Title: 'Functional' inspiratory and core muscle training enhances running performance and economy

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ABSTRACT

We compared the effects of two 6-week high-intensity interval training interventions. Under the control condition (CON), only interval training was undertaken, whilst under the intervention condition (ICT), interval training sessions were followed immediately by core training, which was combined with simultaneous inspiratory muscle training - 'functional' IMT. Sixteen recreational runners were allocated to either ICT or CON groups. Prior to the intervention phase, both groups undertook a 4-week programme of 'foundation' IMT to control for the known ergogenic effect of IMT [30 inspiratory efforts at 50% maximal static inspiratory pressure (P_0) per set, 2 sets.d^{-1}, 6 d.wk^{-1}]. The subsequent 6-week interval running training phase, consisted of 3-4 sessions.wk^{-1}. In addition, the ICT group undertook four inspiratory-loaded core exercises [10 repetitions.set^{-1}, 2 sets.d^{-1}, inspiratory load set at 50% post-IMT P_0] immediately after each interval training session. The CON group received neither core training nor functional IMT. Following the intervention phase, global inspiratory and core muscle functions increased in both groups ($P<0.05$), as evidenced by P_0 and a sport-specific endurance plank test performance (SEPT), respectively. Compared to CON, the ICT group showed larger improvements in SEPT, running economy at the speed of the OBLA, and 1-hr running performance (3.04% vs 1.57%, $P<0.05$). The changes in these variables were inter-individually correlated ($r\geq0.57$, $n=16$, $P<0.05$). Such findings suggest that the addition of inspiratory-loaded core conditioning into a high-intensity interval training program augments the influence of the interval program upon endurance running performance, and that this may be underpinned by an improvement in running economy.

Keywords: core muscle, respiratory muscle training, interval training, running economy

INTRODUCTION

The lumbopelvic-hip region is commonly referred to as the "core" region of the body. Musculatures in this region are essential in prevention of buckling of the vertebral column and returning the trunk to postural equilibrium following perturbation (29). In the sporting environment, core muscles (CM) play a role in controlling the position and motion of the torso over the pelvis. However, during many everyday activities, especially those associated with sports, the entire torso is involved in optimising the transfer of energy to the extremities (14). A substantial portion of the torso musculature is involved in breathing, and it is well known that breathing and postural control are coordinated (8). The dual role of the respiratory muscles, in particular the diaphragm, is implied by the fact that the frequency of posturally destabilising limb movements is superimposed upon tonic respiratory-related diaphragm EMG (11). Furthermore, global inspiratory muscle (IM) fatigue is associated with impairment of postural stability in healthy people (13). Recently, we have shown that the heavy, fatiguing respiratory work of intense running, independently led to global CM fatigue in runners (27). Furthermore, the magnitude of the global IM fatigue correlated (r^2>59%) with the magnitude of the global CM fatigue, suggesting that the two muscle groups work synergically during heavy exercise. However, the specific contribution of IM function to function of the core stabilising system is unclear.

During running activities, when the body in an upright position, CM are actively involved in providing torso and lumbopelvic stiffness that helps to optimise running form and the kinetic chains of upper and lower extremities (3, 14). After high-intensity running, we have previously shown a decline in performance of a sport-specific endurance plank test, which suggests the presence of CM fatigue (27). In the same study, the occurrence of CM fatigue was also shown to impair individual's endurance running performance. The apparently crucial role of the CM during exercise has led to the suggestion that enhancing CM function would improve sports performance. However, most previous studies have failed to support this suggestion (10, 18, 19, 22). Given the closely integrated relationship between CM and IM contributions to sports performance, it is perhaps unsurprising that interventions focussing only on the CM should fail to identify an improvement in sports performance. Breathing pattern is not typically controlled during CM training, and it is frequently the case that people hold their breath or breathe with a low tidal volume in order to focus the activity of the torso muscles on the core stabilising challenge. It has recently been suggested that adopting a 'functional', holistic approach to CM and IM training might be beneficial (16). However, the effectiveness of a dual CM/IM training intervention has never been tested.

The present study was designed to test whether a CM training regimen that included IM training (IMT) improved performance in a 1-hr treadmill run test in recreational runners. Since IMT *per se* improves running performance (4) the baseline IM function of all participants was standardised by subjecting them to a 4-week phase of IMT (foundation IMT) prior to the intervention phase. The intervention phase consisted of a 6-wk treadmill interval training programme; under the intervention condition, IMT was undertaken during CM training (ICT), which took place immediately after the interval training. Under the control condition (CON), only interval training was undertaken. We hypothesised that the improvement in the 1-hr treadmill run test would be greater in the ICT group than the CON group.

METHOD

Experimental Approach to the Problem

Participants with matched gender, physical characteristics, and training background were assigned randomly to ICT or CON groups (Table 1). To distinguish the effects of the CM/IM intervention from the known effects of IMT upon running performance (4, 12), all participants completed a 4-week period of IMT prior to the interval training intervention phase of the study. Subsequently, both groups undertook 6-week interval running training, but only the ICT group received the CM/IM intervention. This study occurred during the annual break and early preparation phase of the yearly training plan of the participants. During the 10-week period, participants received no other specific running training.

