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ORIGINAL ARTICLE

Pulmonary and respiratory muscle function in response to 10 marathons in 10 days

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Abstract

Purpose Marathon and ultramarathon provoke respiratory muscle fatigue and pulmonary dysfunction; nevertheless, it is unknown how the respiratory system responds to multiple, consecutive days of endurance exercise.

Methods Nine trained individuals (six male) contested 10 marathons in 10 consecutive days. Respiratory muscle strength (maximum static inspiratory and expiratory mouth-pressures), pulmonary function (spirometry), perceptual ratings of respiratory muscle soreness (Visual Analogue Scale), breathlessness (dyspnea, modified Borg CR10 scale), and symptoms of Upper Respiratory Tract Infection (URTI), were assessed before and after marathons on days 1, 4, 7, and 10.

Results Group mean time for 10 marathons was 276 ± 35 min. Relative to pre-challenge baseline (159 ± 32 cmH_2O), MEP was reduced after day 1 (136 ± 31 cmH_2O, $p = 0.017$), day 7 (138 ± 42 cmH_2O, $p = 0.035$), and day 10 (130 ± 41 cmH_2O, $p = 0.008$). There was no change in pre-marathon MEP across days 1, 4, 7, or 10 ($p > 0.05$). Pre-marathon forced vital capacity was significantly diminished at day 4 (4.74 ± 1.09 versus 4.56 ± 1.09 L, $p = 0.035$), remaining below baseline at day 7 ($p = 0.045$) and day 10 ($p = 0.015$). There were no changes in FEV_1, FEV_1/FVC, PEF, MIP, or respiratory perceptions during the course of the challenge ($p > 0.05$). In the 15-day post-challenge period, 5/9 (56%) runners reported symptoms of URTI, relative to 1/9 (11%) pre-challenge.

Conclusions Single-stage marathon provokes acute expiratory muscle fatigue which may have implications for health and/or performance, but 10 consecutive days of marathon running does not elicit cumulative (chronic) changes in respiratory function or perceptions of dyspnea. These data allude to the robustness of the healthy respiratory system.

Keywords Ultramarathon · Endurance · Lung function · Fatigue

Abbreviations

FVC	Forced vital capacity
FEV_1	Forced expiratory volume in 1 s
PIF	Peak inspiratory flow
PEF	Peak expiratory flow
MVV	Maximum voluntary ventilation
MIP	Maximum inspiratory mouth pressure
MEP	Maximum expiratory mouth pressure
URTI	Upper respiratory tract infection
VAS	Visual analogue scale
SD	Standard deviation
CV	Coefficient of variation
SEM	Standard error of measurement
CI	Confidence interval
ICC	Intra-class correlation
ANOVA	Analysis of variance

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Introduction

Respiratory muscle fatigue is a phenomenon whereby the inspiratory and/or expiratory musculature exhibit a transient reduction in force-generating capacity, relative to baseline values (Romer and Polkey 2008). Respiratory muscle fatigue has been assessed objectively following high-intensity, exhaustive cycling and running, manifesting as a 15–30% pre-to-post-exercise reduction in transdiaphragmatic or gastric twitch pressure in response to nerve stimulation (Johnson et al. 1993; Taylor et al. 2006). When respiratory muscle fatigue has been assessed indirectly using maximum voluntary mouth-pressure manoeuvres, similar pre-to-post-exercise reductions were observed following rowing and swimming time-trials (Lomax and McConnell 2003; Volianitis et al. 2001). Using a proportional assist ventilator to offload the respiratory muscles during exercise, Babcock et al. (2002) found that the workload endured by the diaphragm was a critical determinant of exercise-induced diaphragmatic fatigue. Moreover, using objective nerve-stimulation techniques, we recently observed expiratory, but not inspiratory, muscle fatigue following maximal upper-body exercise (Tiller et al. 2017). Given that the exercise trial induced only a modest ventilatory demand, the data support the notion that high minute ventilations are a prerequisite for diaphragm fatigue, whereas the expiratory muscles may be less fatigue-resistant. Respiratory muscle fatigue is thought to be underpinned by peripheral, rather than central, mechanisms (Jones 1996; Wuthrich et al. 2015), and contractile function typically returns to baseline within 1–2 h of exercise.

There is a growing body of work pertaining to respiratory muscle function following endurance and ultraendurance running. Reductions in maximum inspiratory mouth-pressure in the region of ~ 15% have been observed immediately following single-stage marathon (Chevrolet et al. 1993; Ross et al. 2008), although no evidence of expiratory muscle fatigue was reported. Evidence of post-marathon decreases in respiratory muscle endurance (~ 27%) has been noted when assessed via time-to-exhaustion (Tlim) during sustained inspiratory pressure (Ker and Schultz 1996), with similar observations made following 24 h of treadmill running when respiratory muscle endurance was assessed via maximum voluntary ventilation in 12 s (MVV_{12}) (Warren et al. 1989). The only study to use magnetic nerve stimulation to assess respiratory muscle fatigue following ultramarathon (defined as a race that exceeds the traditional marathon distance of 42.2 km; Millet and Millet 2012) observed a reduction in mouth twitch-pressure of ~ 19% immediately following a 110 km mountain race (Wuthrich et al. 2015); such a response is indicative of low-frequency inspiratory muscle fatigue.

