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Research article

Pulmonary and Inspiratory Muscle Function Response to a Mountain Ultramarathon

Ignacio Martinez-Navarro [1,2]✉, Eladio Collado [3], Bárbara Hernando [4] and Carlos Hernando [5,6]
[1] Physical Education and Sports Department, University of Valencia, Valencia, Spain; [2] Sports Health Unit, Vithas 9 de Octubre Hospital, Valencia, Spain; [3] Faculty of Health Sciences, Jaume I University, Castellon, Spain; [4] Department of Medicine, Jaume I University, Castellon, Spain; [5] Sport Service, Jaume I University, Castellon, Spain; [6] Department of Education and Specific Didactics, Jaume I University, Castellon, Spain

Abstract
The study aimed to provide within-race data on the time course of pulmonary function during a mountain ultramarathon (MUM). Additionally, we wanted to assess possible sex differences regarding pre- to post-race change in pulmonary and inspiratory muscle function. Lastly, we were interested in evaluating whether changes in respiratory function were associated with relative running speed and due to general or specific fatigue. 47 athletes (29 males and 18 females; 41 ± 5 years) were submitted to a cardiopulmonary exercise test (CPET) before a 107-km MUM. Spirometric variables: forced vital capacity (FVC), forced expiratory volume in 1 s (FEV1), FEV_1/FVC and peak expiratory flow (PEF); maximal inspiratory pressure (MIP); squat jump (SJ) and handgrip strength (HG) were assessed before and after the race. Additionally PEF was measured at three aid stations (33rd, 66th and 84th km) during the race. PEF declined from the 33rd to the 66th km ($p = 0.004$; $d = 0.72$) and from the 84th km to the finish line ($p = 0.003$; $d = 0.90$), while relative running speed dropped from the first (0-33 km) to the second (33-66 km) race section ($p < 0.001$; $d = 1.81$) and from the third (66-84 km) to the last race section ($p < 0.001$; $d = 1.61$). Post-race, a moderate reduction was noted in FVC (-13%; $p < 0.001$; $d = 0.52$), FEV_1 (-19.5%; $p < 0.001$; $d = 0.65$), FEV_1/FVC (-8.4%; $p = 0.030$; $d = 0.59$), PEF (-20.3%; $p < 0.001$; $d = 0.58$), MIP (-25.3%; $p < 0.001$; $d = 0.79$) and SJ (-31.6%; $p < 0.001$; $d = 1.42$). Conversely, HG did not change from pre- to post-race (-1.4%; $p = 0.56$; $d = 0.05$). PEF declined during the race in parallel with running speed drop. No sex differences were noted regarding post-race respiratory function, except that FEV_1/FVC decay was significantly greater among women. The magnitude of pre- to post-race respiratory function decline was uncorrelated with relative running speed.

Key words: Maximal inspiratory pressure; peak expiratory flow; cardiopulmonary exercise test; ultraendurance; performance.

Introduction

Lower-limb neuromuscular function decay following a mountain ultramarathon (MUM) has been thoroughly described (e.g. Balducci et al., 2017; Besson et al., 2020; Easthope et al., 2010; Millet et al., 2011; Saugy et al., 2013; Temesi et al., 2014). However, only three investigations have assessed respiratory function following such a competition (Martinez-Navarro et al., 2020b; Vernillo et al., 2015; Wuthrich et al., 2015). The three studies reported a significant decline in pulmonary function after the race. Vernillo et al. (2015) also reported a greater decline in inspiratory function compared to expiratory function and a correlation between respiratory muscle endurance (i.e., MVV12, maximum voluntary ventilation in 12 s) and performance; while our group showed that respiratory function decline was larger following a 107-km MUM as compared with a 65-km MUM (Martinez-Navarro et al., 2020b). Nevertheless, although respiratory muscle fatigue has been suggested as a potential factor conferring females a physiological advantage in ultra-endurance sport (Tiller et al. 2021), no studies have yet evaluated whether sex differences exist regarding pulmonary and inspiratory muscle function after a MUM. Previous studies have supported the notion of a better fatigue resistance in the female respiratory muscles (Gonzales and Scheuermann 2006; Guenette et al., 2010). On the other hand, however, males exhibit a lower work of breathing at a given ventilation during exercise (Dominelli et al. 2015a; Dominelli et al. 2015b). Consequently, it seems valuable to compare females with males respiratory response to a MUM.

