Endurance and Resistance Respiratory Muscle Training and Aerobic Exercise Performance in Hypobaric Hypoxia

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INTRODUCTION: Hypoxia-induced hyperventilation is an effect of acute altitude exposure, which may lead to respiratory muscle fatigue and secondary locomotor muscle fatigue. The purpose of this study was to determine if resistive and/or endurance respiratory muscle training (RRMT and ERMT, respectively) vs. placebo respiratory muscle training (PRMT) improve cycling performance at altitude.

METHODS: There were 24 subjects who were assigned to PRMT ($N = 8$), RRMT ($N = 8$), or ERMT ($N = 8$). Subjects cycled to exhaustion in a hypobaric chamber decompressed to 3657 m (12,000 ft) at an intensity of 55% sea level maximal oxygen consumption ($\dot{V}O_{2max}$) before and after respiratory muscle training (RMT). Additionally, subjects completed a $\dot{V}O_{2max}$, pulmonary function, and respiratory endurance test (RET) before and after RMT. All RMT protocols consisted of three 30-min training sessions per week for 4 wk.

RESULTS: The RRMT group increased maximum inspiratory (P_{Imax}) and expiratory (P_{Emax}) mouth pressure after RMT (P_{Imax}: 117.7 ± 11.6 vs. 162.6 ± 20.0; P_{Emax}: 164.0 ± 33.2 vs. 216.5 ± 44.1 cmH_2O). The ERMT group increased RET after RMT (5.2 ± 5.2 vs.18.6 ± 16.9 min). RMT did not improve $\dot{V}O_{2max}$ in any group. Both RRMT and ERMT groups increased cycling time to exhaustion (RRMT: 35.9 ± 17.2 vs. 45.6 ± 22.2 min and ERMT: 33.8 ± 9.6 vs. 42.9 ± 27.0 min).

CONCLUSION: Despite different improvements in pulmonary function, 4 wk of RRMT and ERMT both improved cycle time to exhaustion at altitude.

KEYWORDS: respiratory muscle training, altitude, performance, hypoxia.

Wheelock CE, Hess HW, Johnson BD, Schlader ZJ, Clemency BM, St. James E, Hostler D. *Endurance and resistance respiratory muscle training and aerobic exercise performance in hypobaric hypoxia*. Aerosp Med Hum Perform. 2020; 91(10):776–784.

In healthy humans, the respiratory muscles are rarely challenged to the point of fatigue. However, during high intensity exercise (i.e., > 85% $\dot{V}O_{2max}$) or exposure to extreme environments,[7,28] respiratory muscle fatigue can occur and reduce performance.[2,10,20] Respiratory muscle fatigue increases metabolite concentrations in the respiratory muscles and stimulates group IV muscle afferents to elicit a metaboreflex.[26] A subsequent sympathetic vasoconstriction occurs in the exercising locomotor muscles that reduces blood flow and oxygen delivery, and reduces sustainable exercise intensity and performance.[9] Respiratory muscle training (RMT) has been utilized to prevent respiratory muscle fatigue and improves endurance exercise in a variety of activities (e.g., running, cycling, rowing, swimming).[8,14]

Two common methodologies have been used for RMT. Resistance respiratory muscle training (RRMT) consists of brief inspirations and expirations against resistance [e.g., 40–60% inspiratory and expiratory maximum pressures (P_{Imax} and P_{Emax}, respectively)].[1,13,14] This training improves respiratory muscle strength and can reduce the work of breathing in instances of elevated inspiratory or expiratory resistance (e.g., scuba diving). In contrast, voluntary isocapnic hyperpnea

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This manuscript was received for review in March 2020. It was accepted for publication in July 2020.

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DOI: https://doi.org/10.3357/AMHP.5624.2020

training, also known as endurance respiratory muscle training (ERMT), improves respiratory muscle endurance and consists of continuous breathing at higher breath frequencies (f_B) and volumes.[16] Due to complexity and/or commercial availability, RRMT has been selected in the majority of RMT studies.[1,13,14] However, the specificity of training may be a limitation to the application of RMT because of the differences in the work of breathing during various sports and/or environments that require either resistive or endurance respiratory muscle work.

Altered pressure environments at altitude (hypobaria) or depth (hyperbaria) pose specific demands on the respiratory system and increase work of breathing. At altitude the partial pressure of oxygen is reduced and induces hypoxemia. This results in a reflex activation of the peripheral chemoreceptors, known as the hypoxic ventilatory response, and increases ventilation at rest and during exercise at altitude.[25] This increase in ventilation may lead to premature fatigue in the respiratory muscles and is one mechanism thought to limit performance at altitude. RMT has been reported to improve endurance exercise performance during hypoxic breathing at sea level and at altitude, and the mechanisms have been recently reviewed.[1,13] However, most studies have used a reduced fraction of inspired oxygen ($F_IO_2 = 0.11–0.16$) to simulate altitude while remaining at sea level (i.e., normobaric hypoxia).[13] This is an important distinction to make as normobaria fails to mimic the reduction in air density at altitude. Moreover, only one study has examined the effect of ERMT on performance in hypobaric hypoxia.[12] In contrast, work of breathing in the water and at depth is increased through elevated inspiratory and expiratory resistance.[11] In these situations, RRMT has been shown to improve performance and to a greater extent when compared to ERMT.[22,23,30] Despite the potential importance of specificity of RMT for resistive or endurance respiratory muscle work during events and/or in special environments, the majority of studies have employed RRMT for performance at altitude.[1,13]

While the efficacy of RRMT and ERMT have been directly compared in swimming performance at depth, no study has directly assessed these two methodologies in a randomized, placebo-controlled trial of performance at altitude.[30] Therefore, the purpose of the study was to determine if RRMT and/or ERMT improves cycling performance at altitude compared to a placebo RMT (PRMT). Additionally, given the differential training adaptations (i.e., strength vs. endurance) and specific application to the ventilatory responses at altitude, it was hypothesized that both RRMT and ERMT would improve performance at altitude, but that ERMT would improve performance to a greater extent during a cycling time to exhaustion test via augmented respiratory muscle endurance.

METHODS

Subjects

All study visits were completed by 24 healthy men (**Table I**). All procedures were approved by the Institutional Review Board at the University at Buffalo and performed in accordance to the Declaration of Helsinki. Subjects provided written informed consent prior to beginning the study protocol. Additionally, subjects completed a health history questionnaire and medical screening with a study physician. Subjects were excluded if they reported a history of any respiratory or cardiovascular disease or condition, gastrointestinal disease or surgery, medications that would blunt the physiological responses to exercise, tobacco use, or a relative $\dot{V}O_{2max}$ less than 35 mL · kg^{-1} · min^{-1}. Subject anthropometrics (i.e., height and mass) and body composition were measured.

