The purpose of this study was to assess the efficacy of inspiratory flow resistive loading (IFRL) on respiratory muscle function, exercise performance and cardiopulmonary and metabolic responses to exercise. Twenty-four recreational road runners (12 male) were randomly assigned from each gender into an IFRL group (n = 8) and sham-IFRL group (n = 8), which performed IFRL for 6 weeks, or a control group (n = 8). Strength (+43.9% Δ), endurance (+26.6% Δ), maximum power output (+41.9% Δ) and work capacity (+38.5% Δ) of the inspiratory muscles were significantly increased (P<0.05) at rest following the study period in IFRL group only. In addition, ventilation (−25.7% Δ), oxygen consumption (−13.3% Δ), breathing frequency (−11.9% Δ), tidal volume (−16.0% Δ), heart rate (HR) (−13.1% Δ), blood lactate concentration (−38.9% Δ) and the perceptual response (−33.5% Δ) to constant workload exercise were significantly attenuated (P<0.05), concomitant with a significant improvement (P<0.05) in endurance exercise capacity (+16.4% Δ) during a treadmill run set at 80% VO2max in IFRL group only. These data suggest that IFRL can alter breathing mechanics, attenuate the oxygen cost, ventilation, HR, blood lactate and the perceptual response during constant workload exercise and improve endurance exercise performance in recreational runners.

In general, it has been accepted that ventilation is not a limiting factor to maximum exercise in healthy humans (Dempsey, 1986), even though a substantial portion (14–16%) of the cardiac output is directed to the respiratory muscles to support their metabolic requirements during maximum exercise in highly fit individuals (Harms et al., 1998). However, it has been shown in numerous studies that diaphragmatic fatigue occurs during high-intensity, exhaustive, constant-load running or cycling exercise of at least 80–85% VO2max or 80% Wmax (Babcock et al., 2002). Inspiratory muscle fatigue has been shown to occur in short-duration, high-intensity rowing (Volianitis et al., 2001), after a single 200-m freestyle swim (Lomax & McConnell, 2003) and after simulated cycling time trials (Romer et al., 2002c). Evidence suggests that inspiratory muscle training (IMT) may attenuate inspiratory muscle fatigue in healthy individuals, and thus influence exercise tolerance (Volianitis et al., 2001; Romer et al., 2002c).

Respiratory muscle training (RMT) protocols utilizing either voluntary isocapnic hyperpnea (VIH) or IMT have been shown to improve exercise performance in rowing (Volianitis et al., 2001; Griffiths & McConnell, 2007), cycling (Stuessi et al., 2001; Romer et al., 2002a; Gething et al., 2004b) and swimming (Wells et al., 2005). Interestingly, Leddy et al., 2007 have shown reductions in breathing frequency, ventilation and VO2 during a treadmill run at 80% VO2max following 4 weeks of VIH training. Specifically, IMT has been associated with reduced exercise blood lactate concentration [Lac]b (McConnell & Sharpe, 2005; Griffiths & McConnell, 2007; Brown et al., 2008), ventilation (Gething et al., 2004a) and breathing frequency (Hanel & Secher, 1991), increased diaphragm thickness (Enright et al., 2006b; Downey et al., 2007), structural changes within the inspiratory muscles (Bisschop et al., 1997) and increased inspiratory muscle strength (Witt et al., 2007; Mickleborough et al., 2008) and endurance (Mickleborough et al., 2008).

Data on the impact of RMT on running exercise performance and cardiopulmonary responses has been equivocal. While some RMT protocols utilizing...
Methods

improve the performance of recreational runners and pulmonary function tests in order to remove any week orientation period for all laboratory-based respiratory procedures were approved by the Local Research Ethics Committee. All subjects gave written informed consent to participate in the study and agreed to maintain their usual running schedule (same intensity, duration and type of training) and to keep a log to record their physical activity for duration of the study.

Study design

Before entering the study protocol, all subjects underwent a 1-week orientation period for all laboratory-based respiratory muscle and pulmonary function tests in order to remove any potential learning effect. Before the start of the training phase of the study all subjects reported to the laboratory to complete medical history and physical activity questionnaires, undertake pulmonary and respiratory muscle (strength and endurance) function tests and to complete an incremental treadmill exercise test to exhaustion in order to determine each subjects VO2max. Seventy-two hours later the subjects returned to the laboratory to complete a submaximal treadmill test to exhaustion at a workload, which had been determined to elicit \( \sim 80\% \) VO2max. After all baseline measurements were completed the subjects were randomly assigned from each gender into one of three groups. The experimental (IFRL) group \((n = 8; 4 \) males) and sham-IFRL \((n = 8; 4 \) males) performed IFRL 3 days/week for 6 weeks, while a control (CON) group \((n = 8; 4 \) males) performed no IFRL, during the course of the 6-week study period. Following the 6-week IMT study period, pulmonary and respiratory muscle function tests and the submaximal treadmill test to exhaustion were completed by all subjects in the same manner and sequence as performed before the IMT study period (baseline). All these tests were completed at a similar time of day and under similar environmental conditions.

