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ORIGINAL ARTICLE

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Effect of specific inspiratory muscle warm-up on intense intermittent run to exhaustion

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Abstract The effects of inspiratory muscle (IM) warm-up on the maximum dynamic IM function and the maximum repetitions of 20-m shuttle run (Ex) in the Yo-Yo intermittent recovery test were examined. Ten men were recruited to perform identical IM function test and exercise test in three different trials randomly. The control trial was without IM warm-up while the placebo and experimental trials were with IM warm-up by performing two sets of 30 breaths with inspiratory pressure-threshold load equivalent to 15% (IMW_P) and 40% (IMW) maximum inspiratory mouth pressure, respectively. In IMW, maximum dynamic IM functions including the maximal inspiratory pressure at zero flow (P_0) and maximal rate of P_0 development (MRPD) were increased compared with control values ($P < 0.05$). The Ex was also augmented [mean (SD)] [19.5% (12.6)] while the slope of the linear relationship of the increase in rating of perceived breathlessness for every 4th exercise interval (RPB/4i) was reduced ($P < 0.05$). In IMW_P, although increase in Ex and reduction in RPB/4i were occurred concomitantly in some subjects, the differences in Ex, RPB/4i and dynamic IM functions between control and IMW_P trials were not statistically significant. For the changes (Δ) in parameters in IMW and IMW_P ($n = 20$), negative correlations were found between Δ RPB/4i and Δ Ex ($r = -0.92$), ΔP_0 and Δ RPB/4i ($r = -0.48$), and Δ MRPD and Δ RPB/4i ($r = -0.54$). Such findings suggested that the specific IM warm-up in IMW may entail reduction in breathlessness sensation, partly attributable to the enhancement of dynamic IM functions, in subsequent exhaustive intermittent run and, in turn, improve the exercise tolerance.

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Introduction

The prior application of physical activity at moderate intensity is widely accepted as an effective means to warm-up the locomotor muscles to work at intense level (Burnley et al. 2005). However, the accompanied mild ventilatory activity may not be effective to enhance the ventilatory muscles to work at optimal synergy. Volianitis et al. (1999) reported that the rowing warm-up that was similar to the routine adopted in preparing for a rowing race had no effect on inspiratory muscle (IM) strength despite the significant improvement in leg muscle peak torque the rowing warm-up elicited. On the other hand, they found that ventilatory activity applied to IM at moderate intensity could increase the force-generation capacity of the muscle (Volianitis et al. 2001a). Such specific IM activity ("warm-up") in addition to a rowing-specific warm-up protocol was further shown to improve subsequent performance in a 6-min all-out rowing test and the improvement was partly attributed to the reduction in intensity of breathlessness sensation (Volianitis et al. 2001b).

Recently, the breathlessness sensation elicited during intense intermittent exercise at exhaustion in normal active persons was shown to play a part in limiting the exercise maintenance (Tong et al. 2001a, 2003a, 2004). It was also noted that the intensity of breathlessness sensation during the exercise was proportional to the magnitude of IM force output relative to the maximum dynamic force utilized by the muscles (Tong et al. 2004). Romer et al. (2002a, 2002b) reported that improving the maximum dynamic IM function could reduce the intensity of breathlessness sensation during maximal incremental exercise and sub-maximal shuttle run. It was therefore hypothesized that the addition of the IM warm-up to a general whole-body warm-up protocol could enhance the maximum dynamic IM function. The plausible enhancement may potentially improve one's ability to sustain subsequent intense intermittent exercise by lessening the noxious breathlessness sensation. However, Steinacker et al. (1993) reported that the ventilatory muscles including the IM of rowers during rowing are not only recruited for moving the chest wall for ventilation purpose. The muscles also work to stabilize the thorax for the promotion of stroke. In addition of the entrainment of breathing with the stroke rate, the ventilatory muscle work and the elicited breathlessness sensation during rowing are beyond those for ventilation. It was not clear if the beneficial effect of the IM warm-up on rowing performance shown previously was just resulted from the compensation for the extra stress in the IM, which was rowing-specific and non-ventilatory related, with the improved IM function.

In contrast to rowing, the IM of athletes during running exercise mainly works for meeting the ventilatory demand. Further, the breathing mechanics in the crouched position of rowing/cycling differs from that in the upright position of running. One of the discrepancies is that the crouched position increases the abdominal impedance, thus the diaphragmatic work for given ventilation (Boussana et al. 2003). To our knowledge, whether the ergogenic effect of the IM warm-up shown in short-term all-out rowing also existed in intense intermittent run has not been investigated. The present study was designed to examine the effect of the addition of the IM warm-up to a general whole-body warm-up protocol on the maximum dynamic IM function and on the intensity of breathlessness sensation and exercise tolerance during subsequent intense intermittent run.

Methods

Subjects

Ten healthy young males who were asymptomatic for cardiovascular or respiratory disease and engaged in regular various sports training (soccer, rugby, etc.) volunteered for the study (Table 1). After receiving explanations of the purposes and constraints of the study, and the potential benefits and risks involved in the exercise tests, subjects gave their written consent. This study was approved by the Committee on the Use of Human and Animal Subjects in Teaching and Research of Hong Kong Baptist University.