Participants

Sixteen recreational runners (4 females, 12 males) who had received training at a local sports club in Hong Kong, China, volunteered to participate. Participants had no familial history of cardiovascular disease, and consumed no related medication. Moreover, none had prior experience of specific IM or CM training. Following an explanation of the purpose and requirements of the study, participants gave written informed consent. Local Ethics Committee approval was obtained.

Procedures

Figure 1 summarises the phases of testing and training of the study. Prior to the 6-wk intervention phase, 4-wk phase of foundation IMT was undertaken, according to the established guidelines of functional IMT (16). Prior to IMT, baseline IM and CM function was assessed, and exercise tests were performed. Identical tests were repeated after completion of the subsequent 6-wk intervention. Both IM and CM function were also assessed between the two phases of the study. All tests were performed in an air-conditioned laboratory. Before each test, the participants refrained from eating for at least two hours, and from participation in strenuous physical activity for at least one day. All tests were scheduled to occur at the same time of day and were separated by a minimum of 3 days.

Preliminary Tests and Familiarization Trials. Prior to the experimental trials, physical characteristics, including lung function were assessed. Following this, participants were familiarised with the assessment of CM and IM, as well as the 1-hr treadmill performance test. This familiarisation period introduced, the testing equipment and protocols, as well as providing the participants with the experience of exercising to the limit of tolerance.

Incremental Treadmill Test. The onset of blood lactate accumulation (OBLA), running economy at OBLA (RE_{OBLA}), and maximal oxygen uptake ($\dot{V}O_{2max}$) of the participants were determined by performing a standard maximal incremental treadmill test held on a separate day. The test protocol designed for the combined measurements has been described previously in detail (5). The OBLA was defined as the running speed at the stage during which blood lactate concentration was at or close to 4 $mmol.l^{-1}$. The RE_{OBLA} in $ml.kg^{-1}.km^{-1}$ was calculated based on the average $\dot{V}O_2$ during the final minute of the 3-min stage corresponding to OBLA. The $\dot{V}O_{2max}$ was the highest 10-s mean value. Following the incremental test, a running speed that elicited approximately 65% $\dot{V}O_{2max}$ was identified from the linear relationship of steady-state $\dot{V}O_2$ *versus* speed. The defined speed was utilised in the subsequent 1-hr treadmill run.

Inspiratory Muscle and Core Muscle Function Tests. Global IM function was measured by performing maximal inspiratory efforts at residual volume against an occluded rubber-scuba-type mouthpiece with a 1 mm orifice. The inspiratory mouth pressure at quasi-zero flow (P_0 in cmH_2O) provided a surrogate measure of IM strength. The maximum rate of pressure development (MRPD in $cmH_2O.ms^{-1}$) that occurred during the initial onset of the P_0 effort was also recorded. The maximal inspiratory efforts were repeated at least 5 times until the results were stable (vary by <10% in consecutive three manoeuvres), and the highest value was recorded for analysis (9).

The protocol of the sport-specific endurance plank test (SEPT), which has been shown to be valid and reliable for assessing athletes' global CM function, has been described in detail previously (24). Briefly, participants were required to maintain the prone bridge with good form throughout the following stages with no rest in between: (1) hold the basic plank position for 60 sec; (2) lift the right arm off the ground and hold for 15 sec; (3) return the right arm to the ground and lift the left arm for 15 sec; (4) return the left arm to the ground and lift the right leg for 15 sec; (5) return the right leg to the ground and lift the left leg for 15 sec; (6) lift both the left leg and right arm from the ground and hold for 15 sec; (7) return the left leg and right arm to the ground, and lift both the right leg and left arm off the ground for 15 sec; (8) return to the basic plank position for 30 sec; (9) repeat the steps from (1) to (9) until the maintenance of the prone bridge failed.

The conditions of the SEPT were standardised by using identical body posture. The distances between the left and right elbows (medial epicondyle), the left and right feet (1st metatarsal), and the elbow and feet on the left and right sides of the body were measured during the familiarisation trial while the participants were comfortably performing the prone bridge on a bench. Further, two elastic strings of ~80 cm length which were attached horizontally to a pair of vertical scales were placed beside the bench during the test. The two strings maintained at a distance of 10 cm were adjusted up and down until a height was reached that was at the same level as the participants' hip (the iliac crest was evenly in between the two strings). This setting acted as a reference for the objective monitoring of hip displacement during the test. The measured distances between elbows and feet, as well as the hip height, remained constant in subsequent experimental trials. During the assessment, the test administrator sat one meter away from the bench with the seat height adjusted to a level so that the hip displacement of the participants could be monitored horizontally. The participants were then asked to maintain the prone bridge throughout the test with maximum effort. For each time that the hip was beyond either of the reference lines, a warning was given. The test was terminated when the hip failed to be maintained at the required level after receiving two consecutive warnings. The measured time to the limit of tolerance was used as the index of global CM function.

