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Controlled-frequency breath swimming improves swimming performance and running economy

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Respiratory muscle fatigue can negatively impact athletic performance, but swimming has beneficial effects on the respiratory system and may reduce susceptibility to fatigue. Limiting breath frequency during swimming further stresses the respiratory system through hypercapnia and mechanical loading and may lead to appreciable improvements in respiratory muscle strength. This study assessed the effects of controlled-frequency breath (CFB) swimming on pulmonary function. Eighteen subjects (10 men), average (standard deviation) age 25 (6) years, body mass index 24.4 (3.7) kg/m^2, underwent baseline testing to assess pulmonary function, running economy, aerobic capacity, and swimming performance. Subjects were then randomized to either CFB or stroke-matched (SM) condition. Subjects completed 12 training sessions, in which CFB subjects took two breaths per length and SM subjects took seven. Post-training, maximum expiratory pressure improved by 11% (15) for all 18 subjects ($P < 0.05$) while maximum inspiratory pressure was unchanged. Running economy improved by 6 (9)% in CFB following training ($P < 0.05$). Forced vital capacity increased by 4% (4) in SM ($P < 0.05$) and was unchanged in CFB. These findings suggest that limiting breath frequency during swimming may improve muscular oxygen utilization during terrestrial exercise in novice swimmers.

During intense exercise, the demands on proper functioning of the respiratory system are markedly increased. Research has shown that the respiratory system often "lags behind," while cardiovascular function and skeletal muscle improve with aerobic training (Bye et al., 1983; Wagner, 2005). Swimmers are often cited as the exception to Wagner's hypothesis that exercise does not "grow the lungs" (Wagner, 2005), with early studies showing that competitive swimmers consistently have larger lung volumes than predicted, even when controlling for body size (Clanton et al., 1987). Several features unique to swimming are postulated to bring about such changes in these athletes. For example, inspirations are typically larger than those in land-based sports (Dicker et al., 1980) and breathing must be well-timed and coordinated (Troup, 1999; Seifert et al., 2005); additionally, the constant hydrostatic pressure exerted on the chest by the water creates a constant adaptive stressor for the lungs (Hong et al., 1969; Silvers et al., 2007), and the prone position facilitates perfusion and decreases respiratory dead space (Mostyn et al., 1963; Rohdin et al., 2003).

Limiting the frequency of breaths during swimming may impose more intense stressors on the athlete; this practice has been shown to produce higher levels of inspiratory muscle fatigue without affecting swimming performance (Jakovljevic & McConnell, 2009). Whereas hypoxic swim training does not produce significant training adaptations (Truijens et al., 2003), it is shown that the mechanism of controlled-frequency breathing (CFB) induces hypercapnia (partial pressure of carbon dioxide in arterial blood, $PaCO_2$, > 45 mmHg) rather than hypoxia (Dicker et al., 1980). Hypercapnia may fatigue working muscles more quickly, as metabolite clearance cannot keep pace with CO_2 production (Babcock et al., 1996; Jonville et al., 2002). Additionally, limiting breath frequency necessitates larger inspirations (Dicker et al., 1980), which decrease lung compliance and reduce endurance capacity of the respiratory muscles (Tzelepis et al., 1988). It is possible that these stressors can prompt respiratory adaptations that bring about the superior lung function characteristic of swimmers.

Swim training produces notable improvements in pulmonary function with or without respiratory muscle training (RMT; Clanton et al., 1987), suggesting that the respiratory musculature is already well-tailored to exercise as a result of these sport-specific demands. However,