Table 1 Physical characteristics of the subjects ($n = 10$)

Age (years)	21.3 (1.2)
Height (cm)	175.4 (6.9)
Weight (kg)	69.9 (8.1)
FVC (l)	4.8 (0.7)
FEV_1 (l)	3.9 (0.6)
FEV_1/FVC (%)	81.5 (5.3)
12-s MVV (l min^{-1})	171.1 (25.9)
$\dot{V}O_{2\,max}$ (ml kg^{-1} min^{-1})	62.9 (4.2)
$\dot{V}_{E\,max}$ (l min^{-1})	149.5 (18.2)
HR_{max} (beats min^{-1})	197.3 (9.0)

Values are means (SD)
FVC is forced vital capacity, FEV_1 is forced expiratory volume in 1 s, 12-s MVV is maximum voluntary ventilation measured in 12 s, $\dot{V}O_{2\,max}$, $\dot{V}_{E\,max}$ and HR_{max} are maximum oxygen consumption, maximum minute ventilation and maximum heart rate, respectively, recorded in the maximum graded treadmill-running test

Procedures

Preliminary testing and familiarization

Before experimental trials, forced spirometry and aerobic capacity were assessed. The details of these assessments were previously reported (Tong et al. 2001b). After the preliminary testing, a familiarization trial identical to the control trial was undertaken to familiarize the subject with the sensation of exercising to exhaustion, and with the testing equipment and procedures.

Experimental trials

The subject was required to perform identical maximum dynamic IM function test and Yo-Yo intermittent recovery test in three conditions randomly. One was without IM warm-up (CON) and the other two were with IM warm-up by performing two sets of 30 breaths with inspiratory pressure-threshold equivalent to 15% (IMW_P) and 40% (IMW) maximum inspiratory mouth pressure, respectively. The CON was the control trial. The IM warm-up in IMW_P which had no significant effect on maximum dynamic IM function in normal persons shown in pilot tests served as the placebo while the IMW was the experimental trial. The exercise test in the IMW condition was performed twice. The repeated trial was used to examine the repeatability of the change in the maximum performance of the exercise test from control. The IM function test and the exercise test in each condition were conducted separately on two different days. The IM function tests were conducted in an air-conditioned laboratory with a temperature and relative humidity set at 22°C and 70%, respectively. The exercise tests were conducted in an indoor sports hall that was next to the laboratory with environment similar to that in the laboratory. The subject was refrained from eating at least 2 h before the maximum dynamic IM function test and from participation in strenuous physical activity at least 1 day before the exercise trial. The tests were scheduled to occur at the same time of day and were separated by a minimum of 3 days.

Protocol

After reporting to the laboratory, the subject performed a standardized whole-body warm-up exercise. The protocol of the standardized warm-up exercise composed of 5-min moderate treadmill running at self-selected speed, 10-min stretching exercise followed by 5-min free running on ground at self-selected pace. The treadmill-running speed and the free running pace of the subject during the warm-up exercise were identical in all trials. In CON, either the maximum dynamic IM function assessment or the Yo-Yo intermittent recovery test was conducted immediately following the standardized whole-body warm-up exercise. In IMW_P and IMW, the IM warm-up activity was performed in between the stretching exercise and the free running exercise. After the integrated warm-up activity, either the IM function assessment or the exercise test would be started.

The IM warm-up protocol used in the present study has been described in the study of Volianitis et al. (2001b). Briefly, it consisted of two sets of 30 breaths using a POWERbreathe IM-trainer (Gaiam Ltd, Warwickshire, UK) at 15 and 40% maximum inspiratory mouth pressure in IMW_P and IMW trials, respectively. In IMW, the subject was instructed to initiate every breath from residual volume in a powerful manner. The inspiratory effort was continued until the inspiratory capacity for the preset loading limited further excursion of the thorax. Inspiratory pressure, flow and volume of each breath were monitored throughout the warm-up activity. The breathing pattern of the warm-up was with low duty cycle in avoidance of the occurrence of IM fatigue. In IMW_P, the protocol was the same while the load was reduced as mentioned. The breaths were performed gently and the respiratory time of each breath was protracted. The subjects were blinded to the true purpose of the study by a misled message that they were participating in a study to compare the effects of the powerful-type and the endurance-type IM warm-up protocols on subsequent intermittent exercise performance.

The method of assessment of the maximum dynamic IM function has been reported in previous study (Romer et al. 2002a). Briefly, maximal inspiratory pressure at zero flow (P_0 in cmH_2O) was measured by performing maximum inhalation at residual volume against an occluded airway with a 1-mm orifice. After the determination of P_0, the subject performed maximum inhalation initiated from residual volume against six discrete pressure-threshold loads (~0, 20, 25, 35, 50 and 65% P_0) of the POWERbreathe device. The six loads were randomly assigned to the subject while the order was maintained in all trials. All the maximum inhalations were performed while seated. The inspiratory pressure and flow during the maximum inhalation were recorded synchronized. The data of three technical correct maximum inhalation trials were collected and the trial with the highest IM power output, i.e. the largest product of inspiratory pressure and flow, was the result. The linear relationship of the pressure–flow data corresponding to the highest IM power output for the different loads were expressed by formulating an equation [pressure $= a \times$ flow $+ b$] where a and b are constants. Maximal inspiratory flow ($\dot{V}_{max}$ in $l\,s^{-1}$) of the subject was derived by extrapolation. Maximal IM power (W_{Imax} in cm $H_2O l\ s^{-1}$) was calculated by differentiation from a zero tangent to the curve constructed by plotting the highest IM power outputs for the different loads with the corresponding flows. Optimal pressure (P_{opt} in cm H_2O and $\%P_0$) and flow ($\dot{V}_{opt}$ in $l\,s^{-1}$ and $\%\dot{V}_{max}$) were defined as the inspiratory pressure and flow corresponding to the W_{Imax}. The MRPD (in cm H_2O ms^{-1}) occurred during the initial incline of the curve of P_0 was defined as the positive peak of the pressure derivative as a function of time.