Table I. Subject Characteristics for Placebo (PRMT), Resistance (RRMT), and Endurance (ERMT) Training Groups.

SUBJECT CHARACTERISTIC	PRMT (*N* = 8)	RRMT (*N* = 8)	ERMT (*N* = 8)	*P*-VALUE
Age (yr)	24 ± 4	24 ± 3	24 ± 3	0.38
Height (cm)	171 ± 8	175 ± 6	177 ± 5	0.27
Mass (kg)	80 ± 13	82 ± 10	82 ± 10	0.90
Body Fat (%)	18 ± 7	17 ± 5	15 ± 5	0.70
$\dot{V}O_{2max}$ (mL · kg^{-1} · min^{-1})	38 ± 9	39 ± 6	39 ± 5	0.95

Values are mean ± SD.

Procedure

This was a randomized-controlled trial that compared the effects of two RMT protocols against those of a placebo. Subjects were randomized into three groups: ERMT, RRMT, or PRMT. Subjects completed testing before and after RMT, which consisted of: 1) pulmonary function testing, 2) a respiratory endurance test (RET), 3) maximal oxygen consumption ($\dot{V}O_{2max}$), and 4) a cycle time to exhaustion test (55% of sea level $\dot{V}O_{2max}$) at altitude.

$\dot{V}O_{2max}$ testing was completed at ground level (~182 m/597 ft) on a cycle ergometer (Bodyguard Fitness V9×, Bodyguard Fitness, QC, Canada) beginning at 50 W and a self-selected cadence between 70–80 rpm. The resistance increased by 25 W every 2 min until subjects reached exhaustion. $\dot{V}O_{2max}$ was defined as reaching at least three of the following: a plateau in $\dot{V}O_2$ with increasing workload, maximal perceived effort rating on the Borg Scale, a respiratory exchange ratio above 1.15, or reaching at least 90% of maximum age-predicted heart rate. All subjects met criteria for true $\dot{V}O_{2max}$. Expired CO_2 and O_2 concentrations and ventilation ($\dot{V}_E$) were measured using a metabolic cart (TrueOne® 2400, Parvo Medics, UT, USA).

Subjects completed a cycle time to exhaustion test at an intensity equal to 55% of the subject's ground level $\dot{V}O_{2max}$ before and after RMT (PRMT: 120 ± 30 W; ERMT: 125 ± 15 W; RRMT: 130 ± 20 W). The intensity for each subject was determined based on their pre-RMT $\dot{V}O_{2max}$ and remained the same for posttesting. At steady state exercise at altitude (5 min), this workload corresponded to approximately 54% and 51% normobaric $\dot{V}O_{2max}$ for all groups before and after RMT, respectively (pre-RMT PRMT: 55.8 ± 6.0%; ERMT: 52.7 ± 6.2%; RRMT: 54.6 ± 5.6%; and post-RMT PRMT: 54.0 ± 3.4%; ERMT: 49.0 ± 4.5%; and RRMT: 50.5 ± 4.8%). Subjects were seated on a cycle ergometer (Bodyguard Fitness V9×, Bodyguard Fitness, QC, Canada) and decompressed in a hypobaric chamber from ground level [744 mmHg (182 m or 597 ft)] to 483 mmHg (3657 m or 12,000 ft) ambient barometric pressure. This altitude was selected based on previous work in our lab and operational relevance for military personnel.[12] Following a 3-min resting baseline, subjects cycled to exhaustion at the same self-selected cadence as the $\dot{V}O_{2max}$ test, between 70–80 rpm. Exhaustion was defined as the time at which subjects could no longer maintain within $\pm$ 5 rpm of their self-selected cadence or voluntarily discontinued cycling. Following the end of exercise, subjects were monitored for 20 min at altitude before returning to ground level. The primary outcome was duration to exhaustion or the time point when arterial oxygen saturation (S_pO_2) decreased below 60%.

Subjects were randomized to an ERMT, RRMT, or PRMT protocol. The RMT protocols employed were developed in our lab.[16,17] Training for each group consisted of 30-min training sessions, 3 d/wk, for 4 wk (12 total sessions). Subjects completed one training session per week in the lab and completed the additional two training sessions on their own. Training days were separated by at least 24 h. The RMT device consisted of a nose clip and mouthpiece equipped with one-way inlet and outlet valves. The valves allowed fresh air to be inspired in order to maintain a constant (isocapnic) end-tidal CO_2. The breathing apparatus was connected to a pressure sensor and custom RMT device which paced the breathing frequency and recorded all training sessions to verify compliance.

The PRMT protocol was performed using the same respiratory training device as the RRMT and ERMT with sham resistance springs ($<$ 10% P_{Imax} and P_{Emax}) and the rebreathing bag removed. Respiratory cycles were completed every 30 s for 30 min. Specifically, the subjects completed a 5-s inspiration, followed by a 5-s breath hold, and then a 5-s expiration. Subjects then returned to spontaneous breathing for the remaining 15 s.

For the RRMT protocol, subjects completed a 5-s inspiration followed by a 5-s expiration taken against an opening pressure of 60% P_{Imax} and P_{Emax} by properly spring loading the inspiration and expiration valves, respectively. At time zero, subjects took a deep full inspiration from residual volume followed by a complete expiration from total lung capacity. The subject then removed the mouthpiece, breathed normally, and waited for the next timed cycle. The subject performed 45 vital capacity breaths against resistance during each training session. In the beginning of each weekly training session, under supervision of an investigator, P_{Imax} and P_{Emax} measurements were performed and the load pressures of the valves were adjusted to 60% of the newly measured P_{Imax} and P_{Emax}. If the value of P_{Imax} and P_{Emax} measured in a training week were less than or equal to the one in previous training week, the resistance either remained the same or was increased if tolerable to the subjective observation of the subject and the investigator's approval.

