Ventilation and locomotion coupling in varsity male rowers

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Ventilation and locomotion coupling in varsity male rowers. J. Appl. Physiol. 87(1): 233–242, 1999.—Ventilation and locomotion coupling (entrainment) has been observed and described in rowers during incremental exercise protocols but not during simulated race conditions. The purpose of this descriptive study was to examine ventilation and locomotion entrainment on a breath-by-breath and stroke-by-stroke basis in varsity male rowers during a maximal 2,000-m ergometer test. Eight of eleven rowers entrained ventilation at integral multiples of stroke rate (1:1, 2:1, or 3:1) for at least 120 consecutive seconds, with a 2:1 entrainment pattern being most common. In all 2:1-entrained subjects, inspiration occurred at catch and finish and expiration occurred during the latter portions of drive and recovery. In entrained and unentrained breaths from all rowers, peak flow rates and tidal volumes varied depending on when the breath was initiated during the stroke cycle. Entrained rowers made use of these differences and breathed in a pattern by which they avoided initiating breaths that resulted in reduced tidal volumes. The present data indicated that ventilation was impaired at stroke finish and not at catch, as hypothesized by some previous researchers. Ventilation also appeared to be subordinate to consistent locomotive patterns under race conditions.

METHODS

Subjects. The sample population consisted of 11 experienced male oarsmen (scullers and sweepers) from the University of British Columbia men's heavyweight and lightweight 8-man rowing teams. Physical characteristics of the participants are shown in Table 1. All participants were regularly practicing with the rowing team and had 7–96 mo (median = 8-mo training program that did not focus on breathing patterns.

Rowers may elect to couple ventilation to locomotion to improve athletic performance (8). Cunningham et al. (4) speculated that, at catch, the body is in a cramped position with both knees and hips flexed. Increased intra-abdominal pressure in this position may impair downward excursion of the diaphragm and therefore inspiration. Conversely, during the drive phase of the rowing stroke, the knees and hips extend and inspiration may be assisted. To date, entrainment in rowers has been studied primarily by using incremental exercise tests. Although Mahler et al. (9) showed no statistical differences in maximal physiological parameters between a 6-min “all-out” test and a progressive incremental test, the rower’s goal during these two tests differs. Rowers train for and compete at a 2,000-m distance, and their primary goal is to minimize time while remaining synchronized with their teammates. In progressive-interval tests, the goal is to maintain a specific power output, and incremental increases in power are often achieved by increasing stroke rate (13).

The purpose of this descriptive study was to examine ventilation and locomotion entrainment in varsity rowers during a simulated 2,000-m race. On the basis of earlier studies (10), some variability in entrainment pattern was expected. With entrained rowers, the specific pattern of entrainment was explored, whereas with unentrained rowers the relationship between ventilation and locomotion rates was examined for insight into how locomotion affected ventilation.

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highly motivated and familiar with this type of ergometer. All data on the ergometer’s display were available.

Instrumentation. Ventilatory parameters, including ventilation frequency, tidal volume (VT), and minute ventilation (VE) were recorded for the duration of the test by using a pneumotachograph and nose clamp (MedGraphics CPX-D Metabolic Cart, St. Paul, MN). The pneumotachograph was calibrated with a 3-liter syringe at various expected flow rates before each test. Measured gas-exchange parameters included volume of oxygen uptake (V\textsubscript{O\textsubscript{2}}), volume of expired carbon dioxide (V\textsubscript{CO\textsubscript{2}}), and partial pressure of end-tidal oxygen (P\textsubscript{ETO\textsubscript{2}}) and carbon dioxide (P\textsubscript{ETCO\textsubscript{2}}). Carbon dioxide and oxygen analyzers were calibrated with gases of known concentration before each test. Average ventilatory and gas-exchange parameters were recorded every 5 s as was average heart rate (Polar Vantage XL). An oximeter (Ohmeda Biox 3740) attached to the earlobe measured the percentage of hemoglobin saturated with oxygen (\%Sa\textsubscript{o}). A vasodilator nicotine cream (Finalgon, Boehringer Ingelheim) was applied to the earlobe to improve perfusion for the oximeter clip. Force was measured with a custom-made load cell inserted between the ergometer handle and chain. Chain speed was measured with a direct-current generator fastened to the final chain pinion. Both force and speed signals were low-pass filtered by using an active second-order Butterworth filter (\(-3 \text{ dB} \at \text{22 Hz}\)) and recorded digitally by using a 12-bit analog-to-digital card (Data Translation DT2801, Marlboro, MA) at 60 Hz. Continuous ventilatory flow, available as an analog output from the metabolic cart, was also recorded at 60 Hz.