The ability of the subject to perform intense intermittent run to exhaustion (Ex) was assessed using the Yo-Yo intermittent recovery test (level 1). Details of the testing protocol were reported in the study of Krustrup et al. (2003). Ex in this study was defined as the maximum repetitions of the exercise bout of 20-m shuttle run.

Measurements

During the assessment of maximum dynamic IM function, inspiratory flow was measured using a bi-directional gas flow meter (UVM 17125, CA, USA) that was connected in between a mouthpiece and the POWERbreathe pressure-threshold valve. Inspiratory mouth pressure was measured with a differential pressure transducer coupled with a signal conditioner (Collins, MA, USA) that was connected to a 4-mm ID vent located near the mouthpiece by using polyethylene tubing. The inspiratory flow and pressure signals were digitized at 50 ms intervals with the PowerLab data recording system (ML785, ADInstruments, Sydney, NSW, Australia). The flow was integrated on-line to provide the inspiratory volume. Before the assessment, the pressure transducer was calibrated by applying different levels of pressure indicated by the water- or mercury-filled U-tube manometer to the equipment. After the assessment, the flow meter connected with the pressure-threshold valve was calibrated for each load by applying known volume of gas at the flow rate with magnitude and pattern similar to that performed by the subject in the prior test. The recorded inspiratory flow data for each load was corrected individually according to the results of the calibration before further analyses.

During the Yo-Yo intermittent recovery test, heart rate (HR), ratings of perceived intensity of breathlessness sensation (RPB) and perceived exertion (RPE) were recorded before the exercise; at the subsequent 10-s recovery of every 4th exercise bout starting from the 13th level of the Yo-Yo test; and at exhaustion. HR was recorded using a HR monitor (Polar, Finland). The RPB and RPE were assessed with the aid of Borg category scales (0–10) and (6–20), respectively. The two scales were described in detail in our previous studies (Tong et al. 2001a, 2003a).

For examining the ventilatory and metabolic responses during the intermittent exercise tests, three of the subjects were selected randomly to repeat the exercise test in the three conditions. The procedure was to avoid the instrumentation in subjects during exercise tests that might have detracted from their exercise performance and limited their ability to quantify the intensity of breathlessness reliably. During the repeated trials, minute ventilation ($\dot{V}_E$), breathing frequency, tidal volume, inspiratory and expiratory times, duty cycle and $\dot{V}O_2$ of the subjects were recorded with a portable cardiopulmonary measuring instrument (MetaMax, Cortex, Leipzig, Germany).

Statistical analysis

The repeatability coefficient of Bland–Altman plot was calculated for determining the reliability of Ex in IMW. One-way ANOVA with repeated measurements was computed to examine the difference in the above-mentioned parameters among the three conditions. Post-hoc analyses using Newman–Keuls were performed when main effects of ANOVA were significant. Relationships between variables were determined using simple regression. All tests for statistical significance were standardized at an alpha level of $P < 0.05$, and all results were expressed as mean (SD).

Results

Maximum dynamic IM function

The IM functions in CON, IMW_P and IMW are shown in Table 2. One-way ANOVA with repeated measurements showed that the interaction effects on P_0, W_{Imax}, P_{opt}, MRPD and $\dot{V}_{max}$ among CON, IMW_P and IMW were significant ($P < 0.05$). Post-hoc analyses revealed that none of the parameters of the IM function was changed in IMW_P from CON ($P > 0.05$). In contrast, the P_0, W_{Imax}, P_{opt} and MRPD in IMW were increased by comparing with those in CON and IMW_P. The increase in $\dot{V}_{max}$ in IMW was little with significant difference only found when compared with that in CON ($P < 0.05$). The P_{opt}/P_0, $\dot{V}_{opt}$ and $\dot{V}_{opt}/\dot{V}_{max}$ in IMW were not different from those in either CON or IMW_P ($P > 0.05$).

Intense intermittent run to exhaustion

In this study, Ex in the two identical IMW trials was 31.2 (7.2) and 32.9 (7.3) bouts, respectively. The repeatability coefficient for the Ex in IMW trials was 9.72%; the mean difference between the first and second IMW trials was 1.3 (0.8) bouts. As the Ex was reproducible in this study under IMW condition, the data of all variables recorded in the second IMW trial were selected for analyses. For the Ex among CON, IMW_P and IMW, one-way ANOVA with repeated measurements showed that the interaction was significant ($P < 0.05$).

