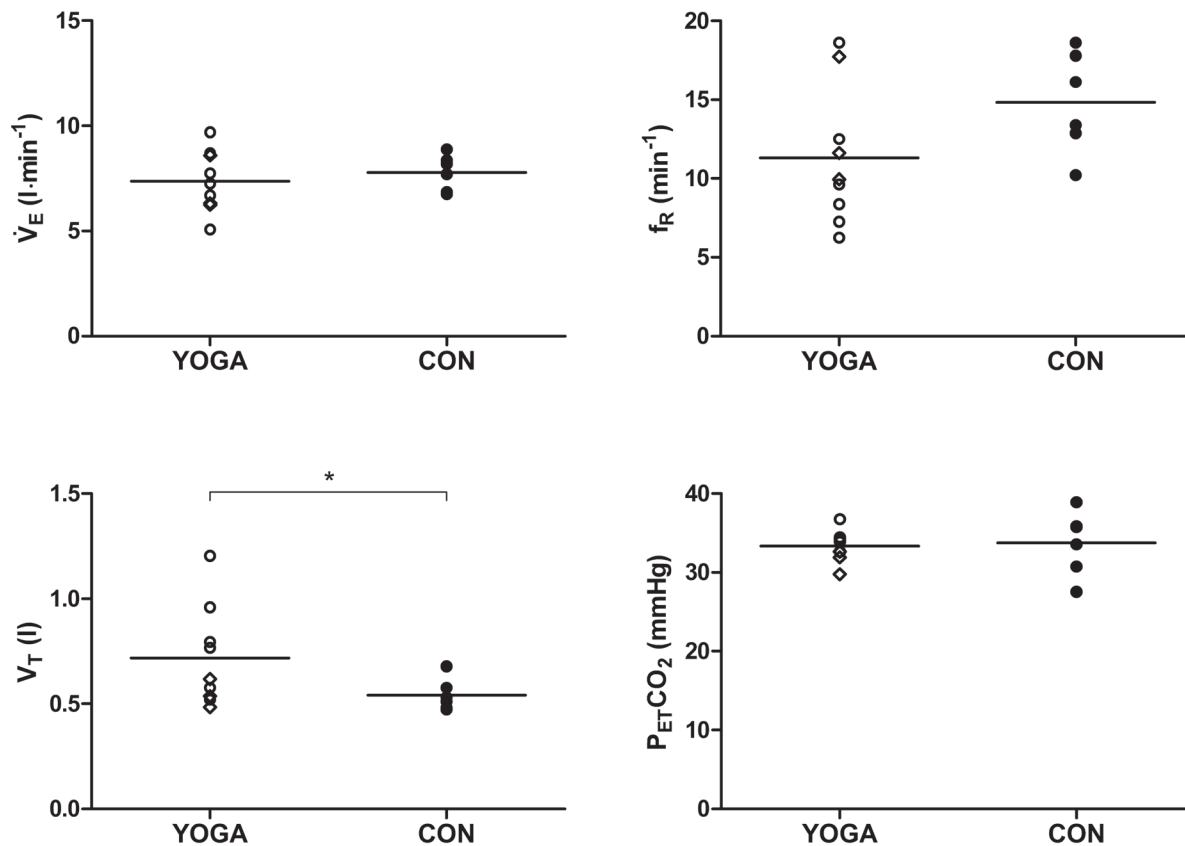


Fig 1. Ventilation and pattern of breathing at rest (mean \pm SD) in yoga (YOGA, empty circles, empty rhombus for less fit subjects, see 3.6) and control (CON, full circles) groups. \dot{V}_E , ventilation; V_T , tidal volume; f_R , respiratory frequency; $P_{ET}CO_2$, end-tidal CO_2 partial pressure. Significances are indicated for differences between YOGA and CON. * $p < 0.05$.

doi:10.1371/journal.pone.0153159.g001

not reach statistical significance (Fig 1). \dot{V}_E ($p = 0.268$) and $P_{ET}CO_2$ ($p = 0.412$) did not differ significantly. Resting $\dot{V}O_2$ ($p = 0.443$) and $\dot{V}CO_2$ ($p = 0.434$) did not differ between the YOGA and CON groups (data not shown).

Hypercapnic ventilatory response

The average ventilatory level in the range between the point where all subjects started to increase ventilation and no subject had quit the test (i.e. $P_{ET}CO_2$ between 55 and 61 mmHg, average $P_{ET}CO_2$ 58 ± 0.1 mmHg) was significantly different between the YOGA and CON groups, i.e. \dot{V}_E ($p = 0.048$) and f_R ($p = 0.006$) were significantly lower in YOGA whereas V_T ($p = 0.466$) was similar compared to CON (Fig 2). HCVR-slopes (YOGA: 2.4 ± 0.7 vs. CON: 2.8 ± 0.8 ; $p = 0.139$) were not statistically different between the two groups.

Passive exercise

Changes in the ventilatory response from baseline to passive exercise are illustrated in Fig 3. \dot{V}_E increased significantly from baseline to passive exercise in both the YOGA and CON groups, with CON showing a higher \dot{V}_E during passive leg movement ($p = 0.039$). In the YOGA group, V_T remained constant while f_R and $P_{ET}CO_2$ increased significantly. In the CON group, both

