

Acute effects of high-volume compared to low-volume resistance exercise on lung function

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The aim of this study was to examine whether a high-volume compared to low-volume resistance exercise session acutely impairs lung function. Fourteen males (age 23.8 ± 6.5 years) with resistance training experience participated in this study. Participants completed two resistance training protocols (high- and low-volume) and a control session (no exercise) with the sequence randomised. High- and low-volume sessions involved 5 sets (5-SETS) and 2 sets (2-SETS), respectively of 10 repetitions at 65% one-repetition maximum for each exercise (bench press, squat, seated shoulder press, and deadlift) with 90-sec recovery between sets. Lung function was evaluated pre- and postsession and respiratory gases were measured during the recovery between sets of exercises. An increase in the ratio of forced expiratory volume in 1 sec (FEV₁) to forced vital capacity was found following the 5-SETS compared to 2-SETS ($P=0.033$). There was a significant reduction in inspiratory capacity following 5-SETS compared to control session ($P=0.049$).


No other lung function parameter was affected postsession. During training sessions, the squat and deadlift required greater ventilatory demands compared to the bench press and shoulder press ($P<0.001$). Across most exercises during 5-SETS compared to 2-SETS, there was a lower end-tidal CO₂ partial pressure. Across most exercises during 5-SETS compared to 2-SETS there was a lower end-tidal CO₂ partial pressure (PETCO₂) ($P \leq 0.013$), although there were no other differences in physiological responses between the sessions. The findings tend to suggest that the ventilatory and respiratory muscle demands of a strenuous resistance exercise session are not great enough to acutely impair indices of lung function.

Keywords: Lung function, Respiratory muscles, Resistance training, Muscle strength, Exercise performance

INTRODUCTION

Resistance training is an effective exercise modality for increasing muscle strength and mass, which are important components of fitness and health (Bird et al., 2005; Winett and Carpinelli, 2001). To optimize training response requires manipulation of acute training variables (e.g., frequency, intensity, and volume) with careful consideration given to training experience to ensure the program is individualized (Kraemer and Ratamess, 2004). Resistance training volume (sets \times repetitions) is considered to be an important determinant of muscle strength and hypertrophy. Even though increases in muscle strength can be achieved when performing lower-volume resistance training (< 3 sets per exercise), it appears that higher volume resistance training (≥ 3 sets per ex-

ercise) results in larger gains (Krieger, 2009, 2010). Consequently, to maximize muscle hypertrophy it is recommended that higher volume (3–6 sets of 6–12 repetitions) and moderate load (70%–85% one-repetition maximum [1RM]) resistance training sessions are prioritized (Ratamess et al., 2009). These training practices are associated with increased metabolic acidosis and ventilatory demand compared to lower-volume resistance training sessions (Kang et al., 2005; Wirtz et al., 2014). The increased physiological demands from higher volume resistance training sessions may lead to adaptations that may enable training with heavier loads for longer (i.e., improved muscle endurance) (Radaelli et al., 2015), thus better session tolerance (e.g., less symptoms of dizziness and nausea) (Kraemer and Ratamess, 2004). Additionally, it seems plausible that higher volume resistance training may induce posi-

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tive changes in lung function. Improved lung function has been shown following resistance training in people with chronic obstructive pulmonary disease (Strasser et al., 2013), however, there is a paucity of research on this topic in apparently healthy populations.