Notwithstanding the implications of respiratory muscle fatigue, marathon and ultramarathon are also thought to negatively impact on pulmonary function. The first study to investigate this phenomenon measured lung capacity in the first 22 finishers of the 1923 Boston Marathon, noting that post-race values were significantly reduced by 0.8 L (17%) (Gordon et al. 1924). More recently, (Ross et al. 2008) reported an acute decrease in peak inspiratory flow (PIF; 6.3–4.9 L s^{-1}) and forced vital capacity (FVC; 5.73–5.46 L) immediately following a marathon, but parameters had recovered within 24 h. Races of extreme duration (330 km mountain ultramarathon) have also elicited reductions in peak inspiratory and expiratory flow, as well as forced expiratory volume in 1 s (FEV_1) (Vernillo et al. 2015). Given the positive correlation between pulmonary function and marathon performance (Salinero et al. 2016), and the negative correlation between the pre-to-post-exercise reduction in MVV_{12} and ultramarathon finish time (Vernillo et al. 2015), it is reasonable to suppose that pulmonary dysfunction might negatively impact on exercise performance.

Despite the available literature on the respiratory responses to single-stage endurance running, an important, as of yet undetermined, component of pulmonary and respiratory muscle function is the impact of chronic endurance exercise that is performed on multiple, consecutive days. Multi-stage endurance running presents an excellent model with which to study the limits of human physiological function. Data on the respiratory responses to stage-racing would offer a novel insight into the robustness or fallibility of the human respiratory system in responding to repeated exercise stimuli. Furthermore, such data might influence endurance running training strategies, as well as inform medical best-practice of personnel supporting the events.

Accordingly, this study assessed respiratory muscle and pulmonary function in a group of endurance runners who contested a pre-determined ultraendurance exercise challenge comprising 10 marathons in 10 consecutive days. It was hypothesised that: (1) there would be an acute (within-day) reduction in respiratory muscle and pulmonary function following any given marathon and (2) there would be a chronic (between-day) reduction in baseline parameters as the challenge progressed.

Materials and methods

Participants

Eleven recreationally-active endurance runners (8 male, 3 female) volunteered to participate in data-collection protocols. Two participants withdrew from the study due to injury at days 6 and 8, respectively; therefore, statistical data are presented for $n = 9$ (6 male, 3 female) (mean ± SD age = 48.6 ± 9.4 years; mass = 74.7 ± 14.2 kg; stature = 174.1 ± 10.8 cm). Participants had been training for 10 ± 4 years (range = 5–14 years), ran 47 ± 16 miles (7.7 ± 2.8 h) per week, and exhibited a group mean season's best marathon time of 217 ± 22 min (3 h 37 min ± 22 min). Participants were free from known cardiorespiratory diseases, with the exception of one participant who had previously been treated for asthma [FEV_1/FVC, 0.65 (77% predicted)]. There were three ex-smokers in the group, all with > 4-year smoking cessation (mean = 9.0 ± 8.7 years). Procedures were approved by the institution Research Ethics Committee, and performed in accordance with the 1964

Declaration of Helsinki. Prior to data collection, participants were issued with a Participant Information Document, completed a pre-test medical questionnaire, and provided written, informed consent.

Experimental overview

Participants contested 10 marathons in 10 consecutive days on courses of varying terrain (The Great Barrow Challenge '10-in-10'; Suffolk Academy, Suffolk, UK). The marathons began from the same location at 08:00 each day, affording participants consistent recovery time between races. Mean temperature and humidity throughout the challenge were 22.2 ± 1.5 °C and 69 ± 4%, respectively. Assessments of respiratory muscle strength, pulmonary function, and perceptual responses were made before and within 10 min of finishing marathons on days 1, 4, 7, and 10. Prior to testing, participants were familiarised with the respiratory manoeuvres, aided by demonstrations and tutorial videos.

Respiratory measures

Maximum inspiratory and expiratory mouth-pressure

Maximum static inspiratory mouth pressure (MIP, from residual volume) and maximum static expiratory mouth pressure (MEP, from total lung capacity) were assessed as a simple, convenient, and non-invasive index of respiratory muscle strength (Evans and Whitelaw 2009). The merits and limitations of volitional manoeuvres for assessing respiratory muscle function are discussed later (see *Technical Considerations*). Manoeuvres were performed using a handheld device (MicroRPM; CareFusion, Hampshire, UK), attached to a phlanged mouthpiece with a 1-mm leak to prevent glottic closure during the MIP manoeuvre and to reduce the use of buccal muscles during the MEP manoeuvre (American Thoracic Society/European Respiratory Society 2002). Participants were seated, and given verbal encouragement to maintain a maximal effort for ~ 2–3 s, with the largest of three values within 5% variability recorded (Wen et al. 1997).

Spirometry

Pulmonary volumes, capacities, and flows were assessed via spirometry, whereby participants performed between three and eight FVC manoeuvres into a two-way disposable mouthpiece connected to a portable pneumotachograph (Alpha Touch; Vitalograph Ltd., Buckingham, England), with the nose occluded. Participants were seated, and verbal encouragement was given to ensure consistent efforts. Spirometry was performed in accordance with ATS/ERS guidelines (Miller et al. 2005).