The ERMT protocol used voluntary isocapnic hyperpnea training previously used in our lab.[12,30] Subjects breathed through a mouthpiece that had inspiratory and expiratory check valves and a rebreathing bag attached. This apparatus was designed to have a low respiratory resistance that allowed for high ventilation rates. Isocapnia was maintained with the rebreathing bag, which was filled with part of the expiration and then inhaled during the next inspiration. As the rebreathing bag empties, fresh air enters through the spring-loaded inspiration valve. The volume of fresh air inspired in each breath is regulated by the natural regulation of breathing, which is generally adequate to maintain isocapnia. This has been verified by measurements of expired air end-tidal CO_2 during training sessions in an earlier study in our laboratory using the same techniques and equipment.[30] The subject's breathing frequency was monitored by an electronic pressure gauge at the mouthpiece to verify that breath cycles kept pace with synchronized visual and auditory signals from an electronic RMT device. The volume of the rebreathing bag was initially set at a volume representing approximately 50% of the subject's slow vital capacity (SVC). The f_B was selected by dividing 60% of the subject's measured maximal voluntary ventilation (MVV) by the bag volume such that f_B = MVV*(0.60) / bag volume. If needed, the bag volume was adjusted so that it corresponded with an f_B that the subject could maintain for each 30-min session. In each successive daily session, the subject increased the f_B by 1–2 breaths per min after 20 min of training. When possible, the subjects then continued at this higher frequency for the last 10 min of training. The next training session began at the highest frequency achieved in the previous session and this was then maintained for 20 min, followed by an increase of 1–2 breaths per min for the remaining 10 min. When the f_B reached 50 breaths per min, the bag volume was increased by 0.1 L and f_B was reduced to the volume that would maintain the same level of ventilation, and the cycle was then repeated.

Each RMT session was recorded by a microprocessor in the RMT device and compliance determined by breath counts. Training sessions were downloaded to a PC during the weekly in-lab training session for investigator review. The data ensured that all subjects adhered to the RMT. Subject compliance was confirmed by the investigators and all data were included in the data analysis.

Equipment

A PC-based spirometer (SpiroPerfect™ PC-Based Spriometer, Welch Allyn Inc., NY, USA) was used to obtain forced vital capacity, forced expiratory volume in 1 s, SVC, and MVV in 15 s. All pulmonary function testing was done in accordance to American Thoracic Society standards and reported as BTPS. Maximal pressures were measured with a manometer connected to a mouthpiece. A small hole in the manometer tube generated a leak that prevented the use of buccal muscles to generate false pressure readings. P_{Imax} was measured at residual volume and P_{Emax} at total lung capacity. Respiratory muscle endurance was assessed by a timed, isocapnic respiratory muscle endurance test (RET). Using a tidal volume of ~50% SVC and an f_B determined by dividing 60% of the MVV value ($L \cdot min^{-1}$) by the tidal volume, subjects breathed through a mouthpiece and rebreathing bag until they were unable to maintain the target ventilation presented to each subject via a custom computer display.

During the cycle time to exhaustion, subjects breathed through a mouthpiece connected to a metabolic cart (TrueOne® 2400, Parvo Medics, UT, USA) that had been calibrated at altitude (483 mmHg) to correct for the change in barometric pressure. Breath-to-breath expired gases were collected to measure $\dot{V}_E$, V_T, f_B, and CO_2 and O_2 concentrations to calculate $\dot{V}O_2$. Additionally, subjects were fitted with a heart rate monitor (Polar T31, Polar Electro Inc., NY, USA) and pulse oximeter (Lifesense® II, Nonin Medical Inc, MN, USA). Subjective ratings of perceived exertion (RPE; OMNI-RPE scale) were recorded. Breath-to-breath measures of expired gases were averaged every minute of exercise. Heart rate, S_pO_2, and RPE were collected every 5 min during exercise and immediately post-exercise.

Statistical Analyses

Results are presented as mean ± SD unless otherwise noted. A one-way analysis of variance (ANOVA) was used to examine differences between RMT groups pre-RMT. A two-way, repeated measures ANOVA was used to assess differences from pre- to post-RMT and between RMT groups for pulmonary function and performance (i.e., respiratory muscle endurance, cycle time to exhaustion, and $\dot{V}O_{2max}$). A robust outlier removal (ROUT) method was used to identify outliers and extract nonphysiological performances on the respiratory endurance test. At a sensitivity Q = 0.1% (i.e., remove definitive outliers), five outliers were identified from the data set. However, only one subject (RRMT group) had a performance that was nonphysiological, while the other four outliers were large improvements during the RET following ERMT, so their data was ultimately included in our analysis. The one outlier removed from the respiratory endurance test analysis was likely due to poor effort during the SVC and MVV pulmonary tests, from which intensity for the respiratory endurance test was derived.

Two methods were used to assess differences from pre- to post-RMT and between RMT groups for dependent variables ($\dot{V}O_2$, V_T, f_B, $\dot{V}_E$, S_pO_2, and RPE) collected during exercise at altitude. In the first method, data were normalized into quartiles of percent of total cycle time to exhaustion (i.e., rest, 25%, 50%, 75%, and 100%) to account for variance in exercise time between RMT groups. This also allowed comparisons between each quartile pre- and post-RMT. The second method used area under the curve (AUC), calculated for dependent variables, to assess differences from pre- to post-RMT and between group while accounting for equal cycle duration within subject. For this analysis, AUC was calculated for the lowest cycle time to exhaustion and compared to AUC at an equal stop time for each subject. For each analysis, a two-way, repeated measures ANOVA was used to determine differences between RMT groups (group main effect) and differences from pre- to post-RMT (training main effect). If a main effect or interaction were found, Sidak multiple comparison tests were used to determine differences from pre- to post-RMT and/or between RMT groups. Data were analyzed using Prism software (Version 8; GraphPad Software Inc., La Jolla, CA). Significance was set a priori at an alpha level of 0.05.

RESULTS

Pulmonary function is reported mean ± SD in **Table II**. There were no differences in any pulmonary function parameters between groups before RMT. Additionally, there were no changes in pulmonary function after PRMT. MVV increased after RMT [group main effect: $F(2,42) = 6.84$; $P=0.002$]. Following RRMT and ERMT, MVV was greater compared to PRMT ($P = 0.04$ and $P = 0.06$, respectively). There was a main effect of training [$F(1,40) = 4.95$; $P = 0.03$] and group [$F(2,40) = 5.22$; $P = 0.009$] for respiratory endurance (**Fig. 1**). ERMT increased the time to respiratory muscle fatigue during the RET ($P = 0.001$) and was greater than both RRMT ($P = 0.001$) and PRMT ($P = 0.002$). There was a main effect of training [$F(1,42) = 4.75$; $P = 0.03$] and group [$F(2,42) = 5.72$; $P = 0.006$] for P_{Imax}. RRMT improved P_{Imax} following training ($P = 0.009$) and was higher than both ERMT ($P = 0.007$) and PRMT ($P = 0.002$). Additionally, there was a main effect of

Table II. Pulmonary Function Tests Before (Pre) and After (Post) Respiratory Muscle Training (RMT) for Placebo (PRMT), Resistance (RRMT), and Endurance (ERMT) Training Groups.