Moreover, the time course of pulmonary function during an ultramarathon remains unclear. Wuthrich et al. (2015) tested athletes only at pre and post-race. Vernillo et al. (2015) showed a significant decline in pulmonary function at mid-race; conversely, during a flat 24-h ultramarathon, Warren et al. (1989) identified no significant changes in pulmonary function measured at 3-h intervals. However, given the shared role of respiratory muscles (i.e., postural control and respiration) (Tong et al., 2014) and the high demands of postural stabilization during a MUM (Degache et al., 2018; Marcolin et al., 2016), it may be reasonable to think that changes in pulmonary function during a MUM may differ from a flat ultramarathon. In addition, previous studies have suggested that the time course of respiratory function during an ultramarathon could be related to exercise intensity (Vernillo et al., 2015; Warren et al., 1989), yet no study has previously assessed the changes in respiratory function in relation to relative exercise intensity (i.e., percentage of threshold speed obtained in a maximal incremental exercise test). By using relative instead of absolute values of running speed we could argue whether changes in respiratory function are related to the degree of individual effort. Lastly, Wuthrich et al. (2015) demonstrated that the reduction in inspiratory muscle strength results from significant peripheral fatigue with only little contribution of central fatigue. However, no previous studies have assessed the magnitude of post-MUM decline in inspiratory muscle strength as compared with upper-limb strength loss

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(as minimally exercising muscles during the race) and lower-limb function loss (as main exercising muscles during the race) (Ozkaplan et al., 2005; Tong et al., 2014). Therefore, further data about respiratory function response to a MUM and their time-course during the race may result helpful in the design of athletes' training programs (Tiller, 2019).

Given this scenario, the purposes of our study were three-fold. Firstly, to assess how peak expiratory flow developed during the race comparatively with the changes in relative running speed. Secondly, we wanted to evaluate possible sex differences regarding pre- to post-race change in pulmonary and inspiratory muscle function. Lastly, we were interested in checking whether changes in respiratory function were associated with relative running speed and due to general or specific fatigue. Our hypotheses were the following: (1) Peak expiratory flow may start to decline at mid-race and keep decreasing until the end of the race; (2) pre- to post-race changes in respiratory function would be related with relative running speed; (3) inspiratory muscle function decay could be attributable to specific rather than general fatigue.

Methods

Participants

All participants in the Penyagolosa Trails CSP race 2019 received a communication through email describing the study and requesting their participation. Race track consisted of 107.4 km, starting at an altitude of 40 m and finishing at 1280 m above sea level, with a total positive and negative elevation of 5604 and 4356 m respectively. Inclusion criteria were the following: having previously completed at least one MUM longer than 60 km; being free from respiratory, cardiac or renal disease and from taking any medication on a regular basis. All eligible volunteers were included in the study. Forty seven ultra-endurance athletes (29 males and 18 females) composed the sample. All subjects gave their written consent to participate in the research and were fully informed about the procedure. Demographic information, as well as training and competition history, were collected by means of an online questionnaire, as previously reported (Martinez-Navarro et al., 2020a; Martinez-Navarro et al., 2020b). The investigation was conducted according to the Declaration of Helsinki and approval for the project was obtained from the research Ethics Committee of the University (Expedient Number CD/007/2019). The study is enrolled in the Clinical Trails.gov database, with the code number NCT03990259 (www.clinicaltrials.gov).

Cardiopulmonary Exercise Test

Cardiopulmonary exercise tests (CPET) were performed on a treadmill (H/P/cosmos pulsar, H/P/cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany) between 2 to 4 weeks prior to the race. After a 4 min warm up at 6 $km \cdot h^{-1}$, CPET protocol started at 8 $km \cdot h^{-1}$ and speed was increased 1 $km.h^{-1}$ every 2 min. When subjects reached a respiratory exchange ratio (RER) > 1.0 increments of 1 $km \cdot h^{-1}$ were induced every minute until voluntary exhaustion. This CPET layout was employed to enable the calculation of fat oxidation rates as a part of another study (Martinez-Navarro et al., 2020a). VO_2max values were accepted when a plateau (an increase of <2ml/kg/min) or a decline in VO_2 was reached despite increasing workloads and a RER above 1.15 was achieved. If this criterion was not met, a VO_2peak value was taken, defined as the highest VO_2 measured over a 30 seconds period. First and second ventilatory thresholds (VT_1 and VT_2) were determined using Skinner and McLellan (1980) guidelines by two independent researchers. VT1 was defined as the first nonlinear increase in the O_2 ventilatory equivalent (VE/VO_2), without a simultaneous increase in the CO_2 ventilatory equivalent (VE/VCO_2). The VT_2 was defined as the second nonlinear increase in VE/VO_2 with a concomitant increase of VE/VCO_2 and a decrease of end-tidal CO_2 pressure ($PETCO_2$).