Within- and between-day reliability of respiratory measures

Six healthy participants, independent from the main study, were recruited to quantify the reliability of maximum static mouth-pressure manoeuvres and spirometry. Within-day reliability was determined by comparing baseline measurements to those made after ~ 4 h passive rest, and between-day reliability was determined by re-assessing participants 3 days later. Tests were performed following similar coaching and instructions to that used with the main study participants. Moreover, reliability data were collected under the same time constraints, following a similar schedule, and with identical apparatus to that applied in the field. Data on the reliability of maximum static mouth-pressure manoeuvres and spirometry are shown in Table 1. There were no systematic differences in measurements ($p > 0.05$), and the between-occasion reliability was excellent (all CV < 5%; low SEM; all ICC > 0.94).

Table 1 Within- and between-day reliability of respiratory measures

	Trial 1	Trial 2	Trial 3	CV (%)	SEM	ICC
FVC (L)	5.07 ± 0.75	5.02 ± 0.76	5.06 ± 0.74	0.7	0.075	0.999 (0.996–1.000)
FEV_1 (L)	3.89 ± 0.71	3.84 ± 0.79	3.78 ± 0.69	2.6	0.103	0.994 (0.975–0.999)
FEV_1/FVC	0.77 ± 0.05	0.76 ± 0.06	0.75 ± 0.03	2.5	0.016	0.943 (0.760–0.991)
PEF (L min^{-1})	607 ± 96	612 ± 135	615 ± 102	4.6	31.4	0.963 (0.842–0.994)
MIP (cmH_2O)	124 ± 30	126 ± 32	124 ± 30	4.0	6.16	0.988 (0.950–0.998)
MEP (cmH_2O)	200 ± 53	194 ± 51	193 ± 51	2.9	7.32	0.996 (0.983–0.999)

Data are means ± SD

FVC forced vital capacity, *FEV_1* forced expiratory volume in 1 s, *PEF* peak expiratory flow, *MIP* maximum static inspiratory pressure, *MEP* maximum static expiratory pressure, *CV* coefficient of variation, *SEM* standard error of measurement, *ICC* intra-class correlation coefficient

Perceptual measures

Symptoms of upper respiratory tract infection (URTI)

Following each bout of respiratory assessments, participants were presented with four questions pertaining to symptoms commonly associated with URTI, and asked to rate the severity of their symptoms by marking a line on a series of 100 mm visual analogue scales (VAS). The questions posed were: (1) since waking this morning, have you experienced any coughing? (Anchored by "completely free of cough" and "worst cough I can imagine"); (2) since waking this morning, have you experienced any wheezing? (Anchored by "completely free of wheeze" and "worst wheeze I can imagine"); (3) since waking this morning, have you experienced any chest tightness? (Anchored by "completely free of chest tightness" and "worst chest tightness I can imagine"); and (4) since waking this morning, have you experienced any mucus secretions? (Anchored by "completely free of mucus" and "worst mucus I can imagine"). Following the final marathon, symptoms were monitored for a 15-day period using a daily online symptom log. An individual was considered symptomatic of an URTI if ≥ 2 symptoms were present for at least 2 days in a 3-day period (Robson-Ansley et al. 2012). As a control, participants were asked to report on the prevalence of symptoms in another member of their household (adult, non-runner) using an identical questionnaire. Prior to testing, participants completed the Allergy Questionnaire for athletes (AQUA), with a score of ≥ 5 positively predicting allergy with a correlation coefficient of 0.94 (Bonini et al. 2009).

Respiratory muscle soreness

In an effort to quantify the degree of respiratory muscle damage, participants were asked to rate their perceived intensity of respiratory muscle soreness by marking a line on a 100 mm VAS—anchored by "no pain" and "unbearable pain", respectively—and to indicate the location of any muscle soreness by shading areas on a body diagram (Mathur et al. 2010). These measures of respiratory muscle soreness were made immediately following each set of MIP (MIP_{VAS}) and MEP (MEP_{VAS}) manoeuvres.

Dyspnea

Following baseline respiratory assessments, participants were asked to rate the intensity of their breathing discomfort since waking, by circling a number on the modified Borg CR10 Scale (Mahler and Horowitz 1994). Following post-race assessments, participants were asked the same question in relation to the sensations experienced during the preceding marathon.

Data analysis

Descriptive and inferential statistics were calculated using SPSS 24 for Windows (IBM; Chicago, IL). Reliability of respiratory measures was assessed using coefficient of variation (CV), standard error of measurement (SEM), and intraclass correlation coefficients (ICC; mean of trials one and two versus trial three). Two main comparisons were made on mouth-pressure, pulmonary function, and perceptual data: (1) pre-challenge baseline to post-marathon values on days 1, 4, 7, and 10 (acute response) and (2) pre-challenge baseline to pre-marathon baseline values on days 4, 7, and 10 (chronic response). Respiratory and perceptual responses were assessed for differences using repeated-measures ANOVA (eight timepoints; pre-to-post days 1, 4, 7, and 10) and Fisher's LSD post-hoc comparisons. The assumption of equal variance was assessed via Mauchly's test of sphericity, and if violated ($p < 0.05$), a Greenhouse–Geisser correction applied. Effect size (Cohen's d) was calculated to estimate the magnitude of the difference between group means, with $d = 0.2$, 0.5, and 0.8 reflecting small, medium, and large effect sizes, respectively (Cohen 1977). Alpha level was set at $p < 0.05$, and data were presented as mean ± SD, unless stated.

