The Influence of Prior Activity Upon Inspiratory Muscle Strength in Rowers and Non-Rowers

S. Volianitis[1], A. K. McConnell[1], Y. Koutedakis[2], D. A. Jones[1]

[1] School of Sport and Exercise Sciences, The University of Birmingham, Birmingham, United Kingdom
[2] School of Health Sciences, The University of Wolverhampton, Wolverhampton, United Kingdom

Volianitis S, McConnell AK, Koutedakis Y, Jones DA. The Influence of Prior Activity Upon Inspiratory Muscle Strength in Rowers and Non-Rowers. Int J Sports Med 1999; 20: 542–547

Accepted after revision: July 10, 1999

The aim of this study was to investigate whether a 'warm-up' phenomenon in the strength of the inspiratory muscles exists, and, under this assumption, whether whole body warm-up protocols or a specific respiratory warm-up is more effective in this respect. Eleven club level rowers performed a rowing warm-up, and twelve university students performed a general cycling warm-up. Both groups also performed a specific respiratory warm-up. Inspiratory muscle strength (Mueller manoeuvre) and lung function (flow-volume loops) were measured before and after the three conditions. Isokinetic strength during knee extension was measured before and after the rowing warm-up. The two whole body warm-up protocols had no effect on inspiratory muscle strength or any lung function parameter despite the significant (3.8 ± SD 1.4%; $p < 0.05$) increase in peak torque that the rowing warm-up elicited. The respiratory warm-up induced a significant increase in inspiratory mouth pressure (8.5 ± 1.8%; $p < 0.0001$) but not in any other lung function parameter. Following the rowing incremental test to exhaustion, maximum inspiratory pressure decreased by 7.0 ± 2.0%, which is an indication of respiratory muscle fatigue. These data suggest that the inspiratory muscle strength can be enhanced with preliminary activity, a phenomenon similar to the one known to exist for other skeletal muscles. In addition, a specific respiratory warm-up is more effective in this respect than whole body protocols.

■ Key words: Warm-up, rowing, Mueller manoeuvre, inspiratory muscles, isokinetic strength.

Introduction

Warm-up may be defined as any preliminary activity that is used to enhance physical performance and to prevent sports-related injuries. There are various types of warm-up techniques that competitors use to prepare for their event. The most widely used methods are classified as *passive, general* and *specific warm-up* [28].

Competitive rowing is considered to be one of the most demanding sports, as rowers work near their maximal physical capacities and recruit a very large muscle mass. Open class rowers generate amongst the highest values of any athletes in selected physical fitness parameters, including those related to cardiorespiratory and muscular function [16]. Warm-up is an integral part of the preparation before the start of the race.

Most general warm-up protocols are of moderate intensity and characterised by a low ventilatory demand [13]. In competitive rowing, however, a higher intensity specific warm-up usually follows the general warm-up in an attempt to practise the racing pace [8]. The higher intensity of the specific warm-up, among other peripheral adaptations, elicits an elevated ventilatory response that may prepare the respiratory muscles for the demanding entrained breathing of rowing [20, 29]. The effect of warm-up upon locomotor muscle strength is well documented [2, 3, 7, 10] but very little scientific attention has been directed towards the effect of warm-up on pulmonary function and specifically inspiratory muscle strength.

The present study sought to address the following questions: a) Does a whole body warm-up influence inspiratory muscle strength? b) Does a specific respiratory warm-up affect the inspiratory muscle strength? Accordingly, we compared the effects of 3 warm-up protocols, a general cycling warm-up, a rowing warm-up, and a specific respiratory warm-up. Our hypothesis was that the inspiratory muscles will exhibit an improvement in performance similar to that observed in other skeletal muscles following at least one of these conditions.

Int J Sports Med 1999; 20: 542–547

ISSN 0172-4622

Methods

Subjects

A total of 23 subjects participated after giving informed written consent to the study that was approved by the local Ethics Committee. Twelve Sport Science students formed the 'rowing' group. Characteristics of the two groups are shown in Table **1**. One of the subjects was removed from the study because he developed a respiratory tract infection within two weeks of the data collection, a condition known to have potential effects on respiratory muscle strength [24].

