

The Mechanics of Breathing during Swimming

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ABSTRACT

LEAHY, M. G., M. N. SUMMERS, C. M. PETERS, Y. MOLGAT-SEON, C. M. GEARY, and A. W. SHEEL. The Mechanics of Breathing during Swimming. *Med. Sci. Sports Exerc.*, Vol. 51, No. 7, pp. 1467–1476, 2019. The thorax undergoes unique conditions while swimming. Hydrostatic pressure from water immersion places an external load on the thorax and increases airway resistance, and the horizontal body position results in central venous engorgement and an associated reduction in lung compliance. The aforementioned factors likely increase the work of breathing (W_b); however, this hypothesis remains untested. **Purpose:** This study aimed to compare W_b during freestyle swimming relative to cycling and to characterize the differences in the cardiorespiratory responses to swimming relative to cycling in the same individuals. **Methods:** Eight collegiate swimmers (four men and four women, age = 22 ± 2 yr) performed an incremental swim test while tethered to a resistance apparatus. On a separate day, subjects performed an incremental cycle test. During swimming and cycling, metabolic and ventilatory parameters were measured using a customized metabolic cart, and inspired W_b was quantified using an esophageal balloon catheter. **Results:** Swimming and cycling elicited statistically similar levels of peak oxygen uptake (3.87 ± 0.92 vs 4.20 ± 0.83 L·min⁻¹, $P = 0.143$). However, peak minute ventilation (\dot{V}_E) (118 ± 3 vs 154 ± 25 L·min⁻¹) and heart rate (164 ± 19 vs 183 ± 8 bpm) were significantly lower during swimming relative to cycling (both $P < 0.05$). Inspired W_b was higher at a \dot{V}_E of 50 L·min⁻¹ ($+27 \pm 16$ J·min⁻¹), 75 L·min⁻¹ ($+56 \pm 23$ J·min⁻¹), and 100 L·min⁻¹ ($+53 \pm 22$ J·min⁻¹) during swimming compared with cycling (all $P < 0.05$). Periods of interbreath apnea were observed while swimming (duration = 0.13–2.07 s). **Conclusion:** We interpret our findings to mean that the horizontal body position and hydrostatic pressure on the chest wall requires swimmers to generate greater inspiratory pressures to sustain adequate \dot{V}_E during exercise. **Key Words:** INTERBREATH APNEA, PULMONARY FUNCTION, SWIMMING, WORK OF BREATHING

The respiratory system does not typically exhibit adaptations to endurance training; however, cross-sectional studies consistently show that highly trained swimmers have larger lungs than their terrestrial counterparts (1–3). Whether the larger lungs in highly trained swimmers is the result of a selection bias or adaptations to chronic swim training is unknown. There is some evidence to suggest that the greater lung volumes in swimmers can be explained, in part, by enhanced inspiratory muscle strength, which has been adapted from exercising while immersed in water (2,4).

Swimming requires entrained breathing patterns, optimized for buoyancy and stroke efficiency (5). During swimming, respiration is synchronized with the rhythm of movement and requires a forced inspiratory phase within the biomechanical constraint of the stroke cycle (6). Entrained breathing can have a substantial effect on breathing frequency (f_b)

and tidal volume (V_T), which can lead to variable degrees of hypoxemia and hypercapnia (7–10). Relative to terrestrial exercise such as cycling, a higher V_T observed during swimming is likely attributed to a combination of entrained breathing, hydrostatic pressure on the thorax, and exercising in a prone or supine body position (10,11). Therefore, ventilatory mechanics are altered during swimming owing to the mechanics of limb movement for propulsion and intermittent face immersion.

In addition to the effect on breathing patterns, the horizontal body position and hydrostatic pressures while swimming increases flow resistance. For example, increased thoracic blood flow while swimming in a prone or supine position engorges pulmonary arterial circulation causing smaller airways (>2 mm) to constrict and lung compliance to decrease (12,13). Moreover, the body position while swimming causes the diaphragm to shift upward, thereby truncating vital capacity and increasing residual volume (14). As such, the altered hemodynamic properties of the thorax may also alter pulmonary mechanics during swimming.

During immersion in a supine position, intrathoracic pressure increases relative to depth (typically by ~6–7 cm H₂O), which increases the elastic forces on lung tissue (15,16). Previous studies observing work of breathing (W_b) while submerged in an upright position at rest showed greater elastic work and dynamic work due to increased flow

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resistance from reduced lung volumes (16). A higher W_b during exercise increases the mechanical and metabolic demand placed on the respiratory muscles (17–19).

It is established that the aquatic environment imposes significant challenges to a swimmer's ability to maintain adequate alveolar ventilation such as frequent breath holds, immersion of the thorax, and a prone body position. Additional challenges include, but are not limited to, other factors such as increased buoyancy with increased lung volume and the effect of stroke efficiency on metabolic work. Given these challenges, it can be hypothesized that W_b would be greater during swimming compared with terrestrial exercise, thereby increasing mechanical stress on the tissues and metabolic demand for working respiratory muscles. Although previous studies have explored the effects of water immersion on W_b at rest (15,16), no study to date has investigated W_b during freestyle swimming. Moreover, the dynamic operating lung volumes during swimming have yet to be characterized. Accordingly, the purpose of this study was to assess W_b and operating lung volumes during freestyle swimming compared with terrestrial exercise in the same individuals. Given the increased respiratory muscle strength of swimmers (1), the hydrostatic pressures applied to the chest wall during immersion, and the horizontal body position associated with swimming, we hypothesized that the W_b while freestyle swimming would be greater compared with cycling, at all ventilations. We further hypothesized that freestyle swimming would result in increased expiratory reserve volume (ERV) and decrease inspiratory reserve volume (IRV) relative to cycling.

METHODS

Subjects. Eight collegiate swimmers (four men and four women) participated in this study. Subjects were healthy nonsmokers and did not have a history of cardiopulmonary disease, apart from asthma. Airway hyperresponsiveness and dysfunction is prevalent in high-performance swimmers; however, only one subject in our study reported having been diagnosed with asthma (3). The subject presented with normal spirometry and used bronchodilators as prescribed by their physician. Exercise testing was not controlled during the follicular phase of the menstrual cycle. Previously, our laboratory demonstrated significant inter- and intrasubject variability with respect to hormone levels throughout the menstrual cycle; therefore, we tested the women at random points throughout their menstrual cycle and oral contraceptives were not an exclusion criterion (20). All subjects were swimmers who competed at the collegiate and/or national level, swam for a minimum of 5 yr before testing, and currently trained a minimum of five 2-h sessions per week. Subjects provided written informed consent before participating, and all procedures were approved by the University of British Columbia Review Ethics Board (H16–02701).