For lung function to be improved following high-volume resistance training it would be expected that lung function parameters would be acutely impaired following a training bout. Such a hypothesis is based on training adaptation theories which suggest that an adequate training stimulus would result in the accumulation of fatigue, which in this case would be a reduction lung function, and upon recovery an improvement in performance (Cunanan et al., 2018). Diminished lung function has been observed following marathon and ultramarathon running (Tiller, 2019) and after a CrossFit (i.e., a form of high-intensity interval training) bout (Shaw et al., 2015). Furthermore, superior lung function performance has been observed in endurance athletes compared to strength and power athletes (Lazovic et al., 2015). This suggests that lung function adaptations from exercise training are dependent on the nature of the exercise (e.g., type, frequency, intensity, and duration). Khosravi et al. (2013) found that changes in lung function parameters following resistance training were minimal compared endurance training. Although, this previous study implemented a resistance training program involving mostly isolated (i.e., single joint) exercises, whereas programs with a greater emphasis on compound (i.e., multi joint) exercises are considered to be more effective for enhancing muscle adaptation and are more commonly used by experienced trainers (Paoli et al., 2017). It should also be noted that compound exercises such as the squats and deadlifts require increased activation of the respiratory muscles such as the diaphragm to assist with spine stability (Martuscello et al., 2013). Therefore, it seems plausible that the increased respiratory muscle work from assisting with spine stability together with elevated ventilation demands from high-volume resistance training would place significant stress on the respiratory system leading to an acute reduction in lung function performance.

To date, no study has investigated whether lung function is acutely affected following physically demanding resistance training sessions. The aim of this study was to examine whether a high-volume compared to a low-volume whole-body resistance exercise session acutely impairs lung function. It was hypothesized there would be evidence of reduced lung function performance following the high-volume compared to low-volume resistance exercise session.

MATERIALS AND METHODS

This study used a crossover, repeated measures design with random allocation of participants into three sequences (high-volume, low-volume, and control sessions). Fourteen males (age, 23.8 ± 6.5 years; body mass, 83.2 ± 7.2 kg; stature, 179.2 ± 4.3 cm) with 4.6 ± 2.1 years of resistance training experience participated in this study. Their one-repetition maximum (1RM) was 97.5 ± 17.1 kg for the bench press, 125.5 ± 18.3 kg for squat, 59.3 ± 13.1 kg for shoulder press, and 139.6 ± 25.0 kg for deadlift. The eligibility criteria for this study included being male, aged 18–45 years, ≥ 1 -year resistance training experience, and having the ability to perform the bench press, shoulder press, squat, and deadlift. The exclusion criteria included asthma, current respiratory illness, medications that could influence lung function and any chronic disease or condition. Verbal and written consent was provided by all participants prior to study commencement. This study was approved by the University of Sydney Human Research Ethics Committee (approval number: 2014/977).

Upon enrolment into the study, participants visited the exercise laboratory to become familiarised with lung function testing which involved performing a minimum of three trials for each measure described below. Based on these initial results all participants were deemed to have normal lung function (Johnson and Theurer, 2014). During the same visit, participants performed 1RM tests for the resistance exercises that were to be performed in the exercise sessions. Following the 1RM testing, each participant was given an opaque sealed envelope which contained a randomly assigned sequence for the three experiment sessions.

Experimental sessions

Lung function tests were conducted 15 min prior to beginning the resistance exercises for the low- and high-volume sessions (pre-session), and 5 min following the completion of these sessions (post-session). Resistance exercise warm-up sets, performed following the respiratory measurements, consisted of 1–2 sets of each exercise at perceived light loads. The control session involved performing the lung function tests, sitting quietly for 50 min, and then repeating these tests. It was estimated that the high- and low-volume resistance exercise sessions would take about 50 and 25 min to complete, respectively. For the low- and high-volume resistance training sessions participants were required to perform 2 sets (2-SETS) and 5 sets (5-SETS) respectively of 10 repetitions (or to failure if unable to reach 10 repetitions in a set) at 65% 1RM of four exercises (bench press, squat, seated shoulder press, and dead-

lift) with 90-sec recovery between sets (Ratamess et al., 2009). These exercises were selected because they target most of the major muscle groups and are commonly performed by experienced resistance trainers to maximize muscle adaptations (Ferland et al., 2020). The order in which participants performed these exercises was bench press, squat, shoulder press, and deadlift. Repetitions were performed at a self-determined tempo for the concentric and eccentric phases while performing the exercise through the full range of motion available. During the 90-sec recovery period between sets for each exercise heart rate was measured and respiratory gases were collected. Prior to all experimental sessions' participants were asked to refrain from using caffeine or pre-workout supplements (2–3 hr prior), not eat within 1 hr of the sessions, and avoid any strenuous physical activity in the preceding 24–48 hr.