1-hr Treadmill Running Test. The 1-hr treadmill running test was performed on a separate day following the muscle function evaluations. The running protocol has been described previously in detail (1). Briefly, participants ran continuously on a treadmill (h/p/cosmos, Pulsar, Germany) for 60-min with gradient of 1%. For the first 30-min, participants ran at fixed speed equivalent to 65% $\dot{V}O_{2max}$. For the second 30-min, participants maximised the running distance they achieved by manually adjusting, at their own will, the running speed. This took place each minute with a resolution of 1 $km.hr^{-1}$. During running, heart rate (Polar HR monitor, Finland), and ratings of perceived exertion (Borg RPE scale 6-20) and of perceived breathlessness (Borg RPB scale 0-10), were collected every 3-min. Respiratory responses were monitored continuously, starting from the 27th minute, until the end of test (Vmax 229d, Sensormedics, US). A 25 µl fingertip blood sample was taken pre-and post-exercise for assessment of blood lactate concentration ($[La^-]_b$; YSI 1500 Sport Analyser, YSI, US). Immediately after post-exercise blood sampling, P_0 and SEPT measurements were performed in sequential order. After the 6-wk interval training phase, the 1-hr performance run was repeated twice, which permitted evaluation of the reliability of the maximum distance covered. Moreover, an additional running trial was completed, during which the pre-intervention trial running speed was replicated (ISO), which permitted direct comparison of the cardio-respiratory and perceptual responses during the entire 1-hr run, as well as the exercise-induced changes in IM and CM global functions. To ensure consistency across trials, participants were blinded to any feedback on the distance covered in any trial, and were provided no verbal encouragement during the treadmill runs.

Inspiratory Muscle Training. The protocol for the 4-wk IMT programme has been described previously and shown to be effective (26). Briefly, participants in both groups performed 30 inspiratory efforts twice per day, six days per week, for four weeks. Each effort required the participant to inspire against a pressure-threshold load equivalent to 50% P_0 by using an inspiratory muscle trainer (POWERbreathe® Classic L3, POWERbreathe International, UK). During the training, the participants were instructed to initiate every breath from the residual volume in a powerful manner. The inspiratory effort was continued until the inspiratory capacity for the preset loading limited further excursion of lung volume. For training progression, the inspiratory load was increased by 10 to 15 cmH_2O, once the participant had adapted (i.e. they were able to complete 30 manoeuvres without a break).

Interval Training. Table 2 shows the protocol of the 6-wk high-intensity interval running training programme recommended by Fox and Mathews (6) for enhancing, mainly, aerobic exercise capacity. The programme consisted of three to four sessions per week. Each session comprised one to three sets with different repetitions of selected distances of 100 m, 200 m, 400 m, 600 m, 800 m, and 2,400 m in each set. The ratio of the work to recovery duration was 1:3 for distances ranging from 100 m - 400 m, 1:2 for the 600 m distance and 1:1 for the

800 m distance. The running training was performed on the high-speed treadmill (h/p/cosmos, Pulsar, Germany) with a gradient of 0%. The initial speed for each distance was set according to the participant's maximal speed during the graded treadmill test (100 m & 200 m: 100%; 400 m: 90%; - 600 m & 800 m: 80%, and 2,400 m: 70%). After the initial trial of each distance in the training program, running speeds in each of the subsequent training distances was adjusted voluntarily on a trial-by-trial basis, such that the limit of tolerance (>90% HR_{max}) was attained at the end of the set. During recovery intervals, the participants walked briskly on the treadmill at 5 $km.hr^{-1}$.

Functional CM/IM Training. For the ICT group, four inspiratory-loaded CM training exercises were performed immediately following all interval training sessions (16). The CM training programme was endurance running-specific (7) and consisted of: (1) Bridge - Lie on the back, prop on the hands with body weight on the heels and maintain a straight body line. Brace the abdominal muscles and raise alternately the straightened left and right legs as high as possible; (2) Swiss ball squat thrust - Maintain a press-up position with ankles resting on the Swiss ball. Lift the pelvis up from the straight body line and bend the knees, and return to starting position; (3) Dynamic 'bird dog' - Lift the left hand and right knee from a plank position and extend the arm and leg until both are horizontal. Return the arm and leg to original position and extend the other arm and leg; and (4) Raised alternating crunch - Maintain body in a "V' shape with flexed hip on the floor while hands are behind the head. Rotate the trunk alternatively with elbow toward the opposed bended knee. During each CM exercise, inspiratory load was imposed simultaneously using a POWERbreathe IM trainer at mouth. Participants inhaled forcefully through the device as they initiated the required body actions from the starting position, and exhaled slowly when returning to the starting position. The load on the pressure-threshold device was set at 50% of the post-IMT P_0 throughout the intervention. The four CM exercises were performed for two sets with 10 repetitions in each set in the first week. The repetitions were increased progressively to 15 in next two weeks. In the following three weeks, the number of sets increased to three, and the repetitions in each set were increased progressively from 12, depended on participants' adaptation. For the incorporated inspiratory-loaded breathing activity, the increase in the number of inspiratory efforts paralleled the changes in the number of repetitions of each CM exercise.