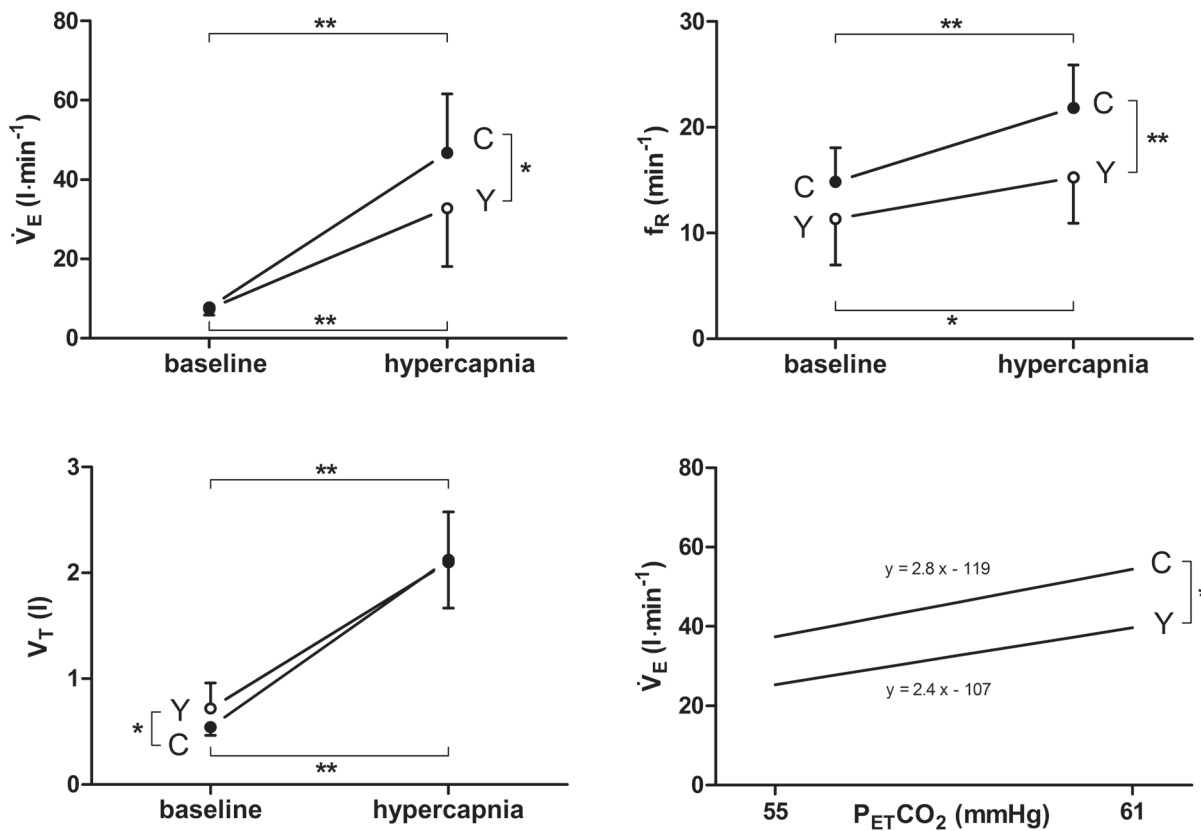


Fig 2. Respiratory data (mean ± SD) of yoga (Y) and control (C) groups at baseline (spontaneous breathing at rest) and during hypercapnia (achieving 55–61 mmHg end-tidal CO₂ partial pressures [P_{ET}CO₂]). VE, ventilation; VT, tidal volume; f_R, respiratory frequency. Bottom right: Slope of the average regression lines (y) between V_E and P_{ET}CO₂. Significances are indicated for differences between Y and C and changes from baseline to hypercapnia. * p < 0.05, ** p < 0.01.

doi:10.1371/journal.pone.0153159.g002

V_T and f_R increased significantly with no change in P_{ET}CO₂. $\dot{V}O_2$ (YOGA: 250 ± 43 to 429 ± 57 ml min⁻¹; p < 0.001 and CON: 239 ± 29 to 459 ± 137 ml min⁻¹; p = 0.006) and $\dot{V}CO_2$ (YOGA: 226 ± 43 to 381 ± 72 ml min⁻¹; p = 0.002 and CON: 218 ± 27 to 427 ± 101 ml min⁻¹; p = 0.003) increased significantly from baseline to passive exercise in both groups.

Incremental exercise test and constant load exercise test

The YOGA group showed a significantly lower W_{max} (p = 0.024) and a trend towards lower $\dot{V}O_{2peak}$ relative to body mass (p = 0.057). Since W_{max} is the baseline for endurance exercise testing, data of the YOGA group was analyzed using a subgroup of those 6 YOGA subjects with the highest W_{max}. Anthropometric data (see Table 1) and recreational exercise activities (mean 2.8 ± 2 vs. 3.4 ± 1 h·wk⁻¹; p = 0.545) of this subgroup did not differ from CON. Also, the reduced data set revealed no significant difference between YOGA and CON in W_{max}, $\dot{V}O_{2peak}$ and endurance capacity (17.29 ± 3.30 vs. 19.56 ± 8.51 min; p = 0.276). During submaximal ICT, the YOGA subgroup showed a trend towards lower and f_R. For the CET, no differences were found in any respiratory or metabolic parameter during the first 8 min (Table 3) or at the time of exhaustion (data not shown). Fig 4 provides a visual illustration of the time course of variables in the ICT and CET in this reduced data set.