Flat-Equivalent Running Speed

The race was divided into four sections based on the three main aid stations established by the organization (33rd km, 66th km and 84th km; 0-33 km, 33-66 km, 66-84 km and 84-107 km). Partial times were obtained from race results (LiveTrail®, LiveTrail SARL, France) and flat-equivalent running speed was calculated according to the procedure established by Saugy et al. (2013). Absolute values ($Speed_{ABS}$) and relative values (i.e., the percentage of the speed at VT_1 reached at the CPET) ($Speed_{VT1}$) were retained for statistical analysis. Speed at VT_1 was chosen as a criterion to establish relative exercise intensity because VT1 represents a boundary of tolerable intensity in this kind of events (Fornasiero et al., 2018).

Respiratory assessment

Pulmonary function testing was performed by the same experienced investigator to guarantee that maneuvers were carried out properly (Pellegrino et al., 2005), using a portable desktop spirometer (Pony FX, Cosmed, Rome, Italy). Participants were seated and wore a nose-clamp, following the American Thoracic Society and European Respiratory Society guidelines for spirometry standardization (Miller et al., 2005). Measurements were performed the day before the race and within 15 min after the race. Forced vital capacity (FVC), forced expiratory volume in 1 s (FEV1), FEV1/FVC ratio and peak expiratory flow (PEF) were determined from the maximal flow volume loop (MFVL). Each participant performed three acceptable (i.e., lasting 6 s or longer) MFVL maneuvers. The spirometric maneuver with the highest sum of FVC and FEV1 was accepted. Percent predicted values for the abovementioned variables were calculated according to reference values (Quanjer et al., 2012). Afterwards, maximal inspiratory pressure (MIP) was measured using a handheld electronic device (Powerbreathe K5, HaB International Ltd, UK) (Minahan et al., 2015). Each participant performed three attempts and the best result that did not differ by more than 5% was considered for analysis. Percent predicted values were calculated according to reference values (Wilson et al., 1984). PEF was also measured during the competition at the start line, at the arrival to the three main aid stations established by

the organization (33rd km, 66th km and 84th km) and immediately after crossing the finishing line using an electronic peak flow meter (eMini-Wright, Clement Clarke International, Harlow, England). Unlike pre-race and post-race assessments, those measurements were performed only once to minimize interference with MUM race performance.

Squat jump and handgrip strength assessment

Subjects were familiarized with procedures concerning strength assessment in an informative session during the week before the race. Handgrip strength (HG) and squat jump (SJ) tests were performed before the race and within 15 min after the race. In the HG assessment, subjects remained in standing position, arm by their side with full elbow extension, holding the grip dynamometer (T.K.K. 5401 GRIP-D, Takei Scientific Instruments Co., Tokyo, Japan) in their dominant hand (previously asked to each participant). They were asked to squeeze the dynamometer for 5 s and the test was performed twice, with a 30-s recovery between attempts. Each individual's peak value was retained for statistical analysis. Following previous studies (Ozkaplan et al., 2005; Tong et al., 2014), pre- to post-race change in HG was measured to evaluate if the potential decline in respiratory function was the result of reduced motivation or general whole-body fatigue, given that upper-limb muscles could be considered as minimally exercising muscles during the race. In the SJ assessment, participants were asked to jump as high as possible in a contact platform (Chronojump, Barcelona, Spain) (Pueo et al., 2018), using a starting position with hips and knees flexed 80 degrees and hands stabilized on hips to avoid arm-swing (Martinez-Navarro et al., 2020b). Jump height was estimated from flight time. The test was performed twice, with a 90-s recovery between attempts. Each individual's best performance was retained for statistical analysis.