Sagittal-plane videos of the complete test sessions were recorded at 60 Hz with an exposure time of 0.002 s. The video camera was positioned 5 m from the ergometer, with its axis perpendicular to the plane of motion. Reflective markers were applied to the left lateral malleolus, the left greater trochanter, the posterior superior iliac spine, the posterior spine of the first thoracic vertebrae, the greater tubercle of the left humerus, and at the end of the rowing handle. A marker was not placed on the lateral femoral epicondyle because it was obstructed by the arm and forearm during the stroke. Instead, markers were applied to the lateral aspect of the left thigh and shank along a line between lateral femoral epicondyle and the greater trochanter or lateral malleous, respectively. Marker spacing along both segments was nominally 30 cm or more. Video and analog data were synchronized by recording a light-emitting diode pulsed at the start and end of each test.

Data analysis. Maximal physiological variables were determined in each subject and averaged. Average physiological measures were calculated from stabilized data (the first 120 s of each subject’s data were excluded). Breath-by-breath volumes were calculated by integrating the ventilatory flow. Expiration was defined as positive flow or volume and inspiration as negative.

The force and chain speed transducers were calibrated over the ranges used in this study. Minor drift in the offset of the load cell during the latter part of some tests was corrected by resetting the offset to the median output voltage during the recovery (unloaded) portion of the stroke. This procedure was validated by using data in which no drift occurred and was subsequently used for all strokes. Instantaneous power at the hand was calculated as the product of force and chain speed, and work per stroke was determined by integrating instantaneous power over stroke duration. To eliminate the transient changes at the start (acceleration) and end (final sprint) of each test, average performance data were calculated for a 300-s interval beginning 30 s into the test.

The video was calibrated by using a 1-m reference in the plane of motion. For each subject, reflective marker positions were digitized from video for three strokes beginning at each minute and for the last three strokes of the test (Peak Performance Technologies, Englewood, CO). The coordinate data were scaled to object-space coordinates and low-pass filtered by using a fourth-order, zero-lag, digital Butterworth filter with a cutoff of 5 Hz. Linear velocity and joint angular acceleration, velocity, and position (angle) were then calculated from filtered position data by using finite differences.

The times of catch (end of the recovery phase and start of the drive phase) and finish (end of the drive phase and start of the recovery) were defined as the instant at which chain speed was zero and was interpolated from discrete chain speed data. Instantaneous stroke rate for each stroke was the inverse of stroke duration. Instantaneous ventilation rates (IVRs) were similarly calculated from flow rate data. Entrainment was assessed by using a ratio of average IVR to average instantaneous stroke rate. Average rates were computed over consecutive 10-s intervals, and subjects were considered to be entrained during a 10-s interval when the computed ratio was \(\pm 10\%\) of an integral value, i.e., one, two, or three. The data were then divided into entrained and unentrained groups on the basis of the 10-s intervals, irrespective of subject.

