Specificity and Reversibility of Inspiratory Muscle Training

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ABSTRACT

ROMER, L. M., and A. K. MCCONNELL. Specificity and Reversibility of Inspiratory Muscle Training. *Med. Sci. Sports Exerc.*, Vol. 35, No. 2, pp. 237–244, 2003. **Purpose:** The purpose of this study was to evaluate the pressure-flow specificity of adaptations to inspiratory muscle training (IMT), in addition to the temporal effects of detraining and reduced frequency of training upon these adaptations. **Methods:** Twenty-four healthy subjects were assigned randomly to one of four groups (A: low-flow–high-pressure IMT; B: high-flow–low-pressure IMT; C: intermediate flow-pressure IMT; and D: no IMT). Subjects performed IMT 6 d·wk^{-1} for 9 wk, and inspiratory muscle function was evaluated at baseline and every 3 wk. Groups A, B, and C were then assigned randomly to either a maintenance group (M) (IMT 2 d·wk^{-1}) or a detraining group (DT) (no IMT). Inspiratory muscle function was reassessed at 9 and 18 wk post-IMT. **Results:** At 9 wk, group A exhibited the largest increase in pressure, B a large increase in flow, C more uniform increases in pressure and flow, and D no changes in pressure or flow. Maximum inspiratory muscle power increased in groups A, B, and C by 48 ± 3%, 25 ± 3%, and 64 ± 3%, respectively (mean ± SEM, $P \leq 0.01$). Maximum rate of pressure development increased in groups A, B, and C by 59 ± 1%, 10 ± 1%, and 29 ± 1%, respectively ($P \leq 0.01$). A decrease in inspiratory muscle function was observed at 9 wk post-IMT in DT. Inspiratory muscle function plateaued between 9 and 18 wk but remained above pre-IMT values. Group M retained the improvements in inspiratory muscle function. **Conclusion:** These data support the notion of pressure-flow specificity of IMT. Detraining resulted in small but significant reductions in inspiratory muscle function. Reducing training frequency by two thirds allowed for the maintenance of inspiratory muscle function up to 18 wk post-IMT. **Key Words:** RESPIRATORY MUSCLE TRAINING, BREATHING EXERCISES, DETRAINING, MAINTENANCE

The training principles of specificity and reversibility are well established for peripheral skeletal muscles. Specificity implies that the nature of the change in muscle structure and function is determined by the nature of the applied stimulus (21). The reversibility principle holds that when physical training is stopped (detraining), the body readjusts in accordance with the diminished physiological demand, and the beneficial adaptations may be lost (22). Few studies have been conducted to determine whether inspiratory muscles also respond to the aforementioned training principles, but it is reasonable to suppose that they do.

The force-velocity specificity of training proposes that training with high-force–low-velocity contractions specifically increases maximal force but not maximal shortening velocity, whereas training with high-velocity–low-force contractions specifically increases maximal rate of shortening but not maximal force (7). Inspiratory airflow is proportional to velocity of muscle shortening, and inspiratory pressure is proportional to force generation. Therefore, increases in maximal inspiratory flow might be expected with high-velocity training and increases in maximal inspiratory pressure with high-force training. Indeed, training with resistive loads and high-flow loads appear to increase maximal static pressures (17,27,28) and maximal inspiratory flow rates (27,28), respectively. The rate of rise in peak tension may also be improved by specific training. For example, training with contractions of high-force and high-velocity increases the maximum rate of force development in peripheral skeletal muscle (9,20). The influence of inspiratory muscle training (IMT) upon the maximum rate of pressure development (MRPD) is less clear. There is evidence that MRPD increases with both high-pressure and high-flow training (27). However, these findings await independent verification, and the time course of the adaptations is unknown.

Although normal whole-body endurance training promotes a variety of physiological adaptations, long periods of inactivity (detraining) are associated with a reversal of many of the adaptations (22). Unfortunately, the extent and time courses of detraining are not well documented for inspiratory muscle function. From a practical perspective, it would be useful to know whether reducing the frequency of IMT while maintaining the training intensity attenuates any decrease in inspiratory muscle function associated with detraining.

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TABLE 1. Descriptive characteristics of the subjects (mean ± SEM).

	Group A[a]	Group B[a]	Group C[a]	Group D[a]
Gender (m/f)	4/2	3/3	3/3	3/3
Age (yr)	24.2 ± 2.1	30.5 ± 4.0	29.7 ± 2.5	25.8 ± 2.6
Stature (m)	1.74 ± 0.02	1.73 ± 0.03	1.74 ± 0.02	1.73 ± 0.05
Body mass (kg)	77.9 ± 5.1	71.2 ± 3.4	71.6 ± 3.1	72.0 ± 6.4
FVC (L)	5.06 ± 0.08	4.85 ± 0.25	5.04 ± 0.19	5.06 ± 0.27
	(100 ± 1)	(100 ± 1)	(103 ± 1)	(103 ± 1)
FEV_1 (L)	4.29 ± 0.06	4.04 ± 0.20	4.17 ± 0.13	4.27 ± 0.20
	(100 ± 1)	(99 ± 1)	(101 ± 1)	(102 ± 1)
PEF ($L \cdot min^{-1}$)	587.6 ± 5.4	570.7 ± 19.4	584.9 ± 16.1	587.7 ± 18.1
	(100 ± 1)	(99 ± 1)	(102 ± 1)	(102 ± 1)

[a] $N = 6$; FVC, forced vital capacity; FEV_1, forced expiratory volume in one second; PEF, peak expiratory flow. Values in parentheses represent percent of predicted values based on age, stature, and gender (24).