Table 1 Characteristics of the two groups

Mean ± SD	Non-rowing (n = 12)	Rowing (n = 11)
Age (yr)	20 ± 1	20 ± 2
Height (cm)	175 ± 8	180 ± 6
Weight (kg)	70 ± 11	74 ± 8
FVC (1)	5.4 ± 0.9	5.3 ± 0.6
FEV_1 (1)	4.6 ± 0.6	4.5 ± 0.5
FEV_1/FVC (%)	86 ± 8	87.2 ± 7
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	47 ± 7	58 ± 7

Procedure

Before data collection, all subjects visited the lab on two occasions to be familiarised with mouth pressure measurements and flow volume manoeuvres. Subsequently, both groups performed an incremental test to volitional exhaustion, a whole body warm-up, and a specific respiratory warm-up, which took place on three separate occasions. The non-rowing group, which used a cycle ergometer for the incremental test and the whole body warm-up, performed a general warm-up while the rowing group, which used a rowing ergometer for the respective exercise sessions, performed a rowing warm-up consisting of a general and a sport specific warm-up. The specific respiratory warm-up was performed using a pressure threshold inspiratory muscle training device. Maximum mouth pressures and pulmonary function were assessed before and after every treatment condition. Additionally, as an index of the warm-up effect on the peripheral musculature, isokinetic strength of the quadriceps was measured before and after the rowing warm-up.

Maximum inspiratory pressures (MIP)

MIP is commonly used to measure inspiratory muscle strength. It reflects the force-generating capacity of the combined inspiratory muscles during a brief, quasi-static contraction (Mueller manoeuvre) [17]. MIP was recorded using a portable hand held mouth pressure meter (Precision Medical, UK). This device has been shown to measure inspiratory efforts accurately and reliably [9]. A minimum of five and a maximum of nine technically satisfactory measurements were conducted, and the highest of three measurements with 5% variability or within 5 cm H_2O difference was defined as maximum [31]. The initial length of the inspiratory muscles was controlled by initiating each effort from residual volume (RV). This procedure was adopted because, from our experience, RV is more reproducible than functional residual capacity (FRC). Subjects were instructed to take their time and to slowly empty their lungs to RV, thereby avoiding problems associated with variability in lung volumes. All manoeuvres were performed in the upright standing position, and verbal encouragement was given to help the subjects perform maximally.

Static spirometry

Pulmonary function was assessed with a Vitalograph 2120 portable spirometer (Vitalograph Ltd., Buckingham, England), which was calibrated prior to each testing session using a 3 litre calibration syringe (Hans Rudolph Inc., Kansas, USA). Following familiarisation, the best of three manoeuvres were recorded. Forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), percentage expired (i.e. $100 \times FEV_1/FVC$) (FEV_1 %) and peak inspiratory flow rate (PIFR) were the parameters recorded before and after every treatment condition.

Incremental test to exhaustion (Peak $\dot{V}O_2$)

The no-rowing group performed a continuous incremental protocol to volitional exhaustion on an Excalibur Sport V2.0 electromagnetically braked cycle ergometer. The work rate was increased every fifteen seconds and was designed to elicit maximal oxygen uptake (peak $\dot{V}O_2$) within ten to twelve minutes. The test was terminated at volitional exhaustion or when the subject failed to maintain a pedalling frequency higher than 50 rpm.

The rowing group performed an incremental test to volitional exhaustion on a wind-resistance braked rowing ergometer (Concept II, model c, Morrisville, USA) starting at an individually chosen light work intensity and increasing the workrate by 50 W every 3 minutes. The wind damper was at the fourth setting. Power was calculated from acceleration of the flywheel and displayed on a monitor. Maximal power (Pmax) was calculated as

$$P_{max} = P_{n-1} + ([[P_n - P_{n-1}] \cdot t_n]/180)$$

with P_n = power of the maximum stage, P_{n-1} = power of the stage before, and t_n = time of work of the maximum stage in seconds [18].

Breath by breath gas analysis was made with an MGA 2000 Mass Spectrometer (Aispec Ltd., Kent, UK) in conjunction with an ultrasonic phase-shift flowmeter (Birmingham Flowmetrics, Birmingham, UK). Data processing was performed on-line (Labview 3, National Instruments, Austin TX, USA) on a Powermac 7100/80 (Macintosh Ltd., USA). Calibration of the flowmeter was performed before each test using a 1 litre calibration syringe (PK Morgan Ltd., Kent, UK). The heart rate was telemetrically monitored with Polar Accurex Plus heart rate monitor (Polar Electro, Finland).