Experimental overview. Subjects performed swimming and cycling exercise tests over two separate days in no specified order. On day 1, anthropometric and descriptive data were obtained, followed by pulmonary function testing and an incremental swim test at the University of British Columbia Aquatic Centre. On day 2, subjects performed pulmonary function testing and incremental cycle test in the Health and Integrative Physiology Lab. Time between day 1 and day 2 ranged from 7 to 21 d.

Pulmonary function. Forced vital capacity (FVC), forced expired volume in 1 s (FEV_{1s}), and FEV_{1s}/FVC were measured using a commercially available portable spirometer (SpiroLab 3; MIR, Rome, Italy) in accordance with standardized procedures and expressed in absolute terms and as a percentage of predicted normal values (21,22).

Maximal exercise testing. On day 1, subjects performed a maximal incremental freestyle swim test while tethered to a resistance apparatus. The resistance apparatus consisted of a barrel and pulley system, connected to a waistband. Once fitted with a waist band, swimmers were instructed to maintain their position while swimming, approximately 4 m from the pulley apparatus secured on the pool deck. The resistance placed on the swimmer could be manipulated by filling barrels with set volumes of water. At the beginning of the incremental swim test, barrels were filled with 30 and 50 kg of water for women and men, respectively, and increased in 10-kg increments every 2 min until volitional exhaustion. On day 2, subjects performed an incremental exercise test on a cycle ergometer (Velotron; RacerMate, Seattle, WA). The initial workload was 75 and 125 W for women and men, respectively, and the workload increased by 25 W every 2 min until volitional exhaustion. Before the incremental swim test, subjects were not instructed on how to breathe and were not informed of previous subjects breathing patterns. During both exercise tests, subjects breathed through a two-way non-rebreathing valve (Series 2700; Hans Rudolph, Kansas City, MO) connected to a mouthpiece. The valve was secured to a fixed apparatus and attached to a 1.1-kg weight to maintain its position under water and to ensure the comfort of the subject. Ventilatory and metabolic parameters were assessed using the same customized metabolic cart for both testing sessions, consisting of calibrated inspired and expired pneumotachographs (3813 Series; Hans Rudolph, Shawnee, KS) as well as oxygen and carbon dioxide analyzers (ML 206; ADInstruments, Dunedin, New Zealand).

Flow, volume, and pressure. During both swimming and cycling, inspired and expired flows were measured using separate heated and calibrated pneumotachographs, in which subjects breathed freely through a two-way Y-shaped non-rebreathing valve (2730 Large; Hans Rudolph, Shawnee, KS). Before and after each exercise test, subjects completed a series of FVC maneuvers at different efforts to construct a maximal expired flow–volume curve for each subject, as previously described (23). On day 1, maneuvers were performed in a prone floating position, and in a cycle position on day 2. Volume was calculated by integrating expired and inspired

flow signals. Inspired duty cycle is defined as the relative inspiratory portion of the breathing cycling. Under the circumstances that subjects held their breath during the incremental swim test, periods of apnea were not included in the determination of the breathing cycle. Esophageal pressure (P_{eso}) was measured using balloon tipped catheter (no. 47-9005; Cooper Surgical, Trumbull, CT) connected to a calibrated pressure transducer (MP45; Validyne, Northridge, CA) (19). The placement of the catheter was performed according to standard procedures, and the validity of P_{eso} was confirmed based on the occlusion test (24,25). Tidal flow–volume and pressure–volume loops were generated by composite averaging data from 5 to 10 breaths during the rest period and within the last 30 s of each exercise stage.

Operating lung volumes. Measurements of ERV and IRV were estimated based on condition-specific measures of FVC (i.e., swimming or cycling). At rest and during each stage of exercise, subjects performed inspiratory capacity (IC) maneuvers, as previously described (26). Before exercise on both days, subjects were thoroughly familiarized with performing IC maneuvers. While cycling, subjects were told to “completely fill up their lungs at the end of a normal breath out.” While swimming, subjects were given identical instructions, but they were prompted to perform an IC maneuver using a red marker placed in their field of vision. IC maneuvers were completed at rest and within the last 10 s of every exercise stage. An additional IC maneuver was performed immediately before test termination. IRV was estimated FVC – (ERV + V_T).

Work of breathing. W_b was assessed at rest and during exercise, on both experimental days. At rest in the water, measures were taken while subjects were submerged in two positions: upright and prone. In the upright position, subjects were submerged up to their clavicles, arms crossed and resting on the pool deck. The prone position was used to simulate the freestyle body position. Subjects were asked to float in a prone position with a floatation device between their legs and arms stretched out overhead holding the edge of the pool deck. Resting W_b on day 2 was collected in a cycling position on the bike. Each resting position was held for a minimum of 2 min. Exercise W_b was derived from the area of the esophageal pressure–volume loops corresponding to each stage of exercise. Total W_b measured at rest was then partitioned into three components: inspiratory resistive, inspiratory elastic, and expiratory work (27). The estimation of inspiratory elastic work was calculated by the triangulation of the area of the esophageal pressure–volume curve between the start of inspiration and the end of inspiration. The estimation of inspiratory resistive work was calculated via the subsequent area outside the triangulated elastic work. The estimation of expired work was calculated by measuring the area of the expiratory portion of the esophageal pressure–volume curve outside the area of inspiratory elastic work (28).

Because of observable interbreath apnea, which will later be discussed, investigators could not justify quantifying and comparing expired W_b and, thereby, quantifying total W_b . Total inspired W_b was calculated during exercise and was determined as the sum of inspiratory resistive and inspiratory elastic work. Dynamic compliance was measured as the slope of the line between the pressure–volume points at end expiration and end inspiration. Therefore, values were determined via the differences in volume per difference in end-inspiratory P_{eso} and end-expiratory P_{eso} .