Table 2 Maximum dynamic inspiratory muscle function in CON, IMW_P and IMW are shown ($n = 10$)

	CON	IMW_P	IMW
P_0 (cm H_2O)	155.3 (15.5)	157.3 (14.8)	169.5 (21.5)^{a,b}
$\dot{V}_{max}$ (l s^{-1})	7.83 (1.04)	8.04 (1.18)	8.25 (1.13)^{a}
W_{Imax} (cm H_2O l s^{-1})	309.4 (63.8)	329.2 (68.5)	374.9 (89.7)^{a,b}
P_{opt} (cm H_2O)	79.2 (11.2)	82.2 (10.9)	91.7 (10.8)^{a,b}
P_{opt}/P_0 (%)	51.3 (8.5)	52.5 (7.5)	54.3 (4.3)
$\dot{V}_{opt}$ (l s^{-1})	3.90 (0.56)	3.99 (0.63)	4.04 (0.55)
$\dot{V}_{opt}/\dot{V}_{max}$(%)	49.8 (2.0)	49.6 (1.9)	49.1 (1.0)
MRPD (cm H_2O ms^{-1})	0.39 (0.06)	0.41 (0.04)	0.44 (0.05)^{a,b}

Values are means (SD)

P_0 maximal inspiratory pressure at zero flow, $\dot{V}_{max}$ maximal inspiratory flow, W_{Imax} maximal inspiratory muscle power, P_{opt} optimal pressure, P_{opt}/P_0 optimal pressure relative to P_0, $\dot{V}_{opt}$ optimal flow, $\dot{V}_{opt}/\dot{V}_{max}$ optimal flow relative to $\dot{V}_{max}$, *MRPD* maximal rate of pressure development

[a] Significantly different from the CON ($P < 0.05$)

[b] Significantly different from the IMW_P ($P < 0.05$)

Post-hoc analyses indicated that there was no difference ($P > 0.05$) in Ex between CON [27.6 (6.0) bouts] and IMW_P [29.1 (6.0) bouts] while the Ex in IMW [32.9 (7.3) bouts] was significantly greater ($P < 0.05$) than those in either CON or IMW_P (Fig. 1).

Physical exertion and perceived intensity of breathlessness sensation

During the intense intermittent exercise in CON, IMW_P and IMW at exhaustion, the physical exertion of subjects were severe with the RPE and RPB close to maximum and the HR close to the maximum value recorded in the maximum graded treadmill test that was taken place prior to the experimental trials (Table 3). No significant differences were found in the comparison of the three parameters at exhaustion among the three trials ($P > 0.05$). For the slope of the linear relationship of the increase in RPB for every 4th exercise interval (RPB/4i), significant interaction among the three trials was shown by one-way ANOVA with repeated measurements ($P < 0.05$). Post-hoc analyses indicated that the RPB/4i in IMW was lower ($P < 0.05$) than those in CON and IMW_P (Table 3) while the difference in RPB/4i between CON and IMW_P was not significant ($P > 0.05$). Although the changes in the RPB/4i and Ex in IMW_P were not statistically significant, increases in Ex and reduction in RPB/4i were occurred concomitantly in six of the ten subjects. In an attempt to elaborate accurately the interrelationships among the changes (Δ) in RPB/4i, Ex and maximum dynamic IM function, the data in IMW_P and IMW expressed as percentage of control values were combined for analyses. It was found that the Δ RPB/4i was negatively correlated to the ΔP_0 ($r = -0.48$, $n = 20$, $P < 0.05$) and the Δ MRPD ($r = -0.54$, $n = 20$, $P < 0.05$). The negative correlation ($r = -0.92$, $n = 20$, $P < 0.05$) was further found between the Δ RPB/4i and the Δ Ex (Fig. 2).

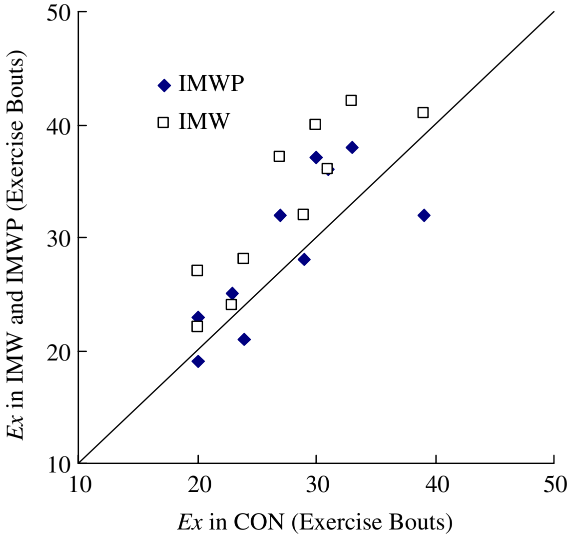

Fig. 1 Changes in exercise tolerance (Ex) from control (CON) in individual subjects during Yo-Yo intermittent recovery test in IMW_P and IMW are shown. *Oblique line* line of identify