General warm-up

Twenty min of cycling was performed on the same cycle ergometer as in the incremental test. The first 10 min were performed at 30% of peak work rate (WRpeak), the next 5 min at 35%, and the final 5 min at 40%. Pedalling frequency was maintained between 70–80 rpm. This modest-intensity protocol was intended to assimilate the general warm-up preceding the sport specific warm-up. Breath by breath gas exchange-analysis and heart rate data were collected as during the peak $\dot{V}O_2$ test. Post warm-up measurements were made within two minutes of completion.

Rowing warm-up

The protocol was designed to mimic as closely as possible the routine that is usually adopted in preparation for a rowing race. Five minutes of very light jogging on the treadmill, at a heart rate of 110–130 b/min, were followed by 10 minutes of stretching. Subseqúently, 12 minutes rowing of gradually increasing intensity were performed during which the heart rate increased from 148 (± 2) to 178 (± 1.7) b/min. The increase in intensity was achieved primarily by increasing the stroke rate. Then 5 sprints with increasing stroke rate and power output were performed. Between each sprint there was an active rest interval of light paddling which lasted approximately 2 minutes. At the end of the sprints the rower rested for approximately 5–7 minutes before any further measurements were made. This rest interval was designed to simulate the small pause between the end of the warm-up and the start of the race. Details of the structure of the rowing warm-up can be seen in Table 2. Breath by breath gas analysis and heart rate data were again collected.

Table 2 Description of the rowing warm-up on the rowing ergometer

Warm-up (time)	Stroke rate/min @	Percent Power Max (% P_{max})
1 × 12 min (4-4-3-1)	18-20-22-24	50-60-70-75
2 × 30 s	26-28	94.7 (± 3.7) – 103.6 (± 2.6)
2 × 45 s	28	108.9 (± 2.9) – 115 (± 2.6)
1 min	30-32	132.2 (± 5.0)

% P_{max} = percentage of maximum power output achieved during the incremental test

Respiratory warm-up

Two sets of 30 breaths were performed using POWERbreath® inspiratory muscle trainer (IMT Technologies Ltd., Birmingham, UK) at 40% of the MIP measured before the start of the protocol. Between the two sets there was a short rest interval while an intermediate MIP measurement was made. Forty percent of maximum capacity has been suggested to approximate the upper loading limit before fatigue of the diaphragm occurs [26]. POWERbreath® is a pressure-threshold device which requires continuous application of inspiratory pressure throughout inspiration in order for the inspiratory regulating valve to remain open. As with the maximal inspiratory pressures subjects were instructed to initiate every breath from RV. They continued the inspiratory effort up to the lung volume where the inspiratory capacity for the given resistance limited further excursion of the thorax. Powerful execution of the manoeuvres was encouraged to ensure maximal voluntary output for the given loading conditions. Because of the increased tidal volume, a decreased but spontaneous breathing frequency was adopted by the subjects in order to avoid hyperventilation.

Isokinetic strength

Dynamic isokinetic strength was measured before and aft the rowing warm-up. Peak torque (Nm) and angle (degree of peak torque was measured during a concentric knee exte sion of the dominant leg on a Cybex Norm isokinetic dyn mometer (Cubex International, Inc. Ronkonkona, New Yor USA). A relatively slow speed of 60°/s was chosen to approx mate the slow velocity encountered in rowing. All subjec had at least two practice trials on previous occasions for fami iarisation with the nature of the dynamometer and the specifi testing velocity. On the test day three practice trials with light effort preceded the three maximum efforts from whic the best value was taken for further analyses.

Statistical analyses

Student's t-test for paired samples was used to compare differ ences between the MIP values before and after the two whole body warm-up protocols. ANOVA with repeated measures and Scheffé post-hoc test was used to assess differences in the RespWU. Values of $P < 0.05$ were considered statistically significant. Data points were means (± SE) unless otherwise stated.