Data processing and statistical analysis. All data were sampled at 200 Hz using a 16-channel data acquisition system (PowerLab/16SP model ML 795; ADInstruments, Colorado Springs, CO) and stored for subsequent analysis. Cardiorespiratory parameters and W_b were compared between modes of exercise using paired *t*-tests at three discrete levels of minute ventilation (\dot{V}_E): 50, 75, and 100 L·min⁻¹. The alpha level was set to 0.05, and data are presented as mean ± SD, unless otherwise noted.

RESULTS

Physical characteristics. Table 1 summarizes participant characteristics and pulmonary function data. Pulmonary function was equal to, or greater than, predicted values (22). All but one subject exceeded predicted FVC, averaging 118% ± 16% of predicted. Lung function values were reduced in a swimming position compared with cycling in FVC (5.36 ± 1.17 vs 5.72 ± 1.51 L), FEV₁ (4.21 ± 1.02 vs 4.71 ± 1.22 L), or FEV₁/FVC (0.81 ± 0.06 vs 0.85 ± 0.08 L) (all $P > 0.05$).

Exercise data. Peak exercise data while swimming and cycling are presented in Table 1. On average, the peak oxygen consumption ($\dot{V}O_2$) achieved while swimming was 10% ± 10% lower compared with cycling ($P > 0.05$). A significantly lower peak \dot{V}_E and heart rate were observed while swimming relative to cycling (both $P < 0.05$). As well as peak exercise, inspired duty cycle was greater throughout all ventilations while swimming than while cycling (all $P < 0.05$; Fig. 1). No significant differences in f_b or V_T were noted at peak exercise ($P > 0.05$). Peak inspired flow was significantly lower at peak exercise in swimming compared with cycling. No difference in peak expired flow at peak exercise was observed between exercise modes.

During submaximal exercise, all subjects were able to achieve three levels of \dot{V}_E under both conditions: 50, 75, and 100 L·min⁻¹ (Table 2). At a $\dot{V}_E = 50$ L·min⁻¹, $\dot{V}O_2$ was significantly greater while swimming compared with cycling ($P < 0.05$); however, no significant differences were found at 75 and 100 L·min⁻¹. A significantly reduced f_b was observed at a \dot{V}_E of 50 L·min⁻¹ while swimming; however, no significant differences were found at 75 and 100 L·min⁻¹. Inspired time while swimming was lower at a \dot{V}_E of 50 L·min⁻¹ (0.92 ± 0.32 vs 1.38 ± 0.26 s), 75 L·min⁻¹ (0.79 ± 0.27 vs 1.27 ± 0.30 s), and 100 L·min⁻¹ (0.63 ± 0.22 vs 0.92 ± 0.14 s) (all $P < 0.05$). No significant differences in expired

TABLE 1. Anthropometric and pulmonary function data.

	Total (n = 8)	
<i>Subject characteristics</i>		
Age, yr	21.9 ± 2.0	
Height, m	1.84 ± 0.06	
Weight, kg	79.3 ± 10.5	
BMI, kg·m ⁻²	23.3 ± 2.0	
<i>Pulmonary function</i>		
FVC, L	6.32 ± 1.52	
FVC, % predicted	118.71 ± 16.3	
FEV ₁ , L	5.27 ± 0.77	
FEV ₁ , % predicted	108.29 ± 18.36	
FEV ₁ /FVC (%)	84.0 ± 0.9	
FEV ₁ /FVC, % predicted	91.53 ± 8.31	
<i>Peak metabolic data</i>		
	<i>Swimming</i>	<i>Cycling</i>
VO ₂ , L·min ⁻¹	3.96 ± 0.95	4.29 ± 0.85
VCO ₂ , L·min ⁻¹	4.52 ± 0.84	4.78 ± 0.92
RER	1.03 ± 0.04	1.07 ± 0.03
HR, bpm	166 ± 21	183 ± 5*
V _I , L	3.06 ± 0.91	3.17 ± 0.76
f _I , bpm	43 ± 11	49 ± 7
V _E , L·min ⁻¹	122 ± 33	155 ± 27*
V _E /VO ₂	31.8 ± 8.7	36.7 ± 5.4
V _E /VCO ₂	26.8 ± 2.72	32.7 ± 2.60
T _I /T _{TOT}	0.56 ± 0.03	0.49 ± 0.02*
PEF, L·s ⁻¹	6.47 ± 1.25	6.37 ± 1.50
PIF, L·s ⁻¹	4.60 ± 0.78	6.04 ± 1.06*

Values are presented as mean ± SD.

*P < 0.05 statistically significant between swimming and cycling.

BMI, body mass index; HR, heart rate; T_I/T_{TOT}, inspired duty cycle; PEF, peak expired flow; PIF, peak inspired flow.

time were found between swimming and cycling at 50 L·min⁻¹ (1.25 ± 0.30 vs 1.18 ± 0.24 s), 75 L·min⁻¹ (1.09 ± 0.31 vs 1.08 ± 0.26 s), or 100 L·min⁻¹ (0.84 ± 0.25 vs 0.86 ± 0.15 s, P > 0.05).

Operational lung volumes. From the first stage of exercise to peak exercise, subjects averaged a +8% ± 27% (from 2.30 ± 0.7 L to 2.37 ± 0.58 L) increase in ERV while

swimming and a 0% ± 30% (from 2.36 ± 0.73 to 2.58 ± 1.34 L) change in ERV while cycling (all P > 0.05). Three subjects demonstrated increases in ERV during both swimming and cycling, from first stage exercise to peak exercise. Of the three subjects, two presented with greater increases in ERV from first stage exercise to peak exercise while swimming compared with cycling (61% vs 17% and 8% vs -29%). From the first stage of exercise to peak exercise, IRV decreased by 1% ± 6% (from 0.58 ± 0.44 to 0.57 ± 0.44 L) while swimming (P > 0.05), but IRV decreased 22% ± 15% (from 1.69 ± 0.71 to 0.58 ± 0.43 L) while cycling (P < 0.05). There was a significant difference between swimming and cycling at first stage exercise (P < 0.05); however, no significant difference was observed at peak exercise (P > 0.05). An increase in IRV from first stage to peak exercise was present while swimming in all but one subject, who presented with a 10% decrease, whereas all subjects presented with an increase in IRV while cycling. No significant differences were observed between swimming and cycling at start and peak exercise (P > 0.05). IC was reduced in both swimming, from 3.65 ± 1.31 to 3.34 ± 1.96 L, and cycling, from 4.09 ± 1.50 to 3.77 ± 0.68 L (both P > 0.05). There were no significant differences in IC between swimming and cycling at start and peak exercise (both P > 0.05).