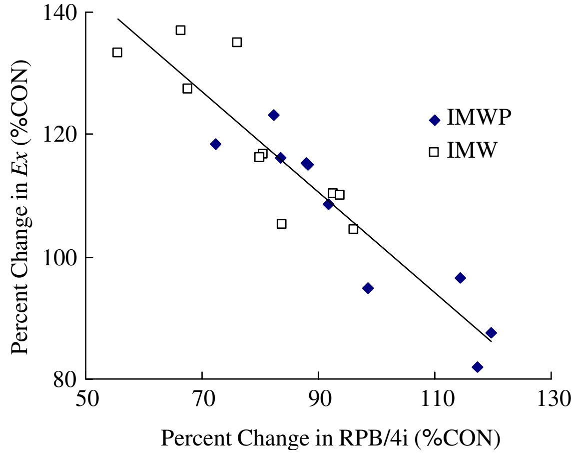

Fig. 2 Percent change in the control value of the slope of the linear relationship of the increase in rating of perceived breathlessness for every 4th exercise interval (RPB/4i) plotted against the percent change in the control value of the exercise tolerance (Ex) during Yo-Yo intermittent recovery test in IMW_P and IMW are shown. The equation describing the relationship is: percent change in control Ex = –0.8215 (percent change in control RPB/4i) + 184.5 ($n = 20$, $r = 0.92$, $P < 0.001$)

Table 3 HR, RPE and RPB at exhaustion in CON, IMW_P and IMW, and the slope of the linear relationship of the increase in rating of perceived breathlessness for every 4th exercise interval (RPB/4i) in the three trials are shown ($n = 10$)

	CON	IMW_P	IMW
HR (beats min^{-1})	192.8 (10.8)	189.2 (12.7)	191.1 (10.8)
RPE	19.3 (1.3)	19.4 (0.7)	19.6 (0.8)
RPB	9.8 (0.4)	9.9 (0.3)	9.9 (0.3)
RPB/4i	0.37 (0.08)	0.35 (0.09)	0.29 (0.08)^{a,b}

Values are means (SD)

HR heart rate, *RPE* rating of perceived exertion, *RPB* rating of perceived breathlessness

[a] Significantly different from the CON ($P < 0.05$)

[b] Significantly different from the IMW_P ($P < 0.05$)

Ventilatory and metabolic responses

The ventilatory and metabolic responses of the three random selected subjects during the exercise bout of 20-m shuttle run and the subsequent 10-s recovery in CON near exhaustion and those during the corresponding periods in IMW_P and IMW are shown in Table 4.

Discussion

Maximum dynamic IM function

In comparison with control, the maximum dynamic IM function was enhanced significantly in the IMW with improvements mainly found in the pressure parameters of P_0, W_{Imax}, P_{opt} and MRPD while it was negligible in the flow parameters of $\dot{V}_{max}$ and $\dot{V}_{opt}$ (Fig. 3a, b). The increase in the P_0 of 9.1% (7.2) in IMW was in agreement with the 8.5 and 11.2% increase in static maximum inspiratory pressure entailed from a similar IM warm-up protocol in previous studies (Volianitis et al. 1999, 2001a). However, the inferior improvement in the flow parameters resulting from prior IM warm-up has not been reported. Nevertheless, Romer and McConnell (2003) have reported that P_0 was definitely more responsive to overloading stimuli than $\dot{V}_{max}$. They found that a pressure-specific IM training could result in 41% increase in P_0 while a flow-specific IM training with identical training volume could improve the $\dot{V}_{max}$ for only 18%. It was postulated that the IM warm-up protocol used in the IMW was effective in enhancing the IM force (pressure) output rather than the muscle shortening (flow) velocity.

Bishop (2003) reported that the physiological mechanisms underlying the warm-up effect on optimizing physical performance are mainly temperature-related although non-temperature-related mechanisms have also been proposed. Increase in temperature in human muscles was shown to decrease the electrically evoked time to peak tension and increase both the maximum velocity of shortening and maximum power, but it has no or only a minor effect on increasing maximal force output (Binkhorst et al. 1977; Davies and Young 1983; Ranatunga et al. 1987). Such findings suggested that the enhancement of the maximum dynamic IM function in IMW might not be mainly due to the increase in IM temperature.

Previous studies showed that following a series of contractile "conditioning" activity in skeletal muscles, postactivation potentiation (PAP) was elicited and caused transient increases in the dynamic force output and the rate of maximum force development in the muscles (MacIntosh and Bryan 2002; Sale 2002). In IMW, although the elicitation of PAP in IM entailed

Table 4 Ventilatory and metabolic responses of the three random selected subjects at the exercise about of 20-m shuttle run and the subsequent 10-s recovery in CON near exhaustion and at corresponding periods in IMW_P and IMW are shown

	Exercise bout of 20-m shuttle run			Subsequent 10-s recovery		
	CON	IMW_P	IMW	CON	IMW_P	IMW
$\dot{V}_E$ (l min^{-1})	134.8 (15.3)	133.9 (12.9)	130.3 (10.5)	122.6 (12.0)	123.1 (10.7)	125.5 (11.5)
f_b (b min^{-1})	77.2 (15.0)	76.1 (10.4)	77.7 (14.1)	53.8 (10.4)	54.7 (6.7)	55.0 (11.9)
V_T (l)	1.79 (0.35)	1.79 (0.29)	1.72 (0.29)	2.33 (0.31)	2.29 (0.33)	2.37 (0.43)
t_i (s)	0.42 (0.11)	0.40 (0.07)	0.41 (0.09)	0.60 (0.12)	0.58 (0.07)	0.61 (0.14)
t_e (s)	0.39 (0.06)	0.40 (0.05)	0.40 (0.09)	0.55 (0.12)	0.54 (0.08)	0.55 (0.12)
t_i/T_{tot} (%)	51.0 (1.7)	50.0 (1.0)	50.7 (0.6)	52.0 (1.0)	51.7 (1.2)	52.7 (2.9)
$\dot{V}O_2$ (ml kg^{-1} min^{-1})	50.6 (7.2)	49.1 (6.7)	50.9 (3.7)	48.9 (7.9)	45.6 (6.5)	48.5 (6.4)