Results

Participants

Individual and group mean marathon times throughout the challenge are illustrated in Fig. 1. Group mean time across all 10 marathons was 276 ± 35 min (4 h 36 min ± 35 min), with a mean range of 221 (3 h 41 min) to 319 min (5 h 19 min). Fifty six percent (5/9) runners exhibited a positive AQUA score (≥ 5) for allergic diseases. The single asthmatic participant exhibited responses consistent with the group mean.

Respiratory responses

Maximum inspiratory and expiratory mouth-pressure

Group mean MIP and MEP responses are illustrated in Fig. 2. Relative to pre-challenge baseline, MEP was reduced after day 1 (− 14 ± 14%, $p = 0.017$, $d = 0.73$), day 7 (− 14 ± 18%, $p = 0.035$, $d = 0.56$), and day 10 (− 19 ± 18%, $p = 0.008$, $d = 0.79$), with a non-significant reduction after day 4 (− 9 ± 18%, $p = 0.111$, $d = 0.52$). There was no change in pre-marathon (baseline) MEP across days 1, 4, 7, or 10 ($p > 0.05$). Relative to pre-challenge baseline, there were

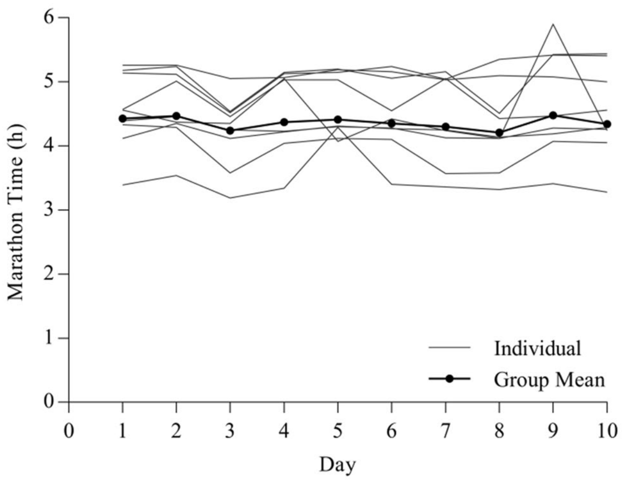

Fig. 1 Individual and group mean marathon times throughout the 10-day challenge

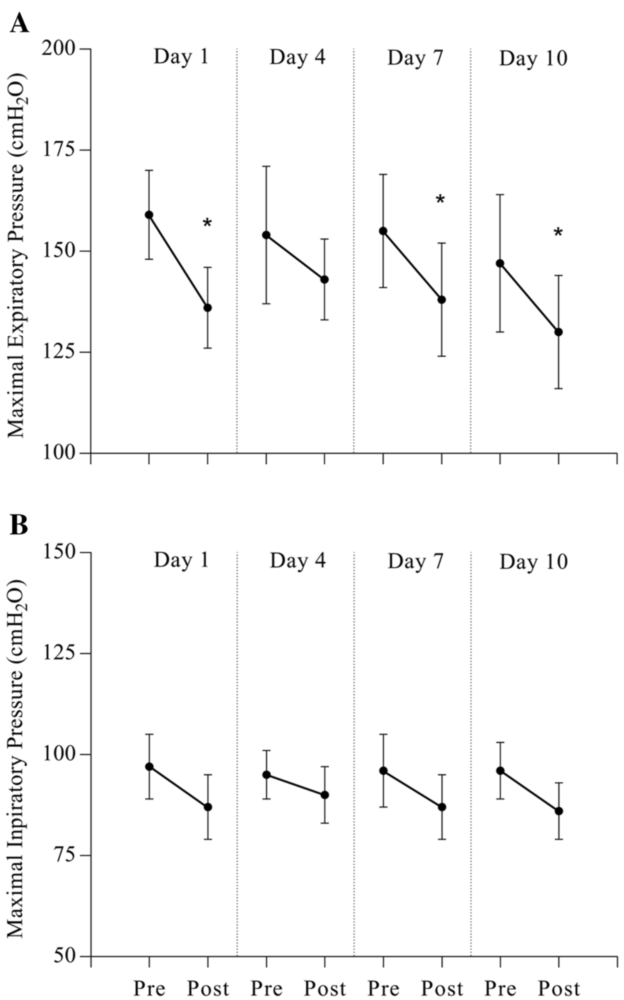

Fig. 2 Maximum static expiratory (**a**) and inspiratory (**b**) mouth-pressure, before and after marathons on days 1, 4, 7, and 10. *Significantly different versus pre-challenge baseline, $p<0.05$

