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ASSESSMENT OF THE TIMING OF RESPIRATION DURING ROWING AND ITS RELATIONSHIP TO SPINAL KINEMATICS

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Abstract. The purpose of this study was to investigate the use of a nasal thermistor to measure respiration events at the nose and mouth, and to provide pilot data to allow experiments to be developed that relate respiration to the mechanics of rowing. Synchronised measures of spinal kinematics, respiratory patterns and force applied were recorded for fourteen male rowers of different abilities while rowing on a Concept II ergometer. The start of inspiration and expiration were measured and related to points in the rowing stroke. Rowers with greater experience showed more consistent synchronisation of breathing with higher stroke ratings. A pattern of 2 breaths per stroke was adopted by the majority of rowers and could be related to spinal kinematics within the stroke. In 8 out of the 9 subjects who took two breaths per stroke, expiration began at 7–16% of the stroke followed by inspiration at 34-40%. A further breath occurred during the recovery phase of the stroke. The nasal thermistor technique can be used to measure the timing of respiration in relation to spinal kinematics during rowing. Entrainment is more consistent in more experienced rowers and is related to the kinematics of the body during rowing. ***(Biol.Sport 23:353-365, 2006)***

Key words: Entrained breathing - Lumbo-pelvic motion - Nasal thermistor - Electromagnetic device

Introduction

Rowing, a competitive sport, is amenable to scientific study due to its repetitive action and well defined goals. Recently, there has been a focus on the biomechanics of rowing in terms of body kinematics [2], however, such studies have not been undertaken in conjunction with physiological investigations. The present study, bridging the two disciplines, explores the biomechanics of the rowing stroke in relation to the physiological requirement for respiration. The

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details of the interaction between the pattern of respiration and stroke were investigated because it was postulated that back function, and particularly postural control might be influenced by the large respiratory demands which may call upon the trunk stabilising muscles of the abdomen. It is proposed that understanding this interaction would provide useful information regarding technique, possibly leading to improvements in both rowing performance and athlete welfare.

The overall coupling of ventilation and locomotion has previously been reported in rowing [13], and referred to as "entrainment". Rowers with varying experience were shown to entrain their breathing, synchronising breaths with the rowing stroke, although inter-individual variations in the patterns observed were noted [8,9]. In addition, the role of an efficient ventilatory pattern in improving rowing performance has been demonstrated through specific respiratory muscle training and warm-up procedures [15,16]. It is also known that the kinematics of the body during rowing can influence performance and injury [6]. However, the detailed pattern of ventilation and entrainment with respect to the different aspects of the rowing stroke remains unclear.

The aims of this study were to develop and validate a technique to measure the respiration patterns in rowers in conjunction with measures of force generation and lumbo-pelvic kinematics, and, secondarily, to ascertains patterns of breathing amongst rowers of different competitive levels in order to allow further experiments to be devised that relate respiratory function to rowing mechanics.

Materials and Methods

Subjects: 14 male subjects, comprised of 4 international, 7 senior and 3 novice level rowers, were recruited from Imperial College Boat Club and other Tideway rowing clubs and written informed consent was obtained from all participants, following approval by the local research ethics committee.

All subjects were asked about the level at which they rowed, their training and injury history prior to testing. Their weight and heights were recorded. The mean age was 24 years (±4.5) with no significant differences between international, senior and novice level rowers. There were also no significant differences in height or weight between these groups. As expected, rowing experience was significantly greater in the groups of senior and international athletes (as tested by ANOVA, $p<0.001$). The number of training sessions per week also increased with competition level from 5 sessions in the novice group to 12±3 sessions in the international group. Subjects were comparable to those of previous studies with respect to the anthropometric variables measured, Table 1.

Table 1
Anthropometric and training data by competition level

	Novice (n=3)	Senior (n=7)	International (n=4)
Weight (kg)	83.1±5.7	78.3±6.2	82.6±6.2
Height (m)	1.88±0.02	1.83±0.05	1.88±0.05
Age in years	21±1	24±5	26±5
Rowing experience in months	14±13	70±22	153±57
On water (*)	2±1	5±4	5±4
Ergometer (*)	1±1	3±1	4±1
Weights (*)	0±1	2±1	2±1
Other aerobic (*)	2±2	1±1	1±1
Total (*)	5±0	10±3	12±3

*training sessions per week
Values are given as mean ± standard deviation

Lung Function Testing: The forced vital capacity (FVC) and forced expiratory volume in 1 second (FEV_1) for each subject were determined before and after every exercise protocol using a vitalograph spirometer (Vitalograph^{TM} Ltd, Bucks). Peak inspiratory pressure (PIP) and peak expiratory pressure (PEP) were also measured using a Mouth Pressure Meter (Precision Medical Ltd, N. Yorks) and determined at residual volume and total lung capacity respectively following the methods described by Hamnegard *et al.* [5].