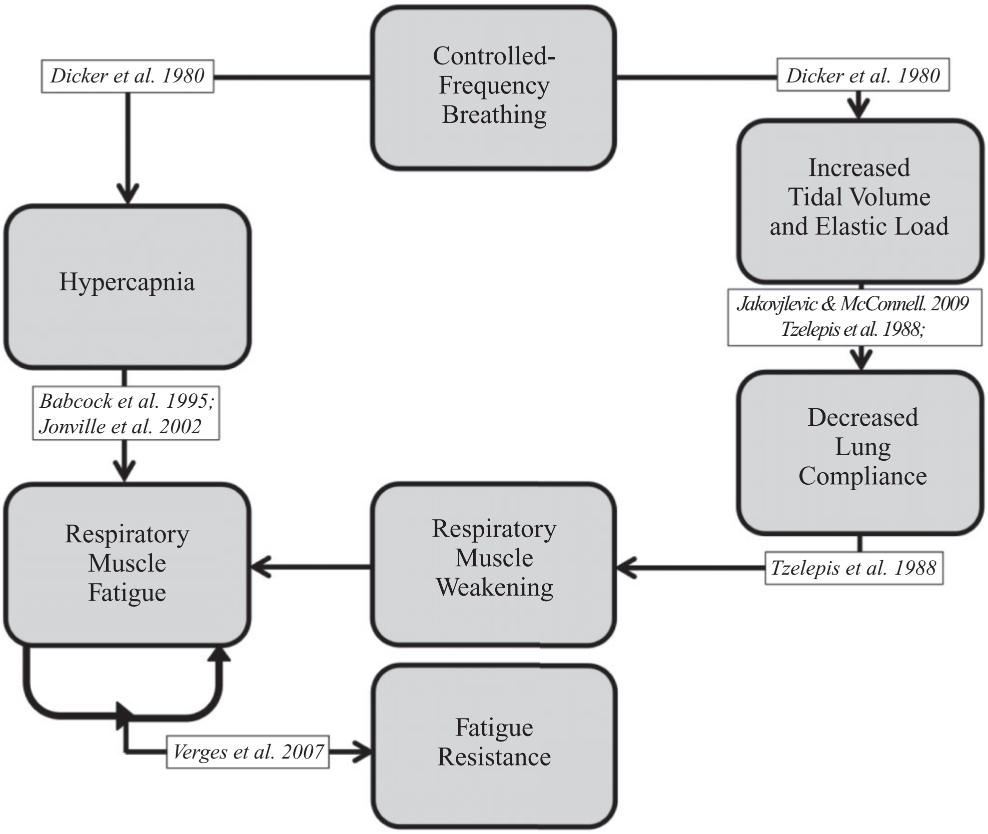

Fig. 1. Proposed mechanism of action of controlled-frequency breathing on pulmonary function. Longer breath-holds necessitate larger inspirations (Dicker et al., 1980), which stress the lungs by increasing elastic load (Tzelepis et al., 1988; Jakovjlevic & McConnell, 2009). Over time, compliance is decreased and fatigue soon develops. Meanwhile, the individual becomes hypercapnic (Dicker et al., 1980); the increased acidity of the blood can decrease fatigue resistance in respiratory muscles (Babcock et al., 1995; Jonville et al., 2002). The combination of these factors may lead to higher levels of respiratory muscle fatigue in controlled frequency breath swimming. It is thus postulated that resistance to such fatigue will be conferred over time (Verges et al., 2007).

high-intensity swimming does reduce maximal mouth pressures, providing indirect evidence that swimmers may experience respiratory muscle fatigue (Jakovljevic & McConnell, 2009); therefore, repeated exposure to fatigue may improve fatigue resistance via progressive overload (Verges et al., 2007).

In addition, it is possible that CFB might mimic the effects of RMT. This practice is often used by land-based athletes in order to prevent "energy stealing" and is shown to be effective in improving several pulmonary function parameters that might translate into enhanced exercise performance (Harms et al., 2000). Most notably, respiratory muscle strength (as reflected by maximum inspiratory and expiratory mouth pressures, MIP and MEP, respectively) and ventilatory capacity (measured by maximum voluntary ventilation, MVV) are improved with RMT (Kroff, 2008; Mickleborough et al., 2010; Hajghanbari et al., 2013). Land-based athletes, such as runners and team-sport athletes, also see consistent improvements in submaximal running efficiency and time to exhaustion, but these changes are not evident in swimmers (Mickleborough et al., 2008).

Founded on the utility of swimming in improving lung capacity, respiratory muscle endurance, and respiratory muscle strength, this study examined the effects of swim training using two different breathing patterns on several pulmonary function parameters. We compared the stroke-matched breathing style as used in a previous study by Jakovljevic and McConnell (2009) with the most extreme breath-limited style possible, controlled-frequency breath, in which swimmers attempt to complete an entire length of a 25-yard pool without breathing. We predicted that subjects trained in the controlled-breath style would experience improvement in respiratory function following training because of hypercapnic stress and mechanical loading (Fig. 1). We hypothesized that this change would manifest in improvements in respiratory muscle function as indicated by maximum mouth pressures and maximum voluntary ventilation. The effects of training on swimming performance, submaximal efficiency, and maximal oxygen uptake during terrestrial exercise were additionally assessed.

Materials and methods

Participant characteristics

All procedures herein were approved by the Marywood University Institutional Review Board and undertaken at Marywood

University. Twenty subjects were recruited for participation; inclusion criteria for this study were age between 18 and 45 years, regular engagement (at least 6 h/week) in physical activity other than swimming, and the ability to complete one length of a 25-yard swimming pool. Subjects were excluded from participation if they were competitive swimmers (unless a de-training period of 3–6 months had passed since competition) or had a history of any cardiovascular or respiratory diseases. Two subjects previously swam competitively, one at the high school level and one at a college level. All subjects provided written, informed consent and completed a Physical Activity Readiness Questionnaire prior to beginning exercise.

