Inspiratory Muscle Warm-up Improves 3,200-m Running Performance in Distance Runners

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Abstract

Barnes, KR and Ludge, AR. Inspiratory muscle warm-up improves 3,200-m running performance in distance runners. *J Strength Cond Res* 35(6): 1739–1747, 2021—This study examined the effects of an inspiratory muscle exercise as part of a warm-up (IMW) using a resisted breathing trainer on running performance. In a randomized crossover design, 17 trained distance runners completed two 3,200-m performance trials on separate days, preceded by 2 different warm-up procedures: IMW or sham IMW (CON). In each condition, subjects performed 30 breaths against either 50% of each athlete's peak strength (IMW) or 30 slow protracted breaths against negligible resistance (CON). Perceived race readiness and inspiratory muscle strength, flow, power, and volume were measured before and after each warm-up. Heart rate (HR), rating of perceived exertion (RPE) and dyspnea (RPD), and expired gases were collected during each trial. A 3,200-m run performance was 2.8% ± 1.5% (20.4-second) faster after IMW (effect size [ES] = 0.37, $p = 0.02$). After each warm-up condition, there was as small effect on peak inspiratory strength (6.6 ± 4.8%, ES = 0.22, $p = 0.02$), flow (5.2 ± 4.4%, ES = 0.20, $p = 0.03$), power (17.6 ± 16.7%, ES = 0.22, $p = 0.04$), and volume (6.7 ± 6.3%, ES = 0.24, $p = 0.01$) after IMW compared with CON. There were no differences in HR, minute volume, peak $\dot{V}O_2$, or $\dot{V}O_2$ at each 800-m interval between conditions (ES ≤ 0.13, $p > 0.17$). There were small differences in RPE at 800 m and 1,600 m (ES = 0.32, $p = 0.17$; ES = 0.21, $p = 0.38$, respectively), but no difference at the last 1,600 m ($p = 1.0$). There was a moderate positive effect on RPD (ES = 0.81, $p < 0.001$) and race readiness (ES = 0.76, $p < 0.01$) after IMW. Overall, the data suggest that IMW improves 3,200-m performance because of enhancements in inspiratory muscle function characteristics and reduction in dyspnea.

Key Words distance running, priming exercise, inspiratory muscle training

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Introduction

Warm-up activities are a widely accepted practice preceding nearly every athletic event to prepare the body for optimal competition performance (3). An active warm-up is arguably the most widely used warm-up technique for distance runners because it is likely to induce specific metabolic, cardiovascular, and neuromuscular changes conducive to distance-running performance (5). However, exercise performance has not been considered limited by ventilation or respiratory muscle function in healthy individuals despite the occurrence of respiratory muscle fatigue after prolonged submaximal exercise (26), as well as short-term maximal exercise (28). Indeed, evidence suggests that competitive distance running presents unique and demanding challenges for the respiratory muscles. The work of breathing during running is between 16 and 26% of the total oxygen cost of exercise (1), thus constituting a substantial portion of energy required during running.

Inspiratory muscle training (IMT) is a form of resistance training for the muscles primarily involved in the processes of breathing using a resisted respiratory breathing trainer. It is now well documented that several weeks of IMT enhance exercise performance in untrained (10,11,14) and trained individuals across a range of endurance sports (10,11,15,22,27,33,34,41), as well as during repeated sprinting (33,37). Inspiratory muscle exercise as part of a warm-up (IMW) has also shown to enhance running (11,27,36), rowing (40), and badminton (25) performance. Other such priming exercise involving previous high-intensity exercise above that typically used during a warm-up also improves subsequent simulated running performance in high-level track athletes by 1–3% (3,20). The physiological mechanisms supporting these effects remain unclear but likely include an improvement in inspiratory muscle function, reduction in breathlessness sensation, overall speeding of $\dot{V}O_2$ kinetics, increased total O_2 consumed, greater peak $\dot{V}O_2$ attainted during running, and changes to motor-unit recruitment patterns (16,20,35).