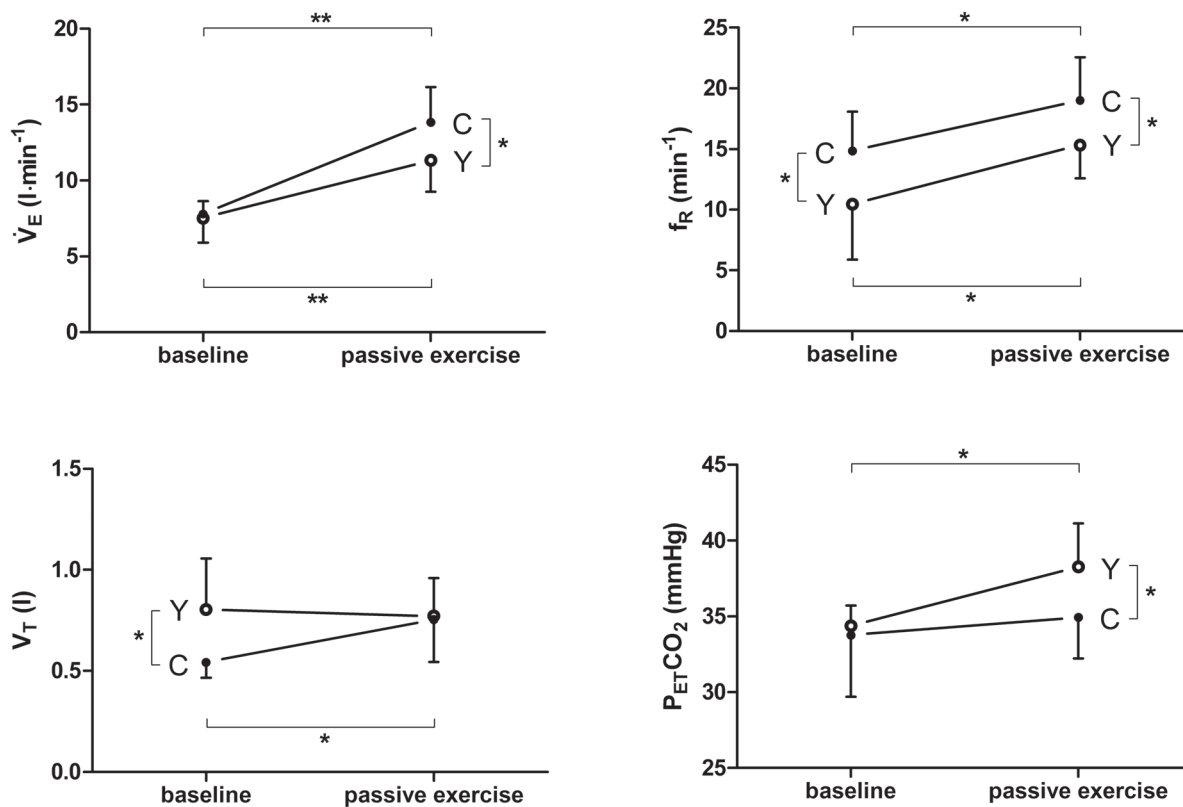


Fig 3. Respiratory data (mean \pm SD) for the reduced dataset of yoga (Y, n = 6, see 3.6) and control (C) groups at baseline and during passive exercise. \dot{V}_E , ventilation; V_T , tidal volume; f_R , respiratory frequency; P_{ET-CO_2} , end-tidal CO_2 partial pressure. Significances are indicated for differences between Y and C and changes from baseline to passive exercise. * $p < 0.05$, ** $p < 0.01$.

doi:10.1371/journal.pone.0153159.g003

Discussion

The major findings of this study were that, despite of differences in breathing pattern and respiratory regulation, YOGA participants did not show enhanced breath-hold duration nor increased exercise capacity, in contrast to our initial hypothesis. YOGA subjects, compared to CON, showed a permanent change in their breathing pattern at rest, characterized by larger V_T . Also YOGA subjects showed a blunted ventilatory response to chemoreceptor and mechanical stimulation, thus supporting the view that long-term performance of breathing exercises during yoga practice affects spontaneous respiratory regulation. However, even when participants were matched for their maximum exercise capacity (W_{max}), these differences did not translate into improved endurance capacity during the constant load exercise test.

Effect of yoga on resting breathing pattern

In YOGA subjects, spontaneous, brainstem-driven breathing pattern at rest was altered in that V_T was significantly increased, in accordance to previous investigations [3, 9, 10], even though differences in f_R did not reach statistical significance. It appears that regular practice of volitional controlled breathing affects the brainstem respiratory center, leading to a permanent modification of the non-volitional, spontaneous breathing regulation, e.g. breathing pattern in YOGA. In spite of differences in breathing pattern at rest, however, there was no detectable

Table 3. Incremental cycling and constant-load endurance cycling data of the reduced data set.

	YOGA (n = 6)	CON (n = 6)	p-Value
ICT (0–8 min)			
\dot{V}_E (l·min ⁻¹)	33 ± 2	36 ± 3	0.094
V_T (l)	1.6 ± 0.3	1.5 ± 0.1	0.193
f_R (min ⁻¹)	21 ± 4	24 ± 2	0.085
$P_{ET}CO_2$ (mmHg)	41 ± 4	39 ± 3	0.146
$\dot{V}O_2$ (ml·min ⁻¹)	1394 ± 109	1352 ± 38	0.145
$\dot{V}CO_2$ (ml·min ⁻¹)	1269 ± 44	1275 ± 67	0.427
$\dot{V}_E / \dot{V}CO_2$	25.7 ± 2.9	29.0 ± 6.0	0.257
Lactate (mmol·l ⁻¹)	2.0 ± 1.1	1.8 ± 0.5	0.314
HR (beats·min ⁻¹)	120 ± 9	116 ± 10	0.266
Perception of breathlessness (points)	1.1 ± 0.8	0.4 ± 0.2	0.106
Respiratory exertion (points)	1.6 ± 0.7	1.1 ± 1.2	0.233
Leg exertion (points)	1.8 ± 0.7	2.0 ± 1.6	0.439
W_{max} (W)	185 ± 42	214 ± 35	0.114
$\dot{V}O_{2peak}$ (ml min ⁻¹ ·kg ⁻¹)	40 ± 6	43 ± 7	0.222
CET (0–8 min)			
\dot{V}_E (l·min ⁻¹)	40 ± 8	46 ± 8	0.139
V_T (l)	1.7 ± 0.2	1.7 ± 0.3	0.353
f_R (min ⁻¹)	24 ± 4	26 ± 3	0.112
$P_{ET}CO_2$ (mmHg)	42 ± 4	40 ± 2	0.144
$\dot{V}O_2$ (ml·min ⁻¹)	1601 ± 249	1683 ± 235	0.273
$\dot{V}CO_2$ (ml·min ⁻¹)	1538 ± 235	1677 ± 228	0.172
Lactate (mmol·l ⁻¹)	2.7 ± 0.9	3.0 ± 0.6	0.125
HR (beats·min ⁻¹)	130 ± 5	130 ± 15	0.469
Perception of breathlessness (points)	2.1 ± 1.6	1.3 ± 1.1	0.194
Respiratory exertion (points)	3.1 ± 1.2	2.0 ± 1.7	0.105
Leg exertion (points)	3.5 ± 1.5	3.4 ± 1.3	0.431

Data is given as mean ± standard deviation at submaximal level during the first 8 min of the incremental cycling test (ICT) and during the first 8 min of constant-load exercise test (CET) of the reduced data set. \dot{V}_E , ventilation; V_T , tidal volume; f_R , respiratory frequency; $P_{ET}CO_2$, end-tidal CO₂ partial pressure; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide production; Lactate, blood lactate concentration; HR, heart rate; W_{max} , maximal workload; $\dot{V}O_{2peak}$, maximal oxygen consumption. No significant differences were found between yoga (YOGA) and control (CON) groups

doi:10.1371/journal.pone.0153159.t003

between-group difference in \dot{V}_E , $\dot{V}_E/\dot{V}O_2$ (data not shown) and $P_{ET}CO_2$, indicating that the change in respiratory regulation specifically affected breathing pattern rather than overall ventilation at rest.