Work of breathing. Because of a malfunctioning pressure line during the incremental swim test, W_b data are only presented for seven subjects. Total W_b values at rest in the upright and prone position in the pool were 46 ± 34 and 48 ± 20 J·min⁻¹, respectively, with no significant differences in inspiratory resistive W_b or inspiratory elastic W_b between body positions (all P > 0.05). The average W_b at rest on the bike was 28 ± 18 J·min⁻¹. As seen in Figure 2, inspiratory W_b was 54% (1%–189%) (P < 0.05) greater at every point

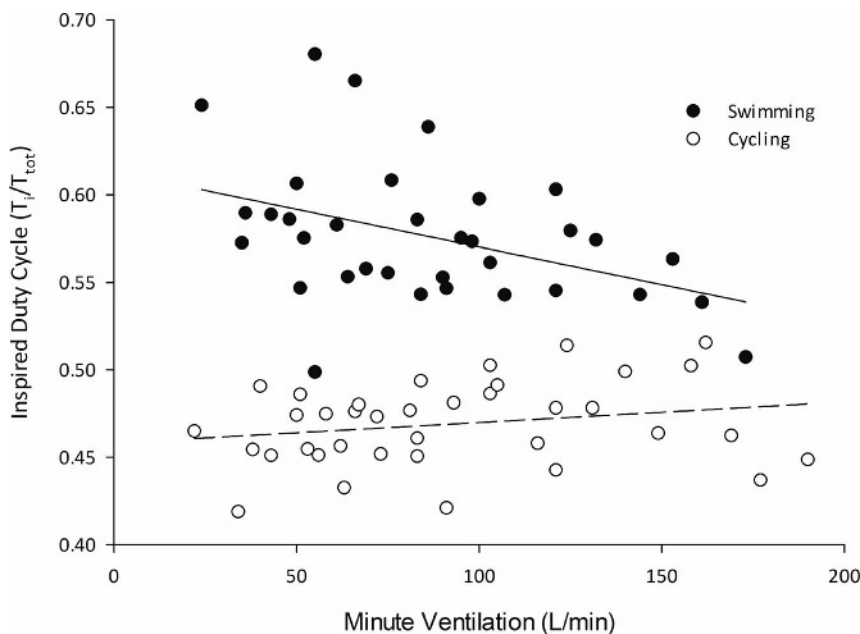


FIGURE 1—Inspired duty cycle of subjects swimming matched for V_E while cycling.

TABLE 2. Mean data at submaximal exercise.

	\dot{V}_E					
	50 L·min ⁻¹		75 L·min ⁻¹		100 L·min ⁻¹	
	Swim	Cycling	Swim	Cycling	Swim	Cycling
$\dot{V}O_2$, L·min ⁻¹	2.72 ± 0.46	2.02 ± 0.31*	3.33 ± 0.63	2.93 ± 0.29	3.87 ± 0.87	3.17 ± 0.59
$\dot{V}CO_2$, L·min ⁻¹	2.07 ± 0.21	1.69 ± 0.29	3.08 ± 0.27	2.81 ± 0.25	4.23 ± 0.48	3.87 ± 0.45
RER	0.73 ± 0.12	0.84 ± 0.07	0.95 ± 0.15	0.96 ± 0.06	1.02 ± 0.10	1.04 ± 0.06*
HR, bpm	122 ± 24	122 ± 24	142 ± 28	152 ± 24	159 ± 25	171 ± 19
V_T , L	2.63 ± 0.65	2.19 ± 0.47*	2.81 ± 0.99	2.51 ± 0.53	2.85 ± 0.93	2.75 ± 0.51
f_b , bpm	19 ± 5	23 ± 5*	25 ± 7	25 ± 3	37 ± 11	34 ± 7
$\dot{V}_E/\dot{V}O_2$	19.1 ± 4.5	23.3 ± 3.2	22.4 ± 2.9	25.4 ± 2.9*	29.6 ± 7.6	29.6 ± 3.8
$\dot{V}_E/\dot{V}CO_2$	24.8 ± 2.4	26.9 ± 3.2	23.6 ± 1.3	26.4 ± 2.6*	26.0 ± 1.9	28.0 ± 2.6

Values are presented as mean ± SD.

* $P < 0.05$ statistically significant between swimming and cycling.

HR, heart rate.

when matched for \dot{V}_E throughout exercise while swimming compared with cycling. During swimming, total inspired W_b was significantly higher at \dot{V}_E of 50 L·min⁻¹ (79 ± 16 vs 52 ± 13 J·min⁻¹), 75 L·min⁻¹ (147 ± 39 vs 101 ± 31 J·min⁻¹), and 100 L·min⁻¹ (234 ± 26 vs 180 ± 9 J·min⁻¹) than during cycling (all $P < 0.05$; Fig. 2). When matched for \dot{V}_E , swimming required greater inspiratory resistive W_b at 50 L·min⁻¹ (30 ± 6 vs 22 ± 5 J·min⁻¹), 75 L·min⁻¹ (68 ± 21 vs 43 ± 18 J·min⁻¹), and 100 L·min⁻¹ (106 ± 16 vs 81 ± 17 J·min⁻¹) (all $P < 0.05$). Inspiratory elastic W_b was similarly increased during swimming compared with cycling at 50 L·min⁻¹ (49 ± 11 vs 30 ± 8 J·min⁻¹), 75 L·min⁻¹ (81 ± 23 vs 56 ± 17 J·min⁻¹), and 100 L·min⁻¹ (128 ± 15 vs 99 ± 11 J·min⁻¹) (all $P < 0.05$).