Spirometry and lung volume measurements

Spirometry was performed with the subject in the sitting position while breathing room air, with the nose being occluded by a clip. All testing was completed using a calibrated computerized spirometer (Superspiro, Micro Medical, Rochester, Kent, UK), according to the ATS/ERS Task Force recommendations on Standardization of Lung Function Testing (Miller et al., 2005), which states that an adequate test requires a minimum of three acceptable forced vital capacity (FVC) maneuvers. Acceptable repeatability is achieved when the difference between the largest and the next largest FVC is \( \leq 0.150 \) L. The best of three consistent trials was recorded. The pulmonary function technician and spirometer were the same throughout the study. The procedure for all spirometry tests was (1) three normal tidal volume breaths, (2) maximal inhalation, (3) forced maximal exhalation and (4) maximal inhalation. The pulmonary function assessment also included a isocapnic maximal voluntary ventilation over 12-s (MVV12) test, which required each subject to inspire and expire deeply as fast as possible for a period of 12 s. Residual lung volume and total lung capacity (TLC) were measured using the nitrogen dilution method with a SensorMedics V6200 Auto-box (VIASYS Healthcare, Warwick, UK).

IMT protocol

The IFRL and sham-IFRL group performed IMT three times per week in the laboratory and under supervision. The device used was the RT2 trainer and associated software (DeVibbiss Sunrise Medical Ltd., Wollaston, UK). The RT2 training device is a pressure manometer with a 2 mm leak, which utilizes an infra-red link to a computer containing the software of the “Test of Incremental Respiratory Endurance” (TIRE) regimen, as previously described (Mickleborough et al., 2008). The 2 mm leak provides a set resistance to inspiratory flow. The TIRE protocol requires each subject to forcefully exhale to residual lung volume (RV) (expiration unloaded), followed immediately by each subject breathing in maximally against the resistance (2 mm leak) from RV to TLC until task failure. This effort was recorded on a computer screen as sustained maximum inspiratory pressure (SMIP), which is the area under the curve (Fig. 1(a) and (b)). The best of three SMIP maneuvers was selected and visually redrawn on the computer screen to a training template set at 80% (IFRL group) or 30%
MIP(b)

Power output (IMPO max) expressed in watts. The work per

Q

Power (∑SMIP) previously (Mickleborough et al., 2008), a leak calibration

conversions from pressure to energy and power. As shown

this data the volume of air entering the manometer was

establish a calibration curve for the manometer. By using

graph of known flow rates against different pressures in order

progressively increased work–rest ratio as previously

screen template was matched or exceeded by participants

progress. A set training regimen then required that the on-

database and provided further feedback of any training

during training, while scores were recorded to the computer

units. This provided computerized biofeedback to each subject

a computer screen together with a countdown clock and scores

(sham-IFRL group) SMIP training template was presented on

inspiratory volume range. The 80% (IFRL group) or 30% (sham-IFRL group) SMIP training template was presented on a computer screen together with a countdown clock and scores based on the pressures achieved expressed in pressure time units. This provided computerized biofeedback to each subject during training, while scores were recorded to the computer database and provided further feedback of any training progress. A set training regimen then required that the on-screen template was matched or exceeded by participants within a progressively increased work–rest ratio as previously described (Mickleborough et al., 2008).

The electronic manometer was calibrated by plotting a graph of known flow rates against different pressures in order to establish a calibration curve for the manometer. By using this data the volume of air entering the manometer was determined at a given pressure, which was then used to give conversions from pressure to energy and power. As shown previously (Mickleborough et al., 2008), a leak calibration constant was calculated, from flow rate (Q), as follows:

\[ Q = 3.226 \times 10^{-6} \times \sqrt{P} \]

where pressure (p) was expressed in N/m² and Q in m³/s. Power (P) developed was derived from the assessment of p and Q, such that \( P = p \times Q \), and the maximal inspiratory muscle power output (IMPOₘₐₓ) expressed in watts. The work per

Inspiratory muscle training and running

Inspiratory muscle strength

Inspiratory muscle strength was measured in all subjects (IFRL, sham-IFRL and CON groups) as the maximum negative inspiratory pressure generated at RV and sustained during a maximal inspiration using the RT2 pressure manometer. MIP and SMIP were measured by asking subjects to maximally inhale against the set resistance from RV to TLC and were again recorded on the computer screen. This was recorded as an indication of the work performed at each maximal breath, as the inspiratory muscles contracted throughout their full range. The inspiratory time of contraction (Tᵢₙₑᵣₜ) during the SMIP maneuver was also recorded.

Inspiratory muscle endurance

Inspiratory muscle endurance in all subjects (IFRL, sham-IFRL and CON groups) was determined by computing the total accumulated SMIPs (∑SMIP) generated for each training load successfully completed and recorded by the RT2 software during a TIRE-IMT session and conducted at the beginning and end of the 12-week study period. As an additional measure of inspiratory muscle endurance, all subjects were asked to match a 75% SMIP target presented every 10 s via the countdown clock, and the time to failure (Tₓlim) (i.e., unable to match at least 90% of the target template) was recorded before and after the 12-week study period.

Maximal exercise testing

An incremental exercise treadmill (Woodway Ergo ELG 2, Rhine, Germany) test to exhaustion was performed in order to determine each subject’s VO₂max. Resting measurements were taken for 3 min before the exercise test. The incremental treadmill test started with a 5-min warm-up followed by 5 min of stretching. On completion of the warm-up subjects began running at 10–13 km/h (females 10–11 km/h; males 12–13 km/h), with increments of 1 km/h every min until voluntary exhaustion. Criteria used for determining whether each subject had attained VO₂max were an respiratory exchange ratio (RER) > 1.10, a HR within 10% of predicted HR max and/or a plateau in VO₂ (<150 mL/min) with an increase in treadmill grade. Ventilatory and metabolic data were collected continuously using breath-by-breath gas analysis throughout the exercise period (Pulmolab EX670, Morgan Medical, Kent, UK). The system was calibrated before each exercise test. The mass flow sensor was calibrated against a Hans Rudolf 3.0 L syringe at various flow rates and ventilation was accepted at ± 0.01 L. Gases were calibrated automatically from a gas cylinder containing known concentrations (14.52% O₂, 4.95% CO₂, 4.78% Ar and 75.5% N₂) (BOC Gases Ltd., Guildford, Surry, UK). HR was recorded at rest, continuously during and following exercise and following exercise (Polar S625X™, Polar Electro, Oy, Finland).