Testing procedures

Over a 1-week period, subjects completed a two-session orientation period, during which they were familiarized to all pool workouts and laboratory testing procedures. For the swimming orientation, a standardized warm-up of 200 yards at a self-selected pace was completed. Next, subjects completed 16 × 25-yard lengths and were given 45 s to complete each length. Completion of the 25-yard distance in the controlled-frequency breath style is manageable, and a total of 16 lengths were chosen to lengthen the workout regimen to best utilize aerobic metabolism. For the purposes of this orientation, the first eight were done in the controlled-frequency style and the last eight in the stroke-matched style. For the controlled-frequency breath condition, all subjects were given specific instructions to inspire almost maximally, to hold their breath for about two-thirds of the length, and to gently release the air through the nostrils to enable successful completion of the length with minimal breathing. For this familiarization session, additional rest time was permitted at the walls if required. Subjects then performed 100 yards at a self-selected "easy" intensity and were then familiarized to the performance measure, a 150-yard front crawl time trial (from the wall). Flip-turns were allowed, but not required, and subjects were permitted to rest between laps if necessary.

Orientation to the laboratory procedures involved measurement of anthropometric data (height, body mass, and age), pulmonary function assessment, and exercise testing. All pulmonary function tests were completed using a HypAir system (Medisoft, Dinant, Belguim), with subjects seated and wearing nose clips. General spirometry was performed according to standardized procedures (Miller et al., 2005). Diffusing capacity was measured using the modified Roughton–Forster technique, yielding diffusion capacity of the lung for both carbon monoxide (DLCO) and nitric oxide (DLNO) (Zavorsky et al., 2008). Maximum inspiratory and expiratory pressures of the mouth were measured from residual volume and total lung capacity, respectively, and the average of the three closest maneuvers (within 10% variance) was recorded. Maximum voluntary ventilation was measured by multiplying expired volume for 10 s by six, and the average value of the two out of three closest trials was then recorded. All pulmonary function parameters were then compared with normal values using established prediction equations developed in previous literature (Campbell, 1982; Hankinson et al., 1999; Zavorsky et al., 2008; Evans & Whitelaw, 2009).

All exercise testing was completed using a Viasys VMax^{TM} Encore metabolic cart (CareFusion, San Diego, CA). A standard treadmill was calibrated before the first subject of this study was tested, and all subjects were required to wear Polar heart rate monitors (Kempele, Finland) during all exercise testing procedures. Running economy (mL O_2/kg/km) was measured as the average oxygen consumption at three submaximal speeds, with each stage lasting 5 min, and with 5–10-min rests between stages to allow recalibration of the testing equipment. Metabolic data from the last 2 min of each stage were averaged to calculate oxygen consumption. Most men ran at 6.0, 7.0, and 8.0 mph and women at 5.5, 6.5., and 7.5 mph, although necessary exceptions were made for individuals less accustomed to treadmill running. The final stage of running economy progressed immediately into a graded exercise test, in which speed was increased 1.0 mph for the first stage and incline raised 2.5% for each subsequent stage (all stages lasting 2 min). This test ended at volitional exhaustion, and maximal oxygen consumption (VO_2max) was recorded.

Within the following week, all subjects reported to the Marywood University Aquatics Center to complete a 200-yard warm-up and the baseline performance measure, a 150-yard time trial. As in the orientation, subjects were permitted to perform flip-turns, but instructed that the number performed in this trial should equal that in the effort performed in the post-training measure. After a standardized cool-down, subjects drew lots to determine assignment to training groups for the duration of the study. For practical reasons, the researcher could not be blinded to condition. Given at least 12 h for recovery from this effort, subjects then reported to the Human Physiology Laboratory for a baseline assessment consisting of the same procedures described earlier for the orientation.

Training sessions were held, on average, three times per week for 4 weeks. Each session was structured to include a standardized 200-yard warm-up, followed by 16 × 25-yard lengths in the prescribed breathing style, with 45 s to complete each length. For consistency, subjects were instructed to maintain the 45-s interval in lieu of making the entire length without a breath. Subjects were also asked to keep track of total breaths for the entire set; a "breath" was counted when taken during the action of swimming, i.e., any breathing done on the walls between lengths or before pushing off was not counted. An investigator monitored each subject for at least one lap to ensure accuracy in breath counting. At the conclusion of practice, subjects reported this number to the researcher supervising the practice and performed a 100-yard easy cool-down. After 2 weeks (or six sessions) of training, the time interval was decreased to 40 s.

After the training period, subjects repeated the same procedures they did at baseline, including pulmonary function testing, running economy, VO_2max, and another timed 150-yard swim. Measurements were taken as described earlier.