Measurement of spinal motion: An electromagnetic device which measured the position and orientation of 4 receivers relative to a transmitter (Flock of Birds^{TM}, Ascension Technology, Burlington, Vt, USA) was used to record spinal kinematics. This system quantifies the rotation and translation of electromagnetic sensors in an electromagnetic field in terms of rotation about and translations along an electromagnetic transmitter axis. In this study only rotations in the sagittal plane were considered. The receivers were placed over the thoraco-lumbar and lumbo-sacral joints and also at the mid point between the lateral femoral epicondyle and the greater trochanter as previously described by Bull and McGregor [1]. The rowing ergometer handle also incorporated a receiver to identify its exact position in space. These were used to calculate body segment angles, joint angles, and handle travel.

Measurement of instantaneous output rowing force: The rowing ergometer handle incorporated a load cell (Oarsum, NSW, Australia) to record tensile force in synchronisation with the kinematic data. This was done using custom written software as described by Holt *et al.* [6].

Respiratory ventilation detection: A DT 1000 disposable thermistor unit (Verifix Ltd, UK) was used to measure temperature changes at the nose and mouth. The thermistor unit consists of three probes; two nasal and one oral connected in series, with the total signal recorded.

The thermistor was attached to the subject in the midline just above the upper lip. The two nasal probes were directed upwards; one positioned at the entrance to each nostril and the oral probe was directed downwards overlying the subject's mouth. The thermistor was attached to a battery-operated custom-made converter box that provided a voltage output between -2.5 (hottest) and +2.5 volts (coldest) over a physiological temperature range of 10 to 40°C. The values for thermistor output were given in arbitrary units where one unit was equal to 0.4% of the temperature range for the system.

The output from the thermistor was fed into an Analogue-Digital converter and synchronised with the output from the load cell and Flock of Birds^{TM} using custom written software. The times of onset of an inspiratory or expiratory manoeuvre were expressed as a percentage time of the total stroke period, starting from the catch.

Thermistor Validation: A study assessing the thermistor performance was conducted prior to its use, since thermistors have not previously been validated for such usage. In calibration tests using a standard rapid hot water immersion technique there was no detectable time delay in the thermistor signal onset. This meant that the system was able to respond appropriately to permit the detection of onset of airflow. Observer controlled software markers were used to record the start of temperature change and then compared with the actual start of the signal change. The markers (n=10) were within 0.005 s (±0.10) of the start of signal change. Since a single breath takes between 1 and 6 seconds this was deemed an appropriate response characteristic. Subject-controlled event markers (the subject pressed a button at the start of each breath) were also used to mark the start of each breath in a subject breathing at rest and there was no significant difference between the event markers and the start of signal change (n=50). The event markers were within 0.15 seconds (±0.07) of the start of signal change.

In addition to response rate it was important to establish the influence of motion and ambient temperature change on the performance of the thermistor. A thermistor was mounted on the forehead in the free air above the skin surface and the subject was asked to row on the ergometer for 10 min. Small temperature changes during rowing were noted but these were independent of the pattern of respiration and did not change the pattern of breathing recorded.

The effect of changes in breathing frequency on the thermistor delay has previously been investigated by Xiong *et al.* [17]. They demonstrated that the measurement delay was reduced at higher breathing frequencies and that small changes in the positioning of the thermistor did not affect the thermistor delay in measuring respiration.

Finally, to obtain an estimate of the effect of repeated placement of the thermistor, two separate 5 min recordings of thermistor output during the same rowing pattern following independent placement were obtained in one subject. No significant differences were identified between the two recordings.

Testing procedure: Prior to exercise testing of the subjects, lung function tests were performed as described below. The subjects were then asked to warm up and row on an indoor rowing ergometer (Concept II, Model C, Morrisville, Vt, U.S.A.) using their normal rowing style. After 3 to 5 min warm up the position of the receivers and thermistor (see below for placement details) were checked and corrected as necessary.