Results

Rowing warm-up and general warm-up characteristics

Compared with the peak $\dot{V}O_2$ test the rowing warm-up and the general warm-up elicited a ventilatory response with the characteristics shown in Table 3.

Table 3 Data obtained from the general and the rowing warm-up expressed as percent peak values observed during the peak $\dot{V}O_2$ test (Data for the rowing warm-up is from the 12 minutes continuous rowing phase)

Mean (± SE)	General	Rowing
V_E%	40.1 (± 6.9)	70.1 (± 2.6)
$\dot{V}O_2$%	62.3 (± 9.5)	80.5 (± 2.4)
f_c%	71.2 (± 3.2)	90.1 (± 1.0)
VT_I%	88.1 (± 12.6)	88.2 (± 1.7)
f_b%	52.7 (± 5.8)	76.6 (± 3.1)
PIFR %	47.4 (± 9.6)	65.1 (± 1.3)

V_E = minute ventilation, VT_I = tidal volume (inspired), f_b = frequency of breathing, PIFR = peak inspiratory flow rate, f_c = cardiac frequency

Isokinetic strength

The peak torque of the leg extension increased significantly after the rowing warm-up by 3.8 (± 1.4)% ($P < 0.05$). The angle of peak torque increased by 2.8 (± 3.1)% but this increase was not significant.

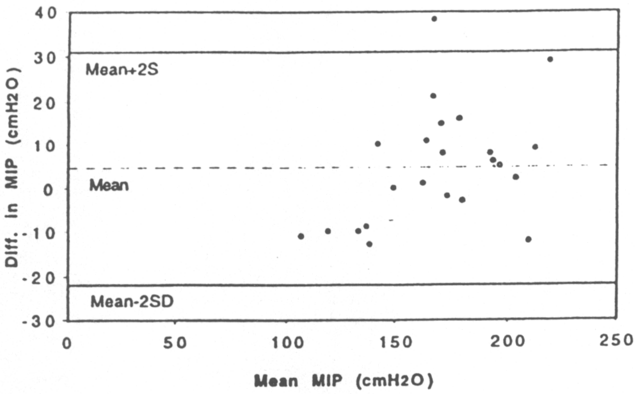

Fig. 1 Bland-Altman plot for reproducibility of baseline MIP between whole body warm-up protocols and respiratory warm-up.

MIP

Test – retest reproducibility of MIP

The two baseline measurements, i.e. before the whole body and respiratory warm-ups, permitted a test-retest assessment of MIP. For the comparison of baseline MIP values the data of both groups were pooled. The mean baseline MIP values of the whole body warm-up protocols and the respiratory warm-up were not significantly different, the mean difference being less than 5 cm H_2O. The mean (± SE) coefficient of variation (CV = 100% × SD/mean) for the baseline MIP measured on the two occasions was 4.65 (± 0.76)%. Additional analysis using the Bland-Altman plot [6] (Fig. 1) revealed a repeatability coefficient of 26.6 cm H_2O.

Influence of maximal testing upon MIP

Immediately after the incremental cycling (peak $\dot{V}O_2$) test MIP decreased by 2.2 ± 3.0% from the baseline; this difference was not significant. After the incremental rowing (peak $\dot{V}O_2$) test MIP decreased by 7.0 ± 2.0% which was significant ($P < 0.01$).

Influence of whole body warm-up on MIP

For the comparison between whole body warm-up protocols the two groups have been analysed separately. After the general warm-up MIP increased from a baseline of 171.4 (± 9.0) cm H_2O to 178.8 (± 12.6) cm H_2O, a mean (± SE) percent increase of 3.4 (± 2.5); this difference was not significant ($p > 0.05$). After the rowing warm-up baseline MIP increased from a mean of 161.1 (± 7.5) cm H_2O to 162.8 (± 10.7), a mean (± SE) percent increase of 0.3 (± 3.2)% which again was not significant ($p > 0.05$).

Influence of respiratory warm-up on MIP

For the comparison of MIP values before and after the respiratory warm-up the data from the two groups were pooled. The respiratory warm-up induced a significant increase in MIP from a mean baseline of 171.2 (± 7.0) cm H_2O to 178.1 (± 6.8) cm H_2O after 30 breaths, a 4.5 ± 1.1% increase ($P < 0.001$). After 60 breaths the mean MIP increased further to 184.2 (± 6.4) cm H_2O, an additional significant increase of 3.8 ± 1.3% ($p < 0.01$). The total increase from baseline was 8.5 ± 1.8% ($p < 0.0001$).