Lung function was assessed via the Medgraphics pulmonary function testing system (Ultima Series CardiO₂ and PFX, Medgraphics, Minneapolis, MN, USA). The measures were performed in a standing position, using a nose clip and instructing participants to keep their lips securely around the mouth piece to prevent any air escaping during the tests. Forced vital capacity (FVC) was the first test performed and involved emptying the lungs of air and then fully inspiring, followed by full expiration. The forced expiratory volume in 1 sec (FEV₁), 3 sec (FEV₃), and 6 sec (FEV₆), ratio of FEV₁ to FVC (FEV₁/FVC), inspiratory capacity (IC), and expiratory reserve volume (ERV) were obtained from the FVC. After the FVC, participants performed the slow vital capacity (SVC) test which involved performing a minimum of four stable tidal breaths followed by a maximal inspiration and then a maximal expiration, performed in a slow manner. The final test conducted was the maximal voluntary ventilation (MVV) which involved the participant breathing deeply and rapidly on the command over a period of 12 sec. Three trials were performed for FVC, SVC, and MVV with ≥30-sec recovery between trials. The best trial for all measures was used for data analysis.

Physiological measures

Respiratory gases were continuously measured by breath-by-breath analysis using open circuit spirometry while resting in a seated position between sets of exercises (Ultima Series CardiO₂ and PFX, Medgraphics). The respiratory gas measures included oxygen uptake (mL/kg/min) (VO₂), minute ventilation (VE), tidal volume, respiratory rate, and end-tidal CO₂ partial pressure (PET-CO₂). Additionally, heart rate measurements (Polar T31, Polar Electro Oy, Kempele, Finland) were recorded during the recovery between sets. The period of gas collection and heart rate measure-

ment was for 60 sec and begun within 5 sec of the last repetition of each set. The rationale for only collecting respiratory gases and heart rate measurements during the recovery between sets of exercises was because of the greater responses that occur within this period for resistance training exercises compared to during the actual exercise (Scott, 2011; Scott et al., 2009). Respiratory gas and heart rate responses were averaged over 60 sec for each set due to the nonsteady state nature of the ventilatory and heart rate responses following resistance exercises. The average values for recovery responses for each exercise following completion of the assigned number of sets (i.e., 2 sets vs. 5 sets) were calculated for each participant.

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics ver. 24.0 (IBM Co., Armonk, NY, USA). Data were inspected visually and statistically for normality using the Kolmogorov–Smirnov test. For data that were not normally distributed log₁₀ transformations were performed. Normally distributed data are presented as mean ± standard deviation and as median with interquartile range for data not normally distributed. A one-way analysis of covariance, with pre-session lung function as a covariate, was used to assess differences between conditions (2-SETS vs. 5-SETS vs. control) for lung function (FVC, SVC, FEV₁, FEV₃, FEV₆, IC, ERV, and MVV). A one-way analysis of variance (ANOVA) was used to assess differences between physiological measures (VO₂, VE, tidal volume, respiratory rate, PETCO₂, and heart rate) and exercises and between sessions. For significant ANOVA results (for exercise analyses), a *post hoc* Bonferroni test was used to determine which condition means differed. If log₁₀ transformations did not result in normal data distribution the data was analysed using the non-parametric Kruskal–Wallis test with pre-post change data for the lung function variables. An alpha level of $P < 0.05$ indicated statistical significance.

