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Effect of Respirator Inspiratory Resistances on Respiratory Muscle Performance Following Long-Term Exercise

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Abstract

Evidence exists to indicate that prolonged ventilatory work fatigues respiratory muscles and may hinder work tolerance. However, the effects of respirator wear during prolonged ventilatory work on respiratory muscle performance have not been assessed. This study tested the hypothesis that respirator wear and its inherent inspiratory resistance would result in respiratory muscle fatigue during long-term exercise. Pulmonary function and respiratory muscle strength were assessed in 5 subjects before and after separate 120 min treadmill exercise tests under three different inspiratory resistance conditions. Pulmonary function measures did not change significantly following exercise with any of the three inspiratory loads. Likewise, measures of inspiratory (peak inspiratory pressure) and expiratory (peak expiratory pressure) muscle strength showed no differences following exercise. These findings indicate that respiratory muscle fatigue did not result from the combined stress of respirator wear and moderate intensity exercise. However, the absence of respiratory muscle fatigue may have resulted from lower levels of ventilation observed during exercise under higher resistance conditions as opposed to the actual non-occurrence of fatigue.

Introduction

In most normal circumstances, the muscles of respiration are exceptionally good at sustaining the contractile forces needed to generate the pressures required for alveolar ventilation. However, respiratory muscle fatigue, defined as the inability of the muscles to generate required forces after a period of muscular contraction, has been demonstrated in pathological states such as obstructive airway disease (Grassino *et al.*, 1979). Evidence also exists to indicate that prolonged ventilatory work fatigues respiratory muscles of healthy individuals and may limit overall exercise tolerance. Martin *et al.* (1982)

found that 150 min of hyperpnea at 66% of maximal exercise minute ventilation led to ventilatory muscle fatigue and decreased exercise tolerance. Likewise, runners tested after marathons and half-marathons have been found to have significantly decreased strength in the muscles of ventilation (Loke *et al.*, 1982).

When an individual must breathe against a load, such as during respirator wear, the muscles of ventilation must work harder in order to overcome airflow resistances caused by air purifying filters and

airflow valves. Under non-exercise conditions, the potential for the development of ventilatory muscle fatigue resulting from respirator wear may be minimal. However, under conditions of respirator wear combined with prolonged exercise that requires increased ventilatory work, an important question is whether the respiratory muscles are pushed to exhaustion, resulting in hypercapnic ventilatory failure and a reduction in work tolerance. Considering this potential impact, the answer to the question

of whether or not respiratory muscle fatigue occurs in healthy individuals during respirator wear is unknown. The purpose of this study was to evaluate respiratory muscle function in healthy individuals before and after completion of relatively long-term, moderate intensity exercise during wear of respirators with different inspiratory loads to determine whether or not respiratory muscle fatigue is a factor of respirator wear.

Methods

Five healthy male volunteers (mean $\pm$ SD, 34 ± 3 yr) gave informed consent prior to participation in this study. Subjects reported to the laboratory on four separate test days. Test days were separated by at least 48 hours. Subjects were instructed to limit their physical activity on the day prior to testing and to get adequate rest the night before each test day. All testing procedures were conducted at ambient room temperature (22°C) in an air-conditioned laboratory. Volunteers wore T-shirts, shorts, socks, and sneakers for all exercise trials.

On their first day of testing, subjects completed a maximal treadmill exercise test to determine peak oxygen consumption ($\dot{V}O_2$ max) and peak exercise ventilation ($\dot{V}E$ max). Following completion of the maximal exercise test, volunteers completed one treadmill exercise trial for each of the conditions listed in Table 1. Respirator inspiratory resistances were measured by fitting each respirator configuration to a headform airflow resistance tester (ATI Q-213 Resistance Tester, Hamilton Associates, Inc., Baltimore, MD). Control conditions using a half-mask (Hans Rudolph model 7900, Hans Rudolph Inc., Kansas City, MO) were completed first by each subject to determine the external workload needed to reach the selected exercise intensity. Presentation of the M40 respirator conditions, one with a high resistance filter canister and one with a modified, lower resistance filter canister, were randomly assigned for each subject. The M40 is a negative pressure, air-purifying, full-facepiece respirator that consists of a molded rubber facepiece, an elastic head harness, and a check mounted filter canister.