Table 4 Mean (SE) percent changes between baseline and the three warm-up protocols. Results shown under respiratory warm-up are pooled data for both groups

	General (n = 12)	Rowing (n = 11)	Respiratory (n = 23)
MIP %	3.4 (2.5)	0.3 (3.2)	8.5 (1.8)*
FVC %	1.9 (2.4)	– 1.0 (1.4)	1.0 (1.2)
FEV_1 %	– 1.0 (1.3)	0.4 (0.9)	0.4 (0.9)
FEV_1/FVC %	– 1.3 (1.5)	1.4 (1.5)	1.4 (1.5)
PIFR %	– 1.2 (2.3)	0.3 (3.1)	1.75 (2.1)

MIP = maximum inspiratory pressure, PIFR = peak inspiratory flow rate. *Denotes significance ($p < 0.0001$)

Lung function

There were no significant changes in the parameters measured other than MIP. Pulmonary function data obtained after the general, rowing and respiratory warm-ups are summarised in Table 4.

Prediction of warm-up effect

Post-respiratory warm-up MIP was significantly correlated with the baseline MIP ($p < 0.001$), and this relationship can be described by the two linear models on Table 5, derived from data taken after the two sets of 30 breaths of the respiratory warm-up.

Table 5 Predictive equations for MIP

Respiratory warm-up	R^2	Regression equation
30 breaths	0.9409	$y = 0.9344 \times + 18.099$
60 breaths	0.8667	$y = 0.8506 \times + 38.539$

Discussion

The main finding of this study was that MIP increased significantly following the respiratory warm-up but not following the two whole body warm-up protocols. This phenomenon, which emerges with at least 30 breaths using POWERbreath®, raises the possibility that the respiratory system may have different warm-up requirements (threshold) than the locomotor system.

Emphasis was given to the methodological issues related with the Mueller manoeuvre. The variability in MIP between baselines is in agreement with previous reports on test-retest reproducibility [17]. The mean coefficient of variation, which was smaller than reported previously [1,4,32], as well as the coefficient of repeatability from the Bland-Altman plot, which is in agreement with the study of Maillard and others [21], suggest that the task learning effect was expressed and reliable baselines were established.

Another interesting observation was that following the incremental rowing test to exhaustion MIP decreased, whilst no significant changes occurred after the incremental cycling protocol. These data are suggestive of respiratory muscle fatigue and are in agreement with previous reports of the effect of exhausting exercise upon respiratory muscle function [11,12, 19,22]. During rowing thoracic muscles are responsible not only for the act of breathing but also for the stabilisation of the thorax [6]. This additional role of respiratory muscles in the locomotive work of rowing might be the reason for the development of inspiratory muscle fatigue in such a short time compared with longer exercise durations reported previously. Even though the entrained breathing observed in rowing is suggestive of a possible scenario for respiratory muscle fatigue, no study has reported it previously. Clearly more work needs to be done in the breathing requirements of rowing to understand the functional significance of these findings.

The precise mechanism(s) responsible for the increase in MIP following the respiratory warm-up cannot be identified easily. A skeletal muscle warm-up has been reported to have an effect on maximum isometric force when the change in the muscle temperature is substantial [2,25]. However, since in the present study it was not possible to measure the temperature of the diaphragm or the intercostal muscles, we can only suggest that a temperature related effect, if any, was unlikely. This suggestion is justified under the assumption that the temperature of the diaphragm and the other inspiratory muscles is essentially equal to the core temperature because of their location.

Thus, by a process of elimination an altered motor control hypothesis is suggested. It is possible that the intermuscular coordination between inspiratory and expiratory muscles is improved in a manner similar to the one identified for other skeletal muscles [15]. Repeated performance of the specific recruitment pattern might decrease the degree of co-contraction known to exist between inspiratory and expiratory muscles at RV and consequently improve force generation.