Based on the aforementioned considerations, the purpose of this study was to determine the pressure-flow specificity of adaptations to IMT, in addition to the temporal effects of detraining and reduced frequency of training upon these adaptations. We hypothesized that 1) training with resistive loads and high-flow loads would increase maximal static pressures and maximal inspiratory flow rates, respectively; 2) detraining would result in a reversal of these adaptations; and 3) reducing the frequency of training while maintaining the training intensity would attenuate any decrease in inspiratory muscle function associated with detraining.

METHODS

Subjects

After approval from the Human Subject Research Ethics Committee of the University of Birmingham and written informed consent, 24 healthy individuals (13 male) were assigned randomly in equal numbers to one of four groups (Table 1). Group A performed IMT with low-flow, high-pressure loads; group B performed IMT with high-flow, low-pressure loads; group C performed IMT with intermediate flow and pressure loads; and group D received no training (i.e., control). None of the subjects had experience in performing respiratory exercises.

Study Design

Pulmonary function and maximum dynamic inspiratory muscle function were assessed. Subjects were familiarized thoroughly with test procedures (visit 1) before the preintervention trial (visit 2). Visits 1 and 2 were separated by at least 48 h and completed within 2 wk. Subjects' inspiratory muscles were trained 6 $d \cdot wk^{-1}$ for 9 wk, and respiratory function was reevaluated every 3 wk. After the intervention, trained subjects (groups A, B, and C) were assigned randomly to either a maintenance group (M) who reduced their training frequency to 2 $d \cdot wk^{-1}$ or a detraining group (DT) who refrained from IMT. Subjects' pulmonary and inspiratory muscle function were reassessed at 9 and 18 wk postintervention. Thus, the overall duration of the study was ~29 wk.

Procedure

Pulmonary function. A pneumotachograph spirometer (Vitalograph 2120, Buckingham, UK) was used to measure resting flow-volume profiles. The following variables were derived: forced vital capacity (FVC), forced expiratory volume in 1 s (FEV_1), and peak expiratory flow (PEF). Pulmonary function measurements were made according to European Respiratory Society recommendations (24) (Table 1).

Maximum dynamic inspiratory muscle function. The pressure-flow relationship for inspiratory muscles working in synergy was assessed using maximal inspiratory efforts performed against a pressure-threshold valve arrangement (6). Inspiratory mouth pressure was measured with a pressure transducer (Mercury M14, Glasgow, UK) connected by polyethylene tubing to a 4-mm ID vent located near the mouthpiece of the breathing circuit. Inspiratory airflow was measured with an ultrasonic phase-shift flow meter (Birmingham Flowmetrics Ltd., Birmingham, UK) located distal to the pressure-threshold valve. Pressure and flow signals were amplified, passed through a 12-bit analog-to-digital converter at a sampling rate of 200 Hz, recorded on a computer, and processed using bespoke software (Labview 3, National Instruments, Austin, TX).

Maximum pressure at zero flow (P_0) was measured with complete closure of the threshold valve. A 1-mm orifice was exposed to prevent the subject from producing artificially high inspiratory pressures with the muscles of the buccal cavity (4). To ensure that inspiratory efforts were performed at the same lung volume (residual volume), changes in vital capacity were measured with a pneumotachograph spirometer (Vitalograph 2120) connected in series to the expiratory port of the pressure-threshold device. After the determination of P_0, individuals performed inspiratory maneuvers with maximal effort against six discrete load settings (~0, 20, 25, 35, 50, and 65% P_0), which were assigned randomly using a balanced Latin square for an even number of treatment conditions. The order of treatments was retained throughout the remaining trials. Three technically correct trials were performed at each of the loading intensities and 30 s was permitted between efforts. Maximal pressure and unloaded flow were reevaluated at the end of each measurement session. No changes were observed compared with initial values, suggesting the absence of pressure and flow

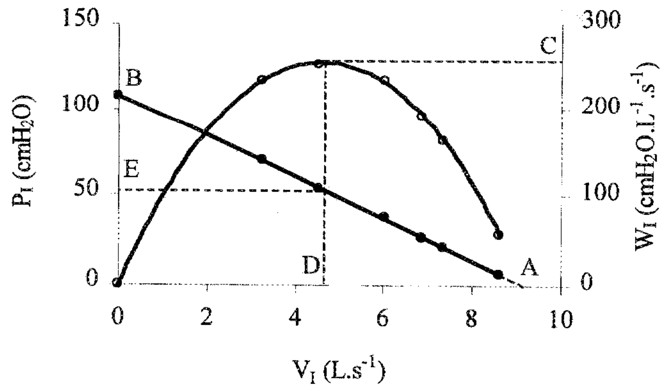

FIGURE 1—Schematic representation of inspiratory pressure-flow-power calculations. $\dot{V}_I$, inspiratory flow rate; P_I, inspiratory mouth pressure; $\dot{W}_I$, inspiratory muscle power. A, maximal flow ($\dot{V}_{max}$); B, maximal pressure at zero flow (P_0); C, maximal power ($\dot{W}_{I\ max}$); D, optimal flow ($\dot{V}_{opt}$); E, optimal pressure (P_{opt}).

fatigue. All maneuvers were performed while seated and were completed within ~15 min. Subjects received visual feedback of pressure and flow to maximize respiratory efforts, and were instructed to inhale maximally and as rapidly as possible.