The subjects were then asked to undertake the experimental exercise protocol, rowing steadily for 10 min at a stroke rate of 18 strokes per min and a work rate equivalent to UT2. This refers to an endurance training pace commonly used where the rower rows at a stroke rate of 18-20 strokes per min and attempts to maintain a heart rate of between 130 and 150 beats per min throughout the exercise.

All lung function tests were then repeated within 2 min of the end of the experimental protocol.

Data collection and analysis: Rowing has previously been broken down into 4 distinct phases, the catch, drive, finish and recovery [8]. The stroke starts at the catch where the rower is in a fully compressed posture at the front of their slide with their arms extended, their back straight but flexed at the hips and the blade in the water. This is followed by the drive phase where the rower moves the blade through the water by extending their legs then their backs and finally by flexing their arms and bringing the blade handle into the body, the rower is now in the finish position. The final phase is the recovery, this involves the rower extending their arms, flexing their back and then bringing their legs back to a compressed position at the front of the slide in the catch position. These terms are further defined below with respect to the motion and force data recorded.

All data was sampled at a rate of 35 Hz and the synchronised output from the Flock of Birds, load cell and thermistor, were run through a custom written computer programme (in C++). The programme used the force data to detect the catch of each stroke and described the stroke in terms of percentage points with 0% representing the catch and 100% representing the return to the catch. The catch was defined as the point of tensile force onset at the handle. This was found to be a repeatable measure of catch and is based on the work of Bull and McGregor [1] and Holt *et al.* [6]. The finish was defined as the point at which tensile force production ceased. A further programme also calculated the average stroke data for each percentage point of the stroke in each recording, data were only recorded during the middle of the rowing piece to avoid the accelerations and decelerations and change in work level at the start and end of the rowing piece. The start of inspiration and expiration were extracted from the thermistor data and plotted against percentage of the stroke.

Results

General: All subjects completed the test protocol; however, some data on two of the subjects were lost due to technical difficulties, this included the last 7 min of one international subject and the last 6 min for the other. However, sufficient rowing strokes were obtained in the time period when recordings were complete. As expected, international athletes were able to produce a greater average stroke power and an increased stroke length. Differences in the shape of the force profile curve were also noted with international rowers achieving greater peak force at an earlier stage in the stroke than the senior or novice rowers. The lung function tests were performed on all subjects and the data for all subjects were consistent with values expected of the general rowing population (Table 2), [4]. There were no significant differences between the pre- and post- exercise protocol lung function tests. Peak mouth pressures for the rowers were consistently higher than those expected for the general population although there was minimal correlation between peak inspiratory pressure and peak expiratory pressure.

Table 2
Lung function data by competition level

	Novice (n=3)	Senior (n=7)	International (n=4)
PIP	-145±13	-137±33	-134±33
PEP	155±11	172±23	162±23
FVC PRE	6.2±0.8	5.6±0.5	7.4±0.5
FEV_1 PRE	5.4±0.9	5±0.5	5.6±0.5
% FEV_1 PRE	87%±4	89%±5	77%±5
FVC POST	6.1±0.9	5.6±0.5	7.3±0.5
FEV_1 POST	5.5±0.7	5±0.5	5.6±0.5
% FEV_1 POST	91%±7	90%±5	77%±5

PIP Peak inspiratory pressure in cm H_2O
PEP Peak expiratory pressure in cm H_2O
FVC Forced vital capacity
FEV_1 Forced expiratory volume in 1 second
% FEV_1=100(FEV_1/FVC)
PRE pre exercise
POST post exercise
Values are given as mean ± SD

International rowers: The average timings for the start of inspiration and expiration in these rowers are summarised in Table 3. Plots of the start of inspiration and expiration over the full 10 min against the percentage of the stroke showed a variation of ±5-7% for each of the international rowers, suggesting that the patterns observed were consistent for each rower. However there were systematic, clear differences between individuals in the timing and phases of breathing relative to the stroke characteristics.

Subject #1 began expiration at 15% of the stroke; this coincided with a change in the rate of change of lumbothoracic and lumbopelvic rotation as the back extended during the drive. Inspiration began at 35% of the stroke as lumbothoracic and lumbopelvic measures showed the spine rotating anteriorly during the start of the recovery. The second expiration began at 60% of the stroke and the second inspiration at 93% of the stroke, both during the recovery phase. Subject #2 had a similar pattern; timing breaths at 10%, 35%, 60% and 90% of the stroke. A final expiration in this subject was associated with lumbothoracic rotation anteriorly and lumbopelvic rotation posteriorly as the subject approached the catch. This subject had been operated on for previous lumbar spine problems which may be of relevance.

