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Critical power for the upper limb in patients with chronic obstructive pulmonary disease: A pilot study

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ABSTRACT

Purpose: To investigated the impact of the ventilatory constraints in the power-duration relationship for upper limbs exercise in patients with chronic obstructive pulmonary disease (COPD).
Methods: Eight patients with COPD and eight healthy subjects performed an arm incremental test on cycle ergometer and four constant workload tests (100%, 90%, 80% and 70% of peak workload). The power-duration (or critical power - CP) estimative was determined. The inspiratory capacity was measured before and after each test.
Results: There was no significant difference in the CP between patients and controls. Also, the curvature constant (W_{AT}, work do able above CP) was similar between patients and control subjects. Finally, the limits of tolerance for all constant workload tests in the patients with COPD were closely associated with the presence of dynamic hyperinflation and ventilatory reserve.
Conclusion: Despite patients typically showed more ventilatory stress compared with control subjects, the ventilatory constraints did not limit the sustained upper limbs exercise at the critical power.

1. Introduction

Exercise intolerance is a usual symptom in patients with COPD and limits their daily activities and quality of life. Dysfunctional muscles strongly contribute to the limitation of vital activities such as walking, climbing stairs or a ramp, daily arm activities, especially those involving unsupported upper limb, and heightened upper limb exercise intolerance in COPD patients (Maltais et al., 2014). Heightened upper limb exercise intolerance in COPD patients is controversial and not well described in the literature. Upper limb activities that require elevation above the shoulder are associated with dynamic hyperinflation and limiting dyspnea in patients with COPD (Celli et al., 1986; Criner and Celli, 1988; Mckeough et al., 2003; Vaes et al., 2011). Mechanical efficiency and exercise capacity of the upper limb are preserved in patients with COPD (Castagna et al., 2007). Meijer et al.(2014), however, reported that the time spent (duration) on daily upper limb activities was similar between patients with COPD and healthy control subjects, while the intensity of these activities was lower in patients with COPD. The hyperbolic power-duration relationship is the most rigorous characterization of high-intensity exercise tolerance (Whipp and Ward, 2009; Moritani et al., 1981). However, the power duration characteristics of upper-limb exercise in COPD have not yet been established.

Based on these assertions, it is reasonable to hypothesize that the power-duration relationship for upper limb exercise is influenced by dynamic hyperinflation (DH) and low ventilatory reserve in these patients. We aimed to investigate the impact of the ventilatory constraints in COPD patients on the power-duration relationship (critical power and the anaerobic capacity work (W_{AT}) in upper limb exercise and to compare the results with those of healthy controls. This study is the first of its kind to use the critical power method in the evaluation of endurance capacity of the upper limb in COPD patients.

2. Methods

2.1. Subjects

This controlled cross-sectional study design was performed at the Pulmonary Function and Clinical Exercise Physiology Unit (SEFICE),

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Table 1
Age, body characteristics and pulmonary function tests of COPD and control subjects.

Variables	COPD n = 8	Control n = 8
Age (years)	67 ± 6	65 ± 6
Weight (Kg)	65.8 ± 14.9	75.6 ± 10.5
height (m)	1.60 ± 0.07	1.64 ± 0.08
BMI (Kg/m^2)	25.2 ± 4.7	28.1 ± 4.3
Baecke	6.9 ± 1.8	7.6 ± 1.3
FEV_1 (L)	1.14 ± 0.41†	2.68 ± 0.60
FEV_1 (% pred)	45.1 ± 1.2†	100.4 ± 0.9
FVC (L)	2.53 ± 0.70	3.26 ± 0.80
FVC (% pred)	76.8 ± 11.1†	98.1 ± 10.8
FEV_1/FVC	0.46 ± 0.10†	0.82 ± 0.02
RV (% pred)	180.8 ± 18.8†	112.3 ± 23.7
TLC (% pred)	113.5 ± 8.5†	94.6 ± 9.1
RV/TLC (%)	146.7 ± 25.2†	100.5 ± 13.1
IC (L)	2.01 ± 0.52†	2.75 ± 0.46
MVV(L/min)	40.9 ± 14.3†	110.6 ± 26.4

Data are expressed as means ± one standard deviation. BMI = body mass index; FEV_1 = forced expiratory volume at first second; FVC = forced vital capacity; RV = residual volume; TLC = total lung capacity; IC = inspiratory capacity; MVV = maximal voluntary ventilation. † $P < 0.05$ = COPD *vs* control subjects.

Division of Respiratory Diseases, Federal University of São Paulo, Brazil. Patients were considered eligible for this study if they presented established clinical and functional diagnosis of moderate-to-severe chronic obstructive pulmonary disease (COPD) comprised the study group. Chronic breathlessness (Medical Research Council dyspnea score) and a long history of cigarette smoking were present in all patients (Table 1). Inclusion criteria were as follows: absence of physiologically significant deoxygenation at rest ($PaO_2 > 55$ mmHg, exercise $SaO_2 > 90\%$), no locomotor or neurological diseases, and no change in medication dosage or symptom exacerbation in the preceding 4-wk period. The control group, matched by age and sex, consisted of healthy non-smoking, who were recruited from the general population by advertisement.