Pressure and flow measures were obtained from the single inspiratory effort at each level of $\%P_0$ that gave the largest product of inspiratory pressure and flow (i.e., power). Pressure-flow data for the different $\%P_0$ trials were fitted by curves drawn according to a linear least squares representation [$P = a\dot{V} + b$], where P is pressure (cm H_2O), $\dot{V}$ is flow ($L{\cdot}s^{-1}$), and a and b are constants. Maximal flow ($\dot{V}_{max}$) was derived for each subject from the experimental data by extrapolation. Inspiratory muscle power ($\dot{W}_I$) was calculated from the product of inspiratory pressure and flow rate. Maximal power of the inspiratory muscles ($\dot{W}_{I\ max}$; cm $H_2O{\cdot}L^{-1}{\cdot}s^{-1}$) was calculated by differentiation from a zero slope tangent to the flow-power data. Optimal flow ($\dot{V}_{opt}$; $L{\cdot}s^{-1}$ and $\%\dot{V}_{max}$) and optimal pressure (P_{opt}; cm H_2O and $\%P_0$) were defined as the flow and pressure values corresponding to $\dot{W}_{I\ max}$ on the power-flow curve, respectively (see Fig. 1). The MRPD occurring during the initial incline of the maximal inspiratory pressure curve was assessed and defined as the positive peak of the pressure derivative as a function of time.

IMT. After completion of the baseline measurements, each training group performed IMT twice daily (6 $d{\cdot}wk^{-1}$) for 9 wk using a pressure-threshold device (POWERbreathe®, IMT Technologies Ltd., Birmingham, UK) identical to that used to measure baseline dynamic inspiratory muscle function. The first training session was supervised, and subsequent sessions were performed in the subjects' own time away from the laboratory. Group A performed 10 sets of three maximal static inspiratory maneuvers with minimal recovery between sets from RV daily. During these maneuvers, inspiratory airflow was negligible although a 1-mm orifice was exposed to prevent contraction of the buccal muscles. Subjects were instructed to contract their inspiratory muscles maximally for ~2 s. Group B performed 30 maximal inspiratory efforts with no added external resistance from RV daily. Group C performed 30 maximal inspiratory maneuvers from RV at 50% P_0. Subjects in Groups B and C were instructed to continue the inspiratory efforts up the lung volume where the inspiratory muscle force output for the given load limited further excursion of the thorax. Because of the increased tidal volume, a decreased breathing frequency was adopted to avoid hyperventilation and the consequent hypocapnia. Control subjects were assigned to group D and received no training. After the intervention, three of the subjects from each of the three IMT groups (A, B, and C) were assigned randomly to a maintenance group (M). These subjects continued with their original training but reduced their training frequency to 2 $d{\cdot}wk^{-1}$. The remaining subjects were assigned to a detraining group (DT) who refrained from IMT. It was impressed upon subjects that all inspiratory efforts should be maximal and rapid. The number of inspiratory efforts completed by subjects during the nonsupervised sessions was monitored using a thermistor suspended within the main body of the training device that sensed acute drops in air temperature associated with changes in airflow. Subjects completed both IMT and physical activity diaries throughout the intervention study.

Data Analyses

Mixed factorial ANOVA was used to test for between group effects due to treatment (group A, B, C, D, M, or DT) and within-group effects due to time (week 0, 3, 6, 9, 18, and 27) on each of the dependent variables. Planned pairwise comparisons were made with repeated measures *t*-tests and the Bonferroni adjustment was used to modify the per family Type I error rate per comparison. Results are expressed as mean ± SEM. An alpha level of 0.05 was chosen *a priori* to represent statistical significance.

RESULTS

Habitual Physical Exercise and IMT Compliance

Physical activity did not vary between or within groups. Furthermore, no differences were observed between and within groups for the number of actual completed IMT sessions relative to the expected number of sessions. Group A completed 98 ± 3 of the 108 IMT sessions (91% adherence), group B completed 95 ± 2 of the 108 IMT sessions (88% adherence), whereas group C completed 96 ± 3 of the 108 IMT sessions (89% adherence). For the 18-wk postintervention period, group M completed 32 ± 2 of the 36 IMT sessions (90% adherence).

Pulmonary Function

For all groups, pulmonary function remained unchanged from baseline values throughout the period of study.