Statistical analysis

All statistical tests were performed using the Statistical Package for the Social Sciences (SPSS) v.20 software (IBM, Inc., Chicago, IL). Independent *t*-tests were used to assess differences between groups prior to training and differences in the magnitude of change between groups post-training; differences pre- to post-training within groups were assessed using paired *t*-tests. A linear regression between initial VO_2max or 150-yard time and the magnitude of change in a variable of interest was used to assess whether changes observed were reflective of initial fitness or swimming skill level, respectively. Statistical significance was declared at an alpha of 0.05.

Indices of responsiveness for variables that changed in either or both groups following training were calculated according to previously established methods (Salbach et al., 2001; Kim et al., 2009). Standard response mean (calculated as the average of the change divided by the standard deviation of the change) and effect size, a measure of the strength of the change in a given parameter, enable assessment of which variables are most responsive to the experimental stimulus.

For variables that did not demonstrate a change after training, pre-training and post-training values were used to calculate indices of reproducibility. For variables that did change, orientation and pre-training measurements were used. Measurement error (the square root of the within-subjects error generated by SPSS repeated measures analysis of variance) and reproducibility were calculated (Bland & Altman, 1996; Murias & Zavorsky, 2007). Day-to-day variation (the average of all measured values divided by the standard deviation of the change) and smallest meaningful change (reproducibility divided by 2) were also calculated (Hopkins, 2000).

Results

Of the 20 participants recruited, 18 were retained to completion of the study. Randomization placed five men and five women in each group, but the CFB group ended with only eight participants (four men). At the outset of the study, no differences in baseline characteristics and exercise performance existed between groups (see Table 1). Baseline pulmonary function testing showed only a significantly higher absolute and percent of predicted fraction of forced vital capacity exhaled in 1 s [forced vital capacity (FEV$_1$)/forced vital capacity (FVC)] in the stroke-matched group (Table 2).

Participants in both groups completed an average (standard deviation) of 11 (1) practice sessions. During training, the stroke-matched group took 7 (2) breaths per lap, whereas the CFB group took 2 (2). Participants breathed once every 4 (1) strokes in the stroke-matched group and once every 12 (4) strokes in CFB (Fig. 2).

Both groups demonstrated an improvement in completion of the 150-yard time trial ($P < 0.05$), with an overall decrease in time of 10 s (15) (95% confidence interval −18 to −3). The CFB group improved by approximately 13 s (9), or 8% (5) ($P < 0.05$), whereas the stroke-matched group improved by 8 s (19), or 4 (11)% ($P = 0.26$); despite this finding, the difference in magnitude of change between groups did not attain statistical significance ($P = 0.46$). Maximum inspiratory pressure and voluntary ventilation were unaffected by training. When data were pooled, an overall effect of training on maximal expiratory pressure was evident [10 (16) cmH$_2$O, $P < 0.05$]. Because of large standard deviations, neither group demonstrated a change in maximal expiratory pressure alone (Table 4).

Efficiency, or running economy, improved overall following training ($P < 0.05$). However, the effects of training were more pronounced in the CFB group, where a change of −15 mL/kg/km was evident, relative to −8 mL/kg/km in the stroke-matched group (Table 4). Seven of eight subjects in the CFB group exhibited an improvement in running economy, relative to six in the stroke-matched group (Fig. 3). VO$_2$max did not change as a result of training in either group, and no other changes in submaximal exercise variables (e.g., heart rate, respiratory exchange ratio, or rating of perceived exertion) were found.

Following training, a significant improvement in FVC and subsequent decrease in FEV$_1$/FVC were apparent in the stroke-matched group ($P < 0.05$). No other changes in pulmonary function were observed (Table 3), apart from an apparent decrease in alveolar volume (V$_A$, $P < 0.05$); however, this change did not exceed the smallest meaningful change for V$_A$ (Table 5), suggesting this change was not likely physiologically important.

Linear regressions revealed a negative relationship between initial VO$_2$max and improvement in maximum voluntary ventilation when groups were combined [$r^2 = 0.24$, standard error of the estimate (SEE) = 13.3 L/min, $P < 0.05$]. This suggests that less fit participants experienced greater gains in MVV following training. Within groups, there was a stronger relationship between stroke-matched ($r^2 = 0.21$, SEE = 12.8 L/min, $P = 0.06$) than in CFB ($r^2 = 0.03$, SEE = 15.5 L/min, $P = 0.15$). Improvements in maximum expiratory pressure appeared to be related to swimming performance, such that MEP improved in faster swimmers to a greater extent