Effect of yoga on pulmonary function and respiratory muscle strength

Although in the present study yoga experts were investigated, their lung function did not differ from CON, similar to findings in some of the previous studies [3, 13, 14] but in contrast to several others [2, 8–12]. Likewise, a difference in respiratory muscle strength was expected as result of increased neuromuscular coordination in the YOGA group due to regular practice of voluntary activation of respiratory muscles during yoga breathing, but this was also not the case. Instead, MEP was in fact even smaller in the YOGA group.

The reasons for this controversy in the literature regarding lung function and respiratory muscle strength are not immediately clear. Possibly respiratory exercises during yoga practice

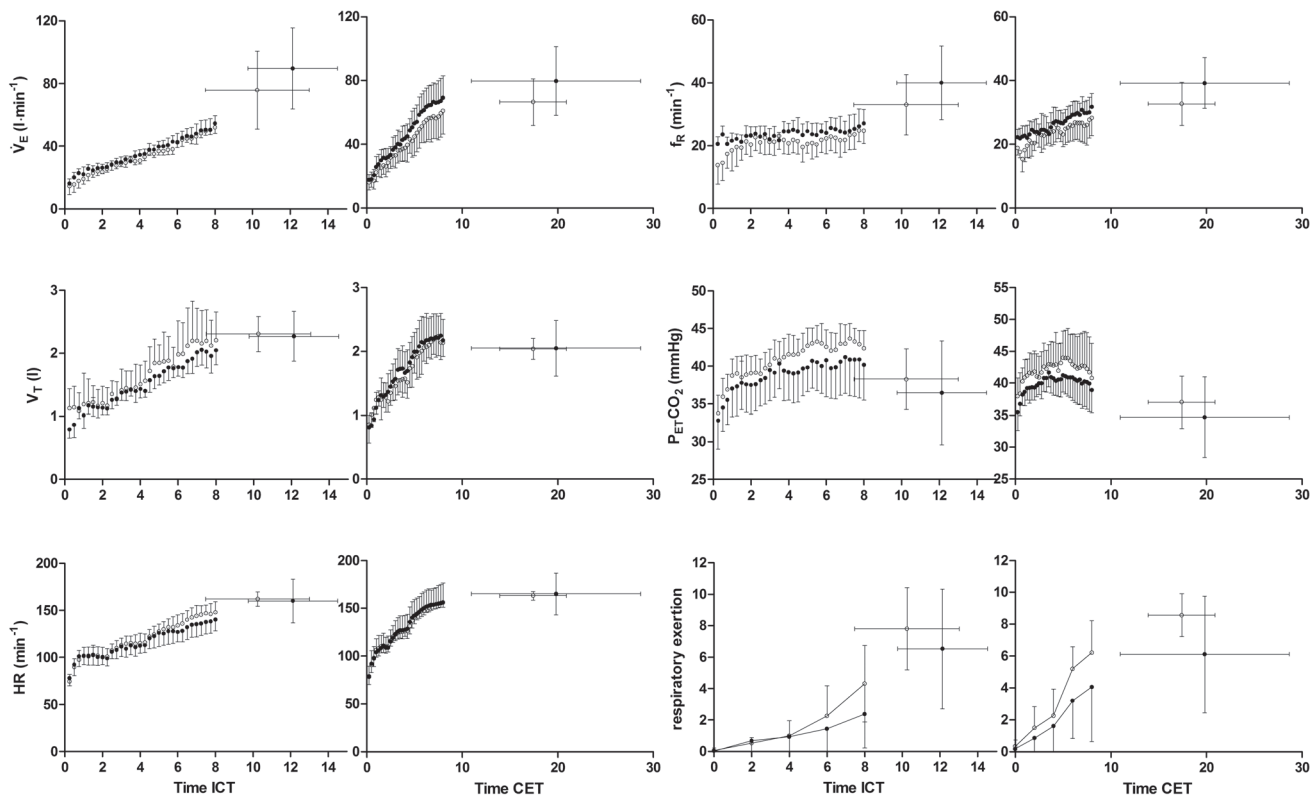


Fig 4. Time course of 15s data (mean ± SD) of the reduced data set (YOGA, n = 6) during the first 8 min of ICT and during the first 8 min of CET and at exhaustion of the yoga (empty circles) and control (full circles) groups. \dot{V}_E , ventilation; V_T , tidal volume; f_R , respiratory frequency; $P_{ET}CO_2$, end-tidal CO_2 partial pressure; HR, heart rate.

doi:10.1371/journal.pone.0153159.g004

do not sufficiently enhance neuromuscular coordination or the contractions of respiratory muscles are not intense enough to improve muscle strength. In this light, the different results found by studies using healthy young individuals might simply reflect the low impact of yoga in these parameters.

Effect of yoga on stimulated ventilation

Although HCVR slopes in this study did not differ, contrasting with previous studies [13, 15], the two groups had significant different \dot{V}_E at similar $P_{ET}CO_2$. Together with similar \dot{V}_E at rest, this clearly indicates a difference in chemosensitivity to hypercapnia. In this context it is necessary to point out that previous investigators [13, 15] did not clearly indicate the evaluation method of HCVR, which might be a critical point, when comparing results of different studies. A change in chemosensitivity seems plausible as yogic subjects are repetitively exposed to hypercapnia during specific respiratory exercises, as reported by Miyamura et al. (2002) [6]. It is noteworthy, however, that in spite of the seemingly reduced chemosensitivity to hypercapnia YOGA did not display increased breath-hold time compared to CON. The reason may be based in the fact that breath-hold time is not only limited by the increased CO_2 -drive to breathe but also by the complete and extended suppression of pulmonary stretch receptor activity [40–42], while with pranayama techniques ventilation is highly controlled but in most cases breathing is not fully stopped.