Submaximal endurance exercise testing

Endurance exercise capacity was determined on a motorized treadmill to volitional fatigue at a workload corresponding to ~ 80% VO₂max, which was determined from the maximal

Fig. 1. (a) Tests of incremental respiratory endurance (TIRE) templates before the 6-week study period (baseline). MIP, maximal inspiratory pressure; SMIP, sustained maximal inspiratory pressure (area under the curve); IFRL, inspiratory flow resistive loading. (b) TIRE templates post-6-week study period. MIP, maximal inspiratory pressure; SMIP, sustained maximal inspiratory pressure (area under the curve); IFRL, inspiratory flow resistive loading.
exercise test data. All subjects completed a 3-min warm-up directly followed by treadmill running at a 4% grade and a subsequent speed that corresponded to 80% $\dot{V}O_2\text{max}$. Ventilatory and metabolic data and HR were collected in the same manner as during maximal exercise test. Endurance run time to exhaustion (ERTE) was recorded and used for data analysis. At rest, at 3 and 9 min during exercise and 1 and 5 min during recovery, a 25–50 $\mu$L capillary blood sample from the earlobe was obtained and analyzed for [Lac] using an Analox GM7 multi-assayer (Analox Instruments Ltd., London, UK). The instrument was calibrated with a known lactate standard (8.0 mmol/L) before each test in accordance with the manufacturer’s instructions. In addition, at 3 min and then at 5 min intervals during the exercise test, each subject was asked to estimate their rating of perceived dyspnea using the modified Borg scale (Borg, 1982).

**Statistical analysis**

Data were analyzed using SPSS version 15.0 statistical software (SPSS Inc., Chicago, USA). All data were assessed for normality using the Kolmogorov–Smirnov test, and Levene’s test was used to test for homogeneity of variance between groups. Data were analyzed using a $3 \times 2$ (group × condition) ANOVA. Where a significant F-ratio was found, Fisher’s protected least-square difference post hoc test, with a Bonferroni adjustment (used to maintain an overall type-I error rate of 5%), was used to isolate differences in group means. Pulmonary and respiratory muscle function data are expressed as mean ± standard deviation. Pearson product moment correlation coefficients were computed in order to evaluate the relationship between relative changes in selected dependent variables following IFRL. Statistical significance was accepted if $P < 0.05$.

**Results**

**Subjects**

There were no significant difference ($P>0.05$) between mean height, body mass or age between groups. No significant difference ($P>0.05$) were detected between genders in any of the measured variables, although this was to be expected because this study was not statistically powered to detect gender differences between groups ($n = 4$ from each gender in each group). There was no significant difference in baseline $\dot{V}O_2\text{max}$ between groups. According to the physical activity questionnaires administered at the beginning and end of the training period subjects did not alter their physical activity status during the study.

**Pulmonary and respiratory muscle function**

Pulmonary and respiratory muscle function variables measured at the beginning and end of the 6-week study period were not significantly different ($P>0.05$) within or between the sham-IFRL (Table 2) and CON (Table 3) groups. In addition, all pre-training measurements of pulmonary and respiratory muscle function for the IRFL group were not statistically different ($P>0.05$) compared with the sham-IFRL and CON groups (Table 1, 2 and 3). However, while post-training values for FVC, forced expiratory volume in 1 s (FEV$_1$), residual lung volume (RV) and total lung capacity (TLC) for the IFRL group were not significantly altered ($P>0.05$) at the end of the study period, or significantly different ($P>0.05$)