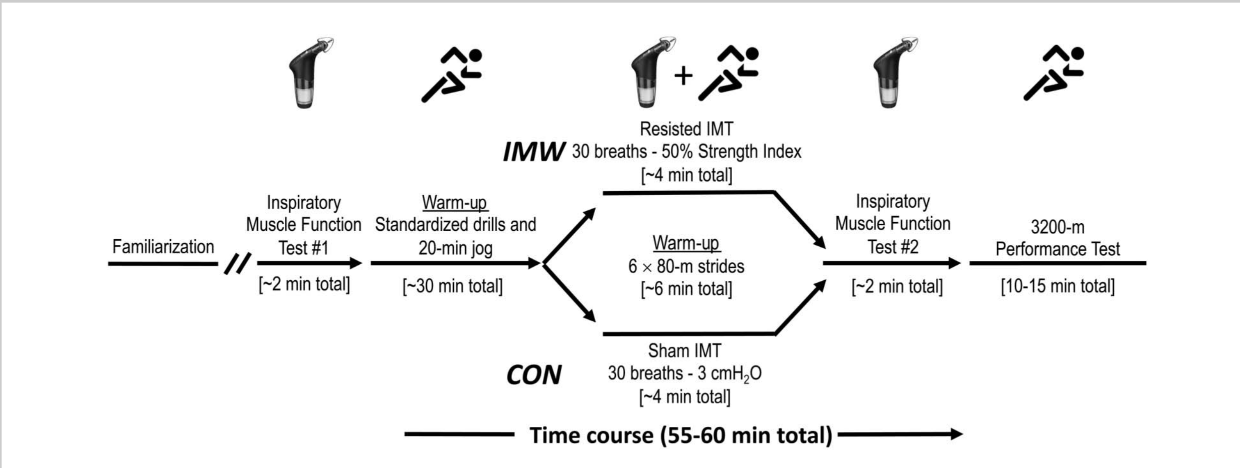

Figure 1. Schematic representation of random crossover study design, indicating the inspiratory muscle warm-up (IMW) and control (CON) conditions. Initially, subjects participated in a familiarization session with all testing procedures and equipment. Thereafter, subjects completed two 3,200-m performance trials, preceded by 2 different warm-up conditions (IMW or CON), in random order, at the same time of day, separated by 7 days. Each 3,200-m performance trial was always preceded by standardized mobility drills and a 20-minute self-paced jog. In the CON condition, runners preceded the performance trial with a sham breathing protocol involving 30 slow protracted breaths against 3 cmH_20 resistance. In the IMW condition, runners completed 30 dynamic maximal inhalations against a resistance equivalent to 50% of each athlete's peak inspiratory muscle strength. After both IMW and CON, subjects performed 6 × 10-second strides, with 60–90 seconds of recovery at each subject's 1,500-m race pace. The respective warm-up procedures were preceded and followed by an inspiratory muscle function test. [ ] Indicates approximate length of time spent during each phase of protocol.

An enhancement in inspiratory muscle function represents a greater utilization of inspiratory muscles across their full range of movement and is associated with a reduction the oxygen cost of breathing (38), which is related to a reduction in the perception of respiratory and peripheral effort during athletic performance (10,33,40). An increase in speed of $\dot{V}O_2$ kinetics during high-intensity exercise would likely decrease the amount intramuscular metabolic distress and delay the rate of fatigue development thus enhancing performance (20). A greater $\dot{V}O_2$ during high-intensity exercise after priming and alterations in neuromuscular activity could facilitate a potential increase in muscle oxygen delivery along with greater muscle oxygen utilization. Middle- and long-distance running is a sport requiring large aerobic power and high minute ventilation, typically greater than 70 $ml \cdot kg^{-1} \cdot min^{-1}$ and 150 $L \cdot min^{-1}$ in elite men. If the overall $\dot{V}O_2$ response can be augmented by priming such that a greater proportion of total oxygen consumption is used throughout the exercise bout, it would be expected to enhance performance.

Although effective priming exercises have been shown to enhance exercise tolerance, there are mixed findings regarding the addition of IMW on performance. Several studies have shown improvements in exercise performance after various exercise modes (11,25,27,36,40); other studies have shown no improvement in cycling (8,21) or running (12) performance. In addition, most studies use recreational trained subjects, and of the 2 studies using trained athletes (21,40), Johnson et al. (21) found no improvement in cycling time-trial performance compared with a cycling specific warm-up, while Volianitis et al. (40) reported a 1.2% enhancement in rowing performance compared with a rowing-specific warm-up. Furthermore, research has shown that a specific respiratory warm-up protocol is more effective in enhancing inspiratory muscle strength than a general warm-up protocol in rowers (39). The purpose of this study was to examine the effects of a running-specific warm-up with IMW on 3,200-m running performance in moderately trained middle-distance runners.

Methods

Experimental Approach to the Problem

Subjects' initial visit involved a familiarization session with all testing procedures and equipment. Thereafter, runners completed two 3,200-m performance trials (in a randomized crossover experimental design), preceded by 2 different warm-up conditions, either a running-specific warm-up (CON) or a running-specific warm-up with IMT (IMW), at the same time of day, separated by 7 days (Figure 1). In each condition, subjects performed either 30 breaths against either 50% of each athlete's peak strength (IMW) or 30 slow protracted breaths against negligible resistance (CON).

Subjects

Seventeen (10 men and 7 women) moderately trained middle-distance runners participated in the study (4). All subjects competed on the collegiate track team and had competitive racing experience between 800 and 3,000 m at the National Collegiate Athletics Association regional and

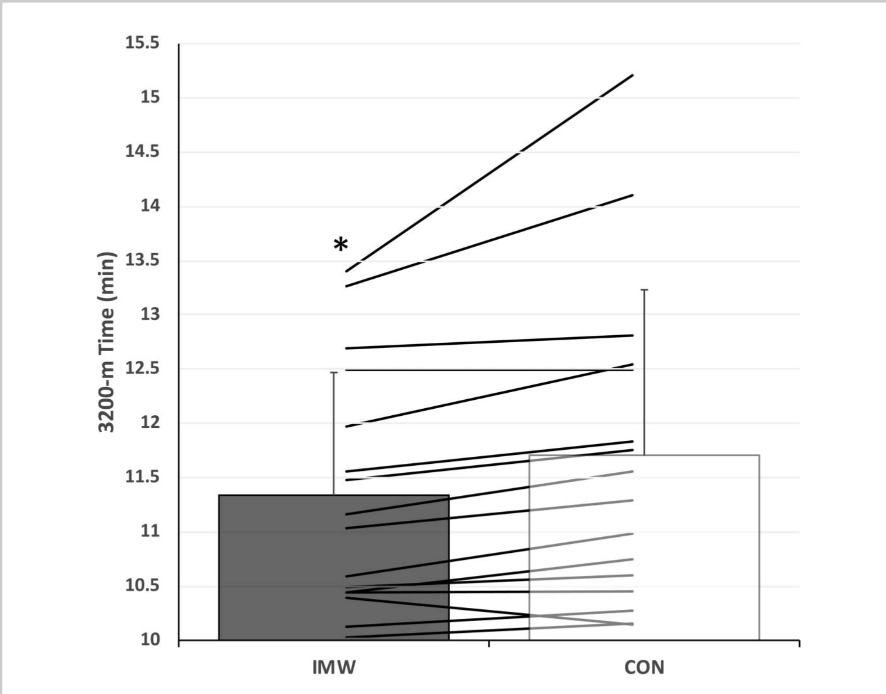

Figure 2. Small effect (ES = 0.37) on 3,200-m performance time after inspiratory muscle warm-up (IMW) compared with control (CON) warm-up. Opaque black and white bars represent mean performance times with *SE* bars for IMW and CON conditions, respectively. Solid lines represent individual values for running performance after IMW and CON warm-ups. *Significantly different from CON ($p = 0.02$). ES = effect size.