Values are means (SD)

$\dot{V}_E$ minute ventilation, f_b is breathing frequency, V_T tidal volume, t_i inspiratory time, t_e expiratory time, t_i/T_{tot} is duty cycle, $\dot{V}O_2$ oxygen consumption

from the prior IM warm-up has not been identified, it may be one of factors of the improvement in the maximum dynamic IM function. It might have contributed to the increases in the W_{Imax}, P_{opt} and MRPD but not the P_0 as the PAP-resulted increase in Ca^{2+} sensitivity of myofilaments offer no benefit in generating maximum isometric force when "saturating" concentration of Ca^{2+} in the cytosol is attained during maximum contraction (Sale 2004). In previous studies, static maximum IM force output was shown to be improved with a prior IM warm-up that was similar to the one used in the IMW trial (Volianitis et al. 1999, 2001a). The improvement was attributed to the neural facilitation. It was suggested that the repeated inspiratory action of the IM during the warm-up activity could improve the intra- and inter-muscular coordination by removing reflex inhibition in IM and decreasing the degree of co-contraction between inspiratory and expiratory muscles, respectively. As a consequence, maximum isometric and dynamic IM force outputs were enhanced (Volianitis et al. 1999, 2001a). It appears that the neural facilitation proposed previously is another possible attribution of the enhancement of the maximum dynamic IM function in IMW.

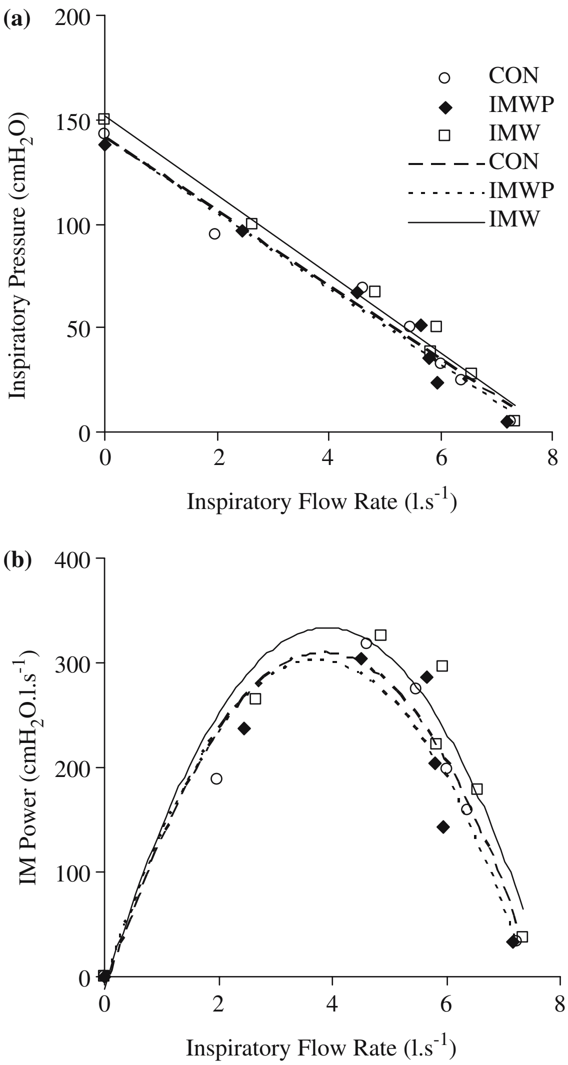

Fig. 3 Maximum dynamic inspiratory muscle (IM) function of a typical subject revealed by **a** the linear regression of flow–pressure and **b** the polynomial regression of flow–power in CON, IMW_P and IMW are shown

Breathlessness sensation and intense intermittent run

In the present study, the repeated 20-m shuttle run in the Yo-Yo intermittent recovery test was severely intense to subjects. In CON at exhaustion, the RPE was close to maximum and the corresponding HR exceeded 97% (ranged from 93.9 to 103.9%) of the maximum HR recorded in the $\dot{V}O_{2max}$ test that was conducted prior to the experimental trials. The vigorous physical exertion in subjects during the test of intense intermittent run was accompanied with huge ventilatory demand. In the repeated CON trial, when the three random selected subjects performed the test to near exhaustion, the $\dot{V}_E$ attained during the exercise bout of 20-m shuttle run was almost the same as the maximum value [97.9% (ranged from 91.6 to 104.7%)] recorded in the $\dot{V}O_{2max}$ test and it did not fall appreciably in the subsequent 10-s recovery [89.2% (ranged from 82.6 to 93.8%)]. Such findings were in agreement with those reported in our previous studies (Tong et al. 2001, 2003a, 2003b, 2004). It revealed that ventilatory muscles including the IM were working continuously at high intensity throughout the intermittent exercise. The muscles worked for provision of adequate ventilation to meet the energy demands for vigorous muscular contractions in exercise bouts and for repletion of phosphagen store of the locomotor muscles in recovery intervals. The sustained heavy ventilatory work performed by subjects during the intense intermittent run eventually elicited noxious breathlessness sensation. In CON at exhaustion, the RPB in most subjects was at maximum.