Table 1. Baseline data for parameters not related to pulmonary function testing

	Controlled-frequency breath (*n* = 8)	Stroke matched (*n* = 10)	Total (*n* = 18)	*P*-value
Age (year)	26 (5) 21–36	24 (10) 19–41	25 (6) 19–41	0.46
Height (cm)	169 (10) 160–186	170 (9) 155–185	170 (9) 155–186	0.91
Weight (kg)	75.5 (15.1) 58.2–94.5	66.8 (12.6) 47.7–90.0	70.6 (14.0) 47.7–94.5	0.20
Body mass index (kg/m^2)	26.1 (3.2) 21.9–30.9	23.1 (3.6) 17.7–29.6	24.4 (3.7) 17.7–30.9	0.08
150-yard swim (s)	156.6 (26.7) 109.1–200.5	174.3 (40.5) 131.0–263.9	166.4 (35.3) 109.1–263.9	0.30
Running economy (mL O$_2$/kg/km)	240.1 (26.6) 212.0–292.5	238.4 (24.6)* 192.8–272.7	239.3 (27.8) 192.8–292.5	0.89
VO$_2$max (mL/kg/min)	48.9 (8.5) 36.3–61.8	49.1 (10.7) 29.0–61.9	49.0 (9.5) 29.0–61.9	0.96
VO$_2$max (L/min)	3.62 (0.59) 2.71–4.46	3.20 (0.65) 2.08–4.08	3.39 (0.64) 2.08–4.46	0.18

All values are reported as mean (standard deviation) and range. Running economy reported in mL/kg/km to account for differences in running speeds between participants.

*For running economy in the stroke-matched group, *n* = 9, as one participant was unable to complete the full 15 min protocol. VO$_2$max, maximal oxygen consumption.

Table 2. Baseline pulmonary function assessment

	Controlled-frequency breath, $n = 8$		Stroke-matched, $n = 10$	
	Observed	% Predicted	Observed	% Predicted
FVC (L)	4.83 (1.22) 3.78–6.94	106 (16) 84–134	4.96 (1.14) 3.57–6.40	107 (9) 93–119
FEV_1 (L)	3.82 (1.01) 2.95–5.71	99 (16) 77–126	4.18 (0.92) 3.00–5.70	107 (12) 91–126
FEV_1/FVC (%)	79 (2)* 76–82	94 (3)* 90–99	84 (6) 75–92	100 (8) 90–113
PEF (L/s)	8.64 (2.30) 5.50–11.58	101 (11) 82–114	8.64 (2.36) 5.59–13.12	101 (12) 82–122
$FEF_{25–75}$ (L/s)	4.29 (1.10) 3.16–6.31	105 (16) 80–125	5.25 (1.39) 3.11–7.88	125 (27) 83–179
DLNO (mL/min/mmHg)	156 (37) 119–221	96 (15) 70–115	169 (36) 122–222	102 (13) 82–117
$DLNO/V_A$ (mL/min/mmHg/L)	26.0 (2.2) 22.6–29.1	–	25.1 (2.7) 20.7–30.0	–
DLNO/BSA (mL/min/mmHg/m^2)	82.4 (12.3) 62.3–100	–	95.1 (14.5) 71.2–120.9	–
DLCO (mL/min/mmHg)	32.1 (7.3) 24.8–44.1	101 (15) 78–121	34.1 (8.4) 23.4–48.1	105 (18) 82–130
$DLCO/V_A$ (mL/min/mmHg/L)	5.4 (0.6) 4.4–6.1	–	5.1 (0.8) 4.1–6.5	–
DLCO/BSA (mL/min/mmHg/m^2)	16.9 (2.4) 12.8–20.0	–	19.2 (3.8) 13.0–26.2	–
V_A (L)	6.00 (1.38) 4.72	107 (14) 87–121	6.78 (1.60) 4.97–9.11	119 (13) 97–139
IV (L)	4.67 (1.18) 3.32–6.64	–	5.14 (1.27) 3.69–7.03	–
MIP (cmH_2O)	105 (30) 69–153	101 (29) 60–136	99 (30) 60–156	94 (29) 63–163
MEP (cmH_2O)	117 (55) 64–232	88 (32) 57–152	109 (32) 60–147	82 (21) 52–120
MVV (L/min)	155 (49) 79–239	100 (16) 67–117	149 (42) 101–240	89 (14) 66–112

*Denotes significant difference ($P < 0.05$) between groups. BSA, body surface area; DLCO, diffusion capacity of the lung for carbon monoxide; DLNO, diffusion capacity of the lung for nitric oxide; $FEF_{25–75}$, forced expiratory volume over the middle half of expiration; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; IV, inspired volume; MEP, maximum expiratory mouth pressure; MIP, maximum inspiratory mouth pressure; MVV, maximum voluntary ventilation; PEF, peak expiratory flow; VA, alveolar volume.