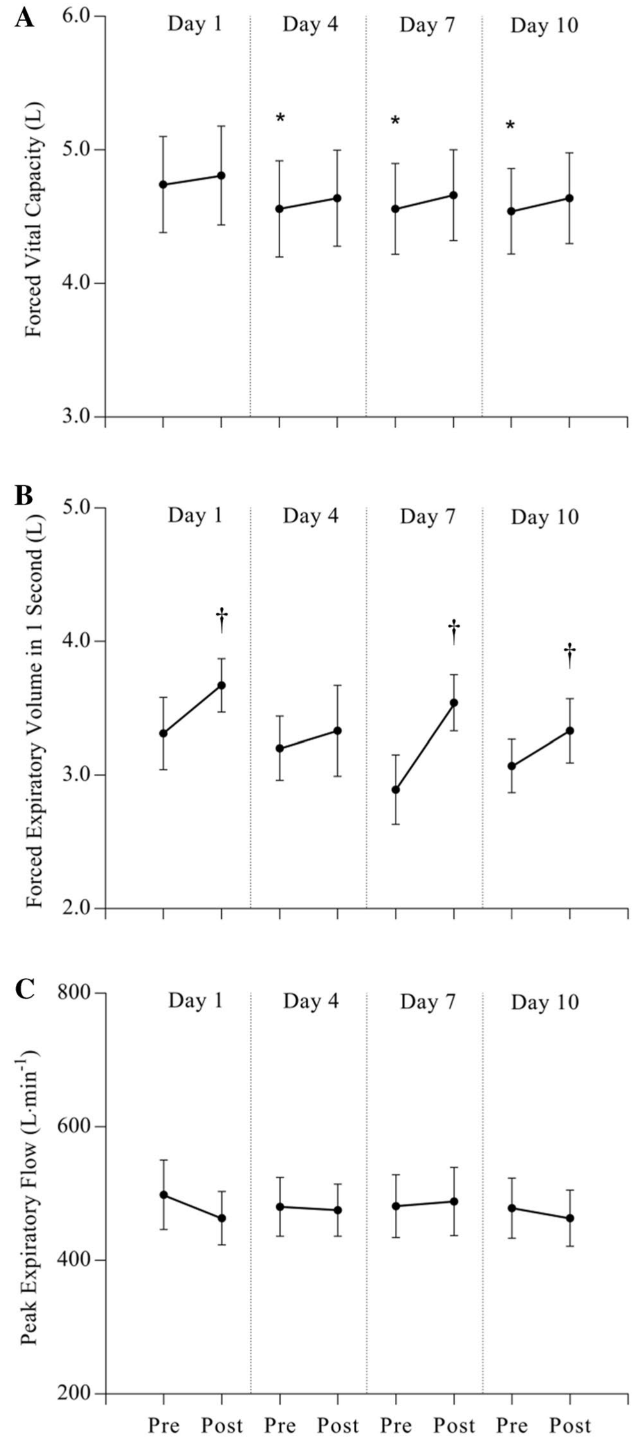

Fig. 3 Forced vital capacity (**a**), forced expiratory volume in 1 s (**b**), and peak expiratory flow (panel C), before and after marathons on days 1, 4, 7, and 10. *Significantly different versus pre-challenge baseline, $p<0.05$; †significantly different versus pre-marathon, $p<0.05$

slight reductions in post-marathon MIP, but with no significant changes in the group mean at any timepoint.

Spirometry

Group mean FVC, FEV_1, and PEF are illustrated in Fig. 3. Relative to pre-challenge baseline, there were no differences in post-marathon FVC on days 1, 4, 7, or 10 ($p>0.05$), but there was a significant reduction in pre-marathon (baseline) FVC at day 4 ($p=0.035$, $d=0.17$), which remained below baseline at day 7 ($p=0.045$, $d=0.17$) and day 10 ($p=0.015$, $d=0.19$). When assessing FEV_1, relative to pre-challenge baseline, there were no differences in post-marathon values on days 1, 4, 7, or 10, and no significant reduction in pre-marathon (baseline) FEV_1 across days 1, 4, 7, or 10 ($p>0.05$). There were significant pre-to-post-marathon increases in FEV_1 on day 1 ($p=0.012$, $d=0.51$), day 7 ($p=0.039$, $d=0.90$), and day 10 ($p=0.038$, $d=0.40$). Relative to pre-challenge baseline, there were no significant changes in group mean PEF at any timepoint. When assessing the FEV_1/FVC ratio, relative to pre-challenge baseline (0.70 ± 0.07), values had increased after day 1 (0.74 ± 0.06, $p=0.047$, $d=0.61$) and day 7 (0.74 ± 0.05, $p=0.015$, $d=0.66$), but there were no differences in pre-marathon (baseline) FEV_1/FVC at days 1, 4, 7, or 10 ($p>0.05$).

Perceptual responses

Group mean symptoms of URTI, perceptions of respiratory muscle soreness, and perceptions of dyspnea are summarised in Table 2. The four symptoms of URTI (i.e., cough, wheeze, chest tightness, and mucus secretions) were assessed independently, with no significant changes in group mean values at any timepoint ($p>0.05$). In the 15-day post-challenge period, 56% (5/9) runners reported symptoms of URTI (i.e., cough, watery eyes, blocked or runny nose, sneezing, sore throat), relative to 11% (1/9) pre-challenge and 11% (1/9) of non-running controls. Respiratory muscle soreness was assessed following MIP and MEP manoeuvres before marathons on days 1, 4, 7, and 10. Relative to pre-challenge baseline, there were no significant changes in group mean values for either MIP or MEP at any timepoint ($p>0.05$). Dyspnea (subjective ratings of the intensity of breathing discomfort) was first compared among the pre-marathon (baseline) scores, and then among the post-marathon scores, with no significant changes in group mean values at any timepoint ($p>0.05$).