national levels. Their mean ± *SD* age, body mass, and height were 20.3 ± 1.5 years, 67.5 ± 6.6 kg, and 1.78 ± 0.09 m, respectively, for male runners and 20.2 ± 1.3 years, 55.4 ± 4.4 kg, and 1.67 ± 0.04 m for the female runners. The study took place at the end of each subject's aerobic development (base) phase of training. In the 8 weeks before the study, the runners undertook 88.1 ± 13.1 km per week of running in 8.5 ± 0.5 sessions$\cdot$wk^{-1} along with 1–2 strength training sessions$\cdot$wk^{-1}. Subjects were blinded to the outcomes of the study. The study was approved by the Grand Valley State University Human Research Review Committee (Reference #: 16-158-H); Allendale, MI, and all subjects provided informed written consent to participate.

Procedures

Subjects reported to the laboratory 2-hours postprandial and having avoided strenuous exercise in the 24 hours preceding a test session. All running tests were performed in controlled laboratory conditions (19–21° C; 65% rH) and run on a motorized treadmill (Woodway ELG; Woodway USA, Inc., Waukesha, WI), which was checked and calibrated for speed accuracy. Each 3,200-m performance trial was always preceded by standardized mobility drills and a 20-minute self-paced jog (recorded and repeated during their second performance trial). In the CON condition, runners preceded the performance trial with a sham breathing protocol involving 30 slow protracted breaths against 3 cmH_20 resistance using a POWERbreathe K-Series K5 breathing trainer and BreatheLink software (HaB International Ltd., Birmingham, United Kingdom), a protocol shown to elicit a negligible training effect (7). In the experimental condition (IMW), subjects completed 30 dynamic maximal inhalations against a resistance equivalent to 50% of each athlete's peak inspiratory strength with their nose plugged, a protocol shown to elicit optimal changes in most inspiratory muscle function characteristics (inspiratory muscle strength, flow, power, volume, energy, and time) (unpublished data). Subjects were instructed to "breathe in as hard, as fast and as deeply as possible" during each inhalation and "breathe out slowly and passively through your mouth until your lungs feel completely empty," during each exhalation. Subjects were trained on this technique during the familiarization session and coached throughout their testing to comply with this breathing technique. Subjects also received visual feedback of inspiratory muscle characteristics during each effort by viewing the BreatheLink software display on the computer to maximize their inspiratory effort during each testing session. After both CON and IMW, subjects performed 6 × 10-second strides, with 60–90 seconds of recovery at each subject's 1,500-m race pace (recorded and repeated during their second performance trial). Strides were defined as bouts of short-duration fast running, which are commonly used during the warm-up procedures of elite athletes to precondition the muscles for subsequent sustained higher intensity exercise (3). The respective warm-up procedures were preceded and followed by an assessment of inspiratory muscle function characteristics (Figure 1). Before the performance trial, the subjects' "perceived race readiness" was assessed using the 1–10 scale of Ingham et al. (20).

The 3,200-m performance trials were performed on a Woodway ELG treadmill (Woodway USA, Inc.) at 1% grade (23) during which heart rate (HR) (Polar H7; Polar Electro Inc., Lake Success, NY) and expired ventilation samples were measured continuously using a metabolic cart (ParvoMedics TrueOne 2,400; ParvoMedics, Salt Lake City, UT) for determination of $\dot{V}O_2$, carbon dioxide production, V_E, and respiratory exchange ratio. The metabolic cart was