The relationship between ventilation and locomotion in entrained and unentrained groups was investigated by using normalized stroke-volume and normalized stroke-flow plots. For all strokes, stroke duration was normalized to a common time base, with time 0 corresponding to catch and a time of 1 corresponding to the end of recovery (catch of the next stroke). For each stroke, the drive and recovery portions were independently normalized to the overall proportion of time spent by all rowers in drive and recovery, respectively. In addition, the onset time of inspiration and/or expiration and time of peak inspiratory and/or expiratory flow for each stroke were scaled to maintain their temporal relationship to catch and finish within the drive and recovery phases, respectively. The magnitude of inspired and expired volume and peak flow was normalized by using a subject’s average inspired volume and average inspired peak flow, respectively.

Statistics. Differences between pretest spirometry in the standing, seated, and catch positions were assessed by using a repeated-measures ANOVA. Post hoc Tukey tests were conducted to determine which conditions were significantly different. The level of significance was set at \(P < 0.05\) for all tests.

Table 1. Anthropometric data and lung parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>Mass, kg</th>
<th>FVC, liters</th>
<th>FEV\textsubscript{1}, liters</th>
<th>FEV\textsubscript{1}/FVC</th>
<th>Maximum forced expiratory flow, l/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24 ± 4</td>
<td>185.1 ± 5.4</td>
<td>81.0</td>
<td>5.83 ± 0.80</td>
<td>4.91 ± 0.50</td>
<td>0.85 ± 0.05</td>
<td>11.45 ± 1.58</td>
</tr>
</tbody>
</table>

Values are means ± SD. FVC, forced vital capacity; FEV\textsubscript{1}, forced expiratory volume in l/s.
RESULTS

All rowers completed the simulated 2,000-m ergometer test. Average completion time was 400 ± 20 (SD) s, with 199 ± 13 strokes and 365 ± 98 breaths. Pretest spirometry showed that peak flow rates in the standing (10.2 ± 1.7 l/s), sitting (10.3 ± 1.0 l/s), and catch (10.0 ± 1.6 l/s) positions were not significantly different (P = 0.91). However, there were significant differences (P < 0.001) in the maximal volume expired between the standing (5.5 ± 0.8 liters), sitting (5.5 ± 0.8 liters), and catch (5.2 ± 0.8 liters) positions. Post hoc tests revealed that catch volumes were less than both standing and sitting volumes.

Across all subjects, \( \dot{V}O_2 \) typically reached a plateau ~60 s into the test. The maximum respiratory exchange ratio exceeded 1.15 in 10 subjects, and peak heart rate exceeded 90% of maximum predicted heart rate (220 – age) in 8 subjects, indicating that this represented a maximal test for these athletes (Table 2). The PETCO2 typically peaked ~120 s into a test and then gradually fell for the remainder of the test. Ventilation rates also increased rapidly over the first 120 s and then increased more slowly to a maximum at the end of the test. \( SaO_2 \) levels fell to 92% or less in eight subjects.

All rowers began their test with four to six powerful strokes and then settled into a stable rowing pattern (Fig. 1). Peak force, speed, power, and work per stroke (Table 3) then remained relatively constant until the final sprint. Ignoring the first 15 s of each test, rowers spent 44 ± 3% of each stroke in the drive phase. The SD of stroke-propulsive measures (peak force, peak power, and work per stroke) varied between 15 and 22% of their means, whereas measures of temporal consistency (stroke rate, peak chain speed, and proportion of time spent in the drive phase) varied between 5 and 7% of their respective means.

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**Table 2. Exercise data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \bar{V}E ), liters</th>
<th>( \dot{V}O_2 ) l/min</th>
<th>( \dot{V}CO_2 ) l/min</th>
<th>RER</th>
<th>( VT ), liters</th>
<th>HR, beats/min</th>
<th>PETCO2, Torr</th>
<th>PETO2, Torr</th>
<th>( SaO_2 ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>169.4 ± 16.8</td>
<td>4.43 ± 0.92</td>
<td>5.10 ± 0.96</td>
<td>1.21 ± 0.07</td>
<td>3.22 ± 0.82</td>
<td>184 ± 9</td>
<td>41.1 ± 4.6</td>
<td>118.9 ± 4.9</td>
<td>92 ± 2</td>
</tr>
</tbody>
</table>

Values are means ± SD; \( n = 10 \) subjects. \( \dot{V}E \), minute ventilation; \( \dot{V}O_2 \) and \( \dot{V}CO_2 \), \( O_2 \) uptake and \( CO_2 \) production, respectively; RER, respiratory exchange ratio; \( VT \), tidal volume; HR, heart rate; PETCO2 and PETO2, end-tidal \( PCO_2 \) and \( PO_2 \), respectively; \( SaO_2 \), arterial \( O_2 \) saturation.