All subjects were considered sedentary; that is, none were involved in regular physical activity programs at least for the past year, according to responses to an activity questionnaire described by Baecke et al.(1982). Before the tests, the procedures, including the known risks, were described in detail, and written informed consent (as approved by the Institutional Medical Ethics Committee – number 346549) was obtained from all subjects. This research study conformed to standards set by the Declaration of Helsinki.

2.2. Physiologic measurements

2.2.1. Pulmonary function tests

A spirometry test was performed using the CPF-S® spirometer (Medical Graphics Corporation-MGC, St. Paul, MN, USA) with the flow measurement conducted using a calibrated pneumotachograph. The subjects completed at least three acceptable maximal forced expiratory maneuvers before and 5 min after the administration of 400 mg of inhaled salbutamol. Technical procedures were those recommended by the Brazilian Society of Pneumology (2002). The values were compared with those predicted from Pereira et al. (2007). Maximum voluntary ventilation (MVV) was recorded by extrapolating the greatest 12-s accumulated volume. The subjects were actively encouraged to maintain the same volume and frequency by following an on-line display of the maneuver on a computer screen; that is, the end-expiratory volume remained relatively constant. At least two acceptable maneuvers were obtained with values differing by no more than 10% and after flow integration, the highest value was recorded by extrapolating the 12-s accumulated volume to 1 min (L/min, BTPS).

Full-body plethysmography was performed using the 1085 ELITE D® system (Medical Graphics Corporation (MGC), St. Paul, MN, USA) to obtain static pulmonary volumes (residual volume (RV); and total pulmonary capacity (TPC) in accordance with the standardized technique recommendations (Wanger et al., 2005). The reference values used for static pulmonary volumes were obtained from a healthy Brazilian population sample (Neder et al., 1999a).

2.2.2. Inspiratory capacity measurement

For analysis of the behavior of pulmonary dynamic hyperinflation (DH), the patients performed inspiratory capacity (IC) measurements at rest and immediately after the end of each exercise test, after four normal respiratory cycles. At least two maneuvers were performed to obtain reproducibility between them (difference of 150 mL) (O'Donnell et al., 2001; Neder et al., 1999a; Yan et al., 1997).

2.2.3. Maximal cardiopulmonary exercise test for the upper limb

Rapidly incrementing maximal cardiopulmonary exercise tests for the upper limb were performed using an Angio® arm cycle ergometer (Lode BV – Groningen, Netherlands), and the data were directed to the CardiO$_2$ System® (MGC). All procedures for this test were performed in accordance with the American Thoracic Society and American College of Chest Physicians statement (2003).

Subjects were seated, and the arm crank height was adjusted so that the fulcrum of the pedals was at the level of the gleno-humeral joints. Each subject was familiarized with the equipment before the beginning of the test and started with a warm-up period of 2 min with zero load while maintaining the rotation at 55–60 rpm during the entire test. Thereafter, the workload rate (W) was increased by 3–7 watts every minute in the COPD subjects and by 7–12 watts every minute in the control group to reach a duration of 8–12 minutes up to their maximum tolerance limit; standard verbal encouragement was given every minute. Subjects could stop the exercise when symptoms occurred or if subjects were not able to maintain minimal rotations in the arm crank exercise (lower than 50 rpm).

During the test, the following variables were obtained (i) metabolic variables: oxygen uptake (VO_2; mL. min^{-1}), carbon dioxide output (VCO_2; mL. min^{-1}) and respiratory exchange ratio; (ii) ventilatory variables: minute ventilation, respiratory frequency, ventilatory equivalents for O_2 and CO_2 (VE/VO_2 and VE/VCO_2) and the VE/MVV ratio; (iii) cardiovascular variables: 12-lead electrocardiogram and resting heart rate. The blood pressure was obtained with the individuals in the sitting position at rest and immediately after each test using an aneroid sphygmomanometer (G-Tech Premium®); and (iv) gas exchange variables: peripheral oxygen saturation with pulse oximetry. The perception of dyspnea and fatigue in the upper limb was evaluated at rest, at one-minute intervals, and at the exercise peak by means of Borg's modified scale (Borg, 1970). Ventilatory limitation was deemed to be present if the VE exercise peak values were greater than or equal to 80% of the MVV estimate. The values obtained were compared with those proposed by Neder et al.(1999c) based on healthy sedentary individuals among the Brazilian population.

2.2.4. Constant-load arm exercise tests

On separate days (at least 2 days apart), each subject undertook a series of four different constant-load arm exercise tests to the limit of tolerance. The work rates were randomly applied to induce intolerance between 1 and 20 min of exercise.