Statistical analysis

Statistical analyses were performed with the aid of the Statistical Package for the Social Sciences software (IBM SPSS Statistics for Windows, version 22.0, IBM Corp., Armonk, NY). Normal distribution of the variables was verified through the Shapiro-Wilks test ($p > 0.05$). Spirometric-derived variables (FVC, FEV1, FEV1/FVC ratio and PEF), MIP, HG and SJ before and after the race were compared using a paired samples Student t-test. In addition, pre- to post-race changes in spirometric-derived variables and MIP were compared between males and females using an unpaired samples Student t-test. A one-factor repeated-measures ANOVA ('Race Section': start line, 1st aid station, 2nd aid station, 3rd aid station and finishing line) was conducted to assess the effect of race development on PEF. To that purpose, PEF values at each race segment were expressed as a percentage of the start line value for each subject. A second one-factor repeated-measures ANOVA ('Race Section': 1st, 2nd, 3rd and 4th race segment) was employed to evaluate the time course of SpeedVT1. Whenever Mauchly's Sphericity test was violated, necessary technical corrections were performed using the Greenhouse-Geisser test, and for each ANOVA, if a significant main effect or interaction was identified, Bonferroni post-hoc comparisons were conducted.

A Pearson correlation analysis was employed to test whether changes in respiratory, upper and lower limb function were either interrelated or correlated with SpeedABS and SpeedVT1. To that purpose, post-race spirometric-derived variables, MIP, HG and SJ were expressed as a percentage of pre-race values for each subject. The meaningfulness of the outcomes was estimated through the partial estimated effect size (η2 partial) for ANOVA and Cohen's d effect size for pairwise comparisons. In the latter case, a Cohen's $d < 0.5$ was considered small; between 0.5 - 0.8, moderate; and greater than 0.8, large. Likewise, correlations >0.5 were considered strong, 0.3 - 0.5, moderate and <0.3, small (Thomas et al, 2005). The significance level was set at p-value <0.05 and data are presented as means and standard deviations (±SD).

Results

From the initial sample, 4 participants did not start the race due to injury and 11 participants had to drop out. Final sample was therefore composed of 32 race finishers (74.4% finishers/starters ratio), whose average finish time was 21 h 23 min ± 3 h 28 min. Finishers/starters ratio and average finish time considering all race participants were 73.8% and 20 h 24 min ± 3 h 11 min, respectively. The characteristics of the final sample are presented in Table 1.

Table 1. Final sample main characteristics (mean ± SD).

	All sample (n=32)	Males (n=19)	Females (n=13)
Age (years)	41 ± 6	40 ± 5	42 ± 6
BMI (kg/m^2)	22.8 ± 2	23.6 ± 1.6	21.7 ± 2
VO_{2peak} (ml O_2/min/kg)	54.1 ± 5.2	55.8 ± 4.5	51.5 ± 5.2
V_{peak} (km/h)	15.9 ± 1.9	16.9 ± 1.5	14.4 ± 1.4
V_{VT1} (km/h)	10.8 ± 1.2	11.2 ± 1.1	10.1 ± 0.9
V_{VT2} (km/h)	13.3 ± 1.4	13.8 ± 1.2	12.5 ± 1.3
Number of years running	8 ± 3	8 ± 2	8 ± 3
Number of races >100 km	2 ± 3	2 ± 3	2 ± 4
Weekly training days	5 ± 1	5 ± 1	5 ± 1
Weekly running volume (km)	70 ± 22	76 ± 25	61 ± 13
Weekly positive elevation (m)	1772 ± 691	1868 ± 765	1631 ± 565
Weekly training hours	10 ± 4	10 ± 4	9 ± 5
Strength training (yes/no)	81% / 19%	74% / 26%	92% / 18%

BMI, Body Mass Index; VO_2peak, peak oxygen uptake; V_{peak}, peak velocity reached at the Cardiopulmonary Exercise Test; V_{VT1}, velocity associated with the first ventilatory threshold in the Cardiopulmonary Exercise Test; V_{VT2}, velocity associated with the second ventilatory threshold in the Cardiopulmonary Exercise Test; Strength training (%), percentage of participants who performed at least one weekly lower-limb strength training in the previous 3 months.

Table 2. Spirometric-derived data and MIP in men and women at pre-race and post-race (mean ± SD).