No significant differences in total inspired W_b between swimming and cycling were observed at 50% (104 ± 53 vs 100 ± 47 J·min⁻¹), 75% (221 ± 118 vs 221 ± 85 J·min⁻¹), or 100% \dot{V}_E (331 ± 165 vs 419 ± 140 J·min⁻¹) (all $P > 0.05$). In addition, there were no differences in inspiratory resistive W_b at 50% (46 ± 27 vs 47 ± 21 J·min⁻¹), 75% (97 ± 57 vs 103 ± 54 J·min⁻¹), and 100% \dot{V}_E (149 ± 82 vs 210 ± 84 J·min⁻¹), or inspiratory elastic W_b at 50% (58 ± 28 vs 53 ±

30 J·min⁻¹), 75% (122 ± 59 vs 118 ± 36 J·min⁻¹), and 100% \dot{V}_E (174 ± 81 vs 209 ± 62 J·min⁻¹) ($P > 0.05$).

DISCUSSION

Main findings. The primary findings from this study are twofold. First, at a given \dot{V}_E , inspiratory W_b is greater during swimming than cycling. Second, no significant changes in operational lung volumes were observed between cycling and swimming. In addition, this study is the first to present observed periods of interbreath apnea found in swimming and its effects on P_{eso} . To our knowledge, no previous study has assessed W_b while swimming or compared it with cycling or any other land-based exercise. The study provides new insight into the conditions under which the lungs operate to maintain adequate ventilation during swimming.

Work of breathing. At any given \dot{V}_E , inspired W_b was greater while swimming than while cycling. Differences in inspired W_b were evident in both the resistive and the elastic components of inspiratory W_b . Our finding of greater inspiratory resistive and inspiratory elastic W_b while swimming is

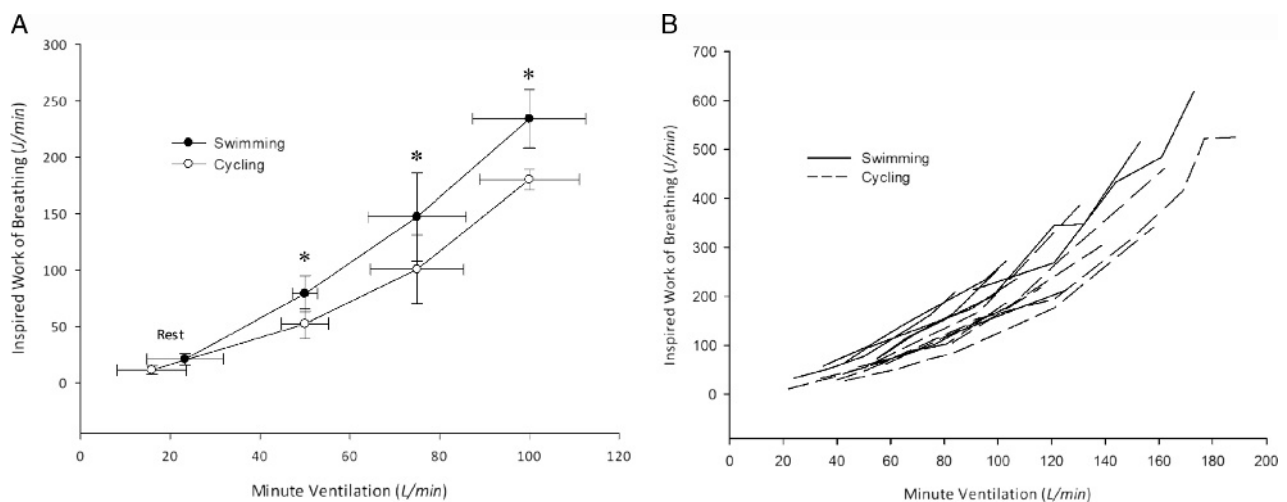


FIGURE 2—The relationship between inspired work of breathing and ventilation in swimming and cycling during maximal incremental exercise tests. A, Composite averages of the inspired work of breathing at rest, 50, 75, and 100 L·min⁻¹. * $P < 0.05$, statistically significant differences in inspired work of breathing between swimming and cycling. B, Individual curves were developed using the methods described above for each subject and averaged for swimming and cycling.

similar to previous studies, which have observed an increased resistive W_b while subjects were seated and immersed in chest-deep water. The authors concluded that the increased W_b at rest during water submersion of the chest was attributed to the increased airway resistance associated with reduced ERV (16). It can be assumed that swimming in a prone position would elicit similar changes in ERV. The reduction in ERV from submersion combined with a possible reduction of compliance associated with hydrostatic pressure on the chest wall and the increased blood flow to the thorax while exercising in a prone position are likely key components in increased inspired W_b observed while swimming (14,16). At peak ventilation achieved while swimming, dynamic compliance was significantly different when ventilation is matched for cycling. Swimming presented with an average compliance at a peak exercise of $0.013 \pm 0.003 \text{ mL}\cdot\text{cm H}_2\text{O}^{-1}$, when matched for ventilation cycling presented with an average compliance of $0.008 \pm 0.003 \text{ mL}\cdot\text{cm H}_2\text{O}^{-1}$ ($P < 0.05$). Differences in the pressure–volume relationship at rest and maximal exercise between swimming and cycling are presented in Figure 3. It is clear in this subject that, when matching for peak swim ventilation, there is a significant difference in pressure and dynamic compliance to sustain a similar ventilation.

As observed in the resting pressure–volume loops seen in Figure 4, body position in the water greatly changes pressures in the thorax. Although there are no statistically significant

differences between a supine and an upright body position at rest in the pool, both present considerable differences compared with cycling. This calls into consideration the likely consistent and variable changes in pressure the thorax undergoes during natural swimming, as any change in water immersion leads to a direct change in pleural pressure, unlike cycling or other forms of terrestrial exercise, in which pressure on the thorax remains constant during exercise.

The increased W_b experienced by swimmers could potentially be cause for increased resting lung volumes observed in this population. Previous studies have observed the relationship of increased mechanical stress and stimulation of lung fibrosis and growth (29,30). High-performance swimmers, including collegiate swimmers, have swum from an early age, during which their lungs have been chronically exposed to exercise with increased mechanical stressors. Consistent exposure to increased W_b , particularly during the prepubescent and pubescent stages of a young athlete's development, could lead to greater resting lung volume and resistance to respiratory muscle fatigue (31). There is evidence that increased parenchymal mechanical strain leads to expression of genes associated with lung growth (19). However, to date, the majority of lung remodeling studies have focused on responses to injury, inflammation, lung resection, and positive pressure ventilation in animal models. Furthermore, studies have presented that chronic alveolar hypoxia in addition to mechanical strain can feedforward a potential