Maximum Dynamic Inspiratory Muscle Function

Pressure-flow-power relationships. For group D, maximum dynamic inspiratory muscle function remained unchanged from baseline values throughout the duration of study. For the training groups, the post-IMT effects upon inspiratory muscle function were dependent on the training protocol. After 9 wk of training, group A increased P_0 (41 ± 1%, $P \leq 0.01$) but not $\dot{V}_{max}$ (7 ± 1%), group B showed an increase in $\dot{V}_{max}$ (18 ± 1%, $P \leq 0.01$) but not P_0 (9 ± 1%,), and group C showed an increase in P_0 (34 ± 1%, $P \leq 0.01$) and $\dot{V}_{max}$ (26 ± 1%, $P \leq 0.01$). The slopes of the maximum inspiratory pressure-flow regression lines measured at baseline were not different between groups. After 9 wk of training, the slopes of these lines were different from baseline values for group A (−15.3 ± 0.7 vs −11.7 ± 0.6 cm $H_2O \cdot L^{-1} \cdot s^{-1}$, $P \leq 0.01$) and group B (−10.8 ± 0.3 vs −11.7 ± 0.3 cm $H_2O \cdot L^{-1} \cdot s^{-1}$, $P \leq 0.01$) but not group C (−12.8 ± 0.8 vs −11.8 ± 0.7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$, $P > 0.05$) (Fig. 2). In line with the changes in pressure and flow, maximum power of the inspiratory muscles ($\dot{W}_{I\ max}$) was increased in groups A, B, and C by 48 ± 3%, 25 ± 3%, and 64 ± 3%, respectively (Fig. 3). Most of the improvements were apparent after 6 wk of IMT and further training resulted in minimal improvement. Pressure-flow-power data for all groups are summarized in Table 2. The percentage changes with training are summarized in Fig. 4.

MRPD. Significant increases in MRPD above baseline values were observed after 9 wk of IMT for group A (59 ± 1%), group B (10 ± 1%), and group C (29 ± 1%), respectively ($P \leq 0.01$) (Table 2). The time course of improvement in MRPD continued up to 9 wk for groups A and C (Fig. 4).

Maintenance of Inspiratory Muscle Function

A decrease in inspiratory muscle function was observed at 9 wk post-IMT in the group abstaining from training. Between weeks 9 and 18, inspiratory muscle function plateaued but remained above pre-IMT values. The maintenance group retained the improvements in inspiratory muscle function (Table 3).

DISCUSSION

Main Findings

The purpose of this study was to determine the pressure-flow specificity of adaptations to IMT, in addition to the temporal effects of detraining and reduced frequency of training upon these adaptations. As hypothesized, high-pressure training produced the largest improvement in pressure, high-flow training produced large improvement in flow, and intermediate training resulted in a more uniform increase in pressure and flow. The maximal power of the inspiratory muscles was improved most by the intermediate training and least by the high-flow training. The MRPD increased in all training groups with the

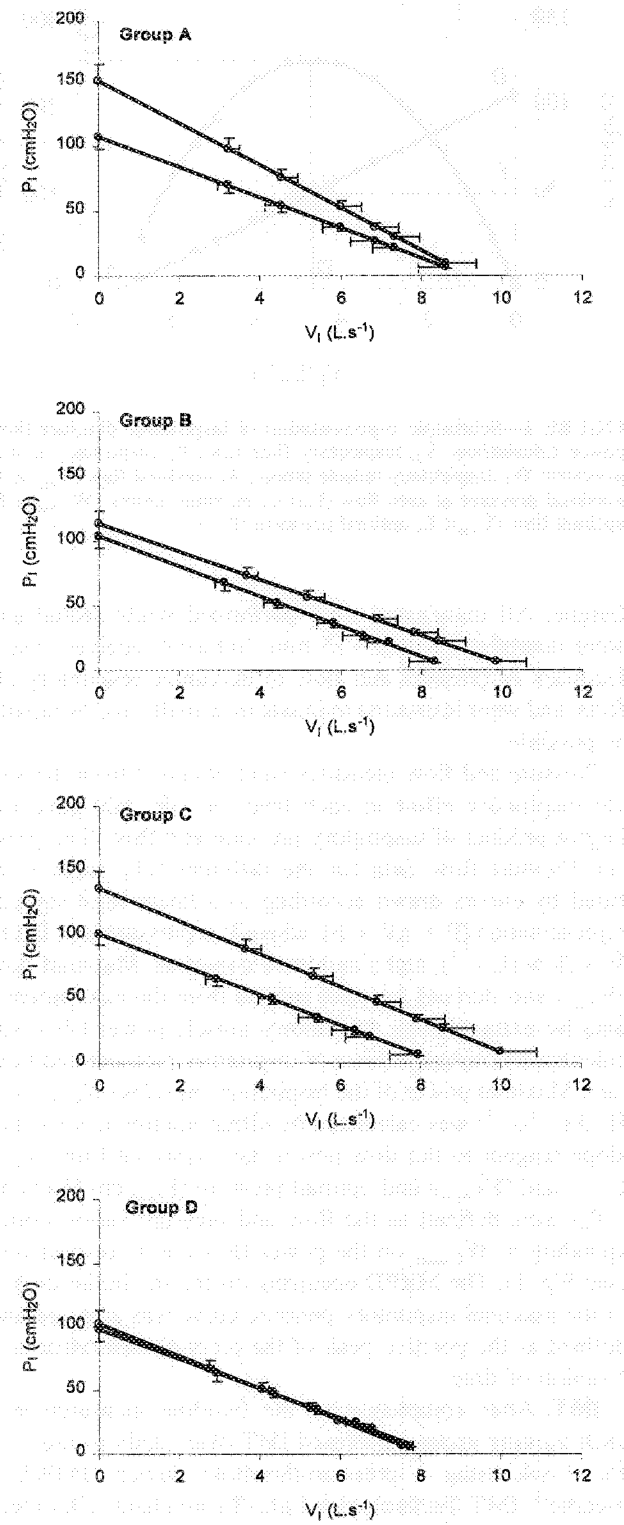

FIGURE 2—Inspiratory mouth pressure (P_I) vs inspiratory flow rate ($\dot{V}_I$) before (*closed circles*) and after 9 wk of IMT (*open circles*) for groups A–D. P_I-$\dot{V}_I$ data are represented in both axes as pooled mean ± SEM.