	Males (n = 19)			Females (n = 13)		
	Pre-race	**Post-race**	**% Change**	**Pre-race**	**Post-race**	**% Change**
FVC (l)	5.04 ± 0.69	4.47 ± 0.71	-12.9%	3.49 ± 0.48	3.08 ± 0.81	-13.2%
(% pred)	*103 ± 11*	*91 ± 15*		*102 ± 9*	*90 ± 20*	
FEV_1 (l)	3.92 ± 0.51	3.49 ± 0.74	-12.5%	2.77 ± 0.42	2.03 ± 0.61	-36.4%
(% pred)	*98 ± 12*	*87 ± 19*		*98 ± 11*	*72 ± 20*	
FEV_1/FVC (%)	78.41 ± 5.23	75.76 ± 10.84	-3.5%	78.67 ± 4.66	67.75 ± 16.9	-16.1% *
(% pred)	*97 ± 7*	*93 ± 14*		*94 ± 5*	*81 ± 20*	
PEF (l/s)	9.53 ± 1.43	8.04 ± 2.02	-18.5%	6.05 ± 1.33	4.84 ± 1.96	-25.1%
(% pred)	*88 ± 13*	*74 ± 19*		*80 ± 17*	*64 ± 25*	
MIP (cm H_2O)	115.74 ± 20.92	92 ± 20	-26.1%	78 ± 20.9	63 ± 20	-23.5%
(% pred)	*115 ± 22*	*91 ± 20*		*110 ± 27*	*88 ± 26*	

FVC, forced vital capacity; FEV_1, forced expiratory volume in 1 s; PEF, Peak expiratory flow; MIP, maximal inspiratory pressure; %pred, percent of predicted value; * Significantly different from males' percentage change ($p < 0.05$).

Values of spirometric variables and MIP at pre-race and post-race in men and women are presented in Table 2. All pulmonary and inspiratory muscle function variables showed a moderate and significant decline following the race: FVC (-13%; $p < 0.001$; $d = 0.52$), FEV1 (-19.5%; $p < 0.001$; $d = 0.65$), FEV1/FVC ratio (-8.4%; $p = 0.030$; $d = 0.59$), PEF (-20.3%; $p < 0.001$; $d = 0.58$) and MIP (-25.3%; $p < 0.001$; $d = 0.79$). Similarly, SJ was significantly and largely reduced post-race (24.2 ± 4.11 vs 18.38 ± 4.24 cm; -31.6%; $p < 0.001$; $d = 1.42$); conversely, HG appeared unchanged after the competition (41.6 ± 10 vs. 41 ± 11.9 kg; -1.4%; $p = 0.556$; $d = 0.05$). Regarding possible sex differences in pre- to post-race changes in pulmonary and inspiratory muscle function variables, FEV1/FVC decay was significantly greater among women ($p = 0.019$; $d = 0.98$). No other sex differences were identified.

Repeated-measures ANOVA showed a significant effect for 'Race segment' on PEF [$F=26.83$; $p < 0.01$; $\eta 2$ partial = 0.48] and further Bonferroni adjusted pairwise comparisons revealed that PEF significantly decreased from the 1st to the 2nd aid station ($p = 0.004$; $d = 0.72$) and from the 3rd aid station to the finish line ($p = 0.003$; $d = 0.90$) (see Figure 1). The magnitude of those changes range from moderate to large. At the same time, the second repeated-measures ANOVA showed a significant effect for 'Race segment' on SpeedVT1 [$F=235.93$; $p < 0.01$; $\eta 2$ partial = 0.88] and further Bonferroni adjusted pairwise comparisons revealed that SpeedVT1 significantly and largely decreased from the 1st to the 2nd race section ($p < 0.001$; $d = 1.81$) and from the 3rd to the 4th race section ($p < 0.001$; $d = 1.61$).

Correlation analyses did not identify any significant association between post-race relative values of pulmonary function, MIP, HG and SJ with either SpeedABS or SpeedVT1. The magnitude of pulmonary and respiratory muscle function decay was neither related to the degree of upper and lower-limb function loss. Finally, pre- to post-race changes in pulmonary function and respiratory muscle function were not correlated.