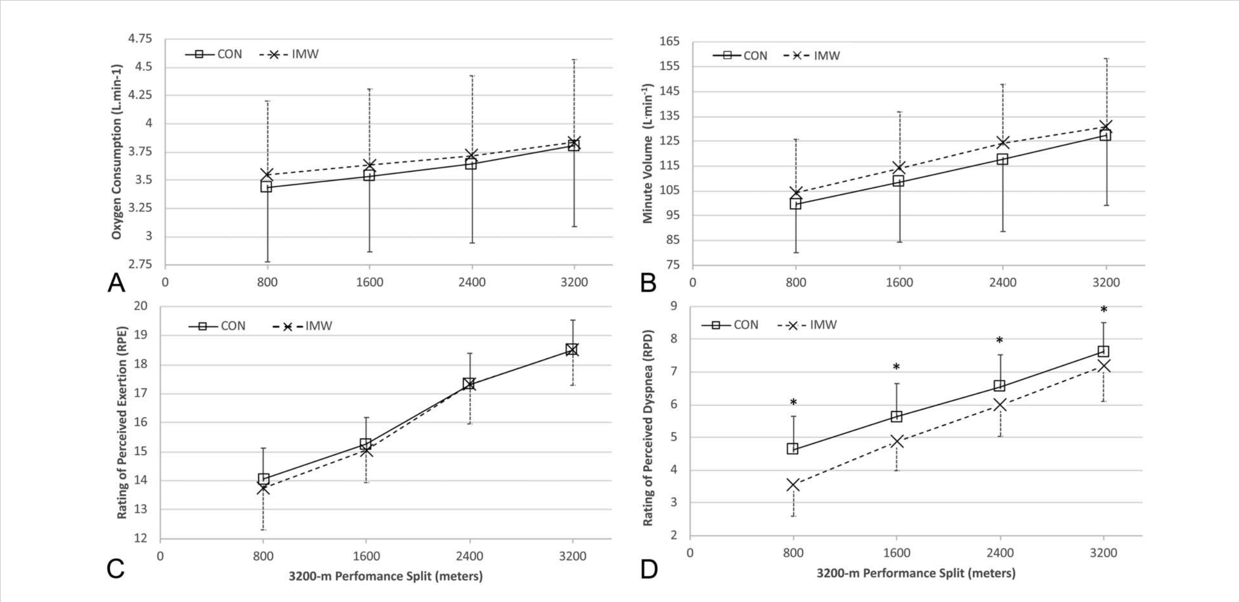

Figure 3. Physiological and perceptual measures at each 800-m interval during the 3,200-m performance trials after both inspiratory muscle warm-up (IMW) and control (CON) warm-ups: (A) oxygen consumption (ml·kg^{-1}·min^{-1}), (B) respiratory minute volume (L·min^{-1}), (C) rating of perceived exertion (RPE), and (D) rating of perceived dyspnea (RPD). *Significantly different from CON ($p < 0.05$).

calibrated before each testing session following the manufacturer's calibration instructions. At each 800-m interval, the subjects rating of perceived exertion (RPE) was assessed using a standardized 6–20 Borg RPE scale and rating of perceived dyspnea (RPD) using a modified Borg scale (6). On a scale of 0 is "no shortness of breath" and 10 represents "so much shortness of breath that you have to stop the activity" the runner was asked to estimate the effort required to *breathe* but not the effort of the exercise. Oxygen consumption and V_E were determined from mean data during the last 30 seconds of each 800-m interval. During the familiarization session, subjects self-selected a treadmill speed they thought they could complete the 3,200-m trial at; both performance trials for each runner were then initiated at that speed. Subsequently, each subject was allowed to adjust the speed accordingly throughout the trial. Subjects were blinded to all measures on the treadmill interface except elapsed distance.

Inspiratory muscle function characteristics were assessed before and after each subject's respective warm-up procedures using the POWERbreathe K-Series K5 inspiratory breathing trainer and BreatheLink software (HaB International Ltd.). The POWERbreathe K-Series K5 breathing trainer has previously been shown to be a highly reliable measure of inspiratory muscle function characteristics in healthy subjects (31). Subjects were instructed to perform 5 dynamic maximal inspiratory efforts (as described previously) against a negligible resistance of 3 cmH_2O. Subjects received visual feedback during each inspiratory effort by viewing the BreatheLink software display to maximize their inspiratory effort. The peak values for inspiratory strength (cmH_2O), inspiratory volume (L), flow (L·s^{-1}), power (W), energy (J), and time (s) were taken from the 5 breaths.

Statistical Analyses

The effects of warm-up condition on performance and physiological measures were analyzed with a spreadsheet for post-only crossovers (18). The pretest value of the dependent variable was included as a covariate to improve precision of the estimate of the effects. Inspiratory muscle function characteristics obtained both before and after warm-up conditions (Figure 1) were also analyzed with a pre-post crossover spreadsheet (18). Effects were estimated in percent units through log transformation, and uncertainty in the estimate was expressed as 90% confidence limits. The effect size (ES), which represents the magnitude of the difference between the 2 conditions in terms of *SD*, was calculated from the log-transformed data by dividing the change in the mean by the average *SD* of the 2 conditions. The outcome for performance (peak speed) was evaluated with the clinical version of magnitude-based inference: the effect was deemed unclear if the chance of benefit was sufficiently high (>25%) to warrant its use with athletes, but the risk of harm was unacceptable (>0.5%); the effect was otherwise deemed clear and reported as the magnitude of the observed effect and the qualitative probability that the true magnitude was at least as large as the observed magnitude. The threshold values for assessing the magnitude of small, moderate,