high-pressure and intermediate pressure-flow training eliciting the largest changes. Most of the pressure-flow-power adaptations were expressed fully by the sixth week of training. Detraining resulted in small but significant

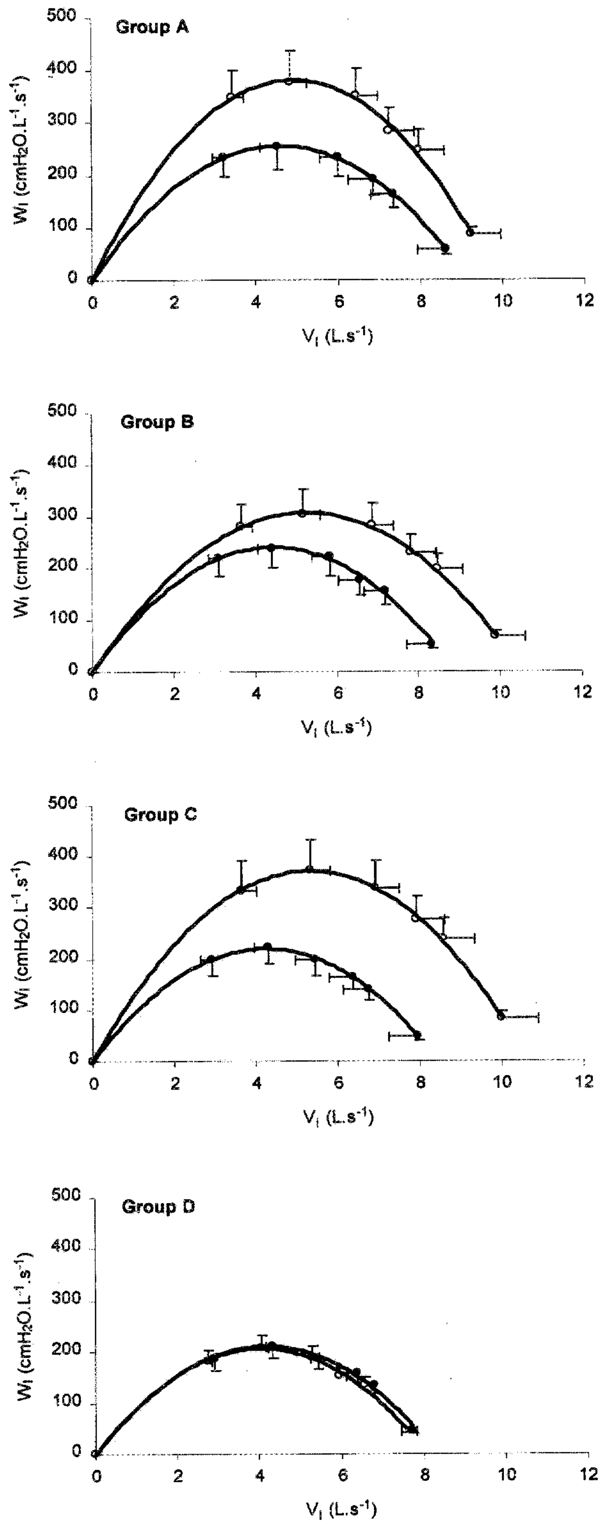

FIGURE 3—Inspiratory muscle work rate ($\dot{W}_I$) vs inspiratory flow rate ($\dot{V}_I$) before (*closed circles*) and after 9 wk of IMT (*open circles*) for groups A–D. $\dot{W}_I$-$\dot{V}_I$ data are represented in both axes as pooled mean ± SEM.

reductions in inspiratory muscle function toward pre-training values. Reducing the frequency of training by up to two-thirds resulted in the maintenance of inspiratory muscle function.

Maximum Dynamic Inspiratory Muscle Function

Pressure-flow-power relationships. Our results support evidence that the general principle of force-velocity specificity of skeletal muscle training applies to the inspiratory muscles. Specifically, training with high-pressure was found to increase maximal static pressures (17,27,28) and training with high-flow to increase maximal inspiratory flow rates (27,28). The finding of an increase in both maximum pressure and flow after training with a mixed protocol, characterized by pressures and flows intermediate in magnitude to their respective maximum, is in agreement with the results from a previous study (28). The posttraining increase in $\dot{V}_{max}$ (18%) with flow training was appreciably smaller than the increase in P_0 with pressure training in the present study (41%) and in previous studies of IMT (17,27,28). This finding suggests that P_0 is more responsive to training stimuli than $\dot{V}_{max}$ and is consistent with our understanding of the factors that determine the force-velocity characteristics of muscle (16).