		PRMT	RRMT	ERMT	GROUP MAIN EFFECT	TRAINING MAIN EFFECT	INTERACTION
FVC (L)	PRE	5.2 ± 0.7	5.8 ± 1.0	5.9 ± 0.8	0.01	0.85	0.84
	POST	5.2 ± 0.5	5.7 ± 0.9	6.1 ± 0.7			
$FEV_{1.0}$ (L)	PRE	4.3 ± 0.6	4.7 ± 0.8	4.7 ± 0.8	0.29	0.99	0.84
	POST	4.4 ± 0.5	4.6 ± 0.8	4.8 ± 0.8			
SVC (L)	PRE	5.4 ± 0.8	5.9 ± 1.0	6.0 ± 1.0	0.18	0.38	0.99
	POST	5.7 ± 0.9	6.2 ± 1.0	6.2 ± 0.8			
MVV ($L \cdot min^{-1}$)	PRE	178.7 ± 32.9	214.6 ± 36.0	211.6 ± 31.8	0.01	0.27	0.93
	POST	184.4 ± 27.51	228.3 ± 37.6*†	224.9 ± 36.7*			
P_{Imax} (cmH_2O)	PRE	104.6 ± 39.7	117.7 ± 11.6	113.4 ± 33.8	0.01	0.03	0.08
	POST	110.7 ± 27.1	162.6 ± 20.0*†#	116.3 ± 29.9			
P_{Emax} (cmH_2O)	PRE	140.5 ± 51.9	164.0 ± 33.2	173.5 ± 37.8	0.01	0.05	0.23
	POST	147.9 ± 37.3	216.5 ± 44.1*†	184.9 ± 35.6			

Values are mean ± SD for functional vital capacity (FVC), forced expiratory volume in 1 s ($FEV_{1.0}$), slow vital capacity (SVC), maximal volume ventilation (MVV), and maximal inspiratory (P_{Imax}) and expiratory (P_{Emax}) pressures.
* $P < 0.05$ from pre; † $P < 0.05$ from PRMT; # $P < 0.05$ from ERMT.

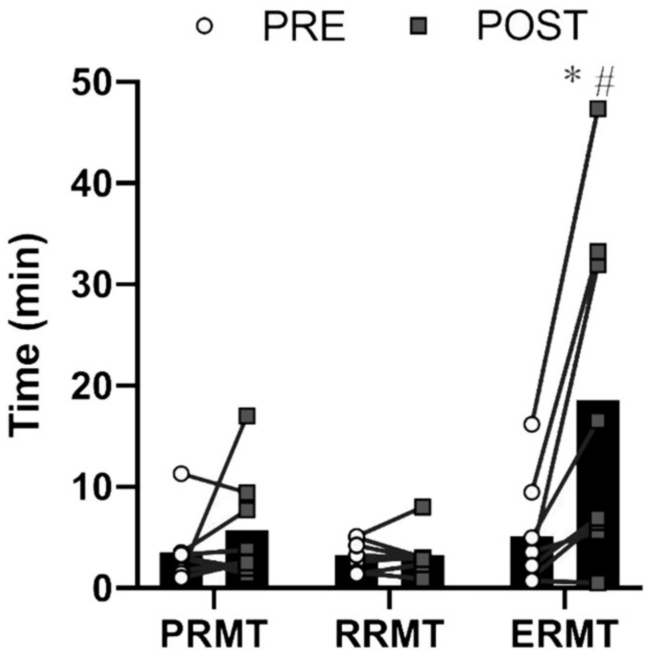

Fig. 1. Respiratory endurance before (pre: circles) and after (post: squares) respiratory muscle training. Data are presented as mean with individual values. PRMT, placebo respiratory muscle training; RRMT, resistance respiratory muscle training; ERMT, endurance respiratory muscle training. *ERMT $P < 0.05$ from pre-RMT; #ERMT $P < 0.05$ from RRMT and PRMT.

training [$F(1,42) = 4.14$; $P = 0.048$] and group [$F(2,42) = 5.64$; $P = 0.007$] for P_{Emax}. RRMT improved P_{Emax} following training ($P = 0.04$) and was higher than PRMT ($P = 0.005$).

All subjects completed both cycle tests to exhaustion and no test was terminated due to low arterial oxygen saturation limits. Cycle time to exhaustion at altitude (**Fig. 2A**) was not different between groups before RMT (PRMT: 32.2 ± 11.4; ERMT: 33.8 ± 9.6; RRMT: 35.9 ± 17.2 min). There was a main effect of training [$F(1,21) = 12.02$; $P = 0.002$] on cycle time to exhaustion. ERMT and RRMT improved cycle time to exhaustion (pre: 33.8 ± 9.6 vs. post: 42.9 ± 27.0 min; $P = 0.047$ and pre: 35.9 ± 17.2 vs. post: 45.6 ± 22.2 min; $P = 0.018$, respectively). However, cycle time to exhaustion was not different between groups after RMT [group main effect: $F(2,21) = 0.51$; $P = 0.60$]. Relative $\dot{V}O_{2max}$ (**Fig. 2B**) was not different between groups before (PRMT: 38.2 ± 8.8; ERMT: 39.0 ± 4.7; RRMT: 39.2 ± 5.9 mL · kg^{-1} · min^{-1}) or after (PRMT: 39.2 ± 7.3; ERMT: 40.6 ± 4.8; RRMT: 39.2 ± 5.9 mL · kg^{-1} · min^{-1}) RMT training [group main effect: $F(2,21) = 0.07$; $P = 0.93$]. Additionally, $\dot{V}O_{2max}$ did not improve after training in any group [training main effect: $F(1,21) = 2.14$; $P = 0.15$].

Dependent variables (**Table III**) during exercise were normalized as a percentage of total time to exhaustion. There were no differences between RMT groups for any variables (i.e., $\dot{V}O_2$, $\dot{V}_E$, V_T, and f_B) pre- or post-RMT. Additionally, there were no differences for any variables within training group from pre- to post-RMT. At the end of exercise, heart rate was not different before (PRMT: 166 ± 18; RRMT: 157 ± 29; ERMT: 163 ± 23 bpm) or after (PRMT: 169 ± 6; RRMT: 162 ± 17; ERMT: 165 ± 16 bpm) RMT in any group [training main effect: $F(1, 21) = 0.56$; $P = 0.46$; group main effect: $F(2, 21) = 0.43$; $P = 0.67$]. S_pO_2 decreased during exercise at altitude after RMT [time main effect: $F(4105) = 5.2$; $P < 0.01$], but was not different over time before RMT. There was also no difference in S_pO_2 at the end of exercise pre- (PRMT: 81 ± 6; RRMT: 77 ± 5; ERMT: 82 ± 6%) or post- (PRMT 82 ± 8; RRMT: 83 ± 7; ERMT: 84 ± 4%) RMT in any group [training main effect: $F(1, 21) = 0.74$; $P = 0.40$; group main effect: $F(2, 21) = 0.38$; $P = 0.69$].