Relative to the peak values obtained at maximum incremental exercise (% peak W), these powers in control subjects and patients corresponded to ˜ 100% (W_A), 90% (W_B), 80% (W_C) and (W_D), which was a fourth test where the load was set to 10% above the CP estimated from the 3 previous tests chosen in an attempt to provide an even point distribution along the 1/time axis. The CP derived from the four tests was obtained (CP_M) and tested as described below. The flowchart of the study protocol can be visualized in Fig. 1.

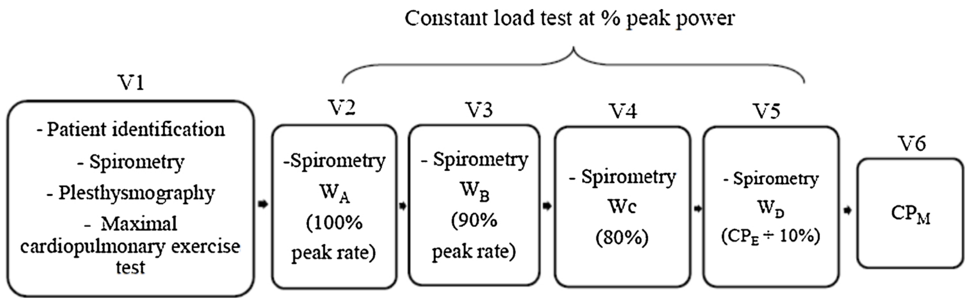

Fig. 1. Flowchart of the study protocol. At baseline, participants underwent lung function assessment (spirometry and pletysmography) and CPET to determine maximal workload. Spirometry was performed every visit (V) to ensure lung function stability. On V2, V3 and V4 participants undertook a constant-load at 100%, 90%, 80% relative to the peak values, respectively. On V5, participants undertook a test at CPE (Critical power estimated from 3 constant load test) + 10%. On V6, participants undertook the test at CP_M (critical power estimated from 4 constant load test).

2.2.5. Critical power test

The load corresponding to the critical power was determined from the linear regression of W-1/tlim of each constant load test (W_A, W_B, W_C, W_D), corresponding to the W value of the y-intercept, where the line touches the y-axis. Absolute values and percentages of peak work rate for the critical power asymptote and the absolute values of the curvature constant (W_{AT}) were obtained for patients and control subjects.

To confirm the estimated value of CP (CP_M), a square-wave test utilizing this load was performed on a different day with a target duration of 20 min; however, the subjects were not told that 20 min was the test's maximum duration. Estimated CP was validated by confirming stability in VO_2, heart rate and ventilation over the final 5 min of the 20-minute task.

2.3. Statistical analysis

The means and standard deviations (SD) or median and range from numerical or categorical variables are reported. A sample size of 8 subjects per group was calculated considering a difference relative workload achieved in the critical power between patients with COPD and controls (81.8 ± 3.3 *vs* 67.5 ± 3.7%peak, respectively), with alpha error of 0.05 and beta error of 0.90, according to the study of critical power of lower limbs in this population (Neder et al., 2000). Between-group differences expressed in absolute values and proportions were assessed using the non-paired Student's and Mann–Whitney tests, respectively. When appropriate, analysis of repeated measures with the Bonferroni post hoc test was used to evaluate differences between variables at different work rate within groups. Non-parametric Friedman's analysis of variance was used to evaluate differences in arm effort and dyspnea symptoms at different powers within groups. Nonlinear (hyperbolic) and linear models were utilized to evaluate the power-time and the power-1/t relationships, respectively. The probability of a type I error was established at 0.05 for all tests. The statistical program used was SPSS version 20.0.

3. Results

Eight patients with COPD (5 men) and eight sex- and age-matched control subjects (5 men) were enrolled in the study. Based on self-reported physical activity, both groups were considered sedentary. In relation to lung function, three patients showed a moderate degree of pulmonary obstruction, four patients showed a severe degree of obstruction, and only one patient was considered to have very severe obstruction. As expected, the markers of pulmonary obstruction, namely, FEV_1 (absolute values and percentage of predicted) and FEV_1/FVC, were significantly different between groups (Table 1). There were also reductions in the percentage predicted values of FVC (76.8 ± 11.1% pred) in the COPD group compared to that in the controls, suggesting static pulmonary hyperinflation, which was confirmed by plethysmographic evaluation. Patients with COPD showed a significant reduction in inspiratory capacity at rest compared to that in the control group (2.01 ± 0.52 *vs*. 2.75 ± 0.46 L, respectively), which was indicative of gas trapping (Table 1).