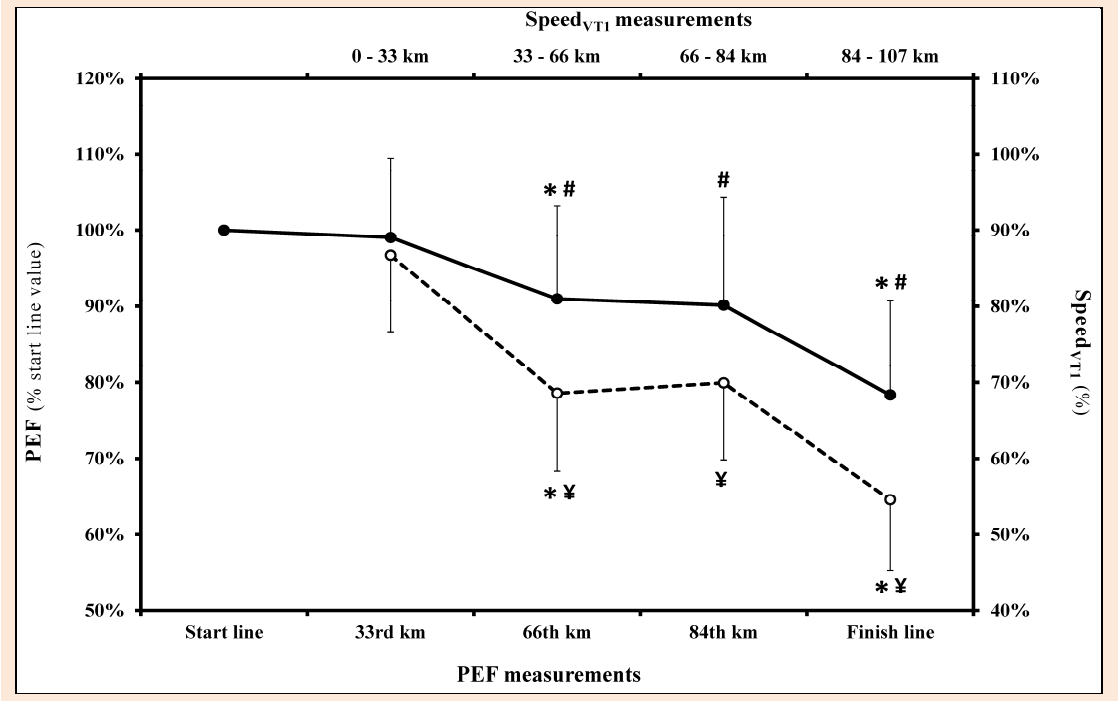

Figure 1. Time course of peak expiratory flow (PEF, continuous line) and race speed expressed as a percentage of the speed at the first ventilatory threshold in the cardiopulmonary exercise test (Speed$_{VT1}$, dotted line). * Significantly different from preceding time point ($p < 0.05$); # Significantly different from start line value ($p < 0.05$); ¥ Significantly different from first race section (0-33 km) value ($p < 0.05$).

Discussion

Our results showed that PEF began to decline at mid-race (66th km) and remained significantly decreased compared to pre-race values until the end of the race, although significant reductions were only identified between the first and the second aid station and between the fourth aid station and the finish line. Moreover, this pattern of PEF function decay was very similar to the one described by SpeedVT1. Secondly, no sex differences were noted regarding post-race pulmonary and inspiratory muscle function, except that FEV1/FVC decay was significantly greater among women. Thirdly, post-race reduction in pulmonary and inspiratory muscle function was not correlated with relative running speed. Lastly, our results lead us to suggest that respiratory muscle decay could be attributable to specific rather than general fatigue, as HG strength (unlike MIP and SJ performance) was not diminished following the race.

The time course of pulmonary function during the race paralleled the changes in relative running speed. SpeedVT1 significantly decreased from the first to the second race section and PEF significantly fell at the 2nd aid station. Afterwards, SpeedVT1 did not change at the third race section and PEF was maintained at the 3rd aid station. Finally, SpeedVT1 significantly dropped from the third to the fourth race section and PEF significantly declined at the finish line. These results contrast with previous findings from Warren et al. (1989), who identified no significant changes in PEF measured at 3-h intervals during a 24-h ultramarathon, while running speed was significantly reduced from the fourth 3-h period onwards (compared to the first 3-h race segment). They neither coincide with previous findings from Maufrais et al. (2016) regarding cardiac function response during a 330-km MUM, as these authors showed that resting heart rate and left ventricle systolic strain rate increase from pre- to mid-race, but return to baseline values from mid- to post-race. Yet, they are in accordance with Vernillo et al. (2015), who showed that PEF was already reduced at mid-race and further declined at post-race during a 330-km MUM. Our results thus provide a more detailed view of the time course of pulmonary function during a MUM, which seems to follow the same pattern as relative running speed decay. Previous research has shown that a stadier pace during a MUM is correlated with faster finishing times (Suter et al., 2020), so it could be that it was also associated with a more gradual decline in respiratory function. Further studies are required to check this hypothesis.