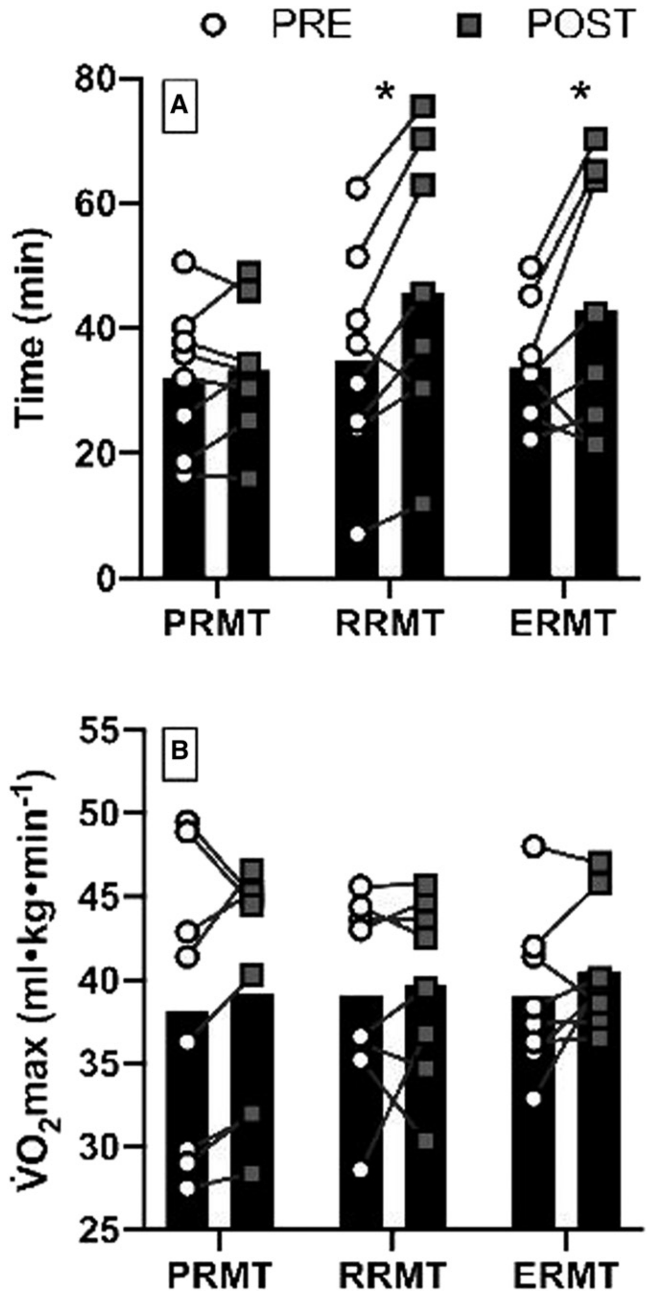

Fig. 2. A) Cycling time to exhaustion at altitude. B) Normobaric maximal oxygen consumption ($\dot{V}O_{2max}$) before (pre: circles) and after (post: squares) respiratory muscle training for three groups: placebo (PRMT), resistance (RRMT), or endurance (ERMT). Data are presented as mean (with individual values). *RRMT and ERMT from pre-RMT, $P < 0.05$.

AUC was calculated before and after RMT, comparing the cycle time before training to an equivalent interval after

Table III. Ventilatory Variables During Cycle to Exhaustion at 3657 m (12,000 ft) Altitude.

	$\dot{V}O_2$ (L · min^{-1})					
	PRMT		RRMT		ERMT	
	PRE	POST	PRE	POST	PRE	POST
REST	0.6 ± 0.2	0.6 ± 0.2	0.5 ± 0.2	0.6 ± 0.3	0.6 ± 0.1	0.6 ± 0.1
25	1.6 ± 0.3	1.6 ± 0.3	1.7 ± 0.2	1.7 ± 0.2	1.8 ± 0.2	1.7 ± 0.2
50	1.8 ± 0.3	1.7 ± 0.3	1.8 ± 0.3	1.7 ± 0.2	1.9 ± 0.2	1.8 ± 0.3
75	1.8 ± 0.3	1.8 ± 0.3	1.8 ± 0.3	1.8 ± 0.2	2.0 ± 0.2	1.8 ± 0.3
100	1.6 ± 0.5	1.8 ± 0.3	1.8 ± 0.4	1.8 ± 0.2	1.8 ± 0.3	1.9 ± 0.3
	$\dot{V}_E$ (L · min^{-1})					
	PRE	POST	PRE	POST	PRE	POST
REST	22.9 ± 8.2	19.2 ± 3.5	18.7 ± 7.9	20.7 ± 9.4	19.1 ± 3.9	20.0 ± 5.6
25	68.4 ± 6.7	63.9 ± 10.1	61.1 ± 12.3	63.1 ± 9.4	64.8 ± 8.8	65.7 ± 4.9
50	76.1 ± 11.3	67.5 ± 10.8	67.4 ± 17.1	68.7 ± 10.4	74.3 ± 10.8	71.0 ± 10.3
75	87.9 ± 13.6	72.9 ± 14.0	73.3 ± 21.1	71.3 ± 14.5	84.5 ± 20.4	78.2 ± 17.1
100	68.8 ± 24.8	87.6 ± 21.3	73.7 ± 22.6	81.1 ± 21.5	64.0 ± 26.2	76.7 ± 19.8
	V_T (L)					
	PRE	POST	PRE	POST	PRE	POST
REST	1.1 ± 0.4	1.0 ± 0.2	0.9 ± 0.4	1.0 ± 0.2	1.1 ± 0.2	1.2 ± 0.3
25	2.3 ± 0.4	2.3 ± 0.4	2.2 ± 0.4	2.2 ± 0.4	2.4 ± 0.3	2.4 ± 0.4
50	2.2 ± 0.5	2.1 ± 0.3	2.0 ± 0.4	2.1 ± 0.5	2.4 ± 0.4	2.4 ± 0.3
75	2.3 ± 0.5	2.1 ± 0.4	2.1 ± 0.6	2.0 ± 0.4	2.2 ± 0.4	2.4 ± 0.3
100	1.7 ± 0.5	2.1 ± 0.5	2.0 ± 0.6	2.0 ± 0.5	1.8 ± 0.4	2.0 ± 0.4
	f_B (breaths/min)					
	PRE	POST	PRE	POST	PRE	POST
REST	21.7 ± 5	20.3 ± 3	20.0 ± 3	20.3 ± 10	18.1 ± 3	17.9 ± 6
25	30.6 ± 4	28.7 ± 5	28.9 ± 6	30.2 ± 11	26.7 ± 2	27.6 ± 4
50	35.8 ± 7.	32.5 ± 5	34.3 ± 10	34.3 ± 14	30.9 ± 4	29.6 ± 4
75	39.7 ± 8	34.8 ± 6	36.5 ± 12	37.0 ± 15	39.0 ± 14	32.1 ± 4
100	39.9 ± 10	42.1 ± 7	37.3 ± 10	43.3 ± 16	34.2 ± 12	37.9 ± 6