The protocols used in the general warm-up and the rowing warm-up did not alter MIP. A possible explanation may be that, due to the modest ventilatory response elicited by the general warm-up, the threshold required for the respiratory muscles 'warm-up' was not achieved. However, during the rowing warm-up the ventilatory response was more pronounced, as can be seen from Table 3, but again MIP did not change. Comparing the breathing patterns of the two whole body warm-up protocols, we notice that thoracic excursions were of similar magnitude. The elevated minute volume of the rowing warm-up was effected through increases in breathing frequency as expected. These sub-maximal unloaded breathing patterns, predominantly characterised by diaphragm participation, are different from the pattern of a relative chest wall muscle recruitment observed during the Mueller manoeuvre [24]. Therefore, the recruitment pattern involved could be suggestive of a relative insensitivity of the Mueller manoeuvre to tension changes effected by diaphragm participation.

In contrast, during the respiratory warm-up the recruitment of the chest wall muscles is substantial, as loading compensation enhances the inspiratory activity of the external intercostal muscles. Furthermore, deliberate inspiratory efforts tend to make greater use of inspiratory intercostal muscles of the chest wall than do spontaneous metabolically stimulated inspirations [31]. It has often been observed in strength-training studies that increases in strength depend on how similar the strength test is to the actual training exercise in terms of muscle fibre length and type of contraction [27]. Indeed, the recruitment pattern of the Mueller manoeuvre is more similar to the pattern of the respiratory warm-up than the pattern of the two whole body warm-up protocols.

The rowing warm-up increased the peak torque measured during concentric knee extension and confirms its effectiveness as a preliminary activity. These data are also in agreement with previous reports on the beneficial effects of sport specific warm-ups [13,28]. The fact that the rowing warm-up failed to enhance MIP suggests that the respiratory muscles may not be optimally prepared before the start of a rowing race. Additionally, the possibility of a discrepancy between the work intensity required, for an enhanced function of the respiratory muscles and the muscles of locomotion, is raised. An improved functional capacity of the inspiratory muscles, as a result of the warm-up, may allow a decrease in recruitment requirements and minimise in doing so the sensation of breathlessness. Indeed, strong relationship between recruitment of the inspiratory muscles and the perception of dyspnea has been suggested [14]. More work is needed to investigate the potential effect of this upon the perception of breathlessness and rowing performance.

Finally, our data suggest that in the clinical and academic fields studies that examine the function of the inspiratory muscles under different treatment conditions should account for a 'warm-up' effect on baseline MIP. Indeed, studies examining postexercise inspiratory muscle fatigue might reveal that the degree of fatigue reported is larger than previously thought. Likewise, results from studies that have failed to observe the presence of fatigue may have done so because it was masked by the 'warm-up' effect.

Conclusions

A warm-up phenomenon, similar to the one present in locomotion, exists in the inspiratory muscles. This enhancement is more effectively elicited by specific inspiratory manoeuvres than by whole body warm-up protocols.

References

1. Aldrich TK, Spiro P. Maximal inspiratory pressure: does reproducibility indicate full effort? Thorax 1995; 50: 40 – 43
2. Bergh U, Ekblom B. Influence of muscle temperature on maximal strength and power output in human skeletal muscles. Acta Physiol Scand 1979; 107: 33 – 37
3. Binkhorst RA, Hoofd L, Vissers ACA. Temperature and force-velocity relationship of human muscles. J Appl Physiol 1977; 42: 471 – 475
4. Black LF, Hyatt RE. Maximal respiratory pressures: normal values and relationship to age and sex. Am Rev Respir Dis 1969; 99: 696 – 701
5. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; i: 307 – 310
6. Dal Monte A, Komor A. Rowing and sculling mechanics. In: Vaughan CL (ed). Biomechanics of sport. Boca Ration, FL: CRC Press, 1989: 53 – 119
7. de Vries HA (ed). Physiology of Exercise for Physical Education and Athletics. Dubuque: William C. Brown, 1980