Statistical Analyses

Kolmogorov-Smirnov test and Levene's test of equality of error variances was applied and revealed that the data were normally distributed in groups, and the error variances of dependent variables were equal across groups. Independent *t*-tests were applied to examine the difference in variables between groups (ICT vs CON). A series of two-factor ANOVAs were applied to analyse the between-group and within-group effects (pre- and post-IMT, post-ICT, ISO) on most of the dependent variables. Post-hoc analyses using Newman-keuls were performed when interaction effects were significant. Intra-class correlation coefficient (ICC) was used to reveal the reliability of the post-intervention running performance. Relationships between variables were determined using Pearson correlation test. All tests for statistical significance were standardized at an alpha level of $P<0.05$, and all results were expressed as the mean ±SD.

RESULTS

In this study, all participants complied with the protocols of IMT, treadmill interval training, and functional CM/IM training.

Global IM and CM Functions

After the 4-wk foundation phase of IMT, P_0 and MRPD increased significantly ($P<0.05$) in ICT and CON groups (Table 3); the increases were similar in both groups. When the variables were expressed as percentage of corresponding pre-IMT values, the increase in P_0 was correlated with the increase in SEPT performance ($r=0.66$, $n=16$, $P<0.05$). Following the 6-wk interval training phase, SEPT performance increased further ($P<0.05$) from post-IMT level in ICT group (Table 3), but not in the CON group. Moreover, no significant change in P_0 or MRPD was found in comparison to the post-IMT values in either group.

OBLA and RE_{OBLA}

Compared to pre-intervention, OBLA increased similarly at the 10-wk time point in both groups during the maximal graded treadmill test (Table 3). However, RE_{OBLA} (measured at the speed corresponding to the pre-intervention OBLA) increased significantly ($P<0.05$) in the ICT group, but not the CON group. The change in RE_{OBLA} was correlated with that in SEPT ($r=0.69$, $n=16$, $P<0.05$, Figure 2a), when both variables were expressed as percentage of pre-intervention values.

1-hr Treadmill Run

For the 1-hr treadmill run, the constant speed for the 1st 30-min for the ICT and CON groups were 11.9±1.4 and 12.4±1.7 $km.hr^{-1}$ ($P>0.05$), respectively. Pre-IMT, the total distance covered in the 1-hr time trial did not differ between groups (12.82±1.47 vs. 12.92±1.69 km, respectively, $P>0.05$). After the 10-wk intervention, the distance covered in the two 1-hr time trials was highly repeatable in both groups (ICT - 1st run: 13.16±1.49, 2nd run: 13.21±1.47 km, ICC=0.998. CON - 1st run: 13.05±1.49, 2nd run: 13.10±1.52 km, ICC=0.991). Only the results of the 2nd post-intervention run were analysed subsequently. Both groups increased the distance covered during the time trial significantly, but the increase for the ICT group was significantly larger (0.39±0.11 vs. 0.18±0.21km, respectively; $P<0.05$). These changes (expressed as percentage of baseline) were correlated with the percentage changes in the OBLA (r=0.52, n=16) and SEPT performance (r=0.57, n=16, $P<0.05$, Figure 2b).

Immediately after the 1-hr run, $[La^-]_b$ was higher, and there was evidence of fatigue, as indicated by significantly lower P_0 and SEPT values post-run ($P<0.05$). Responses did not differ significantly ($P>0.05$) within or between the ICT and CON groups (Table 4). In contrast, the ISO trial elicited a significantly attenuated post-exercise decrease in P_0 and increase in $[La^-]_b$, compared to pre-intervention in both groups, but the response for SEPT performance remained unchanged.

During the final minute of the 30-min time trial (60th minute of exercise), HR, RPE and RPB approached maximum. The HR and RPB were not different between pre- (ICT: 185.0±8.8 beats.min^{-1}, 9.0±0.76; CON: 188.3±5.5 beats.min^{-1}, 8.83±1.60) and post-intervention trials (ICT: 185.3±9.4 beats.min^{-1}, 9.13±0.99; CON: 186.7±3.5 beats.min^{-1}, 8.17±1.47, $P>0.05$). In contrast, the RPE was slightly, but significantly, lower post-intervention (ICT: 19.3±0.7 vs. 19.0±1.1; CON: 18.8±1.6 vs. 17.8±1.7, $P<0.05$). In the ISO trial, all variables were significantly lower (ICT: 177.0±10.2 beats.min^{-1}, 6.50±1.85, 16.0±1.9; CON: 182.8±3.4 beats.min^{-1}, 7.0±1.9, 16.3±2.4, $P<0.05$). The changes did not differ significantly between groups ($P>0.05$).

During the 30-min ISO time trial, there was a significant increase in the mean tidal volume (ICT: 1.55±0.29 vs 1.66±0.34 l; CON: 1.53±0.19 vs 1.60±0.2 l, $P<0.05$) and a significant decrease in breathing frequency (ICT: 59.3±16.7 vs 54.4±17.4 breaths.min^{-1}; CON:

56.1±9.4 vs 53.5±5.4 breaths.min^{-1}, P<0.05) in comparison to the corresponding baseline values. The changes did not differ significantly between groups (P>0.05).