Subject #3 began inspiration at 3% of the stroke and expiration at 23% of the stroke. 23% of the stroke was the point at which the rower achieved maximum posterior rotation of the spine just prior to the finish of the stroke. The second inspiration began at 42% of the stroke as the rower's spine began rotating anteriorly during early recovery and expiration occurred at 77% of the stroke.

Subject #4 entrained at 1 breath per stroke and began exhaling shortly after the catch at about 4% of the stroke and then inhaling at about 54% of the stroke during the recovery. The subject had one break in entrainment after 3 min and 50 s of the test at which time he introduced a second breath beginning with inspiration as the legs reached maximal extension during the drive. This extra breath coincided with a slight increase in flexion of the femur prior to forward movement along the slide which suggests that the extra breath may have interrupted the kinematics of the stroke.

Table 3
The average timing of breath phase with respect to the rowing stroke for four international athletes over a 10 min period

Subject	Percentage of the rowing stroke			
1	15 (e)	35 (i)	60 (e)	93 (i)
2	10 (e)	35 (i)	60 (e)	90 (i)
3	3 (i)	23 (e)	42 (i)	77 (e)
4		4 (e)	54 (i)	

(i) denotes the start of inspiration; (e) denotes the start of expiration
see details in the text

Senior rowers: Rowers entraining at 2 breaths per stroke showed consistency, timing of the start of inspiration and expiration during the rowing stroke with a variation of ± 7-15% of the normalised stroke. Subjects with more experience showed more consistency with a variation of ±7-10% of the normalised stroke. The average timings for the senior level rowers are shown in Table 4.

Entrainment at 2 breaths per stroke had a similar pattern in all members of this group and followed the same pattern as two of the international rowers (subjects #1

& 2). Expiration began at 8-15% of the stroke, during the drive phase and was followed by inspiration at 35-40% of the stroke. Inspiration at this point generally occurred when lumbothoracic and lumbopelvic measures indicated the start of anterior rotation of the spine during the early recovery phase. The second expiration began at 60-70% of the stroke and the second inspiration at 85-90% of the stroke during the recovery phase. This final inspiration occurred with changes in lumbothoracic and lumbopelvic rotation in 4 out of 6 rowers. These changes may be indicative of poor technique with three rowers (subjects #8, #9 & #10) performing extra anterior rotation of the spine (taking extra lean) at the catch and a fourth rower (subject #7) performing posterior lumbopelvic rotation with anterior lumbothoracic rotation (slouching) prior to the catch. Subject #7 had experienced previous back problems that may be of relevance.

Subject #11, who entrained at 3 breaths per stroke, did so with two breaths during the drive and one breath during the recovery. The subject demonstrated a number of breaks in entrainment at which time he switched to either 2 or 4 breaths per stroke for a period of 3 or less strokes. Interestingly this rower had the smallest FVC of all the subjects at 5.05 litres.

Table 4
The average timing of breath phase with respect to the rowing stroke for seven senior level athletes over a 10 min period

Subject	Percentage of the rowing stroke					
5	8 (e)	34 (i)	63 (e)	83 (i)		
6	10 (e)	36 (i)	70 (e)	99 (i)		
7	7 (e)	39 (i)	69 (e)	86 (i)		
8	13 (e)	36 (i)	64 (e)	90 (i)		
9	16 (e)	40 (i)	64 (e)	91 (i)		
10	10 (e)	39 (i)	67 (e)	87 (i)		
11	9 (e)	20 (i)	32 (e)	50 (i)	77 (e)	99 (i)

(i) denotes the start of inspiration; (e) denotes the start of expiration
see details in the text

Small differences were observed between international and senior level rowers with respect to the number of strokes before entrainment (p=0.19) and the number of breaks from entrainment (p=0.08), although these were not statistically significant.

Novice rowers: The novice rowers (n=3) had respiratory patterns of 1 or 2 breaths per stroke, but for short periods only with large variations in breathing pattern over the 10 min period. Plots of the start of inspiration and expiration show that these variations occurred throughout the stroke. The rowers timed some breaths with kinematic events within the stroke although there was very little consistency.