Although our results provide further support for a pressure-flow specificity of IMT, it is unknown whether these adaptations reflect changes in the contractile proteins or are related to differences in inspiratory muscle activation induced by the different protocols. In general, the initial period of improved performance with strength training has been attributed primarily to neural adaptations that occur in the first 5–6 wk of training (20,25). Neural adaptations that may have occurred in response to IMT include an increased number of motor units recruited (1), an increased motor unit firing rate (25), enhanced synchrony of motor unit firing (19), decreased co-activation of antagonist muscle groups (8), or a combination of these factors. Alternatively, the initial velocity-specific adaptation within muscle might reflect acquisition of skill, such that training improves coordination and muscle activation at the training velocity (2). Later in the training cycle, the myogenic phase of training tends to predominate where changes occur in the contractile proteins (25). Muscle hypertrophy and a transformation of Type II muscle fiber subtypes (from Type IIx to IIa) have been reported responses to strength training (26). To what extent, if any, these latter adaptations explain strength increases is unclear, but there is substantial support for the involvement of muscle hypertrophy in the increased strength observed with training (26).

MRPD. The MRPD for the zero flow condition increased in all training groups, with high-pressure (group A) and intermediate pressure-flow (group C) training eliciting the largest changes. This finding is in contrast with the widely held belief that training with static loads increases the maximal force production of a muscle without changing the rate of force development, whereas training with dynamic loads induces smaller changes in force generation but increases the rate of force development (9,12,13). All subjects in the present study undertook training that involved rapid, ballistic contractions, characterized by short times to peak tension development. Thus, the finding of an increase in MRPD in response to both high-pressure and intermediate pressure-flow IMT is in agreement with recent evidence that the intent to make a high-speed

TABLE 2. Summary of pressure-flow-power data for groups A to D (mean ± SEM).

	Pre-IMT	IMT		
Week No.	**0**	**3**	**6**	**9**
P_0 (cm H_2O)				
A	$108 \pm 10_a$	$138 \pm 12_b$	$146 \pm 13_c$	$151 \pm 13_d$
B	$105 \pm 10_a$	$110 \pm 10_b$	$112 \pm 10_c$	$113 \pm 10_c$
C	$101 \pm 9_a$	$119 \pm 10_b$	$131 \pm 11_c$	$136 \pm 13_c$
D	$97 \pm 10_a$	$97 \pm 10_a$	$97 \pm 10_a$	$102 \pm 10_b$
$\dot{V}_{max}$ ($L \cdot s^{-1}$)				
A	$9.2 \pm 0.7_a$	$9.5 \pm 0.7_b$	$9.7 \pm 0.7_c$	$9.9 \pm 0.8_c$
B	$8.9 \pm 0.7_a$	$9.9 \pm 0.7_b$	$10.3 \pm 0.7_c$	$10.5 \pm 0.8_c$
C	$8.6 \pm 0.8_a$	$9.8 \pm 0.9_b$	$10.6 \pm 0.9_c$	$10.7 \pm 1.0_c$
D	$8.3 \pm 0.5_a$	$8.4 \pm 0.4_a$	$8.3 \pm 0.5_a$	$8.1 \pm 0.3_a$
$\dot{W}_{I\ max}$ (cm $H_2O \cdot L^{-1} \cdot s^{-1}$)				
A	$289 \pm 52_a$	$337 \pm 50_b$	$364 \pm 54_c$	$381 \pm 59_c$
B	$248 \pm 41_a$	$279 \pm 41_b$	$297 \pm 44_c$	$307 \pm 47_c$
C	$222 \pm 35_a$	$296 \pm 45_b$	$355 \pm 55_c$	$372 \pm 60_c$
D	$203 \pm 28_a$	$212 \pm 29_a$	$205 \pm 28_a$	$206 \pm 24_a$
P_{opt} (cm H_2O)				
A	$56 \pm 5_a$	$69 \pm 6_b$	$73 \pm 6_c$	$75 \pm 7_c$
B	$54 \pm 5_a$	$55 \pm 5_b$	$56 \pm 5_c$	$57 \pm 5_c$
C	$51 \pm 5_a$	$59 \pm 5_b$	$65 \pm 6_c$	$68 \pm 6_c$
D	$49 \pm 5_a$	$51 \pm 5_a$	$49 \pm 5_a$	$51 \pm 5_a$
$\dot{V}_{opt}$ ($L \cdot s^{-1}$)				
A	$4.4 \pm 0.3_a$	$4.8 \pm 0.4_b$	$4.9 \pm 0.4_c$	$4.9 \pm 0.4_c$
B	$4.4 \pm 0.3_a$	$4.9 \pm 0.3_b$	$5.2 \pm 0.4_c$	$5.3 \pm 0.4_c$
C	$4.3 \pm 0.4_a$	$4.9 \pm 0.4_b$	$5.3 \pm 0.5_c$	$5.3 \pm 0.5_c$
D	$4.2 \pm 0.3_a$	$4.2 \pm 0.3_a$	$4.2 \pm 0.2_a$	$4.0 \pm 0.1_a$
MRPD (cm $H_2O \cdot ms^{-1}$)				
A	$0.530 \pm 0.005_a$	$0.801 \pm 0.007_b$	$0.827 \pm 0.007_c$	$0.842 \pm 0.007_d$
B	$0.525 \pm 0.005_a$	$0.575 \pm 0.005_b$	$0.578 \pm 0.004_b$	$0.578 \pm 0.005_b$
C	$0.517 \pm 0.006_a$	$0.639 \pm 0.002_b$	$0.655 \pm 0.012_b$	$0.665 \pm 0.011_c$
D	$0.521 \pm 0.007_a$	$0.530 \pm 0.006_a$	$0.531 \pm 0.007_a$	$0.531 \pm 0.007_a$