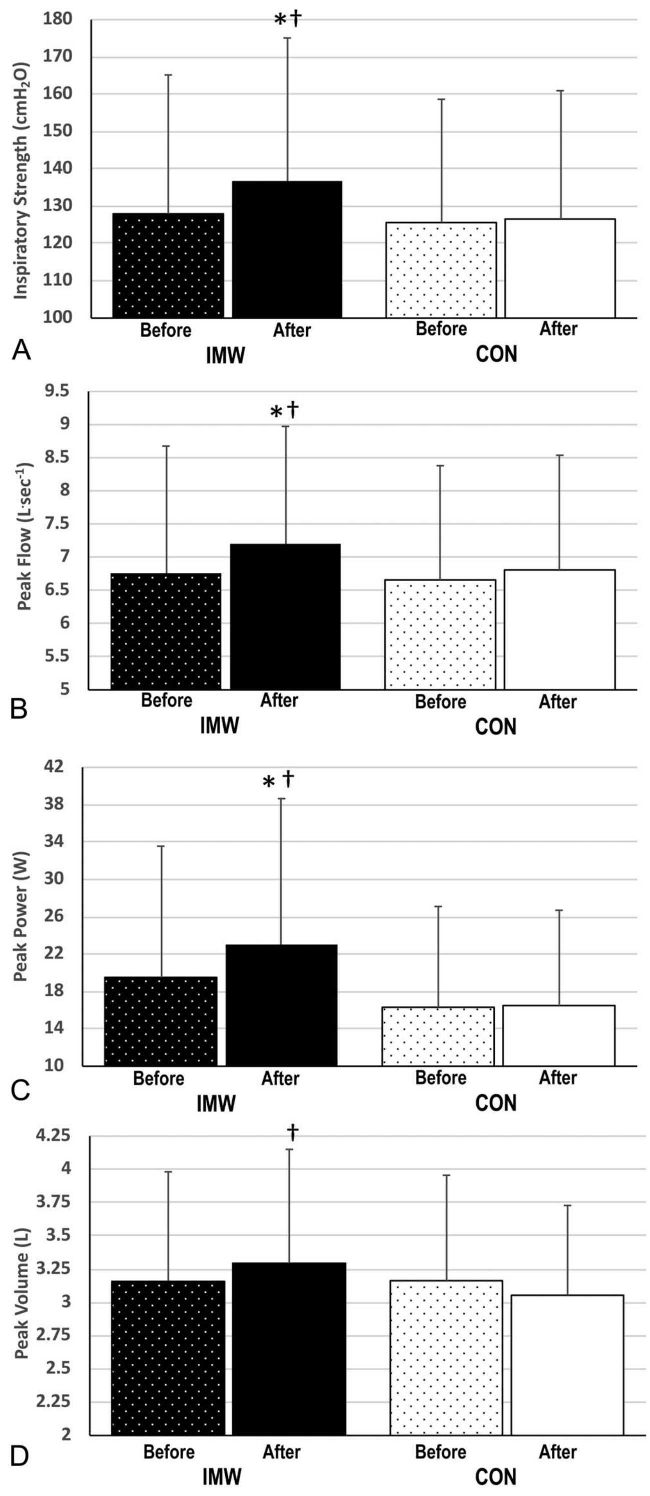

Figure 4. Inspiratory muscle functions characteristics after the inspiratory muscle warm-up (IMW) and control (CON) warm-ups: (A) inspiratory strength (cmH_2O), (B) peak flow ($L \cdot s^{-1}$), (C) peak power (W), and (D) peak volume (L). Baseline (before) warm-up inspiratory muscle function characteristics were not different between groups ($p > 0.31$). *Inspiratory muscle function characteristics were significantly higher after respective warm-up condition ($p < 0.05$). †Inspiratory muscle function characteristic after IMW significantly different from CON ($p < 0.05$).

large, very large, and extremely large effects were respectively 0.3, 0.9, 1.6, 2.5, and 4.0 times the within-subject *SD* a top athlete would show between competitions (19). For top distance runners, this *SD* was 0.8% (17), so the thresholds were 0.24, 0.72, 1.3, 2.0, and 3.2%. Magnitudes of effects on measures other than performance were evaluated nonclinically: if the confidence interval overlapped thresholds for small positive and negative values, the effect was deemed unclear; all other effects were reported as the magnitude of the observed value and were evaluated probabilistically as described above, except that threshold values for small, moderate, large, very large, and extremely large effects were 0.2, 0.6, 1.2, 2.0, and 4.0 of the between-subject *SD* in the control condition (19). Data are presented as mean ± SD.

Results

The effects on 3,200-m run performance were small (ES = 0.37) after IMW (11.3 ± 1.1 minutes) compared with CON (11.7 ± 1.5 minutes). Performance times were 2.8 ± 1.5% (20.4 seconds, $p = 0.02$) faster after IMW than after CON with 15 of 17 subjects running faster after IMW (Figure 2). The 2.8% improvement is substantially greater than the smallest important and worthwhile change (half of the typical variation athletes show between competitions, which is 1.4% for events 3–10 km) described by Hopkins (17) representing a meaningful and practically significant enhancement in performance in well-trained distance runners. There were trivial differences in oxygen consumption ($\dot{V}O_2$) at each 800-m interval (800-m IMW 3.55 ± 0.65 vs. CON 3.46 ± 0.62 $L \cdot min^{-1}$, 2.4 ± 4.1%, $p = 0.26$; 1,600-m IMW 3.64 ± 0.67 vs. CON 3.57 ± 0.64 $L \cdot min^{-1}$, 1.7 ± 3.7%, $p = 0.37$; 2,400-m IMW 3.72 ± 0.70 vs. CON 3.68 ± 0.66 $L \cdot min^{-1}$, 1.0 ± 3.6%, $p = 0.45$) as well the peak $\dot{V}O_2$ at 3,200 m attained during the trial (IMW, 3.84 ± 0.73 vs. CON 3.81 ± 0.72 $L \cdot min^{-1}$, 0.8 ± 1.7%, ES = 0.12, $p = 0.42$) (Figure 3A). Differences in V_E were also trivial between trials (Figure 3B, 2.9 ± 4.2%, ES = 0.13, $p = 0.25$). Average HR during the performance trial was not different between conditions (IMW, 183 ± 9 vs. CON 182 ± 11 bpm, ES = 0.01, $p = 0.92$) or at each 800-m interval ($p > 0.40$). There was a small difference between subjects' RPE during the first 800 and 1,600 m of running (−0.31 ± 0.40 AU, ES = 0.32, $p = 0.17$ and −0.19 ± 0.55 AU, ES = 0.21, $p = 0.38$, respectively) after IMW, but subjects achieved the same RPE (18.5 ± 1.2 AU) during the last 1,600 m (Figure 3C). There was a moderate effect (ES = 0.81) on RPD throughout the performance trial (Figure 3D, −0.70 ± 0.20 AU, $p < 0.001$). The subjects reported moderately greater (ES = 0.76, 0.69 ± 0.30 AU, $p < 0.01$) race readiness after IMW (7.1 ± 0.9 AU) than CON (6.4 ± 0.8 AU).