The responses to incremental and constant-load exercise at CP during upper limb exercise are shown in Table 2. During incremental exercise, patients with COPD, but not controls, presented with marked reduced ventilatory reserve (VE/MVV = 0.93 ± 0.9) and dynamic hyperinflation (ΔIC = -521.2 ± 207.6 mL) in the ramp-incremental exercise test. No significant differences were observed when CP/Peak-Power% was compared between groups (COPD 59.8 ± 11.4% and controls 66.7 ± 9.3%). However, during exercise at CP_M, COPD patients had a lower ventilatory reserve (VE/MVV = 0.89 ± 0.17) and hyperinflation (ΔIC= -395.0 ± 248.4 L) compared with controls. All participants were able to achieve the target duration for the validation of the CP estimate (20 min). The VO_2 and VE responses in the last five minutes showed that a steady state was achieved by the COPD patients during the CP test.

Fig. 2A and B show the different ranges of values for the power axes of the hyperbolic relationship for the COPD group and control group, respectively. Fig. 2 and D show a comparative evaluation between the COPD group and control group, respectively. Note that although there was a lower intercept (critical power), no modification in the slope (W_{AT} - anaerobic capacity of work) was found in the COPD patients compared to the control group.

Interestingly, the ventilatory reserve levels at exhaustion in the series of constant work rate tests (W_A to W_D) in the COPD group did not differ from each other, denoting a "ceiling" effect at the limit of tolerance (Table 3). In contrast, the ventilatory reserve was large in the control group. The inspiratory capacity during the four constant work rate tests was dramatically reduced in patients with COPD (Fig. 3). The following variables were significantly linearly correlated with CP: hyperinflation (ΔIC) (r:- 0.89; $P < 0.01$), VE/MVV (r: 0.76; $P < 0.01$), and hyperinflation in the four constant load tests (r: -0.57; $P = .01$).

4. Discussion

The aim of the study was to investigate the impact of the ventilatory constraints on the power-duration relationship during upper limb exercise in a group of no hypoxemic patients with moderate-to-severe chronic obstructive pulmonary disease. The main findings of this study were as follows: (i) the time to the limit of exercise tolerance decreases hyperbolically as a function of power output, as shown previously for lower limb exercise; (ii) the critical power (absolute values and % of peak power) and W_{AT}, the slope of the linearization of the power-duration relationship (anaerobic capacity of work), were not different in both COPD and control subjects in this exercise modality, but at the expense of a high mechanical ventilation stress in patients with COPD; and (iii) in COPD patients, different from controls, the hyperbolic shape of the power-duration relationship appeared to be influenced by mechanical ventilatory constraints during the sequence of four constant-load tests. This was suggested by the reduced ventilatory capacity and DH during the exercise bouts utilized to estimate CP; however, these mechanical abnormalities did not limit the patients in performing the sustained exercise at the measured critical power.

Following the principle of critical power that represents the highest

Table 2
Exercise variables at peak ramp-incremental (peak) of upper limbs and at the last minute of the test at individual's critical power measured (CP_M) in patients with COPD and control subjects.

				Critical Power (CP_M)		
	UL - Incremental			COPD		Control
Variables	COPD	Control	Absolute	% peak	Absolute	% peak
Power (W)	50.0 ± 21.2	62.7 ± 20.4	30.2 ± 12.7	59.8 ± 11.4	42.2 ± 16.7	66.7 ± 9.3
Time (s)	520.8 ± 88.7 †	420.5 ± 71.7	1200	——	1200	——
VO_2 (L/min)	0.91 ± 0.25	1.16 ± 0.31	0.79 ± 0.28 ‡	85.5 ± 18.6	1.2 ± 0.37	104.6 ± 21.8
W_{AT} (J)	—	—	3455 ± 1434	—	3260 ± 1074	—
RER	0.92 ± 0.13† ††	1.16 ± 0.17	0.79 ± 0.07	87.5 ± 10.8	0.97 ± 0.23	83.5 ± 15.1
HR (b/min)	130.3 ± 15.7	142.2 ± 12.9	122.3 ± 14.6	94.0 ± 7.9	137.5 ± 16.9	97.1 ± 1.2
HR (%pred)	84 ± 8	82 ± 7	79 ± 8	–	89 ± 12	–
O_2pul(ml/b/m)	6.9 ± 1.8	8.1 ± 1.7	6.3 ± 1.9 ‡	87.0 ± 10.0 §	8.6 ± 1.9	107.0 ± 20.0
VE (L/min)	38.0 ± 13.8	51.6 ± 17.6	36.7 ± 14.4	96.3 ± 19.1	46.9 ± 17,6	92.8 ± 30.6
VE/MVV	0.93 ± 0.9 †	0.47 ± 0.13	0.89 ± 0.17 ‡	——	0.43 ± 0.16	——
f_β (bpm)	37.0 ± 9.7	36.1 ± 7.6	31.3 ± 8.0	85.3 ± 7.6	34.0 ± 5.0	97.2 ± 22.7
VE/VO_2	45.0 ± 8.8	44.4 ± 6.8	46.3 ± 11.7	102.8 ± 11.7 §	37.7 ± 9.7	84.7 ± 18.4
VE/VCO_2	49.6 ± 13.2 †	37.8 ± 4.4	55.1 ± 13.6 ‡	112.5 ± 17.0	38.7 ± 4.8	103.0 ± 14.7
ΔIC (mL)	−521.2 ± 207.6†	−18.7 ± 116.3	−395.0 ± 248.4‡	——	−148.5 ± 130.7	——
Borg BL	9.5(4-10)	7 (3-10)	4.5 (0,5-10)	——	4 (4-9)	——
Borg AE	5.5 (2-10)	5.0 (0-7)	4 (0-10)	——	1 (0-5)	——