The decline in pulmonary function was of greater magnitude than that previously reported after flat ultramarathons and MUM (see Tiller 2019 for a comprehensive review), although post-race values remained within an acceptable range of the lower-limit of predicted values (Quanjer et al., 2012; Tiller 2019). For example, FVC was reduced by 13%, as compared with a reduction of 9.5% and 1.8% following a 330-km MUM (Vernillo et al., 2015) and a 110-km MUM (Wuthrich et al., 2015); while a reduction of 12.4% and 6.5% were reported following a 80 to 100-km road race (Mahler and Loke, 1981) and a 24-h ultramarathon (Warren et al., 1989). FEV1 was reduced 19.5%, as compared with 9.7% and 7.3% following a 330-km MUM (Vernillo et al., 2015) and a 110-km MUM (Wuthrich et al., 2015); while a reduction of 9.5% and 3% were reported following a 80 to 100-km road race (Mahler and Loke, 1981) and a 24-h ultramarathon (Wuthrich et al., 2015). PEF was reduced 20.3%, as compared with a reduction of 9.7% and 13.8% following a 330-km MUM (Vernillo et al., 2015) and a 110-km MUM (Wuthrich et al., 2015); while a reduction of 13.7% and 11% were reported following a 80 to 100-km road race (Mahler and Loke, 1981) and a 24-h ultramarathon (Warren et al., 1989). Inspiratory muscle function loss was of higher magnitude than pulmonary function decay and also slightly greater (25% vs 19%) than previously reported following a similar MUM (Wuthrich et al., 2015). Moreover, following flat ultramarathons (87-km and 24-h footraces), MIP was found to be unchanged (Ker and Schultz, 1996; Warren et al., 1989). Our results thus contribute to postulate that a greater respiratory function decay is expected following a MUM compared to a flat ultramarathon. As MUM athletes have to confront uphill and downhill running on uneven surfaces, higher ventilatory requirements (Lemire et al., 2021; Vernillo et al., 2014) and increased postural stabilizing demands placed upon respiratory muscles (Bernardi et al., 2017; Degache et al., 2018; Marcolin et al., 2016) appear to be the main reasons explaining such difference. Conversely, altitude exposure, unlike previous studies conducted in the Alps (Vernillo et al., 2014; Wuthrich et al., 2015), do not appear to have played a key role in the observed respiratory function decay.

Unlike previous studies (Mahler and Loke, 1981; Vernillo et al., 2015; Warren et al., 1989), we also found a significant reduction in FEV1/FVC ratio, suggestive of lower airway obstruction that could be associated with a degree of airway inflammation (Bonsignore et al., 2001; Tiller et al., 2019). Interestingly, women showed indeed a larger FEV1/FVC ratio decay following the race than men, so women could be susceptible of a greater lower airway obstruction following a MUM. Females' lower dysanapsis ratio and greater resistive work of breathing during exercise (Dominelli et al., 2015b) may be a factor accounting for such observed difference. Nevertheless, further studies are needed to confirm this assumption.

Contrary to our hypothesis, the magnitude of post-race pulmonary and inspiratory muscle function decay was uncorrelated with SpeedVT1. This finding may imply that performing the race at a higher relative intensity did not provoke a greater respiratory function decay. Notwithstanding, estimated flat-equivalent running speed, although it has been used in several previous studies (Martinez-Navarro et al., 2020b; Saugy et al., 2013; Vernillo et al., 2015), fails to consider the impact of surface characteristics and altitude changes upon average running speed. Consequently, it could be that SpeedVT1 did not accurately reflect the degree of individual effort. Further studies using alternative ways of quantifying exercise relative intensity during MUM (i.e., heart rate monitoring, accelerometry, running power) and an inclined protocol to assess ventilatory thresholds are required to clarify whether the magnitude of post-race pulmonary and inspiratory muscle function decay is correlated or not with the degree of individual effort.