Values are mean ± SD at each quartile of percent total cycle time to exhaustion at altitude (REST, 25%, 50%, 75%, and 100%). Values are shown for before (pre) and after (post) respiratory muscle training for three groups: placebo (PRMT); resistance (RRMT); and endurance (ERMT). $\dot{V}O_2$, oxygen consumption; $\dot{V}_E$, ventilation; V_T, tidal volume; and f_B, breath frequency.

training. Within each RMT group, there was no difference in AUC for $\dot{V}O_2$ [training main effect: $F(1, 21) = 2.08$; $P = 0.16$], $\dot{V}_E$ [training main effect: $F(1, 21) = 2.55$; $P = 0.13$], V_T [training main effect: $F(1, 21) = 0.42$, $P = 0.52$], f_B [training main effect: $F(1, 21) = 1.38$, $P = 0.25$], or S_pO_2 [training main effect: $F(1,21) = 0.00$; $P = 0.93$] (**Fig. 3A–E**). However, there was a main effect of training on RPE [$F(1,21) = 18.99$; $P < 0.01$]. The RRMT and ERMT groups had a lower RPE AUC after training ($P = 0.021$ and $P = 0.018$, respectively). There were no differences in AUC between RMT groups before or after RMT in $\dot{V}O_2$ [group main effect: $F(2, 21) = 0.15$, $P = 0.86$], $\dot{V}_E$ [group main effect: $F(2,21) = 0.02$, $P = 0.98$], V_T [group main effect: $F(2,21) = 0.11$, $P = 0.90$], f_B [group main effect: $F(2, 21) = 0.78$, $P = 0.47$], S_pO_2 [$F(2,21) = 0.13$; $P = 0.88$], or RPE [$F(2,21) = 0.44$; $P = 0.65$].

To highlight the sustained ventilation during the cycle time to exhaustion test before and after RMT, ventilation is presented for each group in **Fig. 4A–C**. Throughout exercise and at exhaustion, ventilation was not different within groups compared to pre-RMT values (Fig. 4).

DISCUSSION

The primary finding was cycling time to exhaustion at 3657 m (12,000 ft) was improved by 35% and 23% following RRMT and ERMT, respectively. This study compared endurance and resistance respiratory muscle training to that of a placebo on endurance exercise performance at altitude. RRMT and ERMT elicited specific pulmonary function adaptations seen as an increase in respiratory muscle strength and endurance, respectively. In line with our hypothesis, cycling endurance time at altitude was improved after both RRMT and ERMT. However, both RRMT and ERMT equally improved cycling time to exhaustion at altitude in recreationally active men.

RMT has been shown to be a reliable method for improving endurance exercise in normobaric normoxia.[14] However, due to the relative scarcity of studies examining the role of RMT for performance in hypoxia/altitude, there is less of a consensus.[1,13] Following ERMT, Keramidas et al. found no improvement in cycle time to exhaustion at 85% $\dot{V}O_{2max}$ under hypoxic conditions ($F_IO_2 = 0.12$) in recreationally active subjects.[15] However, after similar ERMT, Helfer et al. observed a 44% increase in cycle time to exhaustion at 70–75% $\dot{V}O_{2max}$ while simulating 3000 m and 3600 m (9842.5 and 11,811 ft) altitude.[12] Despite these confounding reports, both studies showed an improvement in pulmonary function and tolerance to hypoxic exercise fatigue shown by increased maximum ventilation and $\dot{V}O_{2max}$ and by increased exercise endurance.[12,15]

RRMT has also been examined at altitude, although most studies have focused on training the inspiratory phase of the ventilatory cycle. In one study, 6 wk of inspiratory muscle training increased hypoxic time trial performance (+6%) and was accompanied by a greater peak and mean power output.[24] However, Downey et al. found no improvement in hypoxic run time to exhaustion after 4 wk of inspiratory muscle training.[8] At submaximal intensities, Lomax et al. reported that inspiratory muscle training reduced ventilation and the physiological work of breathing during hypoxic exercise.[19] Importantly, all studies showed an increase in P_{Imax} and reduced inspiratory muscle fatigue regardless of performance outcome. It is possible that training the entire ventilatory cycle, as done in the current study, may provide more consistent performance improvements since the expiratory phase of ventilation is active during exercise.