Baseline inspiratory muscle function characteristics were not different between groups (ES < 0.18, $p > 0.31$). There was a small effect after IMW but not CON compared with subjects' baseline values on peak inspiratory strength (IMW, 7.2 ± 8.1%, ES = 0.23, $p = 0.003$; CON, 0.5 ± 6.0%, ES = 0.02, $p = 0.64$), flow (IMW, 7.8 ± 9.4%, ES = 0.29, $p = 0.003$; CON, 2.5 ± 6.9%, ES = 0.09, $p = 0.17$), and power (IMW, 19.9 ± 30.0%, ES = 0.25, $p = 0.04$; CON, 2.0 ± 21.1%, ES = 0.03, $p = 0.84$) (Figure 4). There were trivial effects after IMT and CON on inspiratory volume (IMW, 3.9 ± 10.2%, ES = 0.14, $p = 0.08$; CON, −2.7 ± 12.9%, ES = −0.10, $p = 0.23$) compared with baseline (Figure 4). In addition, after the respective warm-ups, but before the 3,200-m performance trial, there were small differences between conditions on peak inspiratory strength (IMW, 137 ± 38 vs. CON 126 ± 34 cmH_2O, 6.6 ± 4.8%, ES = 0.22, $p = 0.02$), flow (IMW, 7.20 ± 1.77 vs. CON 6.81 ± 1.73 $L \cdot s^{-1}$, 5.2 ± 4.4%, ES = 0.20, $p = 0.03$), power (IMW, 23.0 ± 15.6 vs. CON 16.5 ± 10.2 W, 17.6 ± 16.7%, ES = 0.22, $p = 0.04$), and volume (IMW, 3.30 ± 0.85 vs. CON 3.05 ± 0.67 L, 6.7 ± 6.3%, ES = 0.24, $p = 0.01$) (Figure 4).

Discussion

The aim of this study was to examine the effects of a running-specific warm-up with IMW on 3,200-m running performance in moderately trained middle-distance runners. The primary finding of this study indicates there was a small beneficial effect of IMW on running performance, compared with a standard warm-up regimen along with a range of physiological and perceptual measures important to distance-running performance. On average, the IMW warm-up resulted in a ~21-second (2.8%) improvement in 3,200-m performance compared with CON. The effect is similar to those in comparable studies using a variety of performance tests (25,27,36,40), and greater than the smallest worthwhile change in performance athletes show between competitions, which is about half the typical variation athletes show between competitions (~0.8%) (9,13,17). Previous studies have shown that an IMW (36) can improve intermittent run to exhaustion performance (Yo-Yo intermittent recovery test) in trained individuals by 19.5 ± 12.6%. Lomax et al. (27) built on the findings of Tong and Fu (36) by directly comparing the separate and combined effects of IMW and IMT. They reported large effects (ES > 2.3) on distance covered after their own IMW (5.3 ± 2.9%, $p = 0.042$) and combined effects of 4-week IMT and IMW (14.9 ± 4.5%, $p = 0.005$) (27). Lin et al. (25) reported a 6.8 ± 3.7% ($p = 0.0002$) increase in distance covered during a badminton footwork test after IMW. Similarly, Volianitis et al. (40) found mean power output during a 6-minute all-out rowing test increased by 3.2% ($p < 0.01$) after IMW in well-trained rowers. Other studies have found nonsignificant improvements ($p > 0.05$) in 10-km cycling time-trial performance (21) and 2,400-m running performance (12) (while carrying a thoracic load) after IMW as well.

While the $\dot{V}O_2$ response was elevated (Figure 3), the changes were within the typical error of measurement for oxygen consumption and therefore could be an artifact of technical error. However, these data are still consistent with several previous studies using an IMW before high-intensity rowing (40), cycling (21), and running (12) bouts. Several other studies have demonstrated previous "priming" exercise results in an increased oxidative contribution to energy metabolism during subsequent high-intensity running performance trials (3,20). The rationale for increased oxygen consumption after high-intensity priming exercise remains unclear, but previous studies using previous high-intensity exercise have described increased blood flow through the muscle, greater muscle oxygenation, increased activation of rate-limiting enzymes of oxidative phosphorylation, and alterations in neuromuscular activity as reasons for the increased $\dot{V}O_2$ response (3,20). An elevation in $\dot{V}O_2$ kinetics and increases in muscle contractile performance after previous contractile activity have also been reported following active warm-up techniques (30).

The enhancement in running performance was also associated with a reduction in rating of perceived dyspnea (RPD) after IMW, but not perception of effort (RPE). Perceptual responses are generally reduced during submaximal exercise intensities (like those used in the early stages of our performance trial) (33,41); however, if distance covered or speed is increased after IMW, both RPE (36) and RPD (36,40) have been shown to not differ at maximal or near-maximal intensities. Our measurements of RPE throughout the performance trial support these observations. Notably, there were small (statistically nonsignificant, $p > 0.05$) differences in RPE throughout the trial (Figure 3C); however, after IMW, there was an increase in running speed compared with CON given the ~21-second improvement in running performance, therefore, subjects average running velocity was faster at any given RPE after IMW compared with CON. The RPD was significantly lower throughout the trial, but the difference in RPD was attenuated from start to finish (Figure 3C). In the studies reporting RPE and RPD throughout their respective performance trials, Lomax et al. (27) found similar RPE and RPD as distance covered increased after IMW, whereas Johnson et al. (21) found RPE and RPD tended to be lower ($p > 0.05$) after IMW. Previous research has shown that, while exercising at near-maximal intensities, dyspnea can be as important, or more so, than leg fatigue during exhausting exercise (24). In this context, the improvement in running performance after IMW may be attributed, at least partially, to the reduction in dyspnea.