$N = 6$ in each group. P_0, maximum inspiratory pressure at zero flow; $\dot{V}_{max}$, maximum inspiratory flow; $\dot{W}_{I\ max}$, maximum inspiratory muscle work rate; P_{opt}, optimal pressure; $\dot{V}_{opt}$, optimal flow; MRPD, maximum rate of pressure development. Means in the same row that do not share subscripts differ at $P \leq 0.05$.

contraction may be the most crucial factor in determining the degree of adaptation in the velocity of a mechanical response (3). It is also in agreement with previous evidence that the MRPD increases in response to both high-pressure and high-flow training during these respective maximal efforts (27). The precise mechanism(s) responsible for the change in MRPD with training is unknown. The unique firing frequency associated with dynamic contractions suggests possible adaptations in the frequency of motor unit discharge with this type of training (3). This suggestion is supported by more recent experimental data showing that the decrease in time to peak tension after dynamic training is associated with increased maximal firing frequencies of motor units (29).

Time Course of Adaptations

Most of the adaptations in inspiratory muscle function were apparent with 6 wk of IMT and further training up to 9 wk resulted in minimal improvements. In the majority of reported studies in healthy individuals, the duration of IMT has been 4–8 wk. In a few studies, the training period has lasted for as little as 16 d (11) or as long as 11 wk (30). Volianitis et al. (30) did not detect an improvement in inspiratory muscle function between 4 and 11 wk of IMT. In the absence of an objective measure of IMT compliance, those authors concluded that differences in subject motivation might have accounted for the finding. Our data suggest that there is a physiological plateau in strength and power development in response to IMT at 6 wk.

Maintenance of Inspiratory Muscle Function

To the authors' knowledge, this is the first study to investigate specifically the effect of detraining upon inspiratory muscle function. Nine weeks of detraining resulted in small but significant reductions in most measures of inspiratory muscle function. Between weeks 9 and 18, inspiratory muscle function appeared to plateau, although it remained above pre-IMT values. In peripheral skeletal muscle, a limited decay in strength has been observed during short periods of detraining of 2–4 wk in young adult subjects (15,23). In contrast, longer periods of training cessation are usually accompanied by a more pronounced decline in strength, but this loss is still limited to 8–12% during periods of inactivity ranging from 8–31 wk (14,18). This is consistent with our finding that P_0 was reduced by 7% after 9 wk of detraining and remained unchanged thereafter up to 18 wk posttraining. Our subjects exhibited a more pronounced decrease with detraining in maximum inspiratory muscle power compared with strength (17 vs 7%). This finding is consistent with a study that showed a significant 14% reduction in the ability of collegiate swimmers to generate power during actual swimming despite a nonsignificant change in muscular strength as measured on a swim bench (23).

Another unique feature of the present study was the assessment of inspiratory muscle function during a period of reduced training. Subjects who reduced the frequency of training by up to two thirds while keeping training intensity constant maintained inspiratory muscle function for up to 18 wk post-IMT. This is consistent with the results of other studies that found training intensity to be