**Table 1. Respiratory muscle and pulmonary function values for experimental group (IFRL training at 80% SMIP)**

<table>
<thead>
<tr>
<th>Respiratory muscle function</th>
<th>Pre</th>
<th>Post</th>
<th>Diff.</th>
<th>%Δ</th>
<th>P-value</th>
<th>L95% CI</th>
<th>U95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIP (cmH$_2$O)</td>
<td>128.9 ± 17.9</td>
<td>185.5 ± 17.5</td>
<td>56.5*</td>
<td>+43.9</td>
<td>&lt;0.001</td>
<td>37.6</td>
<td>75.6</td>
</tr>
<tr>
<td>SMIP (PTU)</td>
<td>783.1 ± 188.4</td>
<td>1066.5 ± 204.4</td>
<td>283.4*</td>
<td>+26.6</td>
<td>0.006</td>
<td>72.6</td>
<td>494.2</td>
</tr>
<tr>
<td>IMPO$_\text{max}$ (W)</td>
<td>4.60 ± 0.37</td>
<td>7.92 ± 0.51</td>
<td>3.32</td>
<td>+41.9</td>
<td>0.013</td>
<td>1.23</td>
<td>9.64</td>
</tr>
<tr>
<td>IMWC (J/breath)</td>
<td>10.4 ± 3.4</td>
<td>16.9 ± 3.6</td>
<td>6.50</td>
<td>+38.5</td>
<td>0.006</td>
<td>2.97</td>
<td>9.65</td>
</tr>
<tr>
<td>$T_{cont}$ (s)</td>
<td>13.0 ± 2.87</td>
<td>16.0 ± 2.3</td>
<td>3.00*</td>
<td>+18.8</td>
<td>0.019</td>
<td>0.21</td>
<td>5.80</td>
</tr>
<tr>
<td>$\sum$SMIP (PTU)</td>
<td>21735.9 ± 6190</td>
<td>32142.1 ± 5782</td>
<td>10406.2*</td>
<td>+32.4</td>
<td>0.002</td>
<td>3982.5</td>
<td>16830.0</td>
</tr>
<tr>
<td>$T_{end}$ (min)</td>
<td>3.15 ± 1.23</td>
<td>3.90 ± 0.97</td>
<td>0.75*</td>
<td>+23.8</td>
<td>0.001</td>
<td>0.38</td>
<td>1.12</td>
</tr>
<tr>
<td>MVV$_{12}$/L/min</td>
<td>145.0 ± 22.9</td>
<td>159.6 ± 16.2</td>
<td>14.6</td>
<td>+9.2</td>
<td>0.081</td>
<td>-2.63</td>
<td>35.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pulmonary function</th>
<th>Pre</th>
<th>Post</th>
<th>Diff.</th>
<th>%Δ</th>
<th>P-value</th>
<th>L95% CI</th>
<th>U95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVC (L)</td>
<td>4.73 ± 0.79</td>
<td>4.83 ± 0.64</td>
<td>0.10</td>
<td>+2.1</td>
<td>0.447</td>
<td>-0.24</td>
<td>0.56</td>
</tr>
<tr>
<td>FEV$_1$ (L)</td>
<td>4.06 ± 0.57</td>
<td>4.12 ± 0.49</td>
<td>0.06</td>
<td>+1.5</td>
<td>0.172</td>
<td>-0.48</td>
<td>0.71</td>
</tr>
<tr>
<td>FIV$_1$ (L)</td>
<td>3.76 ± 0.34</td>
<td>4.12 ± 0.37</td>
<td>0.36</td>
<td>+9.6</td>
<td>0.002</td>
<td>0.14</td>
<td>0.53</td>
</tr>
<tr>
<td>RV (L)</td>
<td>1.56 ± 0.31</td>
<td>1.32 ± 0.28</td>
<td>-0.24</td>
<td>-15.4</td>
<td>0.280</td>
<td>-0.67</td>
<td>1.07</td>
</tr>
<tr>
<td>TLC (L)</td>
<td>6.29 ± 1.2</td>
<td>6.15 ± 1.1</td>
<td>-0.15</td>
<td>-2.2</td>
<td>0.227</td>
<td>-0.35</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Values are means ± SD.

*Significant difference from pre-value ($P<0.05$). Diff., difference; %Δ, percentage change; L95% CI, lower 95% confidence interval; U95% CI, upper 95% confidence interval; MIP, maximal inspiratory pressure; SMIP, sustained maximal inspiratory pressure (pressure time units); IMPO$_\text{max}$, maximal inspiratory muscle power output; IMWC, inspiratory muscle work capacity; $T_{cont}$, inspiratory time of contraction; $\sum$SMIP, the total area of SMIPs performed to the point of failure summed; $T_{end}$, time to fatigue (performance test); MVV$_{12}$, maximal voluntary ventilation in 12 s; FVC, forced vital capacity; FEV$_1$, forced expiratory volume in 1 s; FIV$_1$, forced inspiratory time in 1 s; RV, residual lung volume; TLC, total lung capacity.
Inspiratory muscle training and running

Table 2. Respiratory muscle and pulmonary function values for placebo group (sham-IFRL training at 30% SMIP)

<table>
<thead>
<tr>
<th>Respiratory muscle function</th>
<th>Pre</th>
<th>Post</th>
<th>Diff.</th>
<th>%Δ</th>
<th>P-value</th>
<th>L95% CI</th>
<th>U95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIP (cmH2O)</td>
<td>131.0 ± 29.4</td>
<td>142.9 ± 34.5</td>
<td>11.6</td>
<td>+9.1</td>
<td>0.240</td>
<td>-22.8</td>
<td>46.0</td>
</tr>
<tr>
<td>IMPO\text{max} (W)</td>
<td>4.70 ± 0.42</td>
<td>5.35 ± 0.46</td>
<td>0.65</td>
<td>+13.4</td>
<td>0.123</td>
<td>-1.24</td>
<td>4.64</td>
</tr>
<tr>
<td>SMIP (PTU)</td>
<td>678.5 ± 211.8</td>
<td>741.1 ± 268.8</td>
<td>62.6</td>
<td>+9.2</td>
<td>0.289</td>
<td>-229.0</td>
<td>173.8</td>
</tr>
<tr>
<td>IMWC (J/breath)</td>
<td>9.8 ± 2.8</td>
<td>10.4 ± 3.1</td>
<td>0.60</td>
<td>+6.1</td>
<td>0.427</td>
<td>-9.6</td>
<td>3.65</td>
</tr>
<tr>
<td>T\text{cont} (S)</td>
<td>11.8 ± 2.78</td>
<td>12.8 ± 2.76</td>
<td>1.0</td>
<td>+8.5</td>
<td>0.067</td>
<td>-1.64</td>
<td>3.24</td>
</tr>
<tr>
<td>ΣSMIP (PTU)</td>
<td>107090 ± 5595</td>
<td>113673 ± 4131</td>
<td>658.3</td>
<td>+9.3</td>
<td>0.397</td>
<td>-5932.5</td>
<td>4616.0</td>
</tr>
<tr>
<td>T\text{lim} (min)</td>
<td>3.30 ± 0.99</td>
<td>3.49 ± 0.94</td>
<td>0.19</td>
<td>+5.8</td>
<td>0.359</td>
<td>-0.89</td>
<td>1.25</td>
</tr>
<tr>
<td>MVV\text{12} (L/min)</td>
<td>126.0 ± 14.5</td>
<td>135.8 ± 20.7</td>
<td>9.8</td>
<td>+22.1</td>
<td>0.147</td>
<td>9.4</td>
<td>28.9</td>
</tr>
</tbody>
</table>