Consistent with the reduction in RPD and improvement in performance, it is suggested that IMW-mediated increases in maximal inspiratory pressure (MIP, or "maximal inspiratory muscle strength" as derived from the BreatheLink software used in this study) reduce the fractional utilization of maximal tension generated with each inspiration, thereby reducing dyspnea and increasing exercise tolerance (21,25,36,40). The ergogenic effect of IMW on dynamic lung function has been attributed to greater voluntary excitability, increased coordination of the inspiratory muscles, and decreasing the degree of cocontraction between inspiratory and expiratory muscle (16,35,39). In the current study, the IMW was effective in enhancing inspiratory muscle pressure and flow parameters (Figure 4) indicating that the inspiratory muscle–specific warm-up protocol was effective in enhancing the inspiratory muscle force output and muscle shortening velocity. Accordingly, the 7.2% increase in inspiratory muscle strength after the IMW is consistent with previous studies (12,21,25,27,36,39,40). However, the improvement in flow parameters resulting from IMW is greater than that in other studies (25,36). It has been postulated that the IMW protocols used in various studies has been effective in enhancing the inspiratory muscle force (pressure) output rather than the muscle shortening (flow) velocity (32). The difference in results could be a function of the subjects training status or methodological differences. In the current study, we used well-trained runners habitually using large proportions of their inspiratory muscle strength at high flow rates across their full range of movement. In addition, in comparison with previous studies, we only used 1 set of 30 dynamic maximal inhalations against a resistance equivalent to 50% of each athlete's peak inspiratory strength compared with other studies using 2 sets of 30 breaths against 40% MIP (12,21,25,27,36,40). However, data from our laboratory indicate that a pressure load equivalent to ~50% MIP is the optimal dose to enhance both force and velocity parameters important to high-intensity running (2).

All these inspiratory muscle characteristics represent an enhancement in the overall performance of the respiratory system and are likely associated with an enhancement in 3,200-m running performance. Given that the effort of breathing during running represents a considerable portion of energy required during running (1), the enhancement in inspiratory muscle function seen here, the muscles responsible for breathing were able to work at a lower percentage of the maximal tension generated with each inspiration, thus delaying the rate of fatigue during the IMW trial as well as reducing the metabolic cost of breathing (Figure 3) (38). In theory, more powerful muscles are also able to generate higher airflow and may increase the body's ability to neutralize lactate during high-intensity exercise (29), thus enhancing performance in the latter stages of the performance test; however, lactate was not assessed in the current study.

Like other studies (12,21,25,39), the modality-specific warm-up (CON in our study) had no effect on inspiratory muscle strength or any other inspiratory muscle function characteristics. This phenomenon, which emerges with at least 30 breaths ≥40% MIP using a resisted breathing trainer, suggests that the respiratory system may have different warm-up requirements than the locomotor system (39). 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

(30). In addition, a specific respiratory warm-up is more effective in this respect than whole body protocols.

Finally, our results support a growing body of literature supporting that traditional warm-up regimens typically used by distance runners may not be optimal (30) and that including an IMW as part of traditional running warm-up could enhance race performance. Consistent with this, subjects reported moderately greater (ES = 0.76, $p < 0.01$) race readiness after IMW than CON. Several other studies have also reported race readiness after priming exercise with mixed findings (3,20). Ingham et al. (20), reported greater race readiness ($p < 0.05$) after a high-intensity warm-up compared to a traditional warm-up (6.3 ± 1.0 and 5.8 ± 1.7, respectively), whereas Barnes et al. (3) found a small negative effect (ES < 0.30) on perceived race readiness after a warm-up that included strides while wearing a weighted vest compared with a traditional running warm-up (7.3 ± 1.0 and 6.7 ± 1.5, respectively) despite an improvement in performance.

Practical Applications

Coaches and practitioners working with distance runners should incorporate an IMW into the warm-up routines of their athletes before subsequent high-intensity running. The findings of the current study are limited to the specific IMW protocol, run-specific warm-up, and subjects used in this study. Future research should focus on optimizing the use of IMT in warm-up procedures by modifying the load parameters and timing to further enhance running performance and elucidate the mechanisms responsible for such improvements.