DISCUSSION

The main findings of the present study were that the addition of a 6-wk period of 'functional' CM/IM training to an interval training programme resulted in significantly greater improvements in 1-hr running performance, running economy at the speed of the OBLA, and in a SEPT.

Prior to the interval training, the participants in both groups undertook a 4-wk IMT programme. This specific training had two purposes, 1) to control for the established ergogenic effects of IMT in both groups (12); 2) to prepare a strong foundation within the inspiratory musculature for the subsequent challenge of the inspiratory-loaded core muscle training in the ICT group (16). As expected, following the IMT, the global IM function of both groups improved significantly. For example, P_0, increased by an average of 23%, which is similar to changes observed using identical IMT in previous randomised, placebo-controlled trials (21, 25). Global CM function, as assessed by the SEPT, also improved in response to IMT, and the change was correlated with the improvement in P_0. The related improvement in the global function of these two musculatures (r=0.66) resulting from a specific IMT has, to our knowledge, never been reported previously. The present findings are consistent with the notion of the dual role of IM in breathing and core stabilisation that has been demonstrated during simultaneous ventilatory challenge and isometric torso task (17). Our findings are also consistent with our previous observation of a correlation (r=0.77) between the severity of fatigue of the inspiratory and core musculatures when participants mimicked their ventilatory responses to a high-intensity running, whilst they were resting in a standing position (27). When the data in the present and previous studies were combined to analyse, the change in P_0 in the participants explained approximately 80% of the variance in the change in SEPT performance. Collectively, these data provide evidence to support the existence of an essential role for the IM in global CM function during postural stabilising tasks (13). The data also raise the possibility that enhancements of CM function and, in turn core stabilisation, may be another contributory mechanism underlying the ergogenic effect of the specific IMT (12).

In agreement with our previous findings (27), there was evidence of running-induced fatigue of the IM and CM in both groups. The occurrence of CM fatigue suggest that the musculature had worked intensively during the run, providing core stiffness that presumably helping to optimise running form (3, 14). We have previously shown that fatigue of the CMs is associated with impairment of high-intensity running performance (27). After the second, 6-wk intervention with inspiratory-loaded CM training (CM/IM training) combined with the high-intensity interval program, global CM function enhanced further in ICT group, compared to that of their CON counterparts. In contrast there was little further improvement IM function, which is consistent with the plateau of improvement in P_0 that has been shown previously after 4 to 6-wk of IMT (20, 28). However, it may also be due to the fact that the volume of IMT was lower, compared to the preceding 4-wk phase of specific IMT. During the CM/IM phase, the inspiratory load was kept constant, and the training frequency and repetitions were dictated by the related prescriptions of the interval and core training programs. At first sight, the absence of a further improvement in P_0 during the CM/IM phase might seem to undermine the importance of the contribution of IM training to this intervention. However, most previous studies that have added CM training alone have failed to observe any improvements in performance (10, 19), or of putative mechanistic factors, such as RE_{OBLA}. The important contribution of the IM to CM performance is supported by the significant improvement in SEPT after the IMT phase. During the second phase of the study, the ICT group experienced the additional challenge of inspiratory loading during tasks that challenged core stabilisation, which led to a further improvement in SEPT performance, as well as running performance. We believe that it is the unique combination of CM/IM training that explains why our study showed a beneficial contribution of CM training, whilst other studies have not (10, 19).

Since the distance covered during the 1-hr time trial phase of the run increased in both ICT and CON groups post-intervention, we can conclude that the interval training improved performance, which was expected. The enhanced performance could be partly attributed to the augmentation of aerobic energy utilisation during exercise in adaptation to the 6-wk high-intensity interval training that was revealed by the significant relationship between the improvements of OBLA and exercise performance. The consequently lower reliance on energy generated from anaerobic glycolysis is evidenced by the lower $[La^-]_b$ in the post-intervention ISO trial. In a previous study we have demonstrated that the response to a similar treadmill interval training is enhanced by a preceding period of IMT (26). Moreover, the improved breathing pattern, post-exercise P_0, and RPB in the post-intervention ISO trial suggested that the enhanced IM function resulting from the IMT might have alleviated the IM fatigue and breathing effort during the running exercise, and, contributed to the enhancement of the exercise performance (25). Given that our combination of interval training, preceded by IMT, has already been shown to maximise the outcome of interval training, it is all the more impressive that the addition of CM/IM improved performance still further.

The ergogenic effect of the IMT almost certainly contributed to the enhancement of the exercise performance in both ICT and CON groups, via the direct ergogenic effect of IMT (15), as well as via the potentiation of the interval training stimulus (26). However, the relatively greater enhancement in the ICT group (3.04% vs 1.57%) may be, at least partly, the result of the additional integrated CM/IM training. The inter-relationships among the improvements of SEPT, RE_{OBLA}, and exercise performance suggest that the augmented global CM function, resulting from the CM/IM training in the ICT group, was responsible for the increased distance covered during the running time trial, and that this was underpinned by optimising running economy.