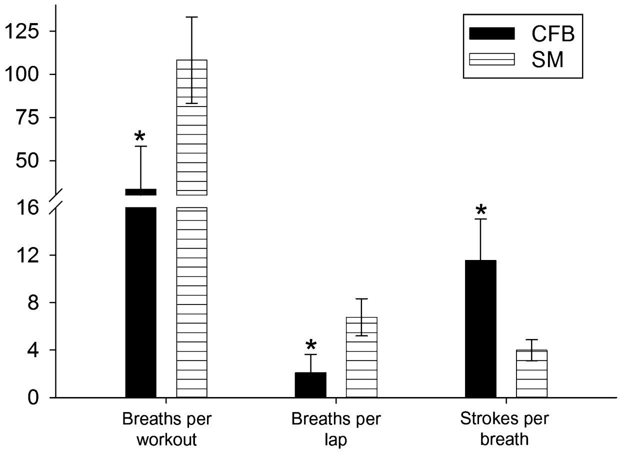

Fig. 2. Training parameters. Significant differences were observed between stroke-matched (SM) and controlled-frequency breath (CFB) groups with respect to number of breaths per 25-yard length and per workout. Strokes per breath also differed significantly ($P < 0.05$) between groups such that controlled frequency breath subjects had a higher stroke/breath value. Thus, the CFB used significantly longer breathholds per lap compared with the SM group.

($r^2 = 0.16$, SEE = 15.0 cmH_2O, $P = 0.05$). No other relationships were observed with regard to any other cardiopulmonary variables. The reproducibility and measurement error for all variables appear in Table 5.

Discussion

This study was the first of its kind to examine the effects of limiting breath frequency on indices of pulmonary function and terrestrial exercise. Our findings suggest that limiting breath frequency during swimming may lead to improvements in swimming performance and movement economy on land, whereas traditional stroke-matched breathing does not confer these advantages. Neither breathing style affected maximum voluntary ventilation or maximum inspiratory pressure. Data pooled from both groups suggest an overall effect of training on maximum expiratory pressure; it is known that the expiratory muscles play a larger role in ventilation during exercise than at rest (Dempsey et al., 1990). Additionally, during swimming, the breath is exhaled during the recovery phase of the stroke, while

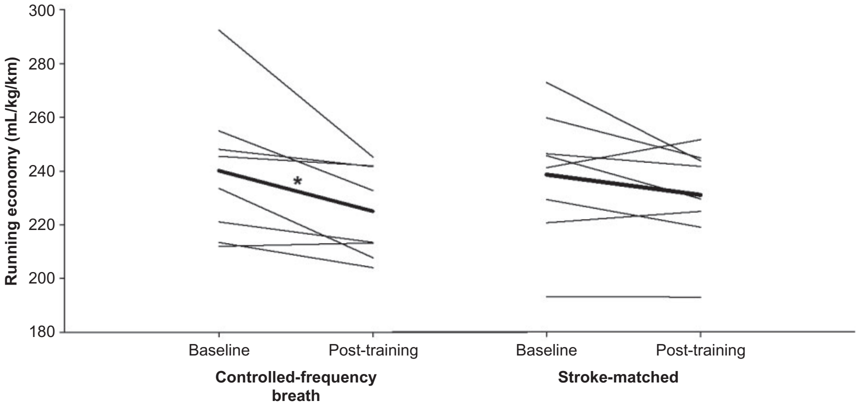

Fig. 3. Improvements in running economy (mL O_2/kg/km) with training. Thick line represents group mean ($n = 8$ for both groups). Asterisk (*) indicates significant improvement in controlled-frequency breath group (−15 mL O_2/kg/km) at $P < 0.05$, where seven of eight subjects exhibited a decrease in submaximal oxygen consumption.

Table 3. Post-training and magnitude of change from baseline in measured variables in all subjects

	Post-training	Mean Δ (SD) [95% CI]	*P*-value vs. pre
Body mass (kg)	70.1 (13.8) 46.9–93.6	−0.5 (1.3) [−1.2, 0.1]	0.09
BMI (kg/m^2)	24.2 (3.6) 17.4–30.5	−0.2 (0.4) [−0.4, 0.0]	0.09
VO_2max (mL/kg/min)	49.2 (8.8) 31.8–64.2	0.2 (2.5) [−1.1, 1.6]	0.74
FEV_1 (L)	4.00 (0.95) 2.71–5.92	−0.01 (0.18) [−0.10, 0.08]	0.82
FEV_1/FVC	80.2 (5.5) 70.6–90.4	−1.88 (3.86) [−3.80, 0.04]	0.06
PEF (L/s)	8.90 (2.68) 5.42–13.49	0.26 (0.66) [−0.07, 0.58]	0.12
$FEF_{25–75}$ (L/s)	4.87 (1.38) 3.02–7.67	0.05 (0.38) [−0.14, 0.24]	0.61
DLNO (mL/min/mmHg)	162 (34) 109–218	−1 (9) [−5, 4]	0.73
DLCO (mL/min/mmHg)	32.3 (7.3) 24.6–45.0	−0.8 (2.3) [−2.0, 0.3]	0.14
IV (L)	4.90 (1.14) 3.17–6.69	−0.04 (0.31) [−1.69, 0.11]	0.58
MIP (cmH_2O)	107 (34) 53–160	5 (14) [−2, 12]	0.13
MVV (L/min)	155 (49) 91–254	4 (14) [−3, 11]	0.27