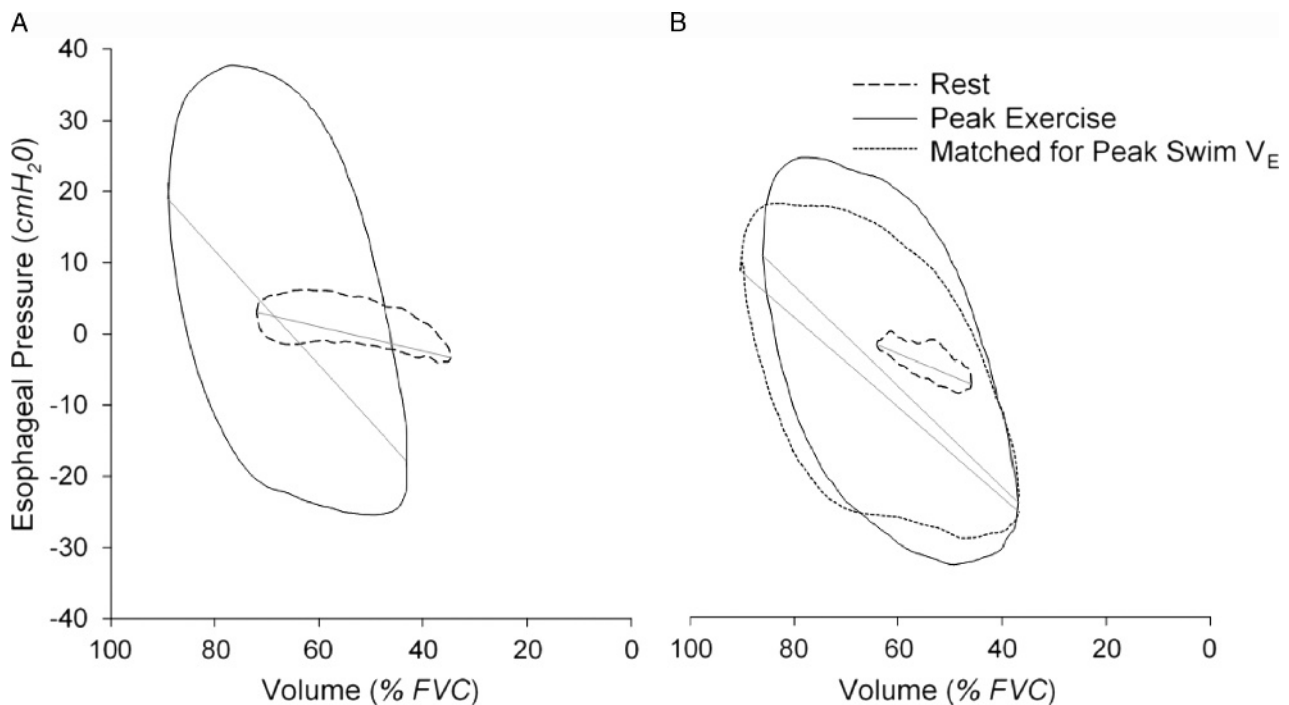


FIGURE 3—Pressure–volume loops of a representative subject observed in two conditions. **A**, While swimming, the *dashed line* presents a composite average of breathing at rest (inspired $W_b = 16.40 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}O_2 = 0.85 \text{ L}\cdot\text{min}^{-1}$). The *solid black curved line* represents breathing average achieved at peak swimming exercise ($\dot{V}_E = 153 \text{ L}\cdot\text{min}^{-1}$, inspired $W_b = 516 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}O_2 = 5.18 \text{ L}\cdot\text{min}^{-1}$). *Straight gray line* connects the zero-flow points at end expiration and end inspiration and represents dynamic compliance. **B**, While cycling, lines present the same conditions (rest: inspired $W_b = 7.90 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}O_2 = 0.59 \text{ L}\cdot\text{min}^{-1}$; peak exercise: $\dot{V}_E = 181 \text{ L}\cdot\text{min}^{-1}$, inspired $W_b = 620 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}O_2 = 5.00 \text{ L}\cdot\text{min}^{-1}$), with an additional *dotted line*, in which a composite pressure–volume average is presented at a ventilation matched for peak exercise achieved while swimming ($\dot{V}_E = 160 \text{ L}\cdot\text{min}^{-1}$, inspired $W_b = 461 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}O_2 = 4.68 \text{ L}\cdot\text{min}^{-1}$).