Running involves continuous alternate unilateral hip flexion and extension that creates corresponding trunk rotation in the runners in reaction to their leg movement (23). During running, the CM is responsible for stabilising the trunk by absorption of the disruptive torques, thus minimising the diversion of leg force exertion (2). The greater CM activation (assessed using EMG normalised to MVC) of endurance trained runners during running exercise, relative to that of untrained individuals, has been suggested to underlie their stable and efficient running form, and resultant superior running capacity (2). In the present study, it is reasonable to postulate that the further increase in CM function of the ICT participants might have improved their running economy by creating a solid base in the lumbopelvic-hip region, such that lower limb movements during the run were performed in a more linear manner, improving running performance. In light of the current findings, and of previous evidence that prior CM fatigue impairs performance during high-intensity treadmill running (27), it is reasonable to suggest that CM function is a factor limiting the capacity for high-intensity endurance running.

In the present study, the CM/IM intervention was designed to address real-world situation during exercise, where there is competition between the respiratory and non-respiratory functions of the IM. Although we did not compare with the outcomes of CM training alone - without loaded-respiratory activity incorporated, it is logical to presume that the current CM/IM conditioning maneuver applied in the ICT group could result in greater adaptations in the global CM function, and the adaptations would be more functionally relevant to endurance running. Nonetheless, the magnitude of CM fatigue (expressed as percentage of pre-exercise SEPT performance) remained unchanged during the ISO run trial. This response differs from that of P_0, which showed a significantly attenuated fatigue in both groups post-intervention. It is unlikely that the lack of change in CM fatigue is due to inadequate sensitivity of the SEPT, as the test has been shown to be capable of detecting changes of as little as 3% (24). Although we do not have a direct measure of CM activation during the running, it is reasonable to assume that the CM output was augmented post-training, providing greater core stabilisation, which was manifest as a reduction in RE_{OLBA}, but resulting in the same magnitude of CM fatigue. Such findings in addition of the marked enhancements in the running economy and the maximum performance of the running time trial inferred that there may be ample space in endurance runners to improve their running performance through the specific CM conditioning. This may seem to be contrary to the uncertainty of the CM training effects on athletic performance reported previously (10), but the current findings suggest that the "functional" element of the training may underpin its success in transferring the effect of CM conditioning to athletic performance.

PRACTICAL APPLICATIONS

This study demonstrates that the application of a 4-wk IMT enhances global IM and CM function simultaneously. Furthermore, integration of CM/IM training into a high-intensity interval training program for 6-wk, enhances CM function further, and augments the summative effects of the IMT and interval training on 1-hr running time-trial performance, possibly by optimising running economy. Based on these findings, it is recommended that IMT and running-specific CM/IM training are included within high-intensity interval programmes for endurance runners. Whether CM/IM training improves performance in shorter running events and team sports remains to be explored.

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Table 1. Physical characteristics and training background of participants in ICT and CON groups

	ICT	CON
Age (yrs)	22.8±3.2	22.4±3.9
Height (cm)	169.2±7.0	166.6±5.5
Weight (kg)	56.4±4.5	59.1±6.7
FVC (l)	4.26±0.50	3.96±0.63
FEV_1 (l)	3.74±0.36	3.41±0.56
FEV_1/FVC (%)	88.8±5.7	86.8±6.1
12-s MVV ($l.min^{-1}$)	164.3±24.2	165.1±40.9
$\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)	60.0±7.0	58.9±9.5
HR_{max} ($b.min^{-1}$)	195.6±5.3	191.6±8.8
$\dot{V}_{Emax}$ ($l.min^{-1}$)	126.1±15.8	135.1±29.8
Years of training (yrs)	6.2± 2.2	5.9 ± 2.8
Training hours per day	2-3	
Training days per week	5-6	
Training Distance ($km.wk^{-1}$)	70-80	

Values are mean ±SD
FVC=forced vital capacity, FEV_1=forced expiratory volume in 1 s, 12-s MVV=maximum voluntary ventilation measured in 12 s; $\dot{V}O_{2max}$=maximum volume of oxygen uptake; HR_{max}=maximum heart rate; $\dot{V}_{Emax}$=maximum ventilation
No significant difference in any variable between ICT & CON (P>0.05)

Table 2. The protocol of the 6-wk high-intensity interval running program

Week	Day / Set / No. of repetition x Distance	Week	Day / Set / No. of repetition x Distance
1st	1st / 1st / 4 x 200 m 1st / 2nd / 8 x 100 m 2nd / 1st / 2 x 400 m 2nd / 2nd / 8 x 100 m 3rd / 1st / 2 x 400 m 3rd / 2nd / 6 x 200 m 4th / 1st / 1 x 800 m 4th / 2nd / 6 x 200 m	4th	1st / 1st / 3 x 600 m 1st / 2nd / 3 x 400 m 2nd / 1st / 4 x 200 m 2nd / 2nd / 4 x 200 m 2nd / 3rd / 4 x 200 m 2nd / 4th / 4 x 200 m 3rd / 1st / 2 x 800 m 3rd / 2nd / 2 x 400 m
2nd	1st / 1st / 2 x 800 m 1st / 2nd / 2 x 400 m 2nd / 1st / 6 x 400 m 3rd / 1st / 3 x 800 m 4th / 1st / 1x 2,400 m	5th	1st / 1st / 4 x 600 m 1st / 2nd / 2 x 400 m 2nd / 1st / 4 x 200 m 2nd / 2nd / 4 x 200 m 2nd / 3rd / 4 x 200 m 2nd / 4th / 4 x 200 m 3rd / 1st / 2 x 800 m 3rd / 2nd / 2 x 400 m
3rd	1st / 1st / 2 x 600 m 1st / 2nd / 2 x 400 m 2nd / 1st / 4 x 200 m 2nd / 2nd / 4 x 200m 2nd / 3rd / 4 x 200 m 3rd / 1st / 1 x 800 m 3rd / 2nd / 2 x 400 m	6th	1st / 1st / 4 x 600 m 1st / 2nd / 2 x 400 m 2nd / 1st / 4 x 200 m 2nd / 2nd / 4 x 200 m 2nd / 3rd / 4 x 200 m 2nd / 4th / 4 x 200 m 3rd / 1st / 2 x 800 m 3rd / 2nd / 2 x 400 m