In the present study, f_R was substantially lower in YOGA during the hypercapnic condition, while V_T was similar and therefore the difference in \dot{V}_E mainly resulted from lower f_R . This might have contributed, at least in part, to the reduced ventilation of YOGA in the HCVR as slow f_R itself was shown to substantially decrease HVR and HCVR in men [43]. However, Spicuzza et al. [15] also showed that a change in chemosensitivity was not only a function of a change in f_R , i.e. yogic subjects did not increase ventilation to values similar to controls when increasing f_R volitionally.

The current passive leg movement trial was designed to compare ventilatory responses resulting from afferent mechanoreceptor activity without the influence of efferent, i.e. corollary discharge (central command) to the respiratory centre with motor output to leg muscles. During passive movement, YOGA and CON increased \dot{V}_E over resting values, but YOGA showed a reduced ventilatory response to passive leg movement compared to CON. This supports the observation of reduced chemosensitivity in YOGA, as YOGA subjects tolerated a higher $P_{ET}CO_2$ than CON also during passive leg movement. The reduced ventilatory response further indicates that long-term performance of breathing exercises affects spontaneous respiratory regulation when the respiratory drive is increased by afferent activity not typical for yoga, e.g. mechanoreceptor stimulation.

Effect of yoga on exercise performance

Interestingly, YOGA showed a smaller W_{max} than CON in spite of similar amounts of habitual physical activity. Even in the YOGA sub-group of similar W_{max} to CON, the suggested positive effects of yoga on endurance performance could not be demonstrated, contrary to our hypothesis based on previous literature [1, 14, 20–25]. While ventilation and breathing frequency showed a trend towards lower values in YOGA during submaximal ICT, $\dot{V}_E/\dot{V}CO_2$ slopes, that can be seen as an indicator as ventilatory chemosensitivity [44] in spite of the possible influence of cycling efficiency [45] and the proportion of dead-space to tidal volume [46] in this variable, did not differ between groups. Also, during submaximal CET changes in ventilation and gas exchange were similar between YOGA and CON. Thus, it is not surprising that exercise endurance capacity was also similar between groups, as the hypothesized reduced ventilatory drive was absent. Finally, although subjective perception of respiratory sensations did not differ significantly between the two groups, perception of breathlessness and of respiratory exertion was actually slightly increased in YOGA. One possible explanation for this is that YOGA subjects are more susceptible to perceive breathlessness and respiratory exertion due to regular performance of breathing exercises, including a specific focus on perception of breathing.

Taken together, our findings suggest that yoga does not produce an exercise training stimulus large enough to induce measureable training responses during whole-body exercise in young, healthy individuals, as demonstrated by similar HR in both groups at any given absolute exercise intensity. Indeed, one session of YOGA at beginner-level was shown to have an equivalent intensity to treadmill walking at 3.2 km.h⁻¹ [47], an intensity which is unlikely to improve exercise capacity in young, healthy individuals. From a longitudinal perspective, studies that have reported increased $\dot{V}O_{2max}$ with yoga training were performed mostly with sedentary elderly [1] or untrained subjects [14], i.e. subjects whose $\dot{V}O_{2max}$ is more likely to improve, while subjects of the present study normally performed 2.7 ± 1.7 h of exercise training per week. In fact, the beneficial effects of yoga on exercise performance in populations such as chronic heart failure patients might be potentiated due to the exacerbated dyspnea that these patients normally exhibit during exercise, as a result of excessive sympathetic stimuli [48]. Regardless of the mechanism, however, yoga or simply practicing respiratory exercises seem to

be of benefit for different patient populations, and thus should not be disregarded as a therapeutic option for specific groups based on the present findings [48].

Technical considerations and limitations

This study was performed on female participants, who possess different chemosensitivity and respiratory control compared with male individuals, even when body mass differences are taken into account [49], which is most likely related to sexual hormone concentrations [50, 51]. In spite of these differences, men and women seem to benefit from respiratory muscle training to a similar extent [52], and also present similar responses of diaphragmatic fatigue following exercise [53] and similar respiratory responses to unloading of the respiratory muscles [54]. Thus, it is tempting to speculate that male yogic individuals would show a similar response with regards to exercise performance compared to our female participants, although this hypothesis requires further testing.

Even though the present studies suggest that yoga practice does not give healthy individuals an advantage during submaximal whole-body exercise, longitudinal studies are required to confirm this hypothesis. Fatigue of the respiratory muscles is just one of many factors influencing whole-body exercise performance, and even though our participants were matched for physical activity level (excluding the hours spent practicing yoga), age and body weight, we cannot exclude the possibility that performance during CET was not improved due to a non-controlled factor, overcoming any possible advantages of the reduced ventilatory response of yogic individuals. In the specific case of female participants, even unexpected differences between the two groups in iron levels—related or not to dietary differences—or haemoglobin concentration, which impact oxygen carrying capacity during exercise, could have affected performance [55]. In this context, it is important to keep in mind that the sub-group of yoga participants was also matched to our control individuals for peak exercise capacity and $\dot{V}O_{2peak}$, which is especially sensitive to differences in factors such as training status or O_2 carrying capacity, strengthening this comparison. Although one might suspect that subjects performing YOGA could favor vegetarianism, nutritional reports of our subjects show that the number of subjects not being vegetarian was similar in both groups and that all participants included several iron-rich foods in their daily meals. Thus we are confident that the nutritional status and the potential effect on hemoglobin did not systematically affect the outcome of our study.

Finally, the sample size was relatively small, and thus more prone to type II errors. However, our post hoc analyses showed that power for the measurements of breathing pattern at rest and ventilatory response to passive and active exercise ranged from 55–78%, in addition to being in line with what is commonly reported in the literature for yogic individuals (that is, decreased ventilatory response to different stimuli compared to non-yogic individuals). We did not, however, test our participants for HVR or ventilatory responses to stimulation of metaboreceptors, which would have expanded our comparison and given a more complete picture of the ventilatory response of yogic individuals to the different stimuli present during exercise. Nonetheless, when comparing exercise capacity during CET, our results, if anything, suggest a decreased endurance capacity for yogic individuals, which were already matched to peak exercise capacity during an exercise test, in opposition to any beneficial effect that a blunted ventilatory response to exercise could have on performance.