Data collection procedures for the three experimental test iterations were identical. Upon reporting to the laboratory, subjects were fitted for a half-mask or M40 respirator. Before treadmill exercise commenced, subjects completed pulmonary function tests on a calibrated computer based spirometer (WinPFT-2001, Diagnostic Monitoring, CA). All

measurements were obtained with subjects seated and wearing a noseclip. Forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), and forced expiratory flow rate at 50% of the FVC ($FEF_{50\%}$) were measured while subjects performed a FVC maneuver. Subjects then hyperventilated maximally for 12 seconds on the spirometer, which calculated maximal voluntary ventilation (MVV). Measurements of peak inspiratory pressure (PIP) and peak expiratory pressure (PEP) were then obtained using a hand-held mouth pressure meter (Micro Direct model MP01, ± 350 cm H_2O , Micro Direct, Inc., Auburn, ME). The device calculated maximum efforts sustained for at least one second and displayed the results on an LCD. Peak inspiratory pressure was measured near residual volume by having subjects inspire maximally after a maximal expiration. The PIP values served as a measure of inspiratory muscle strength (Black and Carroll, 1969; Loke *et al.*, 1982). Peak expiratory pressure, an indicator of the strength of the accessory muscles of respiration as well as the abdominal muscles (Black and Carroll, 1969), was measured near total lung capacity while subjects expired maximally following a maximal inspiration. Because of the effort dependence of the chosen pulmonary function and respiratory muscle strength maneuvers, subjects were carefully instructed on how to perform each maneuver. For all of the above breathing maneuvers, three separate iterations were performed; the highest value for each test was selected.

Following completion of the pulmonary function and respiratory muscle strength tests, subjects completed an exercise regimen of treadmill walking and running while wearing either the half-mask or the M40 respirator. Speed and grade of the treadmill were adjusted to invoke a target work intensity of 55% $\dot{V}E$ max, a moderate ventilatory load that could be maintained over a sustained period of time. The exercise regimen involved three periods that alternated walking and running. Each walk lasted for

Table 1. Respirator experimental conditions.

Condition	Mask/respirator	Inspiratory resistance ¹
Control	Half-mask	0.66 cm H ₂ O • s • L ⁻¹
M40 High	U.S. Army M40	3.25 cm H ₂ O • s • L ⁻¹
M40 Low	U.S. Army M40	1.57 cm H ₂ O • s • L ⁻¹

¹Measured at a constant flow rate of 1.42 L • s⁻¹.

10 minutes and was followed by 30 minutes of running. Total exercise time was limited to 120 minutes for all subjects. Exercise measurements of tidal volume (V_T), respiration rate (RR), and minute ventilation ($\dot{V}_E$) were obtained using a flowmeter (K.L. Engineering K-520 transducer, KTC-3-D compensator, and S-430 spirometric module, K.L. Engineering, Sylmar, CA) mounted to the end of expiratory tubing attached to a mixing chamber (K.L. Engineering). Respired gas concentrations were measured from the mixing chamber with a calibrated respiratory mass spectrometer (Perkin-Elmer MGA 1100, Pomona, CA). Tidal volume, RR, $\dot{V}_E$, O₂ consumption, and CO₂ production were measured on-line (Hewlett Packard 3852, Hewlett Packard, Sunnyvale, CA) for 20 s intervals during each minute of exercise and recorded by a computer (Hewlett Packard model 9000, series 310). Heart rate was monitored continuously using a bipolar 3-lead ECG (Quinton Q3000 ECG Monitor, Quinton Instrument Co., Seattle, WA) during all experimental conditions. Subjective measurements of rating of perceived exertion (RPE) (Borg, 1982) for overall effort and

breathing apparatus comfort (BAC) (Abadie and Carroll 1993) were recorded every 10 minutes of exercise. Performance time was recorded for subjects who elected to terminate exercise before the 120 minute time period expired. Immediately after the completion of exercise, the aforementioned pulmonary function and respiratory muscle strength tests were repeated with subjects in a seated position.