UL = upper limbs; VO_2 = oxygen uptake; W_{AT} = anaerobic capacity of work; RER = respiratory exchange ratio; HR = heart rate; b/min: beats per min; O_2pul = oxygen pulse; VE = minute ventilation; VE/MVV = ventilatory reserve; f_β = respiratory rate; bpm: breaths per minute; VE/VO_2 = ventilatory equivalent for oxygen; VE/VCO_2 = ventilatory equivalent for carbonic gas; ΔIC = variation of inspiratory capacity; BL = breathlessness; AE = arm effort; WR = work rate. All values are means ± SD with the exception of Borg scores, which are presented as median and range. † $p < .05$: patients *vs* control subjects for the UL incremental test; ‡ $P < .05$: patients *vs* control subjects for the absolute values at CP test; § $P < .05$: patients *vs* control subjects for the values of the CP in % pred; †† $P < .05$: UL incremental test *vs* critical power test within COPD group.

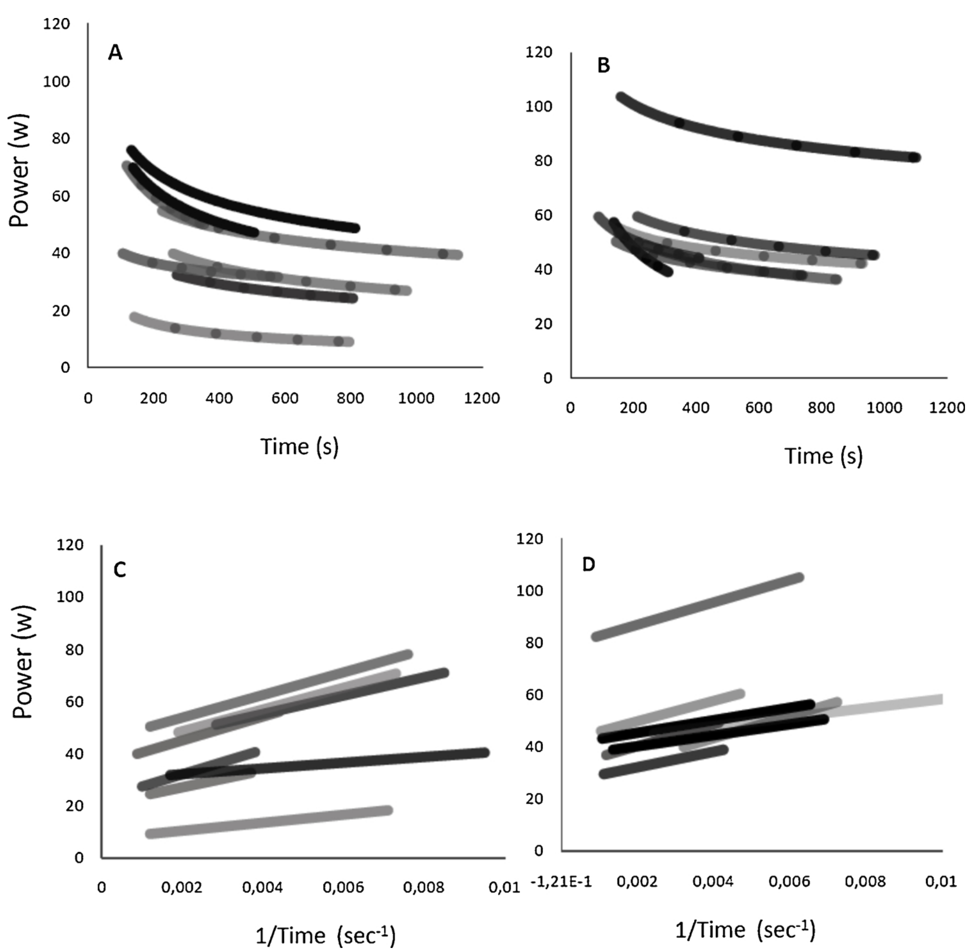

Fig. 2. The power–duration (W–t) in patients with COPD (A- left panel) and control subjects (B- right panels). In (C) hyperbolic relationship and (D) after linearization in a patients and control subject, respectively.