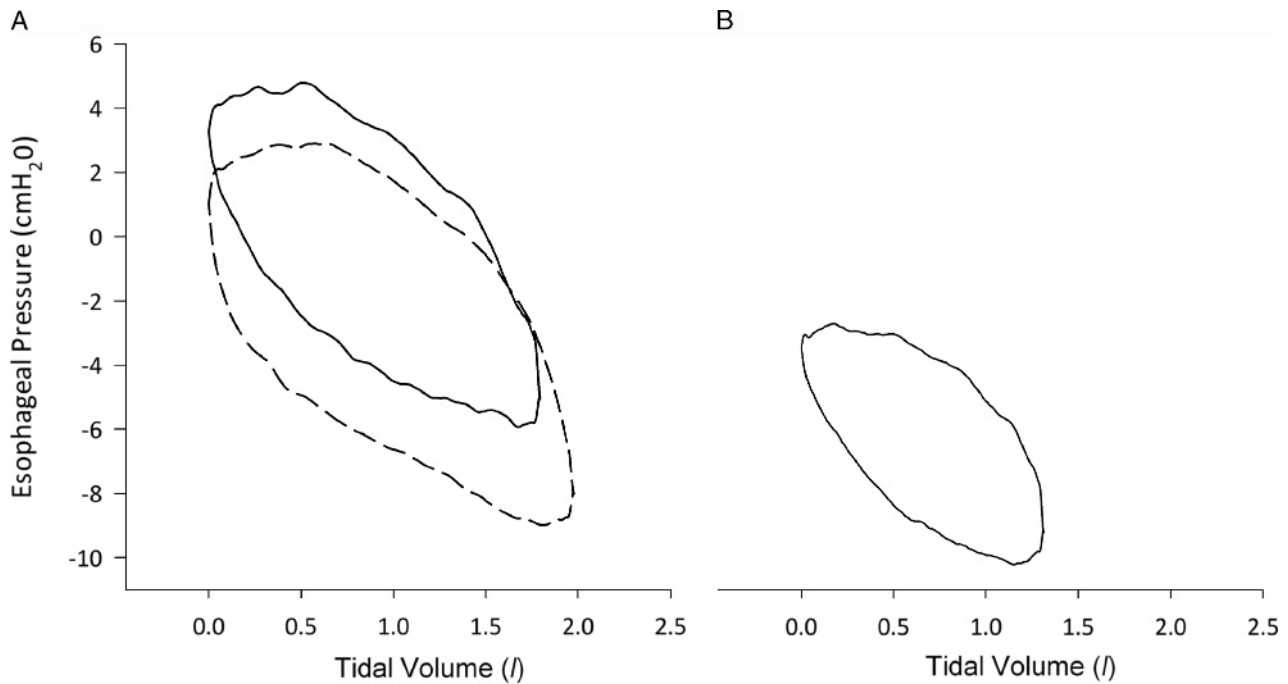


FIGURE 4—Average pressure–volume loops observed in three conditions at rest. A, *Solid line* represents submerged inferior of the clavicle in an upright position, ($W_b = 46 \pm 34 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}_E = 23.9 \pm 13.2 \text{ L}\cdot\text{min}^{-1}$). *Dashed line* presents breathing while floating in a prone position ($W_b = 48 \pm 20 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}_E = 23.3 \pm 8.5 \text{ L}\cdot\text{min}^{-1}$). B, Resting breathing on a bike ($W_b = 20 \pm 11 \text{ J}\cdot\text{min}^{-1}$, $\dot{V}_E = 15.9 \pm 7.8 \text{ L}\cdot\text{min}^{-1}$).

cellular growth response (30). A future longitudinal study design, in combination with modern molecular pathway analysis, could help researchers determine whether the increased W_b and the associated ventilatory challenges during swimming observed in this study contribute to increased lung volumes in competitive swimmers.

Operational lung volumes. Concurrent with previous research, peak \dot{V}_E achieved while swimming was significantly lower compared with cycling (10). This is attributed to the mode of exercise, full body versus predominantly lower body, as well as the likely entrainment of breathing with the freestyle stroke. However, in the aforementioned study, the large differences in \dot{V}_E at peak exercise did not have a significant effect on $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\text{carbon dioxide production } (\dot{V}CO_2)$. In the present study, $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ were lower while swimming at submaximal and peak exercise (Tables 1 and 2). Only differences in $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ were observed at $75 \text{ L}\cdot\text{min}^{-1}$, in which $\dot{V}O_2$ and $\dot{V}CO_2$ were greater while swimming. Peak $\dot{V}O_2$ was less while swimming; however, during submaximal ventilations, $\dot{V}O_2$ was greater at 50, 75, and $100 \text{ L}\cdot\text{min}^{-1}$. This is concurrent with previous findings that swimming requires greater oxygen expenditure, and alveolar ventilation is likely increased per breath in these conditions (32).

A primary purpose of this study was to observe differences in operational lung volume between swimming and cycling. We hypothesized that swimming would cause individuals to breathe at higher operational lung volumes because of the position of the body in the water and the forces imposed on the thorax, thereby reducing respiratory system compliance. Furthermore, previous studies have presented

relationships of increased W_b , particularly increased elastic work, with increases in ERV (33).

As previously mentioned, this study presented no significant patterns of increasing ERV in either swimming or cycling. While swimming, three subjects presented with an increased ERV, two of which were the only subjects to present with greater increases in ERV while swimming compared with cycling. The two subjects who experienced a positive shift in ERV also presented with observable flow limitation at peak exercise, in both modes of exercise. Although there is substantial evidence to support the relationship of hyperinflation and increased W_b (34), results from this investigation do not show consistent differences in lung volume operation. Moreover, whether increased W_b experienced during swimming is the product of differences in dynamic operating lung volumes or submersion is still unclear.

Ventilatory response. Compared with cycling, swimming altered breathing patterns, presumably due to the entrainment of breathing. These results are consistent with those of Holmér (10), who noted that swimmers maintained typical swimming breathing patterns despite breathing through a mouthpiece that allowed them to breathe freely under water. V_T and f_b were not significantly different at peak exercise (Table 1), indicating ventilatory parameters at peak exercise are similar to cycling to meet the metabolic demands of high-intensity swimming and cycling.

Although no significant differences were noted in V_T or f_b , significant differences were observed in inspired time and peak inspired flow. The combined changes associated with inspiration time and increased inspired W_b provide new insight into the mechanical stressors the respiratory system

undergoes while swimming. Within a respiration cycle, more relative time is dedicated to inspiration in swimming compared with cycling. Although less absolute time is spent during any given inspiration while swimming compared with cycling. Given less time for inspiration, mechanically it would be assumed ventilation would compensate with increased flow; however, peak inspired flow was significantly lower while swimming compared with cycling. In addition, subjects spent nearly the same amount of absolute time expiring and presented with similar peak expired flows during both modes of exercise. Our findings are in line with the observations of Skutnik et al. (35), who compared the ventilatory strategies between swimming and cycling and found that swimming results in statistically similar $\dot{V}O_2$ and time expired compared with cycling, with differences in peak \dot{V}_E . Similar to the findings of our study, they observed that peak inspired flow was lower and inspiratory duty cycle was higher during swimming compared with cycling. We interpret these collective findings to mean that the ventilatory strategies during swimming and other terrestrial exercise are

different owing to the environment the swimmers are subjected to, including the pressures associated with immersion that cause an increased W_b .

Interbreath apnea. Because of the interbreath apnea we observed while swimming, total W_b could not be determined without the assumption that all of the pressure generated during expiration was performed by the respiratory muscles. The periods of interbreath apnea did not allow for typical pressure–volume loops to be created and interpreted. By design, pressure–volume loops cannot be used to assess changes in pressure in the absence of changes in volume. During bouts of interbreath apnea, changes in P_{es0} to the order of ~ 20 cm H₂O were noted. Therefore, interpretations of expired W_b have the potential to be overestimated.