Data were analyzed to assess changes in pulmonary function and respiratory muscle strength following treadmill exercise for each experimental condition. Likewise, performance results of pulmonary function tests were compared between experimental conditions. Analysis of variance was used to make all comparisons between conditions and post-hoc multiple comparisons were made using Bonferroni's test. Pre- and post-exercise pulmonary function values were compared within each experimental condition using an independent-samples t-test. Significance was set at the $p < 0.05$ level for all statistical procedures.

Results

Average exercise endurance time, intensity ($\% \dot{V}_{O_2 \text{ max}}$), and minute ventilation in terms of the percentage of maximal exercise ventilation ($\% \dot{V}_{E \text{ max}}$) are presented in Table 2 for each of the experimental conditions. Endurance time did not differ between conditions. However, both average $\% \dot{V}_{O_2 \text{ max}}$ and $\% \dot{V}_{E \text{ max}}$ were significantly ($p < 0.05$) greater for the Control condition compared to both M40 resistance conditions.

The results of pre- and post-exercise pulmonary function and respiratory muscle strength tests for individual subjects are presented in Tables 3 through 5. As a group, no significant changes in PIP, PEP, FVC, FEV₁, FEF_{50%}, or MVV were observed after treadmill exercise for any of the experimental conditions. No decrements in PIP were exhibited by individual subjects following exercise under Control

conditions. However, four subjects demonstrated lower PIP values (range 0.6% to 12% decrement) after running during wear of the M40 High respirator, and three subjects had lower PIP values (1.0% to 8.3% decrement) following exercise with the M40 Low respirator.

Individual differences in pre- and post-exercise PEP measures under Control conditions ranged from an improvement of 5.9% to a decrement of 10.1%. In contrast, individual post-exercise PEP values were essentially unchanged or decreased for both M40 wear conditions. As a group, PEP was approximately 9% lower after exercising with the M40 High respirator and approximately 10% lower after exercising under M40 Low conditions. However, these decrements were not statistically significant.

Table 2. Average exercise duration and intensity for each experimental condition.

Condition	Endurance time (min)	%VO ₂ max	VO ₂ (L · min ⁻¹)	VCO ₂ (L · min ⁻¹)	VE (L · min ⁻¹)	%VE _{max}	V _T (L)	RR (min ⁻¹)
Control	117.4 ± 5.8	60.0 ± 9.8	2.21 ± 0.31	2.19 ± 0.31	66.3 ± 9.2	55.8 ± 7.7	1.59 ± 0.26	42.6 ± 8.0
M40 High	113.2 ± 9.3	49.8 ± 6.4 ¹	1.85 ± 0.25 ¹	1.86 ± 0.31 ¹	51.2 ± 7.1 ¹	43.2 ± 5.6 ¹	1.58 ± 0.50	34.4 ± 7.6 ¹
M40 Low	116.6 ± 7.6	50.5 ± 7.0 ¹	1.87 ± 0.32 ¹	1.88 ± 0.32 ¹	52.0 ± 7.1 ¹	43.7 ± 5.9 ¹	1.52 ± 0.48 ¹	36.7 ± 9.0 ¹

¹ Significant difference from Control at the p<0.05 level.**Table 3. Respiratory muscle strength and pulmonary function before and after exercise under the Control condition.**

Subj	PIP (cm H ₂ O)		PEP (cm H ₂ O)		FVC (L)		FEV ₁ (L · s ⁻¹)		FEF _{50%} (L · s ⁻¹)		MVV (L · min ⁻¹)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	105	105	139	142	5.83	5.64	4.72	4.68	5.40	5.03	170.7	155.8
2	135	153	102	109	3.81	3.41	3.09	2.71	4.34	3.3	134.1	119.4
3	110	120	152	143	4.82	5.03	4.23	4.38	7.53	7.05	172.6	154.7
4	161	172	186	197	10.2	6.71	8.00	5.24	9.01	5.42	174.7	209.9
5	82	89	192	182	5.75	6.89	3.26	4.56	2.17	3.13	171.6	226.6
Mean ± SD	118.6 ± 30.3	127.8 ± 34.2	165.4 ± 22.7	161.2 ± 26.4	6.09 ± 2.46	5.54 ± 1.41	4.78 ± 1.89	4.31 ± 0.95	5.69 ± 2.68	4.78 ± 1.62	164.7 ± 17.2	173.3 ± 43.9
P	NS		NS		NS		NS		NS		NS	

PIP, peak inspiratory pressure; PEP, peak expiratory pressure; FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s; FEF_{50%}, forced expiratory flow rate at 50% of the FVC; MVV, maximal voluntary ventilation; NS, not significant.