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**Table 3. Biomechanical data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke rate, ( min^{-1} )</td>
<td>30 ± 2</td>
</tr>
<tr>
<td>Peak force, N</td>
<td>778 ± 149</td>
</tr>
<tr>
<td>Peak chain speed, m/s</td>
<td>2.35 ± 0.13</td>
</tr>
<tr>
<td>Peak power, W</td>
<td>1,670 ± 390</td>
</tr>
<tr>
<td>Work, J/stroke</td>
<td>677 ± 102</td>
</tr>
<tr>
<td>Proportion of time in drive phase, %</td>
<td>44 ± 3</td>
</tr>
</tbody>
</table>

Values are means ± SD.
All rowers entrained at some portion of their test, although only eight rowers maintained ventilatory and locomotor entrainment for a continuous period of 120 s or more (Fig. 2). Three stable entrainment patterns were observed. One rower (subject 3) maintained a 1:1 entrainment pattern, six rowers maintained a 2:1 entrainment pattern, and one rower (subject 10) maintained a 3:1 entrainment pattern. No stable entrainment patterns were observed at subinteger multiples. Only one rower (subject 1) remained entrained (2:1) for his entire test. Two others (subjects 5 and 10) started to entrain within 30 s and then continued to be entrained for the remainder of the test.

Sixty-two percent of all 10-s intervals (total = 446) were entrained, and 61% of all breaths (total = 3,360 breaths) occurred within these entrained intervals. For all breaths initiated in the entrained intervals, inspiration occurred most frequently during the first 40% of recovery, followed by expiration during the latter part of recovery (Fig. 3A). For all breaths initiated in unentrained intervals, a similar, although less well-defined, pattern of inhalation onset was observed (Fig. 3B). When normalized volume was superimposed onto normalized drive and/or recovery data, a similar pattern between ventilation volume and rowing cycle was observed in both entrained and unentrained intervals (Fig. 3, C and D). Inspiratory volumes were observed to

Fig. 2. Periods during which subjects were entrained. Thin lines, 1:1 entrainment pattern; medium lines, 2:1 pattern; heavy line, 3:1 pattern; +, time to test completion.

Fig. 3. Distribution of normalized onset (A and B) and normalized volume (C and D) of expiration (defined as positive flow or volume) and inspiration (defined as negative flow or volume) for all breaths during entrained (A and C) and unentrained (B and D) intervals for all subjects (except subject 10, who entrained at 3:1). Horizontal axis in A-D, normalized stroke; 0, catch; dashed vertical line at 0.44, mean transition from drive to recovery, i.e., finish; 1, end of recovery (catch for next stroke). Histograms depict percentage of expirations and inspirations initiated during drive and recovery phases in entrained (A) and unentrained (B) portions of rowing stroke (here arbitrarily divided into 50 intervals). Thick lines in A and B, difference between expiration and inspiration data.
be ~25% smaller for breaths initiated during middrive (0.15–0.35 stroke proportion) than throughout the remainder of the stroke. Conversely, expiratory volumes were observed to be ~17% smaller for breaths initiated during early recovery (0.4–0.6 stroke proportion) than throughout the remainder of the stroke. The distribution of the time of peak flow in the rowing cycle (Fig. 4, A and B) was similar to that observed in the ventilation-onset data, except for markedly reduced frequency of inspiratory peak flows at stroke finish in both the entrained and unentrained breaths. Peak expiratory flows were ~12% smaller in the early recovery data (0.45–0.65 stroke proportion) across both entrained and unentrained breaths (Fig. 4, C and D).