Table 3. Changes in global inspiratory muscle and core muscle functions, and in variables during the maximum graded treadmill test between pre- and post-intervention

	ICT			CON		
	Pre-IMT	Post-IMT	Post-ICT	Pre-IMT	Post-IMT	Post-ICT
P_0 (cmH_2O)	156.4 ±15.1	189.5* ±11.8	194.3* ±19.4	145.5 ±22.8	179.2* ±14.7	174.1* ±15.9
MRPD ($cmH_2O.ms^{-1}$)	0.45 ±0.07	0.57* ±0.08	0.60* ±0.10	0.44 ±0.07	0.56* ±0.06	0.57* ±0.08
SEPT (s)	287.3 ±130.4	317.4* ±122.2	459.3*[a] ±246.1	305.8 ±135.0	330.0* ±150.7	330.3* ±127.5
OBLA ($km.hr^{-1}$)	14.3 ±1.8	/	15.0* ±2.1	14.2 ±1.8	/	14.8* ±1.5
RE_{OBLA} ($ml.kg^{-1}.km^{-1}$)	198.0 ±10.7	/	187.7* ±11.8	191.5 ±15.5	/	190.0 ±16.6

Values are mean ±SD

P_0=static maximum inspiratory mouth pressure; MRPD=maximum rate of pressure development; SEPT=sport-specific endurance plank test; OBLA=onset of blood lactate accumulation; RE_{OBLA} was measured at the speed corresponding to OBLA.

* Significant different from corresponding Pre-IMT value ($P<0.05$)

[a] Significant different from corresponding Post-IMT value ($P<0.05$)

Table 4. Changes in global inspiratory muscle and core muscle functions, and in blood lactate accumulation during the 1-hr time trial treadmill run in Pre-IMT, Post-ICT and ISO trials

	Pre-IMT				Post-ICT				ISO			
	Pre-ex	Post-ex	diff	% diff	Pre-ex	Post-ex	diff	% diff	Pre-ex	Post-ex	diff	% diff
					P_0 (cmH_2O)							
ICT	156.4 ±15.1	137.6* ±16.8	18.9 ±7.8	12.1 ±5.1	194.3 ±19.4	177.7* ±15.9	16.6 ±16.0	8.17 ±7.45	194.3 ±19.4	179.0[a] ±17.4	15.3 ±10.3	7.74[b] ±4.80
CON	145.5 ±22.8	124.7* ±30.8	20.7 ±19.3	14.6 ±14.8	174.1 ±15.9	161.4* ±12.8	12.7 ±7.1	7.12 ±3.76	174.1 ±15.9	166.8[a] ±13.6	7.27 ±8.37	4.00[b] ±4.79
					SEPT (s)							
ICT	287.3 ±130.4	181.6* ±45.7	105.6 ±99.6	32.4 ±13.8	459.3 ±246.1	288.4* ±82.1	170.9 ±75.6	38.4 ±8.3	459.3 ±246.1	314.0[a] ±84.2	145.3 ±77.5	31.9 ±10.3
CON	305.8 ±135.0	197.2* ±93.4	108.7 ±59.9	26.8 ±20.1	330.3 ±127.5	200.5* ±97.5	129.8 ±40.4	32.4 ±18.3	330.3 ±127.5	209.5[a] ±97.2	120.8 ±45.2	27.7 ±22.9
					$[La^-]_b$ ($mmol.l^{-1}$)							
ICT	1.10 ±0.33	5.73* ±1.02	4.63 ±0.92	/	1.17 ±0.43	6.51* ±1.79	5.34 ±1.43	/	1.34 ±0.53	4.70* ±1.67	3.36[b,c] ±1.53	/
CON	1.49 ±0.53	6.18* ±2.32	4.69 ±2.60	/	0.87 ±0.39	5.38* ±2.52	4.52 ±2.24	/	1.02 ±0.23	4.78* ±2.22	3.76[b,c] ±2.04	/

Values are mean ±SD

P_0=static maximum inspiratory mouth pressure; SEPT=sport-specific endurance plank test; $[La^-]_b$=blood lactate concentration

* Significant different from corresponding Pre-ex value (P<0.05)