Pulmonary function

| FVC (L)                   | 4.67 ± 0.61 | 4.79 ± 0.60 | 0.12  | +2.6 | 0.357   | -0.54   | 0.76    |
| FEV\text{1} (L)           | 3.95 ± 0.67 | 4.17 ± 0.56 | 0.17  | +5.6 | 0.063   | -0.11   | 0.43    |
| FIV\text{1} (L)           | 3.63 ± 0.30 | 3.78 ± 0.35 | 0.15  | +4.1 | 0.108   | -0.17   | 0.36    |
| RV (L)                    | 1.22 ± 0.55 | 1.28 ± 0.46 | 0.06  | +4.9 | 0.406   | -0.48   | 0.69    |
| TLC (L)                   | 5.89 ± 1.5  | 6.07 ± 1.5  | 0.18  | +3.1 | 0.108   | -0.07   | 0.97    |

Values are means ± SD.

*Significant difference from pre-value (P<0.05).

Diff., difference; %Δ, percentage change; L95%CI, lower 95% confidence interval; U95%CI, upper 95% confidence interval; MIP, maximal inspiratory pressure; SMIP, sustained maximal inspiratory pressure (pressure time units); IMPO\text{max}, maximal inspiratory muscle power output; IMWC, inspiratory muscle work capacity; T\text{cont}, inspiratory time of contraction; ΣSMIP, the total area of SMIPs performed to the point of failure summed; T\text{lim}, time to fatigue (performance test); MVV\text{12}, maximal voluntary ventilation in 12 s; FVC; forced vital capacity; FEV\text{1}, forced expiratory volume in 1 s; FIV\text{1}, forced inspiratory volume in 1 s; RV, residual lung volume; TLC, total lung capacity.

Table 3. Respiratory muscle and pulmonary function values for control group (performed no IFRL training)

<table>
<thead>
<tr>
<th>Respiratory muscle function</th>
<th>Pre</th>
<th>Post</th>
<th>Diff.</th>
<th>%Δ</th>
<th>P-value</th>
<th>L95% CI</th>
<th>U95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIP (cmH2O)</td>
<td>133.9 ± 23.9</td>
<td>133.8 ± 21.0</td>
<td>0.10</td>
<td>-0.08</td>
<td>0.499</td>
<td>-24.1</td>
<td>24.0</td>
</tr>
<tr>
<td>IMPO\text{max} (W)</td>
<td>4.86 ± 0.34</td>
<td>4.87 ± 0.31</td>
<td>0.01</td>
<td>+0.21</td>
<td>0.431</td>
<td>-0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>SMIP (PTU)</td>
<td>1000.1 ± 251.7</td>
<td>906.5 ± 171.4</td>
<td>-93.6</td>
<td>-9.4</td>
<td>0.200</td>
<td>-324.6</td>
<td>137.3</td>
</tr>
<tr>
<td>IMWC (J/breath)</td>
<td>10.7 ± 3.8</td>
<td>9.7 ± 3.3</td>
<td>-0.4</td>
<td>-4.0</td>
<td>0.392</td>
<td>-1.32</td>
<td>2.96</td>
</tr>
<tr>
<td>T\text{cont} (S)</td>
<td>11.9 ± 2.94</td>
<td>11.9 ± 2.97</td>
<td>0.01</td>
<td>0.0</td>
<td>0.457</td>
<td>-3.16</td>
<td>3.14</td>
</tr>
<tr>
<td>ΣSMIP (PTU)</td>
<td>189228 ± 3548</td>
<td>220351 ± 4158</td>
<td>3112.3</td>
<td>+16.5</td>
<td>0.065</td>
<td>-1032.8</td>
<td>7257.5</td>
</tr>
<tr>
<td>T\text{lim} (min)</td>
<td>2.74 ± 1.17</td>
<td>2.71 ± 1.21</td>
<td>-0.03</td>
<td>+1.1</td>
<td>0.477</td>
<td>-1.32</td>
<td>1.23</td>
</tr>
<tr>
<td>MVV\text{12} (L/min)</td>
<td>142.1 ± 19.9</td>
<td>147.0 ± 20.9</td>
<td>4.9</td>
<td>+3.5</td>
<td>0.320</td>
<td>-17.0</td>
<td>26.8</td>
</tr>
</tbody>
</table>

Pulmonary function

| FVC (L)                   | 4.86 ± 0.24 | 4.93 ± 0.20 | 0.07  | +1.5 | 0.274   | -0.17   | 0.30    |
| FEV\text{1} (L)           | 3.98 ± 0.48 | 4.00 ± 0.45 | 0.02  | +0.5 | 0.494   | -0.48   | 0.47    |
| FIV\text{1} (L)           | 3.78 ± 0.39 | 3.84 ± 0.36 | 0.06  | +1.6 | 0.341   | -0.23   | 0.56    |
| RV (L)                    | 1.14 ± 0.60 | 1.13 ± 0.47 | -0.01 | +0.9 | 0.496   | -0.48   | 0.47    |
| TLC (L)                   | 6.00 ± 1.8  | 6.06 ± 1.5  | 0.06  | +1.0 | 0.293   | -0.84   | 0.65    |

Values are means ± SD.