It was observed that subjects who entrained at either two or three breaths per stroke modulated their inspired or expired volume during a stroke by using two dominant strategies. An example of the first dominant strategy is shown in Fig. 5 and consisted of alternating both ventilation rates (Fig. 5A) and expired volumes (Fig. 5B). Figure 5, B and D, shows that inspired volumes over the last two-thirds of this subject's test remained relatively constant (2.4 liters in early recovery and 2.7 liters in late recovery), whereas expired volumes alternated between small (2.1 liters) during recovery and large (3.2 liters) during drive. To achieve this alternating volumetric expiratory pattern, this subject used short-duration breaths during recovery (average IVR of 70 min) and long-duration breaths during drive (average IVR of 54 min) (Fig. 5A). This pattern was achieved while similar peak flow rates were maintained (Fig. 5B). Furthermore, this pattern was visible when flow-volume loops at any point in the last two-thirds of this test were examined (Fig. 5C).

An example of the second dominant strategy is shown in Fig. 6. This strategy achieved less-distinct alternating expiratory volumes by maintaining a regular IVR (Fig. 6A) and alternating between high peak expiratory flow rates (10.9 l/s) during the drive and low peak expiratory flow rates (7.9 l/s) during recovery (Fig. 6, B-D).

Two subjects who were initially entrained at 1:1 did not maintain this ratio for the duration of their tests. One subject maintained a near-constant stroke rate and adapted his ventilation rate to meet the demands of the task (Fig. 7A). This subject achieved high levels of PETCO₂ (Fig. 7B) before abandoning 1:1 entrainment 240 s into his test. Despite decreased VT values after the subject became unentrained (Fig. 7C), VE increased (Fig. 7D) and PETCO₂ decreased (Fig. 7B).
subject maintained 1:1 entrainment for ~50 s and then entered a 120-s transition period before settling into a 2:1 breathing pattern for the remainder of the test (Fig. 8A). Although $P_{ETCO_2}$ (Fig. 8B) and $VE$ (Fig. 8C) remained relatively unaffected, this transition period altered the breath-by-breath $VT$ (Fig. 8D).

The kinematic data were examined graphically for differences between the entrained and unentrained intervals. No marked differences were found, i.e., the kinematics could not be used to discriminate entrainment. Peak force, peak power, and work per stroke were similarly unaffected by entrainment. Hip joint angle (trunk segment relative to the thigh segment) increased to a maximum at stroke finish, decreased only slightly during early recovery, and then decreased more rapidly to a minimum at catch (Fig. 9). Angular acceleration of the hip joint (Fig. 9) peaked at the end of the drive phase, consistent with the rowers using the rearward inertia of the torso to generate the final portion of the drive force. A secondary angular acceleration peak was observed in the early recovery phase after rowing force had dropped to zero (Fig. 9).

**DISCUSSION**

This is the first study that has described in detail the relationships among stroke rate, kinematics, and breathing frequency in well-trained athletes during a competitive simulation. All subjects in this study entrained for some portion of their test, although the duration and pattern of entrainment varied among
subjects. Only integral patterns of entrainment (1:1, 2:1, and 3:1) were observed (Fig. 2). Among periods of entrainment, different subjects modulated different aspects of their ventilation. For example, subjects who alternated between two ventilatory volumes did so by either alternating between short and long breaths (Figs. 5) or alternating between low and high peak flow rates (Fig. 6).

Despite variations among subjects, the present data indicated that breaths entrained at 2:1 occurred at similar times in the stroke cycle for most rowers (Fig. 3A). This temporal pattern of 2:1 entrained breathing was consistent with previous observations in elite rowers (10). Variations in the inspired and expired volumes of unentrained breaths initiated at different times in the stroke cycle suggested that a preferred pattern of entrainment existed. Inspired volumes were smallest for breaths initiated in the middle of the drive phase, and expired volumes were smallest for breaths initiated at or immediately after finish (Fig. 3D). A similar pattern was briefly noted by Steinacker et al. (13) and was present in limited exemplar data reported by Mahler et al. (11). This pattern suggested that there were advantageous times in the stroke for large inspired and expired volumes. Moreover, when rowers were entrained, they appeared to be taking advantage of this pattern.