RESULTS

No significant differences were found between conditions for pre-session results for any lung function measure. There were no significant differences found for FVC, SVC, FEV₁, FEV₃, FEV₆, ERV, and MVV between pre- and post-session for the control, 2-SETS, and 5-SETS (Table 1). A greater increase in FEV₁/FVC was found following the 5-SETS compared to 2-SETS ($P = 0.033$), with a trend approaching significance when compared to the control session ($P = 0.071$). A significant reduction in IC was observed

Table 1. Lung function measures pre- and postcontrol, low-volume and high-volume sessions

Variable	Control		Low-volume		High-volume	
	Pre	Post	Pre	Post	Pre	Post
FVC (L)	5.3 (4.9–5.7)	5.4 (4.8–5.7)	5.4 (4.9–5.8)	5.5 (4.8–5.8)	5.5 (4.8–5.8)	5.2 (4.7–5.8)
FEV ₁ (L/sec)	4.6±0.6	4.5±0.6	4.6±0.6	4.6±0.6	4.6±0.6	4.5±0.6
FEV ₁ /FVC (%)	88.2±6.7	88.0±6.4	88.0±6.4	87.4±6.3	86.5±6.4	89.2±6.9 [†]
FEV ₃ (L/sec)	5.2±0.6	5.2±0.6	5.2±0.7	5.2±0.6	5.3±0.6	5.2±0.6
FEV ₆ (L/sec)	5.4 (4.9–5.7)	5.4 (4.9–5.7)	5.4 (4.9–5.8)	5.4 (4.8–5.7)	5.5 (4.8–5.8)	5.2 (4.7–5.8)
SVC (L)	5.6±0.7	5.6±0.8	5.5±0.6	5.4±0.6	5.5±0.6	5.3±0.6
IC (L)	4.2±0.5	4.2±0.7	4.1±0.4	4.1±0.4	4.2±0.4	4.0±0.6*
ERV (L)	1.6±0.5	1.7±0.6	1.6±0.4	1.5±0.5	1.6±0.5	1.5±0.4
MVV (L/min)	193.2±26.4	196.4±22.5	197.3±27.1	197.4±27.5	200.5±25.2	198.9±25.8

Values are presented as median (range) or mean ± standard deviation.

FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 sec; FEV₃, forced expiratory volume in 3 sec; FEV₆, forced expiratory volume in 6 sec; SVC, slow vital capacity; IC, inspiratory capacity; ERV, expiratory reserve volume; MVV, maximum voluntary ventilation.

*Significantly different compared to control ($P < 0.05$). [†]Significantly different compared to low-volume ($P < 0.05$).