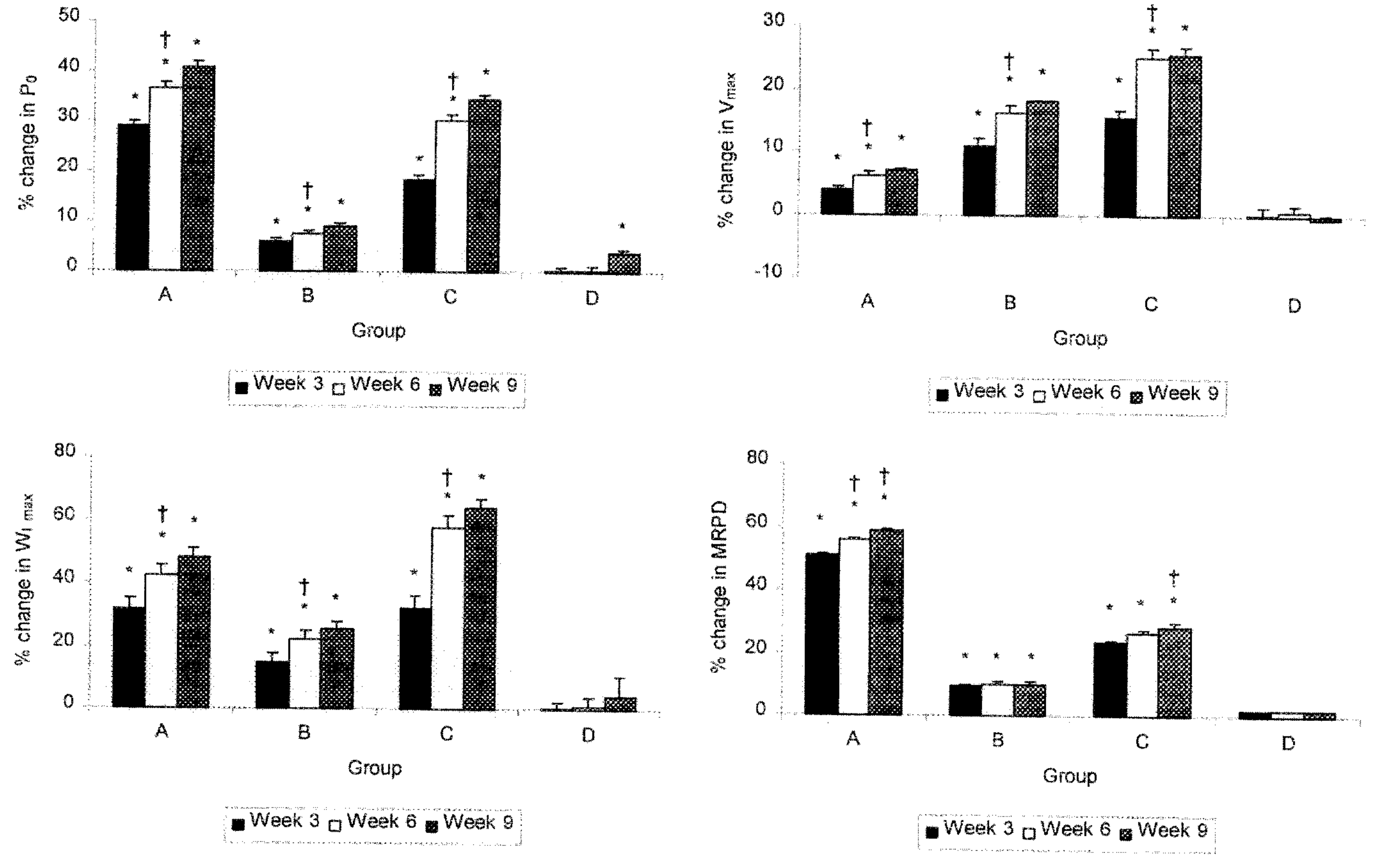

FIGURE 4—Relative changes in maximum dynamic inspiratory muscle function from baseline values for high-pressure (A), high-flow (B), intermediate pressure and flow (C), and control groups (D) (mean ± SEM). P_0, inspiratory pressure at zero flow; $\dot{V}_{max}$, maximum inspiratory flow; $\dot{W}_{I\,max}$, maximum inspiratory muscle work rate; MRPD, maximum rate of pressure development; * significantly different from baseline ($P \leq 0.05$); † significantly different from preceding time point ($P \leq 0.05$).

more important than training frequency for the maintenance of peripheral muscle strength (5,10).

Findings in the present study pertaining to the reversibility of inspiratory muscle function have important practical implications for individuals participating in IMT programs. When training frequency must be reduced for short periods of time, inspiratory muscle function may be maintained by training as little as 2 d·wk^{-1} as long as the intensity of training is maintained. Completely terminating training will result in significant reductions in inspiratory muscle function, mostly within the first 9 wk.

TABLE 3. Summary of post-IMT inspiratory muscle function data for maintenance (M) and detraining (DT) groups (mean ± SEM).

	Pre-IMT	IMT	Post-IMT	
Week No.	0	9	18	27
P_0 (cm H_2O)				
M	$112 \pm 7_a$	$142 \pm 10_b$	$142 \pm 10_b$	$139 \pm 10_b$
DT	$96 \pm 7_a$	$124 \pm 11_b$	$115 \pm 8_c$	$115 \pm 7_c$
$\dot{V}_{max}$ (L·s^{-1})				
M	$9.2 \pm 0.6_a$	$10.7 \pm 0.8_b$	$10.6 \pm 0.8_b$	$10.4 \pm 0.8_b$
DT	$8.6 \pm 0.5_a$	$10.0 \pm 0.6_b$	$9.1 \pm 0.5_c$	$9.1 \pm 0.5_c$
$\dot{W}_{I\,max}$ (cm H_2O·L^{-1}·s^{-1})				
M	$267 \pm 32_a$	$386 \pm 45_b$	$381 \pm 46_b$	$369 \pm 44_b$
DT	$225 \pm 32_a$	$320 \pm 43_b$	$267 \pm 31_c$	$269 \pm 27_c$
P_{opt} (cm H_2O)				
M	$57 \pm 4_a$	$71 \pm 5_b$	$71 \pm 5_b$	$70 \pm 5_b$
DT	$49 \pm 4_a$	$62 \pm 5_b$	$57 \pm 4_c$	$58 \pm 3_c$
$\dot{V}_{opt}$ (L·s^{-1})				
M	$4.5 \pm 0.3_a$	$5.4 \pm 0.4_b$	$5.3 \pm 0.4_b$	$5.2 \pm 0.4_b$
DT	$4.2 \pm 0.2_a$	$5.0 \pm 0.3_b$	$4.5 \pm 0.3_{ab}$	$4.6 \pm 0.2_{ab}$
MRPD (cm H_2O·ms^{-1})				
M	$0.517 \pm 0.005_a$	$0.686 \pm 0.041_b$	$0.683 \pm 0.040_b$	$0.680 \pm 0.041_b$
DT	$0.531 \pm 0.003_a$	$0.704 \pm 0.037_b$	$0.605 \pm 0.034_c$	$0.601 \pm 0.036_c$

$N = 9$. See Table 2 for definitions. Means in the same row that do not share subscripts differ at $P \leq 0.05$.

CONCLUSIONS

Data from the present study support the pressure-flow (force-velocity) specificity of IMT established previously for other peripheral muscle training regimens. Most of the pressure-flow-power adaptations were expressed fully by the sixth week of training. Detraining resulted in small but significant reductions in inspiratory muscle function toward pretraining values, although reducing training frequency by up to two-thirds was sufficient to maintain inspiratory muscle function up to 18 wk post-IMT.

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