Discussion

This study assessed respiratory muscle and pulmonary function in a group of endurance runners who contested 10 marathons in 10 consecutive days. The principal findings were: (1) there was evidence of acute pre-to-post-marathon expiratory muscle fatigue as demonstrated by reductions in maximum static expiratory mouth pressure, but no cumulative (chronic) changes in baseline respiratory muscle strength; (2) despite a fall in baseline forced vital capacity at day 4, other indices of pulmonary function were maintained; and (3) changes in respiratory function were not associated with changes in perceptual responses during the challenge, although 56% of runners exhibited symptoms of URTI within 15 days of the final marathon. These novel data speak to the robustness of the healthy respiratory system to maintain baseline pulmonary and respiratory muscle function during multiple, consecutive days of endurance exercise.

Table 2 Perceptual responses before and after marathons on days 1, 4, 7, and 10

	Day 1		Day 4		Day 7		Day 10	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
MIP_{VAS} (mm)	2.4 ± 4.3	0.3 ± 0.7	0.2 ± 0.4	0.4 ± 1.0	0.1 ± 0.3	0.2 ± 0.4	0.2 ± 0.4	0.3 ± 1.0
MEP_{VAS} (mm)	0.2 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.7	0.0 ± 0.0	0.1 ± 0.3	0.4 ± 1.0	0.3 ± 0.7
Dyspnea (CR10)	0.0 ± 0.0	1.7 ± 0.9	0.1 ± 0.3	2.3 ± 0.7	0.2 ± 0.4	2.0 ± 1.3	0.3 ± 1.0	2.0 ± 1.2
URTI (VAS)								
Cough (mm)	1.2 ± 2.4	0.7 ± 0.9	2.1 ± 5.6	2.8 ± 6.9	3.9 ± 10.6	2.0 ± 5.3	1.3 ± 2.6	3.3 ± 5.3
Wheeze (mm)	1.4 ± 4.3	0.9 ± 1.7	1.2 ± 2.6	3.1 ± 5.9	0.8 ± 2.0	0.6 ± 1.7	0.7 ± 2.0	2.1 ± 4.4
Chest (mm)	0.2 ± 0.7	1.8 ± 4.0	1.6 ± 3.1	5.9 ± 8.5	3.9 ± 7.6	3.3 ± 6.4	3.7 ± 8.4	3.4 ± 7.2
Mucus (mm)	9.2 ± 17.2	10.1 ± 17.2	3.3 ± 5.4	11.6 ± 18.0	9.1 ± 14.6	13.0 ± 24.0	13.0 ± 24.4	13.7 ± 22.1

MIP maximum static inspiratory pressure, *MEP* maximum static expiratory pressure, *VAS* visual analogue scale, *URTI* upper respiratory tract infection, *Cough* current experience of cough, *Wheeze* current experience of wheeze, *Chest* current experience of chest tightness, *Mucus* current experience of mucus secretions

Technical considerations

There are certain technical considerations that should predicate a discussion of our findings. First, maximal static pressure manoeuvres are considered a global measure of respiratory muscle strength (Polkey et al. 1995). The techniques are widely used in the assessment of respiratory muscle fatigue (44% of 77 studies; Janssens et al. 2013), and the manoeuvres show strong test/re-test reliability (Dimitriadis et al. 2011). These techniques are non-invasive, easily applied in the field, and can be reported alongside well-established normative data. Nevertheless, a common limitation is that manoeuvres are volitional, dependent on participant motivation, and might be subject to a practice effect. To increase the likelihood that maximal efforts were given, we followed standard guidelines by recording a minimum of three manoeuvres within 5% variability (American Thoracic Society/European Respiratory Society 2002; Wen et al. 1997). Participants were familiarised with respiratory manoeuvres prior to data collection, and our reliability data show strong between-occasion reliability (Table 1), congruent with previously reported test/re-test reliability coefficients for these techniques (Dimitriadis et al. 2011). Moreover, the finding that MEP was acutely diminished following a given marathon, while maximum indices of pulmonary function (e.g., PEF) were well maintained, suggesting a mechanism that was independent of motivation and/or a practice effect. Although objective measures (i.e., nerve stimulation) are preferable in the assessment of respiratory muscle fatigue, the invasive nature of such protocols, coupled with the ecological nature of our experimental design, made nerve-stimulation inappropriate for this study.

Second, to evaluate the carry-over effects of the previous day's marathon, we would have preferred to have collected additional data before each of the 10 marathons. Respiratory and perceptual assessments are time-consuming, and it was not logistically feasible to take daily measurements from our cohort. Our measures, therefore, strike a balance between obtaining sufficient data to address our research questions, while not overly inconveniencing our participants. Should respiratory muscle strength have not recovered following an overnight rest, we reasoned that function would have steadily fallen on subsequent days, manifesting in lower baseline values. Accordingly, it was deemed appropriate to test baseline function at four timepoints throughout the challenge. Finally, it is likely that our participants implemented pacing strategies which allowed them to exhibit consistent marathon times throughout the 10-day challenge (Fig. 1). This would preclude any concerns that participants did not sufficiently recover between marathons; accordingly, general whole-body fatigue and/or insufficient recovery are less likely to have influenced our data.