Conclusion

This study showed that long-term yoga practice can alter the automatic output of the brainstem respiratory center in resting conditions and also reduce hypercapnic respiratory drive, possibly as the result of repetitive exposure to hypercapnia during specific respiratory exercises. However,

these changes do not seem to give healthy young yogic individuals an advantage during whole-body exercise.

Acknowledgments

The authors would like to thank all the subjects for their time and effort dedicated to this study and Dr. Sabine Illi for help with manuscript preparation.

Author Contributions

Conceived and designed the experiments: EB CMS UB. Performed the experiments: EB. Analyzed the data: EB CMS UB FGB. Wrote the paper: EB CMS UB FGB.

References

1. Bowman AJ, Clayton RH, Murray A, Reed JW, Subhan MM, Ford GA. Effects of aerobic exercise training and yoga on the baroreflex in healthy elderly persons. *Eur J Clin Invest*. 1997; 27(5):443–9. Epub 1997/05/01. PMID: [9179553](#).
2. Telles S, Nagarathna R, Nagendra HR, Desiraju T. Physiological changes in sports teachers following 3 months of training in Yoga. *Indian J Med Sci*. 1993; 47(10):235–8. Epub 1993/10/01. PMID: [8112782](#).
3. Villien F, Yu M, Barthelemy P, Jammes Y. Training to yoga respiration selectively increases respiratory sensation in healthy man. *Respir Physiol Neurobiol*. 2005; 146(1):85–96. Epub 2005/03/01. S1569-9048(04)00326-X [pii] doi: [10.1016/j.resp.2004.11.010](#) PMID: [15733782](#).
4. Joshi M, Telles S. A nonrandomized non-naive comparative study of the effects of kapalabhati and breath awareness on event-related potentials in trained yoga practitioners. *J Altern Complement Med*. 2009; 15(3):281–5. Epub 2009/02/27. doi: [10.1089/acm.2008.0250](#) PMID: [19243275](#).
5. Pomidori L, Campigotto F, Amatya TM, Bernardi L, Cogo A. Efficacy and tolerability of yoga breathing in patients with chronic obstructive pulmonary disease: a pilot study. *J Cardiopulm Rehabil Prev*. 2009; 29(2):133–7. Epub 2009/03/24. doi: [10.1097/HCR.0b013e31819a0227](#) 01273116-200903000-00010 [pii]. PMID: [19305239](#).
6. Miyamura M, Nishimura K, Ishida K, Katayama K, Shimaoka M, Hiruta S. Is man able to breathe once a minute for an hour?: the effect of yoga respiration on blood gases. *Jpn J Physiol*. 2002; 52(3):313–6. Epub 2002/09/17. PMID: [12230808](#).
7. Sarang PS, Telles S. Oxygen consumption and respiration during and after two yoga relaxation techniques. *Appl Psychophysiol Biofeedback*. 2006; 31(2):143–53. Epub 2006/07/14. doi: [10.1007/s10484-006-9012-8](#) PMID: [16838123](#).
8. Joshi LN, Joshi VD, Gokhale LV. Effect of short term 'Pranayam' practice on breathing rate and ventilatory functions of lung. *Indian J Physiol Pharmacol*. 1992; 36(2):105–8. Epub 1992/04/01. PMID: [1506070](#).
9. Makwana K, Khirwadkar N, Gupta HC. Effect of short term yoga practice on ventilatory function tests. *Indian J Physiol Pharmacol*. 1988; 32(3):202–8. Epub 1988/07/01. PMID: [3198241](#).
10. Gopal KS, Bhatnagar OP, Subramanian N, Nishith SD. Effect of yogasanas and pranayamas on blood pressure, pulse rate and some respiratory functions. *Indian J Physiol Pharmacol*. 1973; 17(3):273–6. Epub 1973/07/01. PMID: [4788511](#).
11. Birkel DA, Edgren L. Hatha yoga: improved vital capacity of college students. *Altern Ther Health Med*. 2000; 6(6):55–63. Epub 2000/11/15. PMID: [11076447](#).
12. Yadav RK, Das S. Effect of yogic practice on pulmonary functions in young females. *Indian J Physiol Pharmacol*. 2001; 45(4):493–6. Epub 2002/03/09. PMID: [11883159](#).
13. Stanescu DC, Nemery B, Veriter C, Marechal C. Pattern of breathing and ventilatory response to CO₂ in subjects practicing hatha-yoga. *J Appl Physiol*. 1981; 51(6):1625–9. Epub 1981/12/01. PMID: [6798002](#).
14. Tran MD, Holly RG, Lashbrook J, Amsterdam EA. Effects of Hatha Yoga Practice on the Health-Related Aspects of Physical Fitness. *Prev Cardiol*. 2001; 4(4):165–70. Epub 2002/02/08. PMID: [11832673](#).
15. Spicuzza L, Gabutti A, Porta C, Montano N, Bernardi L. Yoga and chemoreflex response to hypoxia and hypercapnia. *Lancet*. 2000; 356(9240):1495–6. Epub 2000/11/18. S0140-6736(00)02881-6 [pii] doi: [10.1016/S0140-6736\(00\)02881-6](#) PMID: [11081541](#).