Table 4. Respiratory muscle strength and pulmonary function before and after exercise under the M40 High condition.

Subj	PIP (cm H ₂ O)		PEP (cm H ₂ O)		FVC (L)		FEV ₁ (L • s ⁻¹)		FEF _{50%} (L • s ⁻¹)		MVV (L • min ⁻¹)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	99	109	151	125	5.78	5.52	4.61	4.55	5.09	5.19	140.6	148.3
2	138	136	160	150	3.88	3.66	3.10	2.90	3.94	3.51	133.3	120.4
3	87	86	143	145	4.67	5.86	4.20	5.45	7.24	9.25	211.0	190.9
4	157	156	228	195	6.31	6.68	4.89	5.30	5.09	5.38	269.0	239.5
5	100	88	184	174	5.54	5.73	4.02	4.21	4.18	3.21	177.5	184.0
Mean ± SD	116.2 ± 29.8	115.0 ± 30.5	173.2 ± 34.3	157.8 ± 27.1	5.24 ± 0.96	5.49 ± 1.11	4.16 ± 0.69	4.48 ± 1.02	5.11 ± 1.30	5.31 ± 2.41	186.3 ± 55.7	176.6 ± 45.2
P	NS		NS		NS		NS		NS		NS	

See Table 3 for definition of terms.

Table 5. Respiratory muscle strength and pulmonary function before and after exercise under the M40 Low condition.

Subj	PIP (cm H ₂ O)		PEP (cm H ₂ O)		FVC (L)		FEV ₁ (L • s ⁻¹)		FEF _{50%} (L • s ⁻¹)		MVV (L • min ⁻¹)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	92	101	137	137	5.57	5.43	4.55	4.46	5.16	4.90	132.2	132.3
2	101	114	165	154	3.63	3.44	2.77	2.46	2.43	2.59	117.6	107.0
3	97	96	143	127	4.93	4.45	4.23	4.10	6.92	6.86	198.1	220.3
4	168	154	234	189	5.71	5.47	4.38	4.30	4.62	4.53	209.9	226.9
5	101	93	190	171	5.42	5.38	4.05	4.09	4.94	5.14	170.8	142.9
Mean ± SD	111.8 ± 31.6	111.6 ± 25.0	173.8 ± 39.6	155.6 ± 25.1	5.05 ± 0.85	4.83 ± 0.89	4.00 ± 0.71	3.88 ± 0.81	4.81 ± 1.60	4.80 ± 1.53	165.7 ± 40.2	165.9 ± 54.3
P	NS		NS		NS		NS		NS		NS	

See Table 3 for definition of terms.

Subjective ratings of perceived exertion did not differ between experimental inspiratory resistance levels at any time during exercise. On average, subjects reported RPE scores that corresponded to exertion levels between "Fairly light" to "Somewhat hard" from 20 minutes of exercise until the end of the treadmill runs. Breathing apparatus comfort scores reported for each condition plateaued after approximately 30 minutes of exercise (Figure 1).

However, BAC scores were significantly lower from 30 minutes until the end of exercise under the M40 High conditions compared to Control, indicating that subjects felt significantly more discomfort during exercise with the M40 High resistance. Even so, average BAC scores were no worse than "Fairly uncomfortable" under these conditions. Average BAC scores did not differ between M40 resistance conditions.

Discussion

To determine if the combined stresses of exercise and respirator wear may impair respiratory muscle performance, subjects were exposed to three different inspiratory loads during moderate intensity exercise for approximately 120 minutes. The results of this study showed no significant decreases in PIP, PEP, FVC, FEV₁, FEF_{50%}, or MVV following exercise with any of the three inspiratory loads. The findings of no change in FVC, FEV₁, or FEF_{50%} after long-term exercise with high ventilatory demands are consistent with previous reports (Loke *et al.*, 1982; Mahler and Loke, 1981). Maximal voluntary ventilation, a measure of respiratory muscle endurance (Leith and Bradley, 1976; Loke *et al.*, 1982), has been reported to decrease after marathon running. However, no significant changes in MW were observed after any of the exercise conditions in this study, suggesting that ventilatory muscle endurance is unaffected by respirator wear and exercise.