[a] Significant different from corresponding Pre-ex value in Post-ICT (P<0.05)

[b] Significant different from corresponding Pre-IMT value (P<0.05)

[c] Significant different from corresponding Post-ICT value (P<0.05)

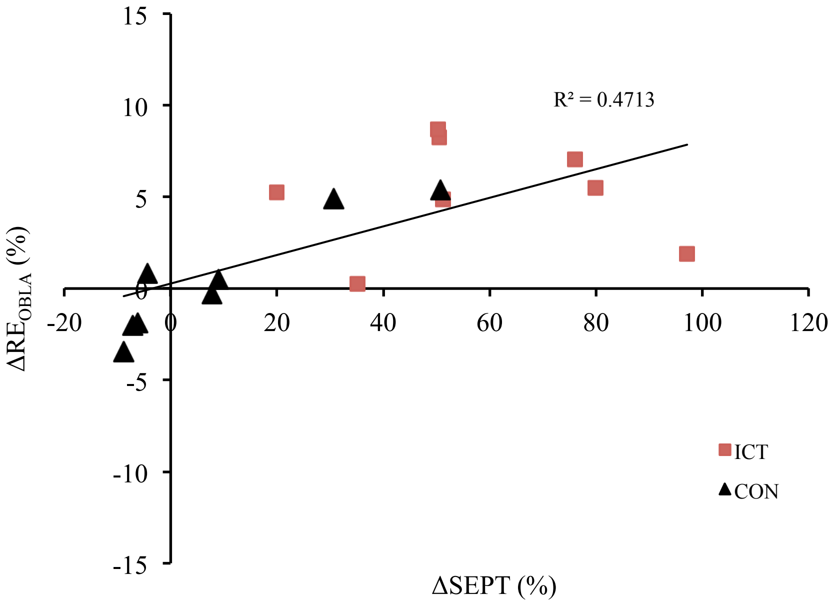
No significant interaction between Pre-IMT, Post-ICT and Post-ICT-ISO and across ICT vs CON (P>0.05)

Figure 1. The timeline of testing and training

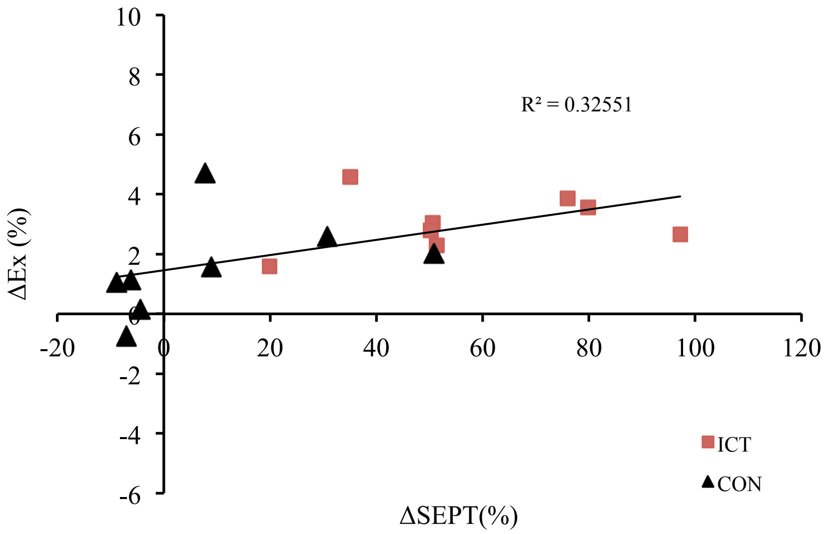
Pre-IMT	Introduction, familiarizations, preliminary testing Measurement of baseline IM and CM functions Maximum graded treadmill test 1-hr time trial treadmill run
~	
4-wk IMT	4-wk foundation IMT in ICT and CON groups
~	
Post-IMT	Measurement of post-IMT IM and CM functions
~	
6-wk interval training	ICT group: high-intensity interval training on treadmill with core conditioning incorporated with inspiratory-loaded breathing (CM/IM training) taken place at the end of each workout CON group: Identical high-intensity interval training on treadmill for 6 weeks with no CM/IM training
~	
Post-interval training	Measurement of IM and CM functions Maximum graded treadmill test 1-hr time trial treadmill run Repeated 1-hr time trial treadmill run for examining performance reliability 1-hr time trial treadmill run with speed identical to that of Pre-IMT trial (ISO)

Figure 2. The change in the performance of sport-specific endurance plank test (ΔSEPT) plotted against the change in (a) the running economy at OBLA (ΔRE_{OBLA}), (b) the 1-hr treadmill run performance (Ex), in ICT and CON participants (n=16). Solid line is the line of regression.

(a)


R² = 0.4713
15
10
5
0
-5
-10
-15
-20
0
20
40
60
80
100
120
ΔRE_{OBLA} (%)
ICT
CON
ΔSEPT (%)

(b)


R² = 0.32551
10
8
6
4
2
0
-2
-4
-6
-20
0
20
40
60
80
100
120
ΔEx (%)
ICT
CON
ΔSEPT(%)