16. Bernardi L, Passino C, Spadacini G, Bonfichi M, Arcaini L, Malcovati L, et al. Reduced hypoxic ventilatory response with preserved blood oxygenation in yoga trainees and Himalayan Buddhist monks at altitude: evidence of a different adaptive strategy? *Eur J Appl Physiol*. 2007; 99(5):511–8. Epub 2007/01/09. doi: [10.1007/s00421-006-0373-8](https://doi.org/10.1007/s00421-006-0373-8) PMID: [17206440](https://pubmed.ncbi.nlm.nih.gov/17206440/).
17. Byrne-Quinn E, Weil JV, Sodal IE, Filley GF, Grover RF. Ventilatory control in the athlete. *J Appl Physiol*. 1971; 30(1):91–8. Epub 1971/01/01. PMID: [5538798](https://pubmed.ncbi.nlm.nih.gov/5538798/).
18. Levine BD, Friedman DB, Engfred K, Hanel B, Kjaer M, Clifford PS, et al. The effect of normoxic or hypobaric hypoxic endurance training on the hypoxic ventilatory response. *Med Sci Sports Exerc*. 1992; 24(7):769–75. Epub 1992/07/01. PMID: [1501561](https://pubmed.ncbi.nlm.nih.gov/1501561/).
19. Verges S, Boutellier U, Spengler CM. Effect of respiratory muscle endurance training on respiratory sensations, respiratory control and exercise performance: a 15-year experience. *Respir Physiol Neurobiol*. 2008; 161(1):16–22. Epub 2008/01/10. S1569-9048(07)00318-7 [pii] doi: [10.1016/j.resp.2007.11.004](https://doi.org/10.1016/j.resp.2007.11.004) PMID: [18182333](https://pubmed.ncbi.nlm.nih.gov/18182333/).
20. Raju PS, Prasad KV, Venkata RY, Murthy KJ, Reddy MV. Influence of intensive yoga training on physiological changes in 6 adult women: a case report. *J Altern Complement Med*. 1997; 3(3):291–5. Epub 1998/01/16. PMID: [9430331](https://pubmed.ncbi.nlm.nih.gov/9430331/).
21. Raju PS, Madhavi S, Prasad KV, Reddy MV, Reddy ME, Sahay BK, et al. Comparison of effects of yoga & physical exercise in athletes. *Indian J Med Res*. 1994; 100:81–6. Epub 1994/08/01. PMID: [7927562](https://pubmed.ncbi.nlm.nih.gov/7927562/).
22. Raju PS, Kumar KA, Reddy SS, Madhavi S, Gnanakumari K, Bhaskaracharyulu C, et al. Effect of yoga on exercise tolerance in normal healthy volunteers. *Indian J Physiol Pharmacol*. 1986; 30(2):121–32. Epub 1986/04/01. PMID: [3818038](https://pubmed.ncbi.nlm.nih.gov/3818038/).
23. Ray US, Mukhopadhyaya S, Purkayastha SS, Asnani V, Tomer OS, Prashad R, et al. Effect of yogic exercises on physical and mental health of young fellowship course trainees. *Indian J Physiol Pharmacol*. 2001a; 45(1):37–53. Epub 2001/02/24. PMID: [11211570](https://pubmed.ncbi.nlm.nih.gov/11211570/).
24. Balasubramanian B, Pansare MS. Effect of yoga on aerobic and anaerobic power of muscles. *Indian J Physiol Pharmacol*. 1991; 35(4):281–2. Epub 1991/10/01. PMID: [1812108](https://pubmed.ncbi.nlm.nih.gov/1812108/).
25. Ray US, Sinha B, Tomer OS, Pathak A, Dasgupta T, Selvamurthy W. Aerobic capacity & perceived exertion after practice of Hatha yogic exercises. *Indian J Med Res*. 2001b; 114:215–21. Epub 2002/06/04. PMID: [12040766](https://pubmed.ncbi.nlm.nih.gov/12040766/).
26. Oosthuysen T, Bosch AN. The effect of the menstrual cycle on exercise metabolism: implications for exercise performance in eumenorrhoeic women. *Sports Med*. 2010; 40(3):207–27. Epub 2010/03/05. doi: [10.2165/11317090-000000000-00000](https://doi.org/10.2165/11317090-000000000-00000) 3 [pii]. PMID: [20199120](https://pubmed.ncbi.nlm.nih.gov/20199120/).
27. Harms CA, Rosenkranz S. Sex differences in pulmonary function during exercise. *Med Sci Sports Exerc*. 2008; 40(4):664–8. Epub 2008/03/05. doi: [10.1249/MSS.0b013e3181621325](https://doi.org/10.1249/MSS.0b013e3181621325) PMID: [18317379](https://pubmed.ncbi.nlm.nih.gov/18317379/).
28. Spengler CM, Czeisler CA, Shea SA. An endogenous circadian rhythm of respiratory control in humans. *J Physiol*. 2000; 526 Pt 3:683–94. Epub 2000/08/02. PHY_0135 [pii]. PMID: [10922018](https://pubmed.ncbi.nlm.nih.gov/10922018/); PubMed Central PMCID: [PMC2270042](https://pubmed.ncbi.nlm.nih.gov/PMC2270042/).
29. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, et al. Standardisation of spirometry. *Eur Respir J*. 2005; 26(2):319–38. Epub 2005/08/02. 26/2/319 [pii] doi: [10.1183/09031936.05.00034805](https://doi.org/10.1183/09031936.05.00034805) PMID: [16055882](https://pubmed.ncbi.nlm.nih.gov/16055882/).
30. ATS/ERS Statement on respiratory muscle testing. *Am J Respir Crit Care Med*. 2002; 166(4):518–624. Epub 2002/08/21. PMID: [12186831](https://pubmed.ncbi.nlm.nih.gov/12186831/).
31. Evans JA, Whitelaw WA. The Assessment of Maximal Respiratory Mouth Pressures In Adults. *Respir Care*. 2009; 54:1348–59. PMID: [19796415](https://pubmed.ncbi.nlm.nih.gov/19796415/)
32. Quanjer PH, Tammeling GJ, Cotes JE, Pedersen OF, Peslin R, Yernault JC. Lung volumes and forced ventilatory flows. Report Working Party Standardization of Lung Function Tests, European Community for Steel and Coal. Official Statement of the European Respiratory Society. *Eur Respir J Suppl*. 1993; 16:5–40. Epub 1993/03/01. PMID: [8499054](https://pubmed.ncbi.nlm.nih.gov/8499054/).
33. Uldry C, Fitting JW. Maximal values of sniff nasal inspiratory pressure in healthy subjects. *Thorax*. 1995; 50(4):371–5. Epub 1995/04/01. PMID: [7785009](https://pubmed.ncbi.nlm.nih.gov/7785009/); PubMed Central PMCID: [PMC474280](https://pubmed.ncbi.nlm.nih.gov/PMC474280/).
34. Wilson SH, Cooke NT, Edwards RH, Spiro SG. Predicted normal values for maximal respiratory pressures in caucasian adults and children. *Thorax*. 1984; 39(7):535–8. Epub 1984/07/01. PMID: [6463933](https://pubmed.ncbi.nlm.nih.gov/6463933/); PubMed Central PMCID: [PMC459855](https://pubmed.ncbi.nlm.nih.gov/PMC459855/).
35. Read DJ. A clinical method for assessing the ventilatory response to carbon dioxide. *Australas Ann Med*. 1967; 16(1):20–32. Epub 1967/02/01. PMID: [6032026](https://pubmed.ncbi.nlm.nih.gov/6032026/).
36. Lorinc Z, Derr J, Snider M, Lydic R. Defining origin of positive slope in hypercapnic ventilatory response curve. *Am J Physiol*. 1991; 261(3 Pt 2):R747–51. Epub 1991/09/01. PMID: [1679610](https://pubmed.ncbi.nlm.nih.gov/1679610/).