In IMW, when the specific IM warm-up was in addition to the standard whole-body warm-up protocol, the RPB/4i during the subsequent intense intermittent run was reduced to 79.3% (13.2) (ranged from 55.6 to 96.3%) of the control value while the control Ex was increased 19.5% (12.6) (ranged from 4.4 to 37.0%). In IMW_P, although the changes in control Ex [105.8% (14.4) (ranged from −18.0 to 23.3%)] and RPB/4i [95.6% (16.4) (ranged from 72.3 to 119.8%)] were not statistically significant, concomitant increase in Ex and reduction in RPB/4i were observed in six subjects with only one of them having definite increased P_0. Such findings supported our notion in pilot tests that the IM warm-up in IMW_P would not affect IM function in most individuals. However, the concomitant reduction in RPB/4i and increase in Ex in more than half of the total subjects in IMW_P, which were similar to those occurred in IMW (Fig. 2), suggested that an IM warm-up effect on reducing RPB independent of augmentation of IM functional capacity might have been elicited vaguely among subjects.

Redline et al. (1991) noted that the perceived intensity of breathlessness sensation in normal persons could reflect the proportion of the maximum force utilized by IM in breathing. Such relationship was shown not to be affected either by augmenting the capacity of IM force output via IM strength training or by reducing the IM tension for inhalation during intense exercise with $He{-}O_2$ breathing (Redline et al. 1991; Tong et al. 2004). In the present study, we found that the Δ RPB/4i in IMW and IMW_P was negatively correlated to the ΔP_0 and Δ MRPD ($r^2 = 0.23$ and 0.29, respectively, $n = 20$). The negative correlation between the Δ RPB/4i and the ΔP_0 was in agreement with the findings of Redline et al. (1991). It further supported the previous notion that IM warm-up could reduce the breathlessness sensation in subsequent intense exercise by enhancing the IM functional capacity (Volianitis et al. 2001b). However, the small r^2 suggested that there should be factors other than the improved IM functional capacity contributed to the reduction in RPB/4i in IMW and IMW_P. Decrease in ventilatory and metabolic demands during the exercise should not be a factor as the related parameters recorded at the selected exercise bout of 20-m shuttle run and subsequent 10-s recovery in CON near exhaustion were not likely to be changed with the IM warm-up either in IMW or IMW_P (Table 4). Previous studies showed that individual's intensity of breathlessness sensation at given ventilatory demand during exercise could be reduced independently of augmentation of IM functional capacity. Wilson and Jones (1990) reported that prior loaded ventilatory activity could lower one's perceived intensity of breathlessness sensation in subsequent exercise in consequence of temporary alternation in the "memorized" association between breathlessness perception and respiratory load. Further, IM warm-up-elicited neural facilitation might partially release one's breathlessness sensation during subsequent exercise by reducing the portion of IM force output that was expended normally on the work against the co-contraction between inspiratory and expiratory muscles (Volianitis et al. 1999, 2001a). Such responses entailed from loaded ventilatory activity in IM might have been elicited subsequent to the IM warm-up in IMW and consequently to contribute to the lessening of the RPB during the exercise. In IMW_P, the IM warm-up implemented with inspiratory load relatively lower than that in IMW might also be effective to elicit the similar responses in some but not all subjects. As a result, vague change in subjects' RPB during the exercise in IMW_P was occurred.

In the present study, the Δ RPB/4i in subjects during the running exercise could account for more than 80% of the variance in Δ Ex (Fig. 2). Such findings implied that the addition of the specific IM warm-up, preferably the one in IMW, to a whole-body warm-up protocol could subsequently improve the tolerance of the intense intermittent run by lessening of the exercise-induced noxious breathlessness sensation. Further, the findings enriched our notion reported in previous studies that the noxious breathlessness sensation elicited during intense intermittent exercise at exhaustion in normal active persons plays a part in limiting the exercise maintenance (Tong et al. 2003a, 2004). In the previous studies, the mode of exercise selected was cycling. It was noted that for performing intense exercise on cycle ergometer, individuals' chest muscles were not solely responsible for the respiratory thoracic excursion but also for the stabilization of upper body including the trunk and the upper limbs on the handlebar (Boussana et al. 2003). Further, the crouched position of cycling-resulted increase in abdominal impedance and thus in diaphragmatic work might lead to premature recruitment of extra-diaphragmatic ventilatory muscles (Johnson et al. 1993). By comparing with the cycling exercise, the upright bodily position during running exercise was thought to be advantageous for IM work due to the lesser abdominal impedance of diaphragmatic contraction and the needless of extra recruitment of chest muscles for stabilizing the upper body (Boussana et al. 2003). However, the findings in the present study revealed that such mechanical advantage of the upright bodily position in breathing did not attenuate the limitation of the noxious breathlessness sensation elicited during intense intermittent run in exercise tolerance. In light of the current findings and those in our previous studies (Tong et al. 2003a, 2004), it was noted that the noxious breathlessness sensation elicited during intense intermittent exercise at exhaustion in normal active persons may play a role in limiting the exercise tolerance regardless of whether the exercise was cycling or running.