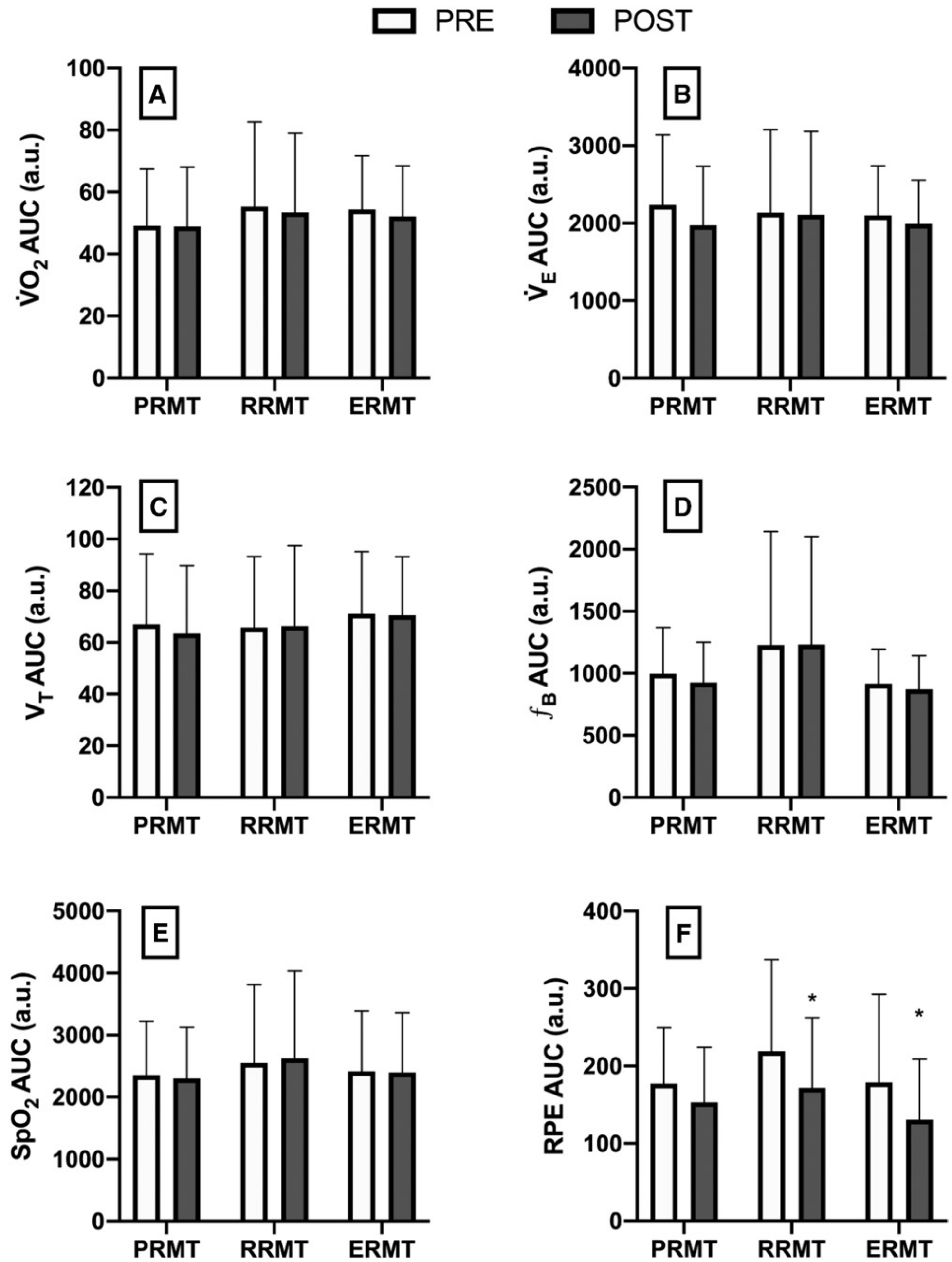

Fig. 3. Area under the curve (AUC) analyses for: A) oxygen consumption ($\dot{V}O_2$); B) ventilation ($\dot{V}_E$); C) tidal volume (V_T); D) breath frequency (f_B); E) arterial oxygen saturation (S_pO_2); and F) rating of perceived exertion (RPE) during cycle time to exhaustion at altitude before (pre: white bars) and after (post: gray bars) respiratory muscle training for three groups: placebo (PRMT), resistance (RRMT), or endurance (ERMT). Data are presented as mean ± SD in arbitrary units (a.u.). *RRMT and ERMT from pre-RMT, $P < 0.05$.

All previous studies on RMT for performance at altitude but one have been conducted using a hypoxic gas mixture (i.e., normobaric hypoxia) rather than in hypobaric hypoxia.[12] This, combined with differences in hypoxic exposure, are likely sources of equivocal findings within those studies.[13] A meta-analysis comparing the two hypoxic conditions showed differences in several physiological variables including $\dot{V}_E$, $\dot{V}O_{2max}$, and S_pO_2 among others, suggesting RMT may affect performance differently in hypobaric hypoxia.[6] Therefore, RMT findings under normobaric hypoxia may not have the same application to performance in true hypobaria. This is important to note, as the findings in the present study are consistent with the only other study conducted at altitude. This further highlights the methodological consideration of the differences between normobaric and hypobaric hypoxia.[5] However, these potential differences between hypoxic conditions have only been speculated on and have not been directly compared in regard to the efficacy of RMT.[1,13]

Ventilation during exercise in hypoxia/altitude increases the energy costs of breathing by 20–30% when compared to normoxia and likely induces respiratory muscle fatigue.[3,26,28] RMT is effective in improving performance in these conditions because it has been shown to consistently improve respiratory muscle endurance and/or reduce respiratory muscle fatigue.[7,14] The ERMT group in the present study improved their respiratory muscle endurance (+257%) during the respiratory endurance test, while the RRMT group showed no change following training. Contrary to other studies, the improvement in pulmonary function was not reflected in our ventilatory data during exercise, per se.[12,30] Helfer et al. showed that following ERMT, subjects could increase ventilation (+49%) for longer (+21%) during hypoxic exercise.[12] Similarly, the use of RRMT for swimming at depth reduced the incidence of subjects reaching ventilatory threshold during a swim to exhaustion.[30] It is not immediately apparent why our results differed from that previously reported. Our data showed no differences in ventilation when normalized to percent exercise time or equal cycling time from pre- to post-RMT. Despite these findings, both RRMT and ERMT groups were able to sustain the same ventilation (tidal volume and respiratory rate) for longer (+35% and +23%, respectively). This highlights that there was an improvement in respiratory muscle endurance and/or delay in respiratory muscle fatigue. Following RMT, there may be metabolic adaptations