Overall changes in variables that did not change significantly with training. Data were pooled from both groups, $n = 18$. BMI, body mass index; CI, confidence interval; DLCO, diffusion capacity of the lung for carbon monoxide; DLNO, diffusion capacity of the lung for nitric oxide; $FEF_{25–75}$, forced expiratory flow rate over the middle half of expiration; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; IV, inspired volume; MIP, maximum inspiratory mouth pressure; MVV, maximum voluntary ventilation; PEF, peak expiratory flow; SD, standard deviation; VO_2max, maximal oxygen consumption.

Table 4. Indices of responsiveness for selected variables between training groups

	Mean Δ (SD) [95% CI]	Effect size	SRM	*t*-statistic	*P*-value
Controlled frequency breath ($n = 8$)					
150-yard swim (s)*	−13.2 (8.5) [−20.4, −6.1]	−0.50	−1.55	−4.398	< 0.01
Running economy (mL O_2/kg/km)*	−15.1 (15.9) [−28.4, −1.8]	−0.57	−0.95	−2.693	< 0.05
FVC (L)	−0.02 (0.23) [−0.21, 0.17]	−0.02	−0.08	−0.277	0.83
V_A (L)	−0.07 (0.15) [−0.20, 0.06]	−0.05	−0.46	−1.288	0.24
MEP (cmH_2O)	14 (21) [−4, 31]	0.25	0.66	1.854	0.11
Stroke matched ($n = 10$)					
150-yard swim (s)	−7.7 (19.2) [−21.5, 6.0]	−0.19	−0.40	−1.274	0.24
Running economy (mL O_2/kg/km)	−7.59 (12.7) [−18.2, 3.0]	−0.31	−0.65	−1.690	0.14
FVC (L)*	0.20 (0.18) [0.07, 0.32]	0.17	1.10	3.465	< 0.01
V_A (L)	−0.20 (0.35) [−0.46, 0.05]	−0.13	−0.57	−1.800	0.11
MEP (cmH_2O)	7 (12) [−2, 15]	0.20	0.56	1.759	0.11

*Denotes significant difference ($P < 0.05$) between baseline and post-training values within the training group. CI, confidence interval; FVC, forced vital capacity; MEP, maximum expiratory mouth pressure; SD, standard deviation; SRM, standardized response mean; V_A, alveolar volume.

the face is submerged, and therefore must be consciously controlled. This may explain the observed increase in pressure generation by the expiratory muscles. Furthermore, the prone body position may induce changes in blood perfusion, capillary recruitment, and ventilatory function that also influence pulmonary function (Mostyn et al., 1963; Mure et al., 2000; Rohdin et al., 2003).

Table 5. Reproducibility in measured pulmonary function variables

	Day-to-day variation (%)	Measurement error	Reproducibility	SMC
FVC (L)	4	0.17	0.47	0.24
FEV_1 (L)	3	0.13	0.35	0.18
PEF (L/s)	5	0.47	1.29	0.65
$FEF_{25–75}$ (L/s)	6	0.27	0.74	0.37
DLNO (mL/min/mmHg)	4	7	19	9
DLCO (mL/min/mmHg)	5	1.6	4.5	2.2
V_A (L)	4	0.23	0.63	0.31
MIP (cmH_2O)	10	10	28	14
MEP (cmH_2O)	18	18	49	24
MVV (L/min)	7	10	28	14

Data were pooled from both groups, $n = 18$. Neither group attained the value for smallest meaningful change with respect to any of these measures following training. As such, we conclude that pulmonary function remained unaltered by controlled-frequency breathing and stroke-matched swim training. DLCO, diffusion capacity of the lung for both carbon monoxide; DLNO, diffusion capacity of the lung for nitric oxide; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; MEP, maximum expiratory mouth pressure; MEP, maximum expiratory mouth pressure; MIP, maximum inspiratory mouth pressure; MVV, maximum voluntary ventilation; PEF, peak expiratory flow; SD, standard deviation; SMC, smallest meaningful change.