Table 3
Variables at progressively intense (WA to WD) constant-load exercise test to the limit of tolerance in patients with COPD and control subjects.

	Patients				Control Subjects			
	W_A	W_B	W_C	W_D	W_A	W_B	W_C	W_D
Power (W)	50 ± 21†	45 ± 19	40 ± 17	35 ± 14	59 ± 20†	53 ± 18	47 ± 16	44 ± 15
% Peak	1 ± 0	0.89 ± 0.1	0.78 ± 0.2	0.65 ± 0.7	1 ± 0	0.89 ± 0	0.79 ± 0	0.74 ± 0.3
Duration (sec)	174 ± 64†	269 ± 91	469 ± 323	743 ± 252	171 ± 53†	264 ± 77	487 ± 172	775 ± 276
VO_2 (ml/min)	881 ± 60‡	915 ± 82	927 ± 78‡	962 ± 114	1191 ± 106	1193 ± 109	1249 ± 98	1201 ± 123
R	1.00 ± 0.18	0.94 ± 0.16‡	0.91 ± 0.19	0.82 ± 0.11‡	1.12 ± 0.57	1.17 ± 0.94	1.11 ± 0.78	1.03 ± 0.61
HR (b/min)	127 ± 5	127 ± 4	130 ± 4	121 ± 5	137 ± 17	139 ± 20	137 ± 13	136 ± 15
HR (%pred)	82 ± 7	83 ± 6	85 ± 6	79 ± 1‡	89 ± 9	90 ± 1	89 ± 6	89 ± 9
O_2pul(ml/b/m)	6.9 ± 0.4‡	7.2 ± 0.6	7.1 ± 0.5‡	7.8 ± 0.8	8.6 ± 0.5	8.4 ± 0.4	9.0 ± 0.5	8.7 ± 0.6
VE (L/min)	40.0 ± 12.9	39.7 ± 13.4	40.2 ± 13.7	40.0 ± 13.6	52.3 ± 4.8	51.5 ± 5.9	50.6 ± 3.7	47.6 ± 6.1
VE/MVV	0.99 ± 0.13‡	0.98 ± 0.15‡	0.98 ± 0.15‡	1.00 ± 0.24‡	0.52 ± 0.14	0.51 ± 0.16	0.51 ± 0.11	0.47 ± 0.18
f (bpm)	38 ± 8	37 ± 8	36 ± 10	35 ± 8	36 ± 8	34 ± 5	35 ± 4	34 ± 7
VE/VO_2	45 ± 8	45 ± 12	43 ± 8	46 ± 17	45 ± 8	45 ± 4	41 ± 7	42 ± 10
VE/VCO_2	45 ± 10	46 ± 11	48 ± 14	49 ± 7‡	38 ± 9	38 ± 9	37 ± 8	39 ± 6
ΔIC,mL	−458 ± 207‡	−466 ± 327‡	−441 ± 292‡	−326 ± 386‡	−77 ± 111	−43 ± 80	−95 ± 98	−88 ± 103
Borg BL	7 (2-10) ‡	7 (2-10) ‡	6 (2-10)	7 (0.5-10) ‡	3 (0-10)	2 (0-7)	3 (0-7)	3 (0-7)
Borg AE	7 (3-10)	6 (3-10)	7 (5-10)	6 (2-10)	6 (3-10)	6 (4-10)	5 (3-10)	5 (3-7)

VO_2 = oxygen uptake; r = respiratory exchange ratio; HR = heart rate; b/min: beats per minute; O_2 pul = oxygen pulse; VE = minute ventilation; VE/MVV = ventilatory reserve; f = respiratory rate; bpm: breath per minute; VE/VO_2 = ventilatory equivalent for oxygen; VE/VCO_2 = ventilatory equivalent for carbonic gas; ΔIC = variation of inspiratory capacity; BL = breathlessness; AE = arm effort; W = work rate. All values are means ± SD with the exception of Borg scores, which are presented as median and range. †$P < .05$: significant difference between work rates within groups. ‡$P < .05$: significant difference between groups within protocols.

sustainable power output associated with a steady metabolic state, demarcating the heavy from the severe exercise intensity domain. In addition, it seems that cardiovascular and/or peripheral variables do not play a primary role in limiting upper limb exercise endurance in moderate-to-severe COPD patients as evidenced by the lower cardiac stress observed during exercise at CP. The correlations among CP and VE/MVV and hyperinflation may suggest that patients with elevated CP may better tolerated dyspnea associated with ventilatory stress or hyperinflation.