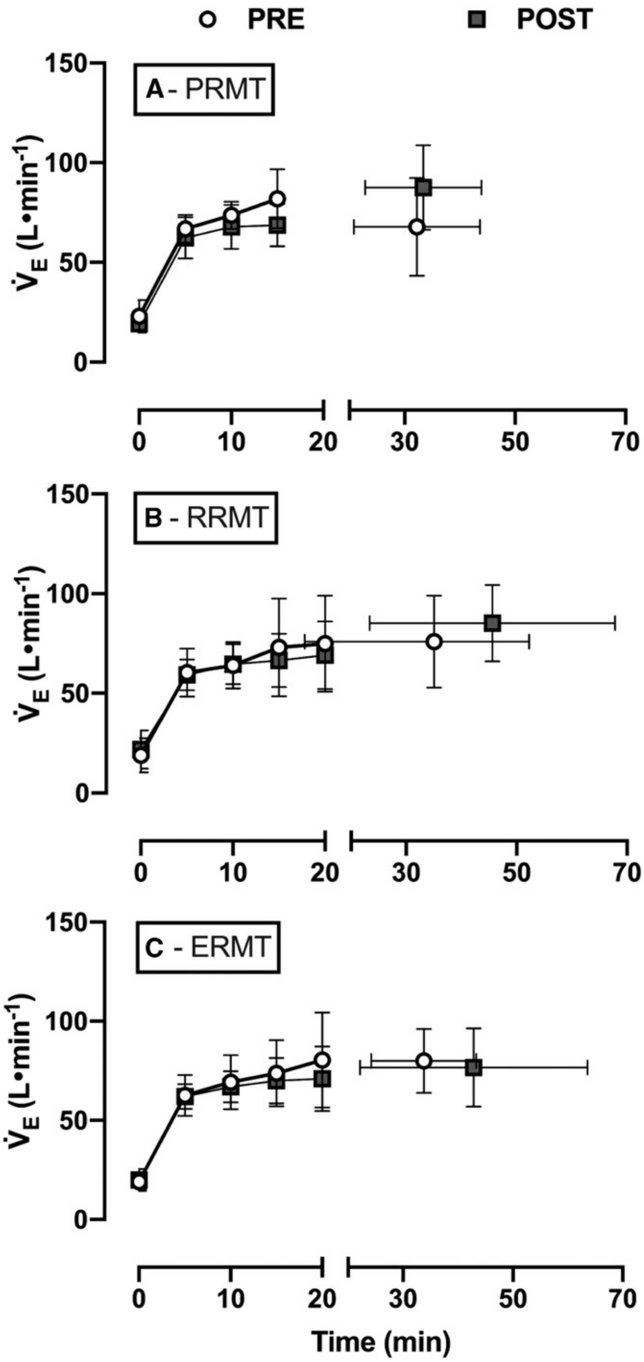

Fig. 4. Ventilation ($\dot{V}_E$) during cycle time to exhaustion at altitude before (pre: circles) and after (post: squares) respiratory muscle training for three groups: A) placebo (PRMT); B) resistance (RRMT; $N = 7$); and C) endurance (ERMT). Data are reported as mean ± SD every 5 min and at the end of exercise as a function of duration.

in the respiratory muscles. Improved tolerance to acidosis and/or removal of lactate and H^+ from the respiratory muscle fibers may be linked to improved respiratory muscle endurance and subsequent exercise performance.[4] Indeed, inspiratory muscle training has been shown to delay the respiratory muscle metaboreflex.[29] Ultimately, this could have attenuated the sympathetic vasoconstriction in the limbs and sustained blood flow to the locomotor muscles, but was not examined in the current study.[2]

Following RMT, both the RRMT and ERMT groups decreased their rating of perceived exertion post-RMT compared to pre-RMT, when compared at the same cycling time point (Fig. 3F). This is a potential mechanism for improved performance following RMT, as it has been shown that the perception of the work of breathing and dyspnea is associated with performance.[1,10,27] The perception of effort in the present study was likely a function of both leg effort and dyspnea. Downey et al. is the only study to separate the two perceptions following RMT for performance in hypoxia, and both were reduced and associated with an increase in performance.[7] Within the time to exhaustion model, the reduction in the perception of effort from pre- to post-RMT is a likely mediator for improvements in performance. Moreover, perception of effort has been shown to be a strong predictor of cycle time to exhaustion in normoxia.[21] Therefore, a decrease in the work of breathing (RRMT) and/or improved respiratory muscle endurance (ERMT) could have reduced perceptions of dyspnea and delayed the onset of the respiratory metaboreflex, sustaining blood flow and oxygen delivery to the locomotor muscles.

In the present study, no change in S_pO_2 was observed during exercise at altitude following RMT compared to pre-RMT, an unexpected finding. Previous studies have consistently found increases in S_pO_2 from 3–6% after RMT during exercise in normobaric hypoxia ($F_IO_2 = 0.11–0.14$).[7,15,18] Coupled with similar ventilatory patterns and oxygen consumption after RMT, this supports greater respiratory endurance without changes to pulmonary mechanics or peripheral oxygen delivery.

Limitations to the current study include the use of "noncyclists," subjects who are less accustomed to the peripheral fatigue and greater lower body workloads associated with cycling. Moreover, noncyclists have less mechanical efficiency compared to trained cyclists and may perceive the work as more strenuous due to unfamiliarity. Without a familiarization time trial, it is possible that the performance improvements observed in the RRMT and ERMT groups could be attributed to cycling familiarity, although if that were the case, a similar increase in PRMT performance would be expected. Women were not included in this study, but have been included in previous studies, and showed similar improvements in performance following RMT.[8] Another limitation of the current study is failure to collect and report dyspnea scores during exercise at altitude. RMT has been reported to alter dyspnea ratings so that perceived work of breathing increased, decreased, or was unchanged.[7,15,18] Additionally, there is likely a dose response to RMT effects on improving hypoxic exercise performance as well as an upper limit to ergogenic benefits. Moreover, exercise modality should also be kept in mind when interpreting these results, as running performance may be affected by RMT differently. Only one study has tested the effects of RMT on runners in hypoxia ($F_IO_2 = 0.14$) and found decreases in inspiratory muscle fatigue (−7.5%) without any improvement in run time to exhaustion.[7] The current study suggests that specificity of training (i.e., ERMT vs. RRMT) may be of less importance for performance in hypoxia compared to prescribed RMT loads, elevation, and changes in pulmonary function.

In conclusion, ERMT and RRMT specifically improved respiratory endurance and strength of pulmonary function, respectively, but equally improved cycling performance in hypobaric hypoxia. Despite no marked improvements in ventilation, arterial oxygen saturation, or oxygen consumption, perceived exertion (at equal cycling time) was attenuated following RMT. Decreased ratings of perceived exertion were likely a reflection of reduced leg fatigue and dyspnea perceptions and contributed to an augmented time to volitional exhaustion. It is speculated that respiratory muscle fatigue was also attenuated following RMT and allowed sustained blood flow to locomotor muscles. Regardless of the method, RMT employed in the present study improved endurance performance in hypobaric hypoxia conditions. This highlights that athletes or military personnel preparing for physical work at altitude may employ the simplest and most practical method of RMT.

ACKNOWLEDGMENTS

We would like to thank Jocelyn Stooks, Corey Carden, Emma Reed, and Brett Siders for their technical assistance during data collection and processing.

This article's contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH.

Courtney Wheelock and Hayden Hess contributed equally to this work.

Financial Disclosure Statement: The present study was funded by the Naval Sea Systems N00024-17-C-4316-P00002. Additionally, B. M. Clemency was supported by the National Heart, Lung, and Blood Institute, National Institutes of Health award number K12HL138052 to the University at Buffalo and by the National Center for Advancing Translational Sciences of the National Institutes of Health under award number UL1TR001412 to the University at Buffalo. The authors have no competing interests to declare.

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