While swimming any stroke at a competitive level, breathing becomes entrained within the movement to increase stroke efficiency, and breath holds must be timed within the biomechanical constraints of the stroke cycle (36). To our knowledge, this is the first study to present raw flow and P_{es0} traces of volitional interbreath apnea while

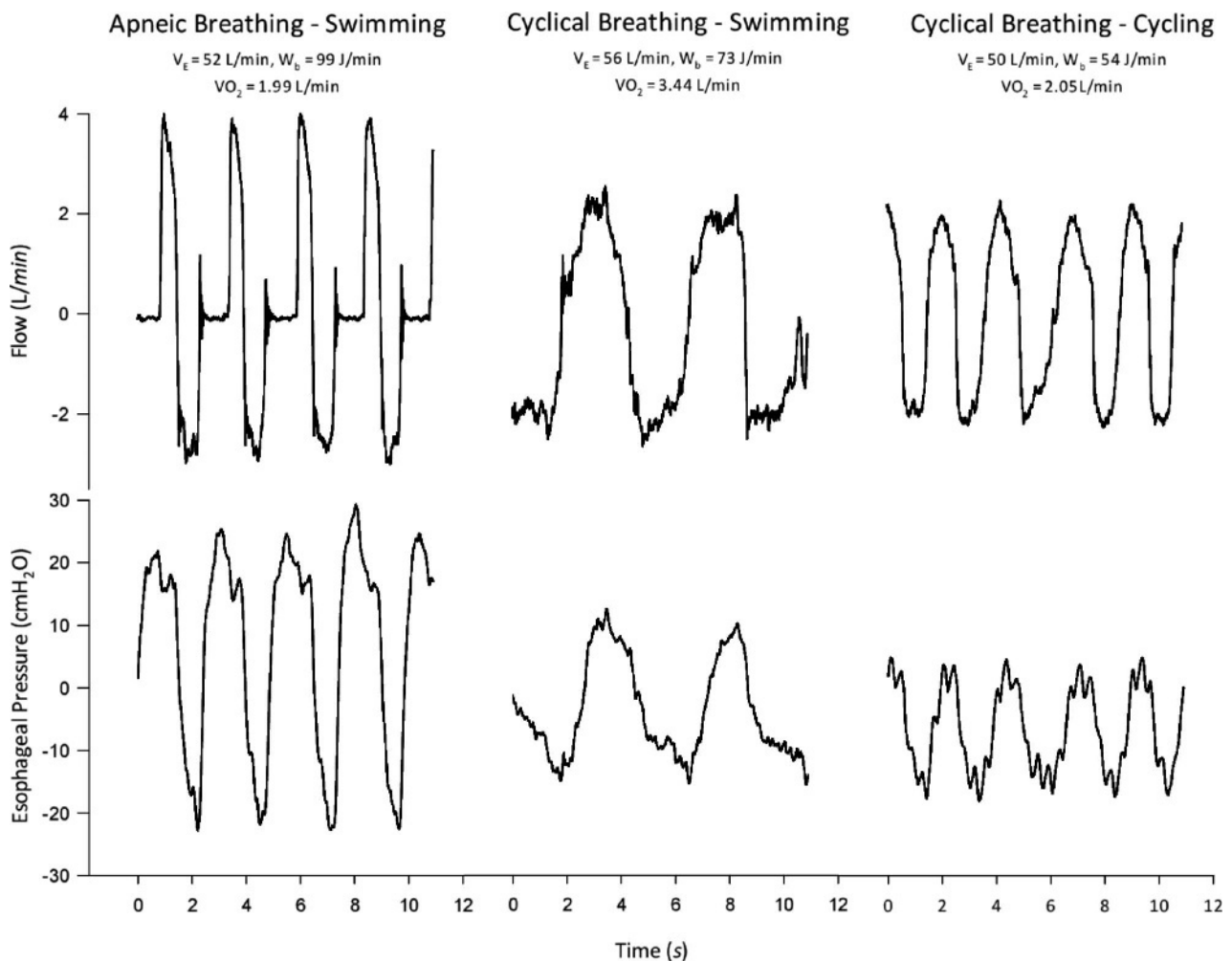


FIGURE 5—Raw dual-flow and esophageal pressure traces during exercise. From left to right: apneic breathing observed in a subject during submaximal freestyle swimming, cyclical breathing observed in another subject during submaximal freestyle swimming, and cyclical breathing observed during submaximal cycling. \dot{V}_E , minute ventilation; $\dot{V}O_2$, oxygen uptake; W_b , inspired work of breathing.

swimming, given the ability to breathe freely with a unidirectional mouthpiece. Interbreath apnea was present in six of the subjects at some point of exercise. Apnea was observed during submaximal stages of exercise; however, the periods were shortened or eliminated with increased exercise intensity. Two subjects maintained apneic breathing throughout the swimming exercise challenge. Observed periods of apnea in measured breaths ranged from 0.13 to 2.07 s. During observed apneic periods, a positive spike in P_{eso} was produced, during which P_{eso} rose to greater than 0 cm H₂O (Fig. 5). It can be assumed that periods of interbreath apnea are developed from breathing entrainment with the stroke. The cause for the observed positive increase in P_{eso} remains equivocal. Lin et al. examined P_{eso} similar to those observed during exercise in this study. The positive increase in P_{eso} could likely be a product of diaphragm and abdominal activation experienced during a breath hold (37,38). Alternatively, the increase in P_{eso} observed during a breath hold could potentially be recoil pressure on “nonactive” lung tissue, which is further magnified by hydrostatic forces applied from immersion (39).

Limitations. The current study requires acknowledgment of limitations. None of the subjects had previously performed a maximal exercise test in the water. Familiarization trials were conducted; however, we cannot overlook the possibility that subjects may have been apprehensive while participating in an invasive, unfamiliar procedure. Therefore, these factors may affect true peak $\dot{V}O_2$ and \dot{V}_E values; consequently, “maximal” values were called “peak” values. There is a great deal of breath-by-breath variability while swimming; therefore, executing multiple IC maneuvers would assist in determining true ERV. However, given the inability to communicate with subjects while swimming, IC maneuvers were still performed adequately with a visual

aid. Furthermore, the interpretation of changes in operational lung volumes during swimming and cycling could have been improved by indexing EELV and EILV to total lung capacity rather than vital capacity. It would be of additional interest to perform the similar procedure on a sample of athletes who are not swimmers, to identify differences in respiratory muscle strength while swimming.

CONCLUSIONS

In this study, the inspired W_b was quantified in high-performance collegiate swimmers during incremental swimming and cycle tests. We found that inspired W_b is greater while swimming compared with cycling at any given \dot{V}_E . We interpret the greater inspired W_b to be attributable to the hydrostatic pressure imposed on the chest wall during water submersion, in association with altered ventilatory mechanics experienced with freestyle swimming. To our knowledge, this is the first study to quantify the W_b while swimming and compare it with land-based exercise. Furthermore, it is the first study to present breath-by-breath P_{eso} values and document interbreath apnea during swimming.

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