37. Lansing RW, Im BS, Thwing JI, Legedza AT, Banzett RB. The perception of respiratory work and effort can be independent of the perception of air hunger. *Am J Respir Crit Care Med*. 2000; 162(5):1690–6. Epub 2000/11/09. PMID: [11069798](#).
38. Harver A, Mahler DA, Schwartzstein RM, Baird JC. Descriptors of breathlessness in healthy individuals: distinct and separable constructs. *Chest*. 2000; 118(3):679–90. Epub 2000/09/16. PMID: [10988189](#).
39. Ingle L, Goode K, Carroll S, Sloan R, Boyes C, Cleland JG, et al. Prognostic value of the VE/CO₂ slope calculated from different time intervals in patients with suspected heart failure. *Int J Cardiol*. 2007; 118(3):350–5. doi: [10.1016/j.ijcard.2006.07.105](#) PMID: [17067694](#).
40. Fowler WS. Breaking point of breath-holding. *J Appl Physiol*. 1954; 6(9):539–45. PMID: [13152037](#).
41. Flume PA, Eldridge FL, Edwards LJ, Houser LM. The Fowler breathholding study revisited: continuous rating of respiratory sensation. *Respir Physiol*. 1994; 95(1):53–66. PMID: [8153453](#).
42. Flume PA, Eldridge FL, Edwards LJ, Mattison LE. Relief of the 'air hunger' of breathholding. A role for pulmonary stretch receptors. *Respir Physiol*. 1996; 103(3):221–32. PMID: [8738898](#).
43. Bernardi L, Gabutti A, Porta C, Spicuzza L. Slow breathing reduces chemoreflex response to hypoxia and hypercapnia, and increases baroreflex sensitivity. *J Hypertens*. 2001; 19(12):2221–9. Epub 2001/11/29. PMID: [11725167](#).
44. Ohtake PJ, Wolfe LA. Physical conditioning attenuates respiratory responses to steady-state exercise in late gestation. *Med Sci Sports Exerc*. 1998; 30(1):17–27. PMID: [9475640](#).
45. McConnell AK, Davies CT. A comparison of the ventilatory responses to exercise of elderly and younger humans. *J Gerontol*. 1992; 47(4):B137–41. PMID: [1624690](#).
46. Clark AL, Volterrani M, Swan JW, Coats AJ. The increased ventilatory response to exercise in chronic heart failure: relation to pulmonary pathology. *Heart*. 1997; 77(2):138–46. PMID: [9068397](#); PubMed Central PMCID: PMC484663.
47. Hagins M, Moore W, Rundle A. Does practicing hatha yoga satisfy recommendations for intensity of physical activity which improves and maintains health and cardiovascular fitness? *BMC Complement Altern Med*. 2007; 7:40. Epub 2007/12/07. 1472-6882-7-40 [pii] doi: [10.1186/1472-6882-7-40](#) PMID: [18053143](#); PubMed Central PMCID: PMC2219995.
48. Bernardi L, Spadacini G, Bellwon J, Hajric R, Roskamm H, Frey AW. Effect of breathing rate on oxygen saturation and exercise performance in chronic heart failure. *Lancet*. 1998; 351(9112):1308–11. doi: [10.1016/S0140-6736\(97\)10341-5](#) PMID: [9643792](#).
49. White DP, Douglas NJ, Pickett CK, Weil JV, Zwillich CW. Sexual influence on the control of breathing. *J Appl Physiol Respir Environ Exerc Physiol*. 1983; 54(4):874–9. PMID: [6853293](#).
50. Tatsumi K, Pickett CK, Jacoby CR, Weil JV, Moore LG. Role of endogenous female hormones in hypoxic chemosensitivity. *J Appl Physiol* (1985). 1997; 83(5):1706–10. PMID: [9375342](#).
51. White DP, Schneider BK, Santen RJ, McDermott M, Pickett CK, Zwillich CW, et al. Influence of testosterone on ventilation and chemosensitivity in male subjects. *J Appl Physiol* (1985). 1985; 59(5):1452–7. PMID: [4066575](#).
52. Guenette JA, Martens AM, Lee AL, Tyler GD, Richards JC, Foster GE, et al. Variable effects of respiratory muscle training on cycle exercise performance in men and women. *Appl Physiol Nutr Metab*. 2006; 31(2):159–66. doi: [10.1139/h05-016](#) PMID: [16604134](#).
53. Ozkaplan A, Rhodes EC, Sheel AW, Taunton JE. A comparison of inspiratory muscle fatigue following maximal exercise in moderately trained males and females. *Eur J Appl Physiol*. 2005; 95(1):52–6. doi: [10.1007/s00421-005-1399-z](#) PMID: [15976996](#).
54. Wilkie SS, Dominelli PB, Sporer BC, Koehle MS, Sheel AW. Heliox breathing equally influences respiratory mechanics and cycling performance in trained males and females. *J Appl Physiol* (1985). 2015; 118(3):255–64. doi: [10.1152/jappphysiol.00400.2014](#) PMID: [25429095](#); PubMed Central PMCID: PMC4312847.
55. Calbet JA, Lundby C, Koskolou M, Boushel R. Importance of hemoglobin concentration to exercise: acute manipulations. *Respir Physiol Neurobiol*. 2006; 151(2–3):132–40. doi: [10.1016/j.resp.2006.01.014](#) PMID: [16516566](#).