*Significant difference from pre-value (P<0.05).

Diff., difference; %Δ, percentage change; L95%CI, lower 95% confidence interval; U95%CI, upper 95% confidence interval; MIP, maximal inspiratory pressure; SMIP, sustained maximal inspiratory pressure (pressure time units); IMPO\text{max}, maximal inspiratory muscle power output; IMWC, inspiratory muscle work capacity; T\text{cont}, inspiratory time of contraction; ΣSMIP, the total area of SMIPs performed to the point of failure summed; T\text{lim}, time to fatigue (performance test); MVV\text{12}, maximal voluntary ventilation in 12 s; FVC; forced vital capacity; FEV\text{1}, forced expiratory volume in 1 s; FIV\text{1}, forced inspiratory volume in 1 s; RV, residual lung volume; TLC, total lung capacity.

Compared with the sham-IFRL and CON groups, forced inspiratory volume in 1 s (FIV\text{1}) was significantly increased (P<0.05) at the end of the study period by 9.6 ± 3.1% in the IFRL group (Table 1), and by 8.2 ± 3.5% and 6.8 ± 2.9% (Table 1) compared with the sham-IFRL and CON group, respectively.

No significant difference (P>0.05) was observed in respiratory muscle function measures at baseline between groups (Tables 1, 2 and 3; Fig. 1(a)). In addition, no significant change (P>0.05) was observed between respiratory muscle function variables measured at baseline and at the end of the study period in the sham-IFRL (Table 2) and CON (Table 3) groups. However, in the IFRL group (Table 1) there was a significant increase (P<0.05) in MIP (43.9 ± 7.4%), SMIP (26.6 ± 6.7%), IMPO\text{max} (41.9 ± 5.1%), IMWC (38.5 ± 5.9%), time of contraction...
(18.8 ± 2.8%) sum of SMIP (32.4±6.1%) and time to fatigue (performance test) (23.8±2.4%) compared with baseline.

Although IFRL failed to improve MVV, significant positive relationships were observed between the relative changes in FIV1 and MVV (r = 0.62, P = 0.010). In addition, in the IFRL group significant positive relationships were observed between the relative changes in MIP and FIV1 (r = 0.72, P = 0.008), MIP and IMPO_max (r = 0.79, P = 0.004) and IMPO_max and FIV1 (r = 0.64, P = 0.009). Furthermore, in the IFRL group significant positive relationships were found between the relative change in MIP and rating of perceived exertion (RPE) (r = 0.71, P = 0.008), IMPO_max and RPE (r = 0.73, P = 0.005) and FIV1 and RPE (r = 0.61, P = 0.021).

Responses to exercise and running time to exhaustion
Baseline measures of V̇O₂ (Fig. 2(a)), (V̇E) (Fig. 2(b)), RER (Fig. 3(a)), breathing frequency (Fig. 3(b)), tidal volume (Fig. 4(a)), dyspnea ratings (Fig. 4(b)), HR (Fig. 5(a)) and \([\text{Lac}^-]_B\) (Fig. 5(b)) were not significantly different (P>0.05) between groups. Following the 6-week training period, V̇O₂, (V̇E), RER, breathing frequency, tidal volume, dyspnea ratings, HR and \([\text{Lac}^-]_B\) were unaltered from baseline during the fixed work-rate submaximal test at all time points (P>0.05) in the sham-IFRL and CON groups. However, while V̇O₂, V̇E, RER, breathing frequency, dyspnea ratings and HR rose progressively with time, these measures were significantly lower (P<0.05) at the majority of time points (e.g., 2, 5, 8, 12 and 17 min) during the submaximal exercise test after the training period in the IFRL group only. Tidal volume (Fig. 4(a)) was significantly attenuated (P<0.05) following the training period in the IFRL group during the submaximal exercise test at 2, 5 and 8 min. Blood lactate concentration (Fig. 5(b)) was significantly reduced (P<0.05) following the training period during the submaximal exercise test, and at 1 and 5 min post-exercise, in the IFRL group only. There were no significant differences (P>0.05) between groups at maximum exercise for V̇O₂, (V̇E), RER, breathing frequency, tidal volume, dyspnea rating and HR when comparing baseline with post-training period measures.

Running time to exhaustion was not significantly different (P>0.05) between groups before training (IFRL, 20.7 ± 1.4 min; sham-IFRL, 20.0 ± 2.3 min; CON, 19.9 ± 3.31 min) (Fig. 6) or between the sham-IFRL (19.6 ± 1.8 min) and CON (20.7 ± 3.4 min) group following training. However, following the training period ERTE significantly improved in the IFRL group (24.1 ± 1.43 min) compared with the sham-IFRL and CON group. In addition, in the IFRL group there was a significant correlation between the change in running performance and the changes in V̇O₂ (r = 0.64, P = 0.019), V̇E (r = 0.68, P = 0.011), RER (r = 0.72, P = 0.008), breathing frequency (r = 0.61, P = 0.028), tidal volume (r = 0.58, P = 0.034), RPE (r = 0.64, P = 0.021), HR (r = 0.75, P = 0.006) and \([\text{Lac}^-]_B\) (r = 0.70, P = 0.010) between baseline and post-intervention.