Respiratory muscle fatigue

Throughout the challenge, the magnitude of the post-marathon fall in maximum expiratory muscle strength ranged from 15 to 20%, and is in accordance with earlier reports of diminished respiratory muscle strength following single-stage marathon (Chevrolet et al. 1993; Loke et al. 1982; Ross et al. 2008), and ultramarathon (Wuthrich et al. 2015). Nevertheless, this is the first study to assess these parameters in response to multiple, consecutive days of endurance exercise. Respiratory muscle fatigue is defined as a condition in which there is a loss in the capacity for developing force and/or velocity of a muscle, resulting from muscle activity under load, and which is reversible with rest (NHLBI 1990). Moreover, respiratory muscle fatigue is considered to be detectable if the measured reduction in pressure-generating capacity (relative to baseline) is two- to threefold the typical pressure variation (Guenette et al. 2010). The mean decrease in MEP was at least fivefold greater than the CV, and at any given point of measurement, between 5 and 7 participants exhibited post-race decreases in MEP > 10% (i.e., >threefold the CV). Based on these criteria, our strong reliability coefficients (Table 1), and the observation of a moderate-to-large effect size with respect to acute reductions in MEP (0.56–0.79), we are confident that our participants exhibited a fatigue that was underpinned by a physiological mechanism. The acute post-marathon fall in expiratory muscle strength is indicative of low-frequency fatigue, which is underpinned by two potential mechanisms: reduced Ca^{2+} release from the sarcoplasmic reticulum and/or damaged sarcomeres caused by overextension of muscle fibres (Jones 1996). Given the time course for the recovery of expiratory muscle strength (i.e., there was no systematic decay in pre-marathon values), we suppose that the transient post-marathon fatigue was due to reduced Ca^{2+} availability in the sarcolemma, rather than damaged sarcomeres, although neither were assessed directly. Furthermore, perceptions of respiratory muscle soreness following MIP and MEP manoeuvres did not rise above baseline at any timepoint (Table 2) and we can, therefore, discount any cumulative mechanical contribution to fatigue. These observations support the notion that respiratory muscle contractility generally recovers within a few hours of exercise [for review, see Romer and Polkey (2008)].

The abdominal muscles have an important role in regulating the ventilatory response to exercise (Abraham et al. 2002); however, it is unlikely that the post-race decreases in expiratory muscle strength were exclusively the result of high ventilation rates. The group mean marathon time over the 10-day challenge was ~20% slower than the group mean season's best single-stage marathon, and individual performance times throughout the challenge were relatively consistent (Fig. 1). It is likely, therefore, that participants implemented strategies of self-regulation (Barkley 2001) to prioritise performance on consecutive days rather than any individual day, and work rate was tempered as a result. This notion of preservation is reflected in the modest ratings of post-marathon dyspnea (Borg CR10 scale; 2.0 ± 0.3), which are lower than that reported elsewhere during single-stage marathon [Borg 6–20 scale; 12 (Ross et al. 2008)]. Expiratory muscle fatigue was more likely attributable to the additional non-ventilatory functions assumed by the abdominals during exercise [e.g., forced expiration and postural support (Hodges et al. 2005)], which render these muscles more susceptible to fatigue during relatively low ventilation ultraendurance activities.

By contrast, although we observed small decreases in post-marathon inspiratory muscle strength relative to baseline (Fig. 2), the extent of the absolute reduction did not reach statistical significance. Respiratory muscle work is a critical determinant of the magnitude of exercise-induced diaphragmatic fatigue (Babcock et al. 2002; Johnson et al. 1993), and it may simply be that the multi-day challenge did not impose a sufficient ventilatory stimulus to significantly fatigue the inspiratory muscles. The diaphragm also has a postural role, but this is only coordinated with its respiratory functions during transient, intermittent disturbances to trunk stability (e.g., brief arm movements) (Hodges and Gandevia 2000). Indeed, when venilation is mediated by humoral factors (e.g., during sustained exercise), postural drive to the phrenic motoneurons is withdrawn, and respiratory input is prioritised (Hodges, Heijnen et al. 2001). A diminished postural drive to the diaphragm, coupled with a modest ventilatory demand, might explain the lack of inspiratory muscle fatigue noted in this study.

Pulmonary function

Relative to pre-challenge baseline, there was a fall in FVC at day 4, which remained below baseline for the remainder of the event (Fig. 3). It was first suspected that these baseline reductions in FVC may have been due, at least in part, to modest (non-significant) reductions in expiratory muscle strength; however, others report no change in pulmonary function when the expiratory muscles are pre-fatigued via expiratory threshold loading (Haverkamp et al. 2001). As such, a more likely explanation for the observed pulmonary dysfunction is a modest degree of lower airway obstruction, which manifested as a fall in the baseline FEV_1/FVC ratio at day 7 (0.65 ± 0.08) and at day 10 (0.68 ± 0.08). Upper-airway obstruction can be discounted, since this is typically characterised by discordance between FEV_1 and PEF (Miller et al. 1990), and the baseline ratio of these parameters was maintained throughout the challenge (day 1 = 6.9 ± 1.2; day 4 = 6.8 ± 1.2; day 7 = 6.3 ± 2.1; day 10 = 6.7 ± 1.4). Despite these observations, lower-airway obstruction as a causative factor in reduced lung function is difficult to assert, because others have observed post-race reductions in pulmonary function both with (Maron et al. 1979) and without (Vernillo et al. 2015) the presence of airway obstruction. Additional lung volume data collected via whole-body plethysmography, in addition to measures of airway resistance, would further elucidate the mechanisms underpinning our observations. Worthy of note is that we also observed acute pre-to-post-marathon increases in FEV_1 (Fig. 3), which were likely attributable to exercise-induced bronchodilation (Freedman 1991).