In conclusion, the addition of the specific IM warm-up consisted of two sets of 30 breaths against an inspiratory pressure-threshold load equivalent to 40% maximum inspiratory mouth pressure to a standard whole-body warm-up protocol could improve individual's maximum dynamic IM function mainly in the P_0, W_{Imax}, P_{opt} and MRPD. Further, the integrated warm-up activity could entail reduction in breathlessness sensation, partly attributable to the enhancement of dynamic IM functions, in subsequent Yo-Yo intermittent recovery test and, in turn, improve the maximum repetitions of 20-m shuttle run.

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References

Binkhorst RA, Hoofd L, Vissers AC (1977) Temperature and force–velocity relationship of human muscles. J Appl Physiol 42:471–475

Bishop D (2003) Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. Sports Med 33:439–454

Boussana A, Galy O, Hue O, Matecki S, Varray A, Ramonatxo M, Le Gallais D (2003) The effects of prior cycling and a successive run on respiratory muscle performance in triathletes. Int J Sports Med 24:63–70

Burnley M, Doust JH, Jones AM (2005) Effects of prior warm-up regime on severe-intensity cycling performance. Med Sci Sports Exerc 37:838–845

Davies CT, Young K (1983) Effect of temperature on the contractile properties and muscle power of triceps surae in humans. J Appl Physiol 55:191–195

Johnson BD, Babcock MA, Suman OE, Dempsey JA (1993) Exercise-induced diaphragmatic fatigue in healthy humans. J Physiol 460:385–405

Krustrup P, Mohr M, Amstrup T, Rysgaard T, Johansen J, Steensberg A, Pedersen PK, Bangsbo J (2003) The yo-yo intermittent recovery test: physiological response, reliability, and validity. Med Sci Sports Exerc 35:697–705

MacIntosh BR, Bryan SN (2002) Potentiation of shortening and velocity of shortening during repeated isotonic tetanic contractions in mammalian skeletal muscle. Pflugers Arch 443:804–812

Ranatunga KW, Sharpe B, Turnbull B (1987) Contractions of a human skeletal muscle at different temperatures. J Physiol 390:383–395

Redline S, Gottfried SB, Altose MD (1991) Effects of changes in inspiratory muscle strength on the sensation of respiratory force. J Appl Physiol 70:240–245

Romer LM, McConnell AK (2003) Specificity and reversibility of inspiratory muscle training. Med Sci Sports Exerc 35:237–244

Romer LM, McConnell AK, Jones DA (2002a) Effects of inspiratory muscle training on time-trial performance in trained cyclists. J Sports Sci 20:547–562

Romer LM, McConnell AK, Jones DA (2002b) Effects of inspiratory muscle training upon recovery time during high intensity, repetitive sprint activity. Int J Sports Med 23:353–360

Sale DG (2002) Postactivation potentiation: role in human performance. Exerc Sport Sci Rev 30:138–143

Sale DG (2004) Postactivation potentiation: role in performance. Br J Sports Med 38:386–387

Steinacker JM, Both M, Whipp BJ (1993) Pulmonary mechanics and entrainment of respiration and stroke rate during rowing. Int J Sports Med 14(Suppl. 1):S15–S19

Tong TK, Fu FH, Chow BC (2001a) Effect of nasal dilatation on prolonged all-out intermittent exercise performance. J Sports Med Phys Fitness 41:189–195

Tong TK, Fu FH, Chow BC (2001b) Nostril dilatation increases capacity to sustain moderate exercise under nasal breathing condition. J Sports Med Phys Fitness 41:470–478

Tong TK, Fu FH, Chow BC, Quach B, Lu K (2003a) Increased sensations of intensity of breathlessness impairs maintenance of intense intermittent exercise. Eur J Appl Physiol 88:370–379

Tong TK, Quach B, Lu K (2003b) The control of normal inspiratory muscle force output restricts the rise of ventilation during intense intermittent exercise. J Exerc Sci Fitness 1:33–40

Tong TK, Fu FH, Quach B, Lu K (2004) Reduced sensations of intensity of breathlessness enhances maintenance of intense intermittent exercise. Eur J Appl Physiol 92:275–284

Volianitis S, McConnell AK, Koutedakis Y, Jones DA (1999) The influence of prior activity upon inspiratory muscle strength in rowers and non-rowers. Int J Sports Med 20:542–547

Volianitis S, McConnell AK, Jones DA (2001a) Assessment of maximum inspiratory pressure. Prior submaximal respiratory muscle activity ('warm-up') enhances maximum inspiratory activity and attenuates the learning effect of repeated measurement. Respiration 68:22–27

Volianitis S, McConnell AK, Koutedakis Y, Jones DA (2001b) Specific respiratory warm-up improves rowing performance and exertional dyspnea. Med Sci Sports Exerc 33(7):1189–1193

Wilson RC, Jones PW (1990) Influence of prior ventilatory experience on the estimation of breathlessness during exercise. Clin Sci (Lond) 78:149–153