Running economy

The improvement in running economy is noteworthy, as this agrees with findings from previous studies using RMT (Mickleborough et al., 2010). Because no changes in ventilatory function were evident, it is possible that the controlled breath training elicited a change at the muscular level, allowing the locomotor muscles to perform the same amount of work using less oxygen. This supports the findings in previous literature that CFB swimming improves oxygen extraction (Dicker et al., 1980). That VO_2max did not change in this group also agrees with previous findings and supports the conclusion that oxygen utilization is better accomplished following CFB training.

The findings of the present study may have important sport performance implications. For example, running economy has been linked to success in distance running, such that faster runners are more economical (Morgan et al., 1995; Lavin et al., 2012) and better metabolic efficiency preserves glycogen and delays the onset of fatigue (Rapoport, 2010). If a 70-kg male athlete experienced the improvements observed herein, he would save approximately 220 kcal in completion of a marathon footrace, assuming that 5 kcal are burned per liter oxygen consumed (Margaria et al., 1963), which might have meaningful ramifications for performance. Although the average running economy from this sample pool was higher than that of the average population (Foster & Lucia, 2007), reductions in submaximal oxygen consumption were observed in seven out of eight subjects (Fig. 3), and secondary analyses revealed that the most and least economical halves of the group did not differ with respect to the magnitude of improvement in economy ($p = 0.46$). Therefore, it is possible for athletes from a diversity of skill levels to benefit from CFB swimming. However, it should be noted that the effects of this technique may be more pronounced in athletes with less swimming experience; i.e., trained triathletes may not see the same results as our novice swimmers did.

FVC

The increase in FVC evident in the stroke-matched was unexpected, as 12 practice sessions lasting collectively 6 h is not likely to produce notable changes in lung size. Nevertheless, this finding was significant; the modest increase is proportional to the training volume. Although we had initially postulated that the CFB group would inspire larger volumes, this breathing pattern might negatively impact lung capacity gains usually garnered through swim training. Conversely, the pattern of breathing used in the stroke-matched group might facilitate lung capacity increases by favoring compliance; controlling breath frequency might have imposed higher elastic loads that discouraged increases in lung capacity (Tzelepis et al., 1988). Thus, the effects of swimming on lung capacity may have been blunted in the CFB group. This finding concurs with the fact that a stronger relationship between MVV and initial VO_2max existed in the stroke-matched group.

Sources of error

Because our findings did not indicate substantial alterations in pulmonary function in either group, it might be argued that the workloads required by the training workouts were not intense enough; subjects performed 700 yards per practice for a total of 8400 yards over the 4-week period. While this is negligible compared with distances covered by competitive swimmers in 1 week alone, the subjects in this study were generally novices (see Table 1 for 150-yard swim times), and we believed that this training program would provide a sufficient stimulus to induce adaptations. Participants' inability to maintain a consistent stroke rate and (in the CFB group) breathing frequency suggests that the protocol was of the appropriate level of difficulty. Additionally, research by Mujika et al. (1996) suggests that swimming performance is dictated more by training intensity than by volume. Furthermore, decreasing the time interval for the last 2 weeks prompted an increase in breathing frequency in both groups, suggesting that this was a reasonable yet difficult alteration of training stimulus.

Potential sources of error in this experiment arise from broad differences in swimming skill level of the participants. It has been suggested that cellular buffering systems of former competitive swimmers, even after de-training for over 2 years, may still operate more efficiently, conferring an advantage in maintenance or achievement of higher workloads (Kapus et al., 2008). Whereas previous studies using novice swimmers allowed a training period for development of proper technique before beginning actual swim training (Gupta & Sawane, 2012), this was not deemed proper for the time frame of this study, and we sought to minimize the effects of swim training by using land-based athletes alone.

Future directions

Future research may choose to utilize a more time-intensive swimming regimen, either by increasing the frequency of practices or the duration of the study. A stronger training stimulus could also be achieved by assigning an individualized time interval for the workout based on skill level of each participant, allowing stratified levels of difficulty. For example, each subject could be afforded 10–15-s rest between lengths rather than following a standardized time interval, as was used in this pilot study. Respiratory muscle fatigue after completion of the workout could also be assessed, and respiratory gases could be collected to assess the severity of hypercapnia.

Perspectives

The results of this study suggest that limiting breathing frequency during swimming may improve economy during submaximal terrestrial exercise. No evidence was found to support that respiratory muscle function improved, which may be due in part to a less than rigorous training regimen. Despite this, CFB swimming may be an alternative to RMT that provides whole-body exercise in addition to improvements in running economy. It remains likely that trends toward higher MIP and MVV (as were observed in this study) might attain statistical and physiological significance with a more intense training regimen. This study supports the use of CFB swimming as a potentially useful low-impact cross-training activity for land-based athletes that might affect respiratory muscle function at higher intensities.

Key words: swimming, respiratory muscle training, respiratory muscle fatigue, exercise training, MIP, MEP, diffusing capacity, submaximal oxygen consumption.

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