Similarities in pressures generated by the respiratory muscles before and after exercise with the different respirators indicate that respiratory muscle fatigue did not result from the combined stress of respirator wear and moderate intensity exercise. Considering that others have reported some degree of respiratory muscle fatigue after long-term (~150 min) ventilatory work of greater than 65% of V_E max (Loke *et al.*, 1982; Martin *et al.*, 1982), it could be argued that the 55% V_E max level of exercise selected for this study was insufficient for inducing respiratory muscle fatigue. However, under the conditions of these earlier works, fatigue was observed in the absence of any imposed resistive respiratory load. Therefore, it seemed likely that slightly reducing the level of exercise while exposing subjects to a large inspiratory load for a long period of time would expose subjects to a significant ventilatory challenge. Thus, it was felt that this model was a valid challenge to the ventilatory muscles. The observed absence of respiratory muscle fatigue following respirator wear in this study may have resulted from the unexpectedly low ventilation levels observed during exercise

with the M40 respirators (~44% of V_E max) as opposed to the actual non-occurrence of fatigue. Due to this shortfall, the finding that respiratory muscles do not fatigue following respirator wear should be applied only to situations that impose levels of ventilatory work similar to those attained for each level of inspiratory resistance.

The respiratory muscles can be selectively trained to increase both their strength and endurance (Leith and Bradley, 1976; Bradley and Leith, 1978; Pardy *et al.*, 1981). Coast *et al.* (1990) have shown that endurance exercise training induces an adaptive change in the muscles of inspiration that protects them from the acute loss of strength seen following short-term exercise in untrained subjects. Based on aerobic capacity, the participants in this study would be classified as moderately trained individuals ($\dot{V}O_2$ max = 43.0 ± 5.1 ml $\cdot$ kg⁻¹ $\cdot$ min⁻¹). Therefore, the relatively good endurance capacity of the test subjects may have limited the occurrence of respiratory muscle fatigue in this study. An additional factor that must also be considered is that all test participants were experienced, although not regular, respirator wearers. Such exposure may have induced adaptive changes in the muscles of inspiration to overcome the resistive loads of the respirators that may have provided some resistance to the development of fatigue. However, the degree to which such adaptive changes may be induced by repeat exposures to respirator wear is not known.

The reduced levels of ventilation observed during wear of the M40 respirators imply that higher levels of inspiratory resistance caused significant hypoventilation in the subjects. In addition, average % $\dot{V}O_2$ max values recorded for the M40 conditions show that these higher inspiratory resistances resulted in decreased levels of oxygen uptake ($\dot{V}O_2$) for the same constant external workload (i.e., speed and grade of the treadmill) performed under Control conditions. The development of hypoventilation and reduced $\dot{V}O_2$ suggest that subjects performed the