Discussion
The results of the present study have demonstrated that IFRL performed 3 days/week for 6 weeks can (1) alter breathing mechanics, lower the oxygen cost and attenuate ventilatory, HR, \([\text{Lac}^-]_B\) and the perceptual response during constant workload exercise, (2) increase inspiratory muscle strength, endurance, IMPO_max and IMWC and (3) improve exercise performance of recreational runners during a laboratory treadmill running time to exhaustion test at 80%...
of VO2max. We observed no changes in cardiopulmonary and metabolic responses to maximum running exercise as a consequence of IFRL, which is a consistent finding within the literature (Inbar et al., 2000; Williams et al., 2002; Edwards et al., 2008).

Pulmonary and respiratory muscle function

Our work supports data from other studies that showed no change in expiratory measures of pulmonary function as a consequence of either IMT or VIH in runners (Hanel & Secher, 1991; Inbar et al., 2000; Williams et al., 2002; Leddy et al., 2007) and cyclists (Gething et al., 2004b). Consistent with our previous work (Mickleborough et al., 2005) FIV1 increased in the IRFL group, which may be the result of an increase in the inspiratory muscle velocity of shortening as a result of improved inspiratory muscle strength. Interestingly, Romer et al., 2002a,b,c, p. 346) similarly found an increase in peak inspiratory flow rate following IMT, and combined with our data from the present study, these findings are in agreement with the pressure-flow specificity of IMT (Tzelepis et al., 1994).

However, similar to the findings of other studies evaluating the efficacy either IMT or VIH in elite and recreational runners (Hanel & Secher, 1991; Chatham et al., 1999; Inbar et al., 2000; Romer et al., 2002b; Williams et al., 2002; Edwards & Cooke, 2004; Downey et al., 2007; Edwards et al., 2008), in the present study inspiratory muscle strength and endurance significantly improved by 30.5% and 19.2%, respectively, in the IRFL group. The magnitude of improvement in inspiratory muscle strength and endurance is consistent with previous studies in runners using a variety of RMT devices/protocols (Hanel & Secher, 1991; Chatham et al., 1999; Inbar et al., 2000; Williams et al., 2002; Leddy et al., 2007) and cyclists (Gething et al., 2004b). Consistent with our previous work (Mickleborough et al., 2005) FIV1 increased in the IRFL group, which may be the result of an increase in the inspiratory muscle velocity of shortening as a result of improved inspiratory muscle strength. Interestingly, Romer et al., 2002a,b,c, p. 346) similarly found an increase in peak inspiratory flow rate following IMT, and combined with our data from the present study, these findings are in agreement with the pressure-flow specificity of IMT (Tzelepis et al., 1994).

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The magnitude of increase in inspiratory muscle strength following IMT varies from 12.6% in untrained individuals to 25.0% in repetitive sprint sport players (Romer et al., 2002b), 19.7% to 31% in elite runners (Inbar et al., 2000; Williams et al., 2002) and up to 45.5% in competitive rowers (Volianitis et al., 2001). However, the magnitude of change in inspiratory muscle endurance in studies is more variable. Inbar et al. (2000) demonstrated an increase of only 10%, while inspiratory muscle endurance increased by 128% in elite runners in the study by Williams et al. (2002).

Consistent with our previous findings in elite swimmers (Mickleborough et al., 2008), this study has shown that IMPO\textsubscript{max} and IMWC increase following IFRL in recreational runners. The use of a fixed 2 mm leak allowed for conversion of SMIP measures to SI units of power and work. Unlike the measurement of MIP, IMWC is a measure of pressure generation over the full range of lung volumes from RV to TLC (Enright et al., 2006a). The practical consequence of a longer and more powerful contraction, as shown by an improvement in T\textsubscript{cont} in the IFRL group, is a functional increase in inspiratory flow. The increase in IMPO\textsubscript{max} in the IFRL group suggests that IMT may increase the velocity of contraction of the inspiratory muscles. As with other skeletal muscles, it has been shown that the inspiratory muscles can be trained to increase their capacity to generate force (pressure) or velocity of muscle shortening (Tzzelepis et al., 1999). The improvement in the velocity of muscle shortening and IMPO\textsubscript{max} with training may be attributed to a change in the intrinsic contractile properties of the muscle fibers or, more possibly, to a different recruitment of muscle fibers.

Responses to exercise and running time to exhaustion

The present study identified a significant 14.1% improvement in running performance in the IFRL group. Our data are consistent with other studies that have observed an improvement in ERTE and 4-mile run time (Edwards & Cooke, 2004; Leddy et al., 2007) and 5000 m running performance (Edwards et al., 2008) after either pressure-threshold IMT or VIH.