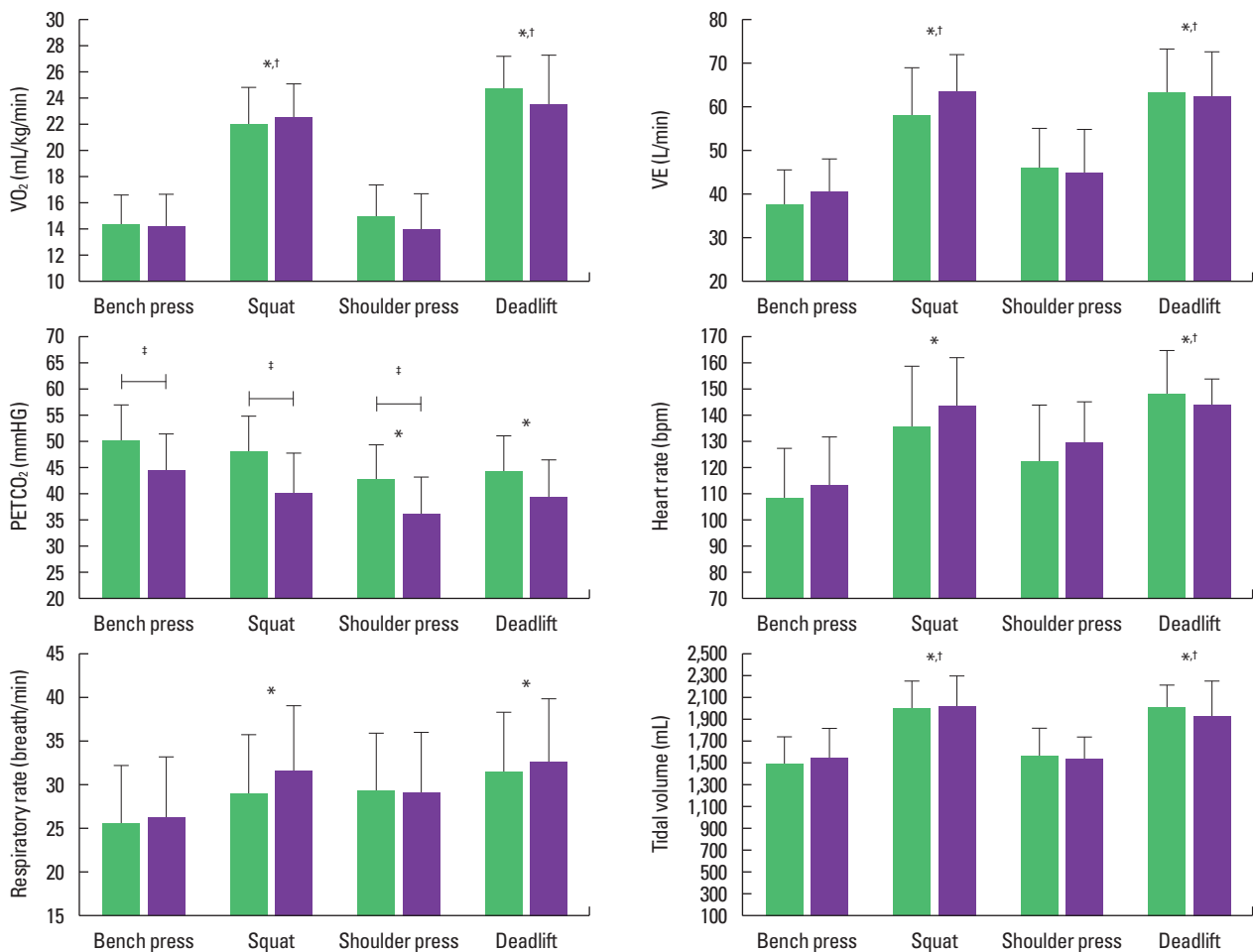


Fig. 1. Recovery responses for each exercise during the high-volume vs. low-volume session. VO₂, oxygen uptake; VE, minute ventilation; PETCO₂, partial pressure of end-tidal carbon dioxide. Green bars indicate low-volume session; purple bars indicate high-volume session. *Significant difference compared to bench press ($P < 0.05$). [†]Significant difference compared to shoulder press ($P < 0.05$). ‡Significant difference compared to low-volume ($P < 0.05$).

following 5-SETS compared to control session ($P = 0.049$) but no difference was found compared to 2-SETS ($P > 0.05$).

Mean recovery VO_2 , VE, and tidal volume were greater for squats compared to bench press ($P < 0.001$) and shoulder press ($P < 0.001$) (Fig. 1). Similarly, greater mean recovery VO_2 , VE, and tidal volume were found for deadlifts compared to bench press ($P < 0.001$) and shoulder press ($P < 0.001$). Mean respiratory rate was higher for squat and deadlift compared to bench press ($P = 0.013$ and $P < 0.001$, respectively). Mean recovery heart rate was higher during deadlifts compared to bench press ($P < 0.001$) and shoulder press ($P = 0.024$). Higher heart rates were also found for squats compared to bench press ($P < 0.001$). The mean recovery PETCO_2 was lower during the shoulder press compared to bench press ($P = 0.001$) and for deadlift compared to bench press ($P = 0.045$). During the 5-SETS there was a lower PETCO_2 for the bench press ($P = 0.013$), squat ($P = 0.003$), shoulder press ($P = 0.008$), and a trend was found with deadlift ($P = 0.082$) (Fig. 1). There were no other significant differences between the 2-SETS and 5-SETS for VO_2 , VE respiratory rate, tidal volume, and heart rate.