Peak inspiratory flow rates in unentrained breaths were rarely achieved at stroke finish, and peak expiratory rates were smaller and less frequent during early recovery (Fig. 4D). This pattern was even more distinct in peak flow data from entrained breaths (Fig. 4C).
near absence of peak inspiratory flow at the end of drive likely accounts for the decreased inspiratory volume for breaths initiated in the middle of the drive phase. The timing of peak flow and volume minima suggests that a greater limitation on ventilation exists in the finish position than in the catch position. Therefore, the present data suggest that a mechanism other than the cramped body position at catch (4) impairs ventilatory volumes.

Kinematic data revealed that, at stroke finish, the torso had reached its maximum extension relative to the thighs. Subsequent flexion between the trunk and thighs, visible as the second negative peak in the angular acceleration of the hip joint (Fig. 9), occurred after the rowing force had dropped to zero (at ~44% of the rowing cycle) and was likely produced by contraction of the abdominal flexor muscles. Although the activity of these muscles was not measured in this study, the timing of this contraction would correspond to the period in which few breaths achieved peak inspiratory flow (Fig. 4, C and D) and would suggest that these two phenomena were linked. Abdominal flexor muscles have been shown to assist in trunk flexion in two ways: first, by generating the force to cause acceleration and, second, by stiffening the trunk to transfer the force to the upper torso. When a subject is in a standing posture, stiffening of the torso is partially achieved through pressurization of the abdominal cavity by cocontraction of the diaphragm and abdominal muscles (7). In rowing, periodic cocontraction of these muscles at stroke finish and the resulting transient abdominal pressure increase may momentarily impair diaphragm function. This mechanism may be responsible for the paucity of peak inspiratory flow data at stroke finish.

Under resting conditions, the maximal inspired volume in the catch position was lower compared with both the standing and seated positions. Although these results appeared to support a theory that a cramped body position in catch affected lung volumes (4), the volume decrement in the catch position was only 5%. Given that maximal VT during exercise averaged 55% of forced vital capacity in the standing position, it was unlikely that this volume decrement limited performance.

Previous studies have observed lower VE (12) and reduced VT (14) for rowing compared with cycling and running, also suggesting ventilatory impairment in rowing. Gavin et al. (6) studied 13 men during an incremental maximal cycle test and used the VE/VCO2 ratio as an index for the ventilatory response to exercise. In the group defined as “high,” subjects reached a maximal VO2 of 4.4 l/min, VCO2 of 5.2 l/min, and respiratory exchange ratio of 1.19, values similar to those in our study. The VE/VCO2 ratio in our data was slightly higher than that in the study by Gavin et al. (6) (33.4 vs. 28.0), suggesting that despite similar levels of VCO2, our
subjects had an adequate ventilatory response to exercise.

On the basis of earlier incremental exercise tests, it has been previously speculated that breathing drives locomotion (13). Under the simulated race conditions used in this study, all rowers maintained a similar stroke rate and stable power output through all but the initial and final portions of their 2,000-m test. These results were expected, given that team rowers must all row at the same stroke rate during a race. Given the observed locomotor consistency and the differing ventilatory strategies used to maintain entrainment, these rowers appeared to alter their ventilation to match locomotion under simulated race conditions. Despite increasing demands to breathe during the test, rowers maintained steady stroke rates and power output. In general, rowers may seek to breathe at times where muscle synergy produces larger volumes for a given amount of respiratory work, or alternatively, the same volume for less respiratory work. The findings of the present descriptive study support the theory that locomotion drives ventilation under simulated race conditions in rowers.

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