Wuthrich et al. (2015) formerly demonstrated that reduction in MIP following a MUM results primarily from peripheral fatigue. Our results reinforce these previous findings and add to the literature the fact that pre- to post-race change in MIP (-25%) approached the one of SJ height (-31%). Meanwhile, HG strength was unchanged following the competition. Accordingly, it seems reasonable to suggest that post-MUM inspiratory muscle decay was essentially local in nature (Ozkaplan et al., 2005; Tong et al., 2014). Moreover, the absence of a relationship between the reduction in SJ performance and MIP suggests that declines in locomotor and inspiratory muscle function following a MUM are not interrelated. Therefore, runners and coaches should consider that inspiratory muscle function could constitute a performance factor in MUM and thus the addition of specific MIP training into their daily routine might improve their race results (Karsten et al., 2018; Mickleborough et al., 2010; Tiller, 2019; Vernillo et al., 2015; Wuthrich et al., 2015). Indeed, as respiratory muscles play an important role regarding trunk stability (Gandevia et al., 2002; Janssens et al., 2010; Tong et al., 2014) and post-MUM reductions in static and dynamic postural control have been documented (Degache et al., 2018; Marcolin et al., 2016), a better muscle inspiratory capacity may minimize the risk of fall and improve, among other factors, ventilatory efficiency and running economy in the last segments of those races (Bernardi et al., 2017; Lemire et al., 2021; Tiller, 2019; Tiller et al., 2019; Vernillo et al., 2015; Wuthrich et al., 2015).

This study has some limitations that should be acknowledged. The pulmonary and inspiratory muscle function measurements were volitional, so we cannot exclude that the voluntary characteristics of these tests may have influenced the results (Suzuki et al., 1999). Nevertheless, non-invasive techniques are usually better tolerated by participants, less time-consuming and have been shown to be valid and reliable when performed by experienced investigators following established guidelines (Miller et al., 2005; Pellegrino et al., 2005). Moreover, we employed HG strength as a way to control whether changes in respiratory function were the result of reduced motivation or general whole-body fatigue (Ozkaplan et al., 2005; Tong et al., 2014). Another study limitation concerns intracompetition PEF measurements. We recognize that performing a single attempt impairs the validity of the measure, but we thought it was the best approach to minimize interference with MUM race performance and ensure participants' compliance with testing procedures. Lastly, although our sample comprised 28% of female race finishers, we could not equate sample size for male and females subsets.

Conclusion

Expiratory function began to decrease at mid-race and a second significant drop was noted in the last race section, following a pattern similar to that shown by changes in relative running speed. Male and female runners showed a moderate reduction in pulmonary and inspiratory muscle function following the race. However, a larger FEV1/FVC decay, suggestive of a greater lower airway obstruction, was found among women. Finally, our results lead us to propose that respiratory function decline may be attributable to specific rather than general fatigue. Further studies are warranted to clarify whether the magnitude of post-race respiratory function decay is correlated or not with the degree of individual effort, on one hand; and whether targeted inspiratory muscles training has the potential to offset inspiratory muscle decline subsequent to running a MUM, on the other hand.

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Key points

- No sex differences were found in pulmonary and inspiratory muscle function reduction after running a 107-km MUM, except that FEV1/FVC decay was significantly greater among women.
- The time course of PEF during the race paralleled the changes in relative running speed; no significant association, however, was observed between relative running speed and pre- to post-race change in pulmonary and inspiratory muscle function.
- Respiratory function decay following a 107-km MUM may be attributable to specific rather than general fatigue.

AUTHOR BIOGRAPHY

Ignacio MARTÍNEZ-NAVARRO
Employment
Exercise Physiologist at Sports Health Unit of the Vithas Valencia 9 Octubre Hospital and Professor of the Physical Education and Sports Department at the University of Valencia, Spain.
Degree
PhD
Research interests
Clinical aspects of exercise, sports physiology and performance, especially in long-distance runners
E-mail:
ignacio.martinez-navarro@uv.es

Eladio J. COLLADO-BOIRA
Employment
Professor and Vice Dean of the Faculty of Health Sciences at the Jaume I University of Castellon, Spain.
Degree
PhD
Research interests
Clinical aspects of exercise, sports physiology and performance, especially in long-distance runners
E-mail: colladoe@uji.es

Barbara HERNANDO
Employment
Medicine Department of the Jaume I University of Castellon, Spain.
Degree
PhD
Research interests
Analyzing specific biomarkers in ultradistance runners
E-mail: hernandb@uji.es

Carlos HERNANDO
Employment
Head of Sports Service and Professor of the Education and Specific Didactics Department at the Jaume I University of Castellon, Spain.
Degree
PhD
Research interests
Clinical aspects of exercise, sports physiology and performance, especially in long-distance runners
E-mail: hernando@uji.es

✉ **Ignacio Martínez-Navarro**
Faculty of Physical Activity and Sport Sciences. Department of Physical Education and Sports University of Valencia, C/Gascó Oliag, 3 - 46010 – Valencia, Spain