Although the CP model of the lower limb has previously been tested in patients with COPD, the extrapolation of this model for upper limb exercise had never been performed in these subjects. CP exercise of the upper limb has been shown in various modalities of exercise and in the most diverse situations, as demonstrated in previous studies (Altimari et al., 2007; Capodaglio and Bazzini, 1996; Chidnok et al., 2013; Dekerle et al., 2002; Nakamura et al., 2005). Duration times and the number of tests for determining CP vary in the literature. Typically, from three to seven bouts of exercise with a duration from one to fifteen minutes were performed on different days (Neder et al., 2000; Malaguti et al., 2006; Hill, 1927).

Furthermore, after linearization of the W-t parameters, similar values of the slopes were found, *i.e.,* the anaerobic work capacity (W_{AT}) (supra-threshold fatigue) in patients compared to that in controls (3455 ± 1434 *vs*. 3260 ± 1074 J, respectively). Interestingly, values close to 3000 J for the supra-CP work capacity for upper limb exercise in patients with COPD are similar to those data reported by Neder et al. (2000) and Van der Vaart et al. (2014) for lower limb exercise in this population. Thus, it can be inferred that despite a lower muscle mass in the upper limb, the W_{AT} may represent a strong relationship between the upper extremity muscles and the rib cage and ventilatory mechanical limitation, especially during higher levels of effort. In a task that requires increased activity of the upper limb, two additional factors become important determinants of the respiratory pattern, namely, pulmonary hyperinflation and the reserve force of the diaphragm. Due to dynamic hyperinflation, the respiratory muscles are placed in an unfavorable position with respect to their length-tension relationship during inspiration, reducing their ability to generate force. Thus, when the function of the diaphragm becomes compromised, the accessory muscles make a greater contribution to inspiration. In this way, the activity of the upper limb can force the muscles of the shoulder girdle

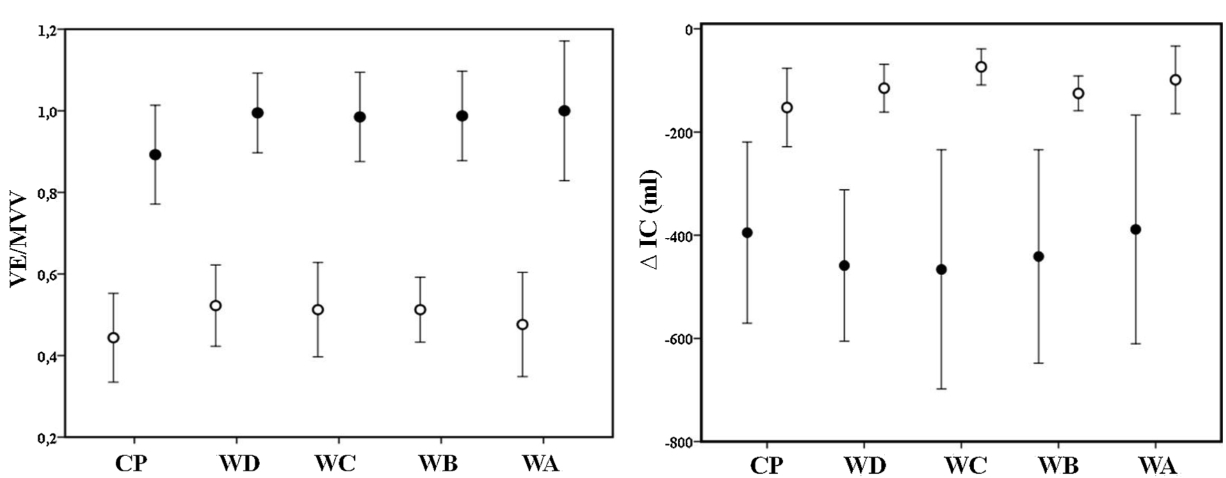

Fig. 3. Behavior of ventilatory reserve and inspiratory capacity variation at critical power (CP) and at constant work rate test (WA to WD) in patients with COPD (●) and controls (○), respectively. Data are expressed as mean and standard error.

and upper part of the trunk to participate simultaneously in ventilatory and non-ventilatory activities. So, in these conditions there is a greater muscle mass than just the arms that get recruited. Simultaneous afferent inputs or outputs from the central nervous system regions that control the tonic and respiratory functions of these muscles may result in significant incoordination of the respiratory muscle action, which may lead to increased work, dyspnea, thoracoabdominal asynchrony that has been observed during the execution of upper limb exercise (Epstein et al., 1995).

Additionally, in the upper limb cycle ergometry tests in patients with COPD, the intense local demand on the upper limb musculature, coupled with a relatively lower oxidative capacity and relative perfusion of the muscles of the upper limbs, and the non-familiarity with the arm cranking task, might contributes to exacerbating lactate formation and accumulation compared with a similar exercise task of the lower limbs. This likely lactate accumulation and its buffering by bicarbonate results in an exacerbated ventilatory response, which gives rise to an early intolerance and may lower W_{AT} in COPD compared with controls (Maltais et al., 1996). On the other hand, the similarities of the anaerobic capacity between the COPD and healthy groups can be attributed to the preserved glycolytic capacity in patients with COPD. Studies by Maltais et al. (1996) and Gea et al. (2001) support this assumption, since they have showed that the activity of the glycolytic enzymes PFK and CK, obtained from upper limb muscle biopsy sample, were similar in patients with COPD and controls.