The results of the present study have shown that IFRL can reduce [Lac\textsuperscript{−}]\textsubscript{B}, perception of dyspnea, HR, VO\textsubscript{2}, (V\textsubscript{E}), RER in association with attenuated \( f\textsubscript{0} \), \( V\textsubscript{T} \) during submaximal run, suggesting that IFRL reduced the work of breathing and/or improved ventilatory system efficiency. The reduced \( V\textsubscript{E} \) and \( \Delta V\textsubscript{O} \text{2} \) during the 80% VO\textsubscript{2max} treadmill run following IFRL is consistent with prior studies in runners (Leddy et al., 2007) and cyclists (Gething et al., 2008).
and with previously reported data for the
ergy cost of breathing (Leddy et al., 2007). An
alternative explanation for the reduction in VO2
post-IFRL may be due to improved running effi-
ciency. In the present study, there was a significant
reduction in VO2 during the submaximal run as the
subjects fatigued. Previous studies have shown that
respiratory muscle work has to be increased to near
fatiguing levels for muscle sympathetic nerve activity
to be increased (St Croix et al., 2000) or for leg blood
flow to be reduced during exercise (Harms et al.,
1997). In addition, exercise-induced diaphragm fati-
gue was only observed in healthy subjects of varying
fitness levels when the intensity of exercise exceeded
80–85% VO2max and the exercise was sustained to
exhaustion (Johnson et al., 1993; Babcock et al.,
1998). Consistent with these observations fatiguing
exercise impairs neuromuscular performance (Komi,
2000). Therefore, the combination of these factors on
the performance of the limb locomotor muscles may
lead to reduced running efficiency and increased
ergy cost of running prior to IFRL. Thus, in the
present study it is possible that an IFRL-induced
improvement in the performance of the limb loco-
motor muscles may have resulted in an enhanced
running economy. At present, the mechanisms re-
sponsible for the ergogenic effect of RMT on exercise
performance are uncertain. Recent evidence suggests
that IMT may generate improvements in exercise
performance through two main mechanisms which
are most likely interrelated: (1) attenuation of effort
sensations, such that exercise feels easier following
IMT (Romer et al., 2002a; Gething et al., 2004b) and
(2) attenuation of the inspiratory muscle metabore-
flex leading to a perseveration of limb locomotor
blood flow during exercise(Witt et al., 2007).
Consistent with our study, it has been shown
previously that IFRL can reduce HR during exercise
(Gething et al., 2004b). Witt et al. (2007) suggests
that this attenuated cardiovascular response suggests
a blunted sympatho-excitation to resistive inspira-
tory work. It is plausible that the reduction in HR
during exercise as a consequence of IFRL may
decrease the cardiorespiratory cost of oxygen trans-
port (Green et al., 2000). Decreased submaximal HR
concomitant with improvements in the oxygen cost
of running after live-high train-low (LHTL) altitude
training have been observed (Saunders et al., 2007),
and there may be a commonality in underlying
mechanisms between IFRL and LHTL training in
lowering the oxygen cost of running.
In the present study, we have shown in runners
that IFRL can attenuate fR, VT and perception of
dyspnea during exercise. Gething et al. (2004b) has
shown previously that both fR and perception of
dyspnea are reduced in cyclists following 10 weeks
of IFRL, while Romer et al. (2002a) have shown a
reduction in both respiratory and peripheral effort
(BorgCR10) during a cycling time trial following 6
weeks of pressure-threshold IMT. Respiratory mus-
cle fatigue could possibly limit exercise tolerance
through an inadequate ventilatory response, a detri-
mental change in breathing mechanics and/or an
increased sensation of dyspnea, and all of which
may be potentially reversed by IFRL.

The present study has shown that IFRL can reduce
[Lac−]B during constant load running, and is con-
sistent with prior studies utilizing either IMT
(McConnell & Sharpe, 2005; Griffiths & McConnell,
2007) or VIH (Spengler et al., 1999; Leddy et al.,
2007) that have shown a diminution of [Lac−]B
during exercise. Interestingly, Brown et al. (2008)
have shown that an increase in [Lac−]B observed
during VIH at 80% VEmax was attenuated following
IMT. The mechanism by which RMT can moderate
[Lac−]B remains equivocal. It has been suggested
that the reductions observed in [Lac−]B result from
increased uptake by the respiratory muscles, rather
than a net decrease in lactate clearance (Spengler
et al., 1999). Alternatively, it is possible that IMT-
mediated changes in respiratory muscle function may
contribute to lowering [Lac−]B via affecting lactate
clearance by and efflux from the trained respiratory
muscles. Finally, the attenuated [Lac−]B response to
IFRL may be due to an IMT-mediated increase in
the oxidative and/or monocarboxylate transport
protein content of the inspiratory muscles (Brown
et al., 2008).

In conclusion, this study has shown that 6 weeks
of IRFL significantly improved respiratory muscle
function, reduced HR and [Lac−]B, attenuated the
ventilatory and perceptual response to exercise and
improved ERTE on a treadmill at 80% VO2max in
recreational runners.

Importantly our data show that IFRL can posi-
tively influence the conscious sensation of fatigue,
alter breathing mechanics and lower the oxygen cost
of running at constant workload exercise.

Perspectives
A great deal research has been conducted on the
response of the respiratory muscles to IMT and its
effects on exercise performance (McConnell & Ro-
mer, 2004). However, there is scant data (Edwards &
Cooke, 2004; Downey et al., 2007; Leddy et al., 2007;
Williams et al., 2002) available pertaining to the
efficacy of IMT on cardiopulmonary and metabolic
measures and running performance. The present
study utilized a novel approach to IMT, specifically
IFRL based on the TIRE training protocol and
incorporating computerized biofeedback. This type
of IMT has been shown to increase diaphragm
thickness, lung volumes and cycling exercise capacity in healthy subjects (Enright et al., 2006b), improve lung function and exercise capacity (Enright et al., 2004), improve cycling time to exhaustion (Gething et al., 2004b) and enhance sputum expectoration in patients cystic fibrosis (Chatham et al., 2004). Therefore, IFRL may prove to be beneficial to inspiratory muscle strength and endurance and whole-body exercise performance in both healthy individuals and patients with cardiopulmonary disease.

Key words: inspiratory muscle training, exercise capacity, runners, ventilation.

References