Discussion

The subjects for our study were recruited from a variety of different rowing clubs in order to sample rowers who were representative of the general rowing population. In seeking generality the Concept II indoor rower was chosen for this study. However, ergometer rowing is different from rowing on water - although there are some similarities in leg and trunk movement [7]. A rate of 18 strokes per min was used in the current study as this is a typical rating for endurance training in rowing.

The nasal thermistor technique described in this study was used successfully to assess the details of the respiratory pattern in relation to body kinematics during rowing. Although the thermistor cannot quantify airflow it is able to detect accurately the start of both inspiratory and expiratory phases. The onset of the thermistor signal change was within 0.005 s of the initiation of the respiratory phase. Exhaled air temperature was significantly higher than the inhaled ambient air temperature and it was possible to distinguish the two from the onset of the change in thermistor output. Visual inspection of the rowers indicated that there were no periods of end expiratory breath-hold and that subjects switched from one phase to the other without interruption. Therefore the reported times for each respiratory phase indicate periods of active thoracic volume change.

The system measured respiratory rates from 18 to 72 breaths per min, the rates that were produced by rowers whilst rowing at normal stroke rates. These data, combined with well-established spinal kinematic and force measurements will allow the interrelationships between respiration timing and rowing mechanics to be investigated. The differences in respiration entrainment found in this study could affect the rowing movement, because of thoracic pressures. These may be related to the greater metabolic demands that the more experienced rowers have due to their increased power.

We observed entrained breathing in both senior and international level rowers and the consistency of that entrainment was dependent upon experience, with more experienced rowers showing more entrainment. Rowers were observed to entrain their breathing to stroke rate with inter-individual variations in the pattern of entrainment adopted; most of our subjects entrained breathing to a pattern of 2 breaths per stroke. This finding is in agreement with Steinacker *et al.* [13], and Mahler *et al.* [9]. Our study further suggests that experience is an important factor with regards to the consistency of entrainment, with the more experienced rowers demonstrating not only less variability in the stroke to stroke pattern of breathing but also more consistency in the timing of breaths within the stroke. The consistency observed here for the international rowers may help to explain the observation of Cunningham *et al.* [3]; that elite rowers experience a smaller reduction in VO_{2max} when rowing compared with cycling, as compared to novice rowers.

The findings of this study also indicate that lung vital capacity may influence the breathing pattern adopted by rowers. Previous studies have examined respiratory patterns during rowing [14] although those studies used a mouthpiece technique to measure respiration and this may itself influence the pattern of breathing [11].

In this study, definite ventilatory patterns and linkage to kinematics were observed which warrant further investigation. Three of the four international and six of the seven senior level rowers began exhaling shortly after the catch of the stroke and continued through to the finish of the stroke. Previous observations by Manning *et al.* [10] suggested that exhaling during the drive could increase intra abdominal pressure and that this might be used by rowers to stabilise their trunk during the drive phase of the stroke. The observations of our study support their hypothesis and demonstrate that in many rowers exhalation occurs during the mid and late drive phase at a time when increased stabilisation of the trunk may be needed. In view of the comparatively high frequency of back pain experienced by the rowing population, this relationship warrants further investigation.

Expiration during the recovery phase appeared unrelated to the body kinematics of the rower. However, the second inspiration of the stroke, initiated prior to the catch, was associated with different kinematic technique in some rowers. It may be that breath initiation during the active phase of the stroke represents a point of kinematic vulnerability and instability due to changing muscle recruitment. If so, this could potentially be important with regard to back injury.

In contrast to the reported observations of Siegmund *et al.*[12], the majority of our rowers avoided initiating breaths during the catch or finish of the stroke. This may be due to a cramped body posture during these stages of the stroke. Our findings suggest that at low stroke ratings and work rates, breathing may be regulated by the kinematics of the stroke rather than the inverse. The majority of our rowers initiated inspiration as the trunk rotated anteriorly during the early recovery phase. This may facilitate better use of the abdominal muscles for respiration.

In summary, this study has shown that it is possible to measure the timing of respiration during rowing using a nasal thermistor technique. This can be synchronised with kinematic data for lumbothoracic, lumbopelvic and femoral rotation in the sagittal plane, together with force production data and used to investigate respiratory patterns with respect to spinal kinematics and force production during the rowing stroke. This may provide useful information for coaches and rowers facilitating improvements in rowing technique.

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