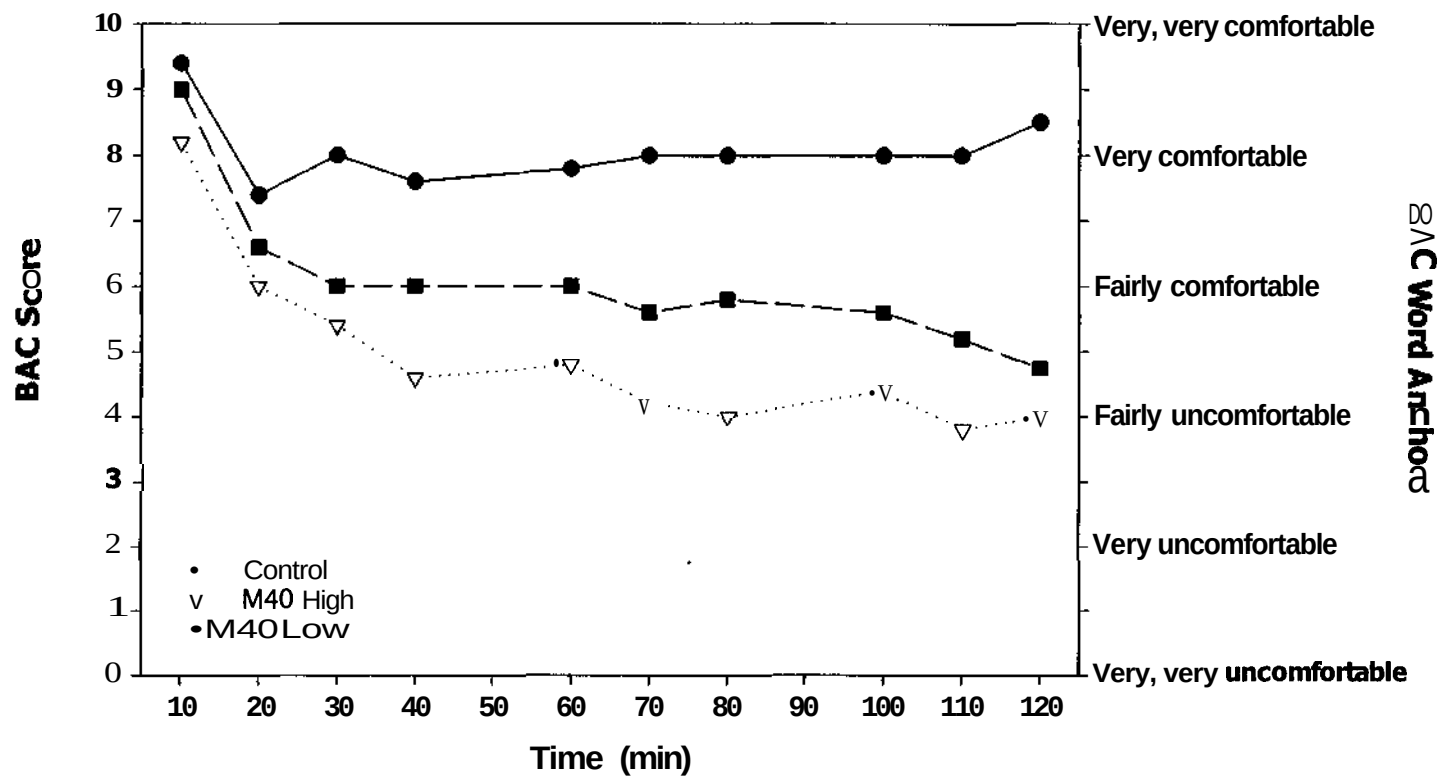


Figure 1. Average breathing apparatus comfort (BAC) scores reported for each condition at 10 minute intervals of exercise. Scores reported at 50 minutes and 90 minutes of exercise were obtained after walking periods and were omitted for clarity. BAC scores were significantly ($p < 0.05$) lower at each 10 minute interval from 30 minutes until the end of exercise under the M40 High conditions compared to Control.

same external work under each resistance condition but at a reduced physiological load with the higher resistances. Johnson *et al.* (1997) reported similar discrepancies in ventilation and oxygen uptake with increased levels of inspiratory resistance under constant external workload. Why the resistances of the two M40 respirators caused these reduced levels of $\dot{V}_E$ and $\dot{V}O_2$ is not readily apparent. These findings may indicate that subjects did not exert themselves to the same level for each test iteration. However, no differences in either average heart rates or ratings of perceived exertion were found between the three experimental conditions, indicating that

subjects exerted themselves similarly during each test. Another possibility for a reduced $\dot{V}O_2$ is that higher levels of inspiratory resistance may result in increased anaerobic metabolism. To assess this possibility, the respiratory exchange ratio (R), a general guide to the contribution of carbohydrates and fats to muscular metabolism, was calculated for each minute of steady-state exercise. No differences in R values were found between resistance conditions, suggesting that anaerobic and aerobic contributions to whole body energy metabolism were not altered by resistance levels.

Conclusions

The findings of this study demonstrate that neither pulmonary function nor strength or endurance of the respiratory muscles were affected by inspiratory loads imposed by respirator wear and exercise that required ventilatory work of approximately 44% of $\dot{V}_E$ max. Therefore, it seems unlikely

that respiratory muscle limitations hinder work tolerance in healthy individuals during respirator wear. Additional research is warranted to determine the cause of decreased ventilation and oxygen uptake observed under conditions of respirator wear.

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