Session duration was greater for 5-SETS (66.4 ± 12.7 min) compared to 2-SETS (21.4 ± 3.7 min) ($P < 0.001$). Total training volume was significantly greater for 5-SETS ($13,235.4 \pm 1,939.9$ kg) compared to 2-SETS ($5,518.2 \pm 762.3$ kg) ($P < 0.001$). For each individual exercise (bench press, squat, shoulder press, and deadlift) training volume was greater during 5-SETS ($P < 0.001$). The full 10 repetitions could be completed for 98.6% of the assigned sets for 2-SETS compared to 87.5% of sets for 5-SETS. For individual exercises during 5-SETS participants performed < 10 repetitions for the shoulder press during 22.9% of sets, followed by bench press (12.9%), squat, and deadlift (both 7.1%).

DISCUSSION

In resistance-trained males, the present study showed there were minimal alterations in lung function following low-volume and high-volume whole-body resistance exercise sessions. There was a slight improvement in FEV_1/FVC following 5-SETS compared to 2-SETS. In contrast, IC was diminished following 5-SETS compared to the control session suggestive of respiratory muscle fatigue. Although, there were no other differences found between conditions for all other lung function measures which is in disagreement with the original hypothesis. Greater physiological demands were found for both the squat and deadlift compared to the upper body exercises as indicated by accentuation of the VO_2 , ventilatory pa-

rameters, and heart rate responses for the former exercises. However, there was higher metabolic stress observed during the high-volume session as indicative by the lower PETCO_2 observed following most exercises during the 5-SETS compared to 2-SETS. Additionally, the strenuous nature of the high-volume session was evident from a larger percentage of participants being unable to complete the desired number of repetitions during exercises. Based on the present study findings it appears that lung function remains relatively stable following an acute physically demanding resistance training bout in resistance-trained males.

It was previously unknown whether lung function would be affected by a more metabolically demanding resistance training bout. The finding of greater FEV_1/FVC following the high-volume compared to low-volume session suggests mild bronchodilation that facilitated increased air flow without a significant increase in airway resistance. A possible explanation could be the increased metabolic demand of the higher volume session acutely improving smooth muscle and bronchial compliance (Milanese et al., 2009; Tipton et al., 2017). Although, it was also observed that IC was diminished following the high-volume session compared to the control session which provides evidence that inspiratory muscle function was acutely impaired. The main inspiratory muscle is the diaphragm (Enright et al., 2006), and this muscle together with other respiratory muscles assists with stabilisation of the trunk during exercises with high axial loading such as deadlifts and squats (Aasa et al., 2019). The high-volume session most likely required slightly greater work to be accomplished by the inspiratory muscles from the perspective of ensuring adequate trunk stabilisation, thus leading to inspiratory muscle fatigue. Previously Gomez et al. (2009) found that sit-ups performed to volitional fatigue resulted in diminished respiratory muscle strength while indices of lung function remained unaffected. Therefore, supporting the theory that fatigue of the respiratory muscles can be induced without high ventilatory demands for sustain periods which seems to be the main culprit contributing to respiratory muscle fatigue following aerobic exercise (Romer and Polkey, 2008).

Impairment in lung function has been reported following a Cross-Fit session (Shaw et al., 2015) as well as following marathon and ultramarathon running (Tiller, 2019). Aerobic exercise is associated with higher VO_2 and VE responses compared to resistance exercise, which is considered to be an anaerobic exercise (Vilaça-Alves et al., 2016). During resistance training, peak VO_2 and VE occur in the recovery between sets of an exercise as opposed to during the actual exercise, and then it plummets back down to pre-exercise VO_2 and VE (Scott, 2011; Scott et al., 2009). The intermit-

tent nature of resistance exercise means that VO_2 and VE are not elevated to levels significantly above pre-exercise values for sustained periods, unlike aerobic exercise. However, during strenuous resistance exercise VE will increase disproportionately in relation to VO_2 due to its relatively large anaerobic component (lactate accumulation) increased carbon dioxide and subsequent H^+ concentrations (De Sousa et al., 2012; Lühker et al., 2017).