Although it has been postulated that the mechanisms limiting tolerance to very intense exercise are common for large muscle groups such as those muscles responsible for locomotion, this mechanism appears not to be the same for small muscle groups. The large muscle groups send modulating afferent inputs from groups III/IV as protection from the magnitude of fatigue in whole-body exercise. This mechanism of peripheral fatigue is constant and does not vary with changes in the supply of oxygen. Moreover, Broxterman et al. (2015) recently showed a significant contribution of central fatigue to the shape of the power duration curve in upper limb exercise in healthy subjects. We note that unlike those observed in healthy subjects in our study, the ventilatory constraints are pronounced in patients with COPD, which limits peripheral muscle stress and consequently peripheral and central fatigue. However, central fatigue is enhanced during lower-limb exercise in COPD compared with controls, in proportion to the resting or exercising ventilatory impairments (Cannon et al., 2016). Thus, we cannot rule out the participation of central fatigue as we did not perform an objective measure of this component.

Interestingly, in the four tests of constant load, the ventilatory "ceiling" was reached close to maximum levels (VE/MMV > .98). Another important finding is that the COPD group presented with dynamic hyperinflation in all tests, which reinforces the concept of association between the increase in power output of the upper limb and the increase in end-expiratory lung volume. In our study, the degree of DH reached during

the CP test (60% of peak work) was greater than that found by Colucci et al. (2010) in the exercise of the upper limb in patients with COPD. However, this fact can be explained by the difference in the degree of pulmonary obstruction in the patients enrolled in two studies, as well as the difference in the upper limb exercise protocol used.

Our results indicate that the critical power concept may also be applied for upper limb exercise in ventilatory-limited patients with COPD in the same way that Neder et al. (2000) showed in the critical power assessment of the lower limb. It is noteworthy in the present study that all patients could sustain 20 min of exercise at the level of critical power with stable VO_2 and VE values. Furthermore, it is well known that upper extremity training is an essential component of a rehabilitation program and that an arm cycle ergometer has been considered the gold standard equipment for upper limb training (Janaudis-Ferreira et al., 2012).

Patients with COPD may develop dynamic lung hyperinflation proportional to the work rate above CP during arm exercise. In this sense, the present study provided an intensity level of upper limb exercise that could be maintained for prolonged periods of time in patients with COPD without limitation by ventilatory constraints.

Therefore, the critical power determination would be an attractive rehabilitation strategy for upper limb training in patients with COPD, if the imposed work load does not limit the patient's training efficiency.

5. Study limitations

The present study has some limitations: (i) a relatively small number of patients were evaluated leading to the possibility of a type II error for the studied variables; however, this limitation was due to the complexity of the protocol that included seven consecutive visits to the laboratory with performance of strenuous exercise tests. Additionally, our sample size was similar to several other studies that investigated the critical power (Neder et al., 2000; Chidnok et al., 2013; Malaguti et al., 2006; Brickley et al., 2002; Bergstrom et al., 2014; Valli et al., 2011); (ii) our results should not be extrapolated for COPD patients with significant hypoxemia; (iii) differences in segmental body composition between patients and controls were not assessed; and (iv) we may have underestimated the role of peripheral muscular factors in limiting exercise tolerance, as we did not assess the objective evidence of arm fatigue (Gea et al., 2001). In addition, further studies using larger samples are needed to confirm our preliminary findings and to test the CP response to different interventions such as bronchodilator therapy, supplemental oxygen, non-invasive ventilation, and arm exercise training.

6. Conclusion

The present study shows that the ventilatory constraint is the most important determinant of the power-duration relationship for upper limb exercise in nonhypoxemic, moderately severe patients with stable COPD; and although patients typically showed more ventilatory stress compared with control subjects, the ventilatory constraints did not limit the sustained exercise at the critical power. Our results warrant further research to evaluate the following: the feasibility of simpler, clinically useful protocols; the behavior of the power-duration relationship in upper limb exercise in hypoxemic patients with different degrees of respiratory impairment; and the effects of different intervention strategies on specific determinants of endurance capacity.

Authors' contributions

The study was conceived and design by CM, SDC, EC and LEN. The data was collected and analyzes by EC, TPS, RP, CM. The interpretation of the data and results were made by all authors. EC, TPS, RP prepared the first draft of the manuscript and successive drafts were contributed by all authors. CM, SDC and LEN contributed with critical revision for the review. The final version was approved by all authors.

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Declaration of Competing Interest

The authors declare there are no competing of interest.

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