Upper respiratory tract infection (URTI)

Finally, in the 15-day post-challenge period, 56% (5/9) runners reported symptoms of URTI (i.e., cough, watery eyes, blocked or runny nose, sneezing, and sore throat), relative to 11% (1/9) pre-challenge, and 11% (1/9) of non-running controls. Symptoms of URTI are a common complaint among endurance runners; for example, there are reports of URTI in 47% of 208 runners who completed a single-stage marathon, relative to 19% of non-running controls (Robson-Ansley et al. 2012). Moreover, URTI occurred in 33% of runners who completed a 56 km single-stage race, relative to 15% of non-running controls (Peters and Bateman 1983). It has been postulated that symptoms of URTI are the manifestation of an allergic or pro-inflammatory response, coupled with a transient suppression of cellular immune functions, although neither were assessed in the present study. Worthy of note is that 56% (5/9) runners exhibited a positive AQUA outcome, suggesting the presence of allergy, which is consistent with 60% prevalence in elite marathoners, whose reported symptoms were predominantly related to the upper respiratory tract (Teixeira et al. 2014). Consequently, both single-stage and multi-stage endurance competitions appear sufficient to cause symptoms of URTI, and in light of the present findings, the development of URTI appears to be mechanistically unrelated to changes in pulmonary function.

Implications for health and endurance performance

There may be several means by which our findings might impact on health and/or endurance performance. First, the respiratory muscles have a critical role in maintaining torso stabilisation during exercise (Celli et al. 1988). The major expiratory muscles contract to increase intra-abdominal pressure which, in turn, increases stiffness and stability of the lumbar spine (Hodges et al. 2001a, b, 2005). This likely helps to protect spinal structures during periods of postural disturbance. As a consequence, exercise that induces expiratory muscle fatigue might place the runner at a greater risk of injury, and render them less able to sustain the rigours of competition. Moreover, given that the limb-locomotor muscles exhibit substantial neuromuscular fatigue following prolonged running (Millet and Lepers 2004), it is plausible that a simultaneous respiratory and locomotor muscle fatigue may further increase the risk of fall and/or injury when traversing challenging terrain. Accordingly, we propose that marathon and ultramarathon runners investigate strategies to attenuate the degree of expiratory muscle fatigue that manifests during competition.

Second, respiratory muscle fatigue results in reflex effects of breathing on vascular function (Dempsey et al. 2008). This metaboreflex causes sympathoexcitation and vasoconstriction of exercising limb vasculature, thereby eliciting a fall in limb blood flow and vascular conductance (Harms et al. 1998). Diminished blood flow to working muscles would be expected to accelerate locomotor muscle fatigue. Indeed, a fatigue-induced reduction in respiratory muscle work capacity has been modelled to significantly predict ultramarathon performance (Vernillo et al. 2015), although further studies are needed to investigate the presence of a metaboreflex in response to ultraendurance exercise.

Third, it is possible that the development of respiratory dysfunction might impact on endurance performance. In a sample of 110 marathon runners (Salinero et al. 2016), there existed a significant negative correlation between indices of pulmonary function and marathon finish time; i.e., faster marathon runners exhibited better metrics of lung function (FVC $= r = -0.41$, $p < 0.001$; $FEV_1 = r = -0.40$, $p < 0.001$; PEF $= r = -0.50$, $p = 0.005$). Moreover, an earlier study (Warren et al. 1989) assessed the predictive power of lung function on ultramarathon performance by testing runners every 3 h throughout a 24 h footrace. The authors reported a significant reduction in MVV_{12} after 24 h, and modelled the variance in MVV_{12} to predict 39% of the variance in running speed. Although the mechanisms that underpin these relationships require further scrutiny, these studies do provide an insight into lung function and its potential predictive power on endurance running performance.

Finally, a pertinent question is whether the observed changes in pulmonary function were clinically meaningful. Given that the majority of values remained within the predicted range (i.e., above the lower limit of normal), it is reasonable to suppose that—with adequate rest between stimuli—the respiratory systems of trained runners are sufficiently robust to recover from multiple, consecutive days of endurance exercise, providing that athletes begin the race with a healthy baseline function. Although speculative, the same responses in individuals with below average baseline parameters or a pre-existing respiratory disorder (e.g., asthma) may result in manifestations of clinical significance.

In conclusion, we present novel data to suggest that the expiratory muscles are prone to acute contractile fatigue during ultramarathon stage racing; however, we found limited evidence of a cumulative baseline drift in respiratory muscle strength. Moreover, relatively well-maintained pulmonary and perceptual responses throughout the challenge suggest that the respiratory systems of trained runners are sufficiently robust to recover from multiple, consecutive days of endurance exercise. Nevertheless, acute fatigue of the expiratory muscles, combined with that of the locomotor muscles during marathon/ultramarathon, might impact on exercise performance and expose the individual to an increased risk of running-related injury. Further studies should aim to assess the pulmonary and respiratory muscle response to stage races of a greater ventilatory demand and/or duration.

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Author contributions NBT conceived and designed the study. NBT and LAT performed data collection and analysis. NBT, LAT, and BJT interpreted results and drafted manuscript. NBT, LAT, and BJT edited and revised the manuscript. NBT, LAT, and BJT approved the final draft.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest associated with the production of this study. Data are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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