8. Grosser M (ed). Schnelligkeitstraining. München: BLV Verlagsgesellschaft mbH, 1991
9. Hamnegard CH, Wragg S, Kyroussis D, Aquilina R, Moxham J, Green M. Portable measurement of maximum mouth pressures. Europ Respir J 1994; 7: 398–401
10. Hill AV (ed). Living Machinery. New York, Harcourt: Brace and World, 1927
11. Hill NS, Jacoby C, Farber HW. Effect of an endurance triathlon on pulmonary function. Med Sci Sports Exerc 1991; 23: 1260–1264
12. Johnson BD, Aaron EA, Babcock MA, Dempsey JA. Respiratory muscle fatigue during exercise: impliations for performance. Med Sci Sports Exerc 1996; 28: 1129–1137
13. Karvonen J. Important of warm-up and cool down on exercise performance. In: Karvonen J, Lemon PWR, Iliev I (eds). Medicine in sports training and coaching. Basel: Karger, 1992; 35: 189–214
14. Killian KJ, Jones NL. Respiratory muscles and dyspnea. Clin Chest Med 1988; 9: 237–247
15. Komi PV (ed). Strength and power in sport. Oxford: International Olympic Committee, Blackwell Publications, 1992: 260
16. Koutedakis Y, Sharp NCC. Fitness assessment of elite competitors. Rheumatology Now 1990; 1 (5): 18–20
17. Larson JL, Covey MK, Vitalo CA, Alex CG, Patel M, Kim MJ. Maximal inspiratory pressure. Learning effect and test-retest reliability in patients with chronic obstructive pulmonary disease. Chest 1993; 104: 448–453
18. Lormes W, Buckwitz R, Rehbein H, Steinacker JM. Performance and blood lactate on Gjessing and Concept II rowing ergometers. Int J Sports Med 1993; 14: S29–S31
19. Mahler DA, Loke J. Pulmonary dysfunction in ultramarathon runners. Yale J Biol Med 1981; 54: 243–248
20. Mahler DA, Shuhart CR, Brew E, Stukel TA. Ventilatory responses and entrainment of breathing during rowing. Med Sci Sports Exerc 1991; 23: 186–192
21. Maillard JO, Burdet L, van Melle G, Fitting JW. Reproducibility of twitch mouth pressure, sniff nasal inspiratory pressure, and maximal inspiratory pressure. Eur Respir J 1998; 11: 901–905
22. McConnell AK, Caine MP, Sharpe GR. Inspiratory muscle fatigue following running to volitional fatigue: The influence of baseline strength. Int J Sports Med 1997; 18: 169–173
23. Mier-Jedrzejowicz A, Brophy C, Green M. Respiratory muscle weakness during upper respiratory tract infections. Am Rev Respir Dis 1988; 138: 5–7
24. Nava S, Ambrosino N, Crotti P, Fracchia C, Rampulla C. Recruitment of some respiratory muscles during three maximal inspiratory manoeuvres. Thorax 1993; 48: 702–707
25. Ranatunga KW, Sharpe B, Turnbull B. Contractions of a human skeletal muscle in different temperatures. J Physiol 1987; 390: 383–395
26. Roussos CS, Macklem PT. Diaphragmatic fatigue in man. J Appl Physiol 1977; 43: 189–197
27. Sale DG, MacDougall D. Specificity in strength training: a review for the coach and the athlete. Can J Appl Sports Sci 1981; 6: 87–92
28. Shellock FG, Prentice WE. Warming-up and stretching for improved physical performance and prevention of sports-related injuries. Sports Med 1985; 2: 267–278
29. Steinacker JM, Both M, Whipp BJ. Pulmonary mechanics and entrainment of respiration and stroke rate during rowing. Int J Sports Med 1993; 14: S15–S19
30. Wen AS, Woo MS, Keens TG. How many manoeuvres are required to measure maximal inspiratory pressure accurately? Chest 1997; 111: 802–807
31. Whitelaw WA, Feroah T. Patterns of intercostal muscle activity in humans. J Appl Physiol 1989; 67: 2087–2094
32. Wilson SH, Cooke NT, Edwards RHT, Spiro SG. Predicted normal values for maximal respiratory pressures in Caucasian adults and children. Thorax 1984; 39: 535–538

Corresponding Author:

Stefanos Volianitis

Sport Medicine and Human Performance Unit
School of Sport and Exercise Sciences
University of Birmingham
Edgbaston
Birmingham B15 2TT
United Kingdom

Phone: +44 (121) 4147379
Fax: +44 (121) 4144764
E-mail: Stefanos.Volianitis@mailexcite.com