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References

1. Aaron, EA, Seow, KC, Johnson, BD, Dempsey, JA. Oxygen cost of exercise hyperpnea: Implications for performance. *J Appl Physiol* 72: 1818–1825, 1992.
2. Barnes, KR, Hopkins, WG, McGuigan, MR, Kilding, AE. Effects of different uphill interval-training programs on running economy and performance. *Int J Sports Physiol Perform* 8: 639–647, 2013.
3. Barnes, KR, Hopkins, WG, McGuigan, MR, Kilding, AE. Warm-up with a weighted vest improves running performance via leg stiffness and running economy. *J Sci Med Sport* 18: 103–108, 2015.
4. Barnes, KR, Kilding, AE. Running economy: Measurement, norms and determining factors. *Sports Med Open* 1: 8, 2015.
5. Bishop, D. Warm up II: Performance changes following active warm up and how to structure the warm up. *Sports Med* 33: 483–498, 2003.
6. Burdon, JG, Juniper, EF, Killian, KJ, Hargreave, FE, Campbell, EJ. The perception of breathlessness in asthma. *Am Rev Respir Dis* 126: 825–828, 1982.
7. Caine, MP, McConnell, AK. Pressure threshold inspiratory muscle training improves submaximal cycling performance. In: Proceedings of the Third Annual Conference of the European College of Sport Science. A Sargeant and H Siddons, eds. Manchester, United Kingdom: Centre for Health Care Development, 1998. pp. 101.
8. Cheng, CF, Tong, TK, Kuo, YC, et al. Inspiratory muscle warm-up attenuates muscle deoxygenation during cycling exercise in women athletes. *Respir Physiol Neurobiol* 186: 296–302, 2013.
9. Chryssanthopoulos, C, Ziaras, C, Zacharogiannis, E, et al. Variability of performance during a 60-min running race. *J Sports Sci* 33: 2051–2060, 2015.
10. Edwards, AM, Wells, C, Butterly, R. Concurrent inspiratory muscle and cardiovascular training differentially improves both perceptions of effort and 5000 m running performance compared with cardiovascular training alone. *Br J Sports Med* 42: 823–827, 2008.
11. Faghy, MA, Brown, PI. Training the inspiratory muscles improves running performance when carrying a 25 kg thoracic load in a backpack. *Eur J Sport Sci* 16: 585–594, 2016.
12. Faghy, MA, Brown, PI. Whole-body active warm-up and inspiratory muscle warm-up do not improve running performance when carrying thoracic loads. *Appl Physiol Nutr Metab* 42: 810–815, 2017.
13. Fisher, J, Clark, T, Newman-Judd, K, Arnold, J, Steele, J. Intra-subject variability of 5 km time trial performance completed by competitive trained runners. *J Hum Kinet* 57: 139–146, 2017.
14. Gething, AD, Williams, M, Davies, B. Inspiratory resistive loading improves cycling capacity: A placebo controlled trial. *Br J Sports Med* 38: 730–736, 2004.
15. Griffiths, LA, McConnell, AK. The influence of inspiratory and expiratory muscle training upon rowing performance. *Eur J Appl Physiol* 99: 457–466, 2007.
16. Hawkes, EZ, Nowicky, AV, McConnell, AK. Diaphragm and intercostal surface EMG and muscle performance after acute inspiratory muscle loading. *Respir Physiol Neurobiol* 155: 213–219, 2007.
17. Hopkins, WG. Competitive performance of elite track-and-field athletes: Variability and smallest worthwhile enhancements. *Sportscience* 9: 17–20, 2005.
18. Hopkins, WG. Spreadsheets for analysis of controlled trials, with adjustment for a subject characteristic. *Sportscience* 10: 46–50, 2006.
19. Hopkins, WG, Marshall, SW, Batterham, AM, Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009.
20. Ingham, SA, Fudge, BW, Pringle, JS, Jones, AM. Improvement of 800-m running performance with prior high-intensity exercise. *Int J Sports Physiol Perform* 8: 77–83, 2013.
21. Johnson, MA, Gregson, IR, Mills, DE, Gonzalez, JT, Sharpe, GR. Inspiratory muscle warm-up does not improve cycling time-trial performance. *Eur J Appl Physiol* 114: 1821–1830, 2014.
22. Johnson, MA, Sharpe, GR, Brown, PI. Inspiratory muscle training improves cycling time-trial performance and anaerobic work capacity but not critical power. *Eur J Appl Physiol* 101: 761–770, 2007.
23. Jones, AM, Doust, JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci* 14: 321–327, 1996.
24. Killian, KJ, Leblanc, P, Martin, DH, et al. Exercise capacity and ventilatory, circulatory, and symptom limitation in patients with chronic airflow limitation. *Am Rev Respir Dis* 146: 935–940, 1992.
25. Lin, H, Tong, TK, Huang, C, et al. Specific inspiratory muscle warm-up enhances badminton footwork performance. *Appl Physiol Nutr Metab* 32: 1082–1088, 2007.

26. Loke, J, Mahler, DA, Virgulto, JA. Respiratory muscle fatigue after marathon running. *J Appl Physiol Respir Environ Exerc Physiol* 52: 821–824, 1982.

27. Lomax, M, Grant, I, Corbett, J. Inspiratory muscle warm-up and inspiratory muscle training: Separate and combined effects on intermittent running to exhaustion. *J Sports Sci* 29: 563–569, 2011.

28. McConnell, AK, Caine, MP, Sharpe, GR. Inspiratory muscle fatigue following running to volitional fatigue: The influence of baseline strength. *Int J Sports Med* 18: 169–173, 1997.

29. McConnell, AK, Sharpe, GR. The effect of inspiratory muscle training upon maximum lactate steady-state and blood lactate concentration. *Eur J Appl Physiol* 94: 277–284, 2005.

30. McGowan, CJ, Pyne, DB, Thompson, KG, Rattray, B. Warm-up strategies for sport and exercise: Mechanisms and applications. *Sports Med* 45: 1523–1546, 2015.

31. Minahan, C, Sheehan, B, Doutreband, R, et al. Repeated-sprint cycling does not induce respiratory muscle fatigue in active adults: Measurements from the powerbreathe(R) inspiratory muscle trainer. *J Sports Sci Med* 14: 233–238, 2015.

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

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

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

35. Ross, EZ, Nowicky, AV, McConnell, AK. Influence of acute inspiratory loading upon diaphragm motor-evoked potentials in healthy humans. *J Appl Physiol (1985)* 102: 1883–1890, 2007.

36. Tong, TK, Fu, FH. Effect of specific inspiratory muscle warm-up on intense intermittent run to exhaustion. *Eur J Appl Physiol* 97: 673–680, 2006.

37. Tong, TK, McConnell, AK, Lin, H, et al. "Functional" inspiratory and core muscle training enhances running performance and economy. *J Strength Cond Res* 28: 2942–2951, 2014.

38. Turner, LA, Tecklenburg-Lund, SL, Chapman, RF, et al. Inspiratory muscle training lowers the oxygen cost of voluntary hyperpnea. *J Appl Physiol (1985)* 112: 127–134, 2012.

39. 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* 20: 542–547, 1999.

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

41. Volianitis, S, McConnell, AK, Koutedakis, Y, et al. Inspiratory muscle training improves rowing performance. *Med Sci Sports Exerc* 33: 803–809, 2001.