In the present study, a hyperventilatory response was demonstrable through decreases in PETCO_2 following each exercise. Since recovery PETCO_2 was significantly lower for the 5-SET compared to 2-SET there is further evidence of greater respiratory muscle demands during the high-volume resistance training bout (Romer and Polkey, 2008). It was hypothesized that the increased ventilatory demands (i.e., hyperventilation) coupled with the requirements of the abdominals to maintain trunk stability during the high-volume session would increase the work performed by the respiratory muscles, thus leading to alterations in indices of lung function (Aliverti, 2016). However, the respiratory demands during the high-volume session were likely insufficient to impair lung function since there was no difference between the 5-SETS and 2-SETS for any lung function parameter.

Minimal improvements in lung function indices have been shown following resistance training of moderate-high volume (2–4 sets per exercise) and intensity (60%–80% 1RM) within healthy adults (Khosravi et al., 2013). In this previous study, MVV was the only lung function parameter which improved following resistance training. The MVV test is commonly used to assess the strength and endurance of the inspiratory and expiration muscles (Green et al., 2002). Due to the diminishment in respiratory muscles strength found by Gomez et al. (2009) following sit-ups to volitional fatigue, if respiratory muscle strength was adversely affected following the high-volume session it is reasonable to assume that MVV performance would also be affected. However, it has been argued that while respiratory muscle strength is important for sustaining ventilation, performance in the MVV test is influenced by many factors (e.g., respiratory system mechanics and respiratory muscle endurance) (Neufeld et al., 2018), therefore a reduction in respiratory muscle strength may not affect MVV performance. This might also explain why other lung function indices were unaffected following the high-volume session. In other words, unless respiratory muscle strength is severely affected as a result of a chronic condition (Fitting, 2001; Singer et al., 2011) or extremely demanding exercise session (e.g., marathon run) (Tiller, 2019), lung function parameters would remain relatively stable, as was found within the present study. Other factors that influence lung function

include the compliance of the lungs, condition of the ventilatory control systems, and resistance of both airways and tissues (Ionescu et al., 2009; Lalley, 2013). Although these factors are unlikely to affect lung function in healthy young adults following exercise performed at lower ventilatory demands than intense or sustained aerobic exercise.

Powerlifters have been shown to possess greater diaphragm mass and respiratory muscle strength compared to untrained healthy adults (Brown et al., 2013). Furthermore, the effectiveness of resistance training on respiratory muscle strength has been confirmed in apparently healthy (DePalo et al., 2004) and clinical populations (Menezes et al., 2016). Therefore, based on training adaptation theories an adequate training stimulus to promote improvement in lung function would present as an acute decrease in lung function (Cunanan et al., 2018). It is possible that the resistance-trained participants could cope with very demanding resistance exercise sessions without experiencing alterations in lung function postexercise due chronic training adaptations to their respiratory systems (Brown et al., 2013; DePalo et al., 2004). Further, potentially a ceiling effect may have resulted in no further improvements in lung function following attaining a certain level of resistance training experience. If an untrained population was used within the present study instead of a resistance-trained group, the effect of the high-volume resistance training session on lung function may have been different. Greater improvements in lung function were found in healthy previously inactive subjects following aerobic training combined with resistance training compared to resistance training alone (Khosravi et al., 2013). Therefore, resistance training might be efficacious for improving respiratory muscle strength, while aerobic training, either alone or in combination with resistance training seems to be most effective for improving lung function in healthy adults.

This study revealed that lung function was largely unaffected within a group of experienced male resistance trainers following a high-volume compared to a low-volume whole-body resistance exercise session. The physical demands of the high-volume session appeared insufficient to lead to any change in lung function compared to the low-volume session. Training adaptations to the respiratory system might have protected resistance trainers from experiencing reductions in lung function following the high-volume session. Another possibility is that resistance exercise is less likely to acutely affect lung function following a strenuous training session compared to intense aerobic exercise.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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