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Influence of an inspiratory muscle fatigue protocol on healthy youths on respiratory muscle strength, vertical jump performance and muscle oxygen saturation: a randomized controlled trial

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Abstract

Background Inspiratory muscle fatigue has been shown to have effects on limbs blood flow and physical performance. This study aimed to evaluate the influence of an inspiratory muscle fatigue protocol on respiratory muscle strength, vertical jump performance and muscle oxygen saturation in healthy youths.

Methods A randomized and double-blinded controlled clinical trial, was conducted. Twenty-four participants aged 18–45 years, non-smokers and engaged in sports activity at least three times a week for a minimum of one year were enrolled in this investigation. Participants were randomly assigned to three groups: Inspiratory Muscle Fatigue (IMFG), Activation, and Control. Measurements of vertical jump, diaphragmatic ultrasound, muscle oxygen saturation, and maximum inspiratory pressure were taken at two stages: before the intervention (T1) and immediately after treatment (T2).

Results The IMFG showed lower scores in muscle oxygen saturation and cardiorespiratory variables after undergoing the diaphragmatic fatigue intervention compared to the activation and control groups ($p < 0.05$). For the vertical jump variables, intragroup differences were found ($p < 0.01$), but no differences were shown between the three groups ($p > 0.05$).

Conclusions Inspiratory muscle fatigue appears to negatively impact vertical jump performance, muscle oxygen saturation and inspiratory muscle strength in healthy youths.

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Keywords Inspiratory muscle fatigue, Vertical jump, Sports performance, Muscle oxygen saturation, Respiratory muscle strength

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Background

The practice of physical exercise automatically entails a series of implications on the respiratory system, such as increased ventilation, facilitation of gas exchange, pH regulation, and increased energy demands by the respiratory muscles [1]. These raises in ventilatory variables are mediated by different structures, such as chemoreceptors, metaboreceptors, thermoreceptors, and the cerebral cortex, among others, reaching the metabolic demand generated by the received stimulus [1, 2]. The respiratory muscles play a fundamental role within the respiratory system, producing the necessary pressure changes through their contraction to carry out gas exchange with the external environment, in order to maintain homeostatic balance [3].

Within the respiratory muscles, diaphragm plays a crucial role. It is the primary inspiratory muscle, responsible for producing around 70–80% of inspiratory volumes, aided by the external intercostal muscles and accessory inspiratory muscles such as scalenes and sternocleidomastoid [1]. Besides its respiratory function, the diaphragm's relevance extends to other physiological aspects, such as its involvement in lumbar stability through its attachments to the lumbar vertebrae, and its influence on cardiac function via its relationship with the vagus nerve and the parasympathetic nervous system [4]. During intense exercise, the increased ventilatory demand places excessive stress and workload on the respiratory muscles, potentially inducing fatigue, increased energy consumption, and a reduction in the contractile capacity of these muscles, especially over diaphragm [5]. In this situation, the phenomenon known as the metaboreflex occurs, whereby a sympathetic reflex-induced vasoconstriction of the peripheral muscles and a redistribution of blood flow towards the respiratory muscles are triggered to maintain the ventilatory process according to the exercise demand [6]. This leads to a performance drop and an increase in fatigue in the peripheral muscles, thus affecting overall performance [7].

Despite the extensive literature on the physiological implications of respiratory muscles on performance and exercise capacity, where most studies focus on analyzing the negative effects of inspiratory muscle fatigue on blood flow and maximal oxygen consumption in the lower limbs [8, 9], there is a scarcity of objective evidence regarding its impact on more specific variables in the sports domain. A broader scientific evidence at our disposal may provide greater insight into the influence of these muscles on more complex sports movements and actions, allowing an evaluation of their impact on sports performance from different perspectives. The hypothesis of this study is that inspiratory muscle fatigue may have a negative effect on inspiratory muscle strength, vertical jump performance, and muscle oxygen saturation. Therefore, the aim of this study is to evaluate the effects of inspiratory muscle fatigue on respiratory muscle strength, vertical jump capacity, and muscle oxygen saturation in healthy youths.

Methods

Study design

This study utilized a parallel randomized clinical trial design, conducted at the Physiotherapy Laboratory of the University of Castilla La Mancha (Toledo, Spain), following the Consolidated Standards of Reporting Trials (CONSORT) guidelines [10]. Informed consent was obtained for all participants. The Research Ethics Committee of the Complejo Hospitalario Universitario de Toledo approved this study (approval number: 1070), and it was registered at ClinicalTrials.gov (NCT06271876, date of first registration: 03/03/2024).

Participants

Twenty-four healthy young individuals were enrolled in the study and randomly allocated by the randomization.com program. Participants were divided into 3 groups: inspiratory muscle fatigue group (IMFG), control group (CG) and activation group (AG). This process was performed by an external member not involved in the study. Both the evaluator and the data analyst were unaware of each participant's group assignment. Inclusion criteria for participants in this study were: aged between 18 and 45 years, non-smokers and taking action in sports activity at least 3 times a week for a minimum of one year. Exclusion criteria included having a medical condition that prevented engagement in any physical activity, subjects with anomalous cognitive capacities, subjects with any chronic disease (cardiorespiratory, neurological, metabolic, oncological, etc.), tympanic perforation or middle-inner ear pathology, lower limb surgery within the past 12 months and individuals experiencing an active episode of lower limb pain.

The sample size was determined using G*Power Software (3.1.9.2), based on maximal inspiratory pressure (MIP) scores obtained on another previous study [11], with an alpha error of 0.05, a beta error of 0.2, and a medium effect size (f=0.25 or Eta partial squared=0.06). A 30% predicted dropout rate was taken into consideration due to the study design. Therefore, a total sample size of 24 participants, divided into three groups (n=8), was determined.

Intervention

IMFG performed the inspiratory muscle fatigue protocol using a threshold valve device (Big Breathe®; GH Innotek Co., Ltd., Busan, Republic of Korea). Participants breathed against submaximal inspiratory loads set at 60% of their MIP until they were unable to exert flow in at

least three maximal inspiratory efforts [12]. The AG followed a protocol of two sets of 30 repetitions at 40% of their MIP using the same threshold device as the IMFG, based on another study [13]. Finally, CG did not receive any intervention. Participants simply sat and waited for the same duration (10 min) just as the intervention and activation groups took to finish their protocol.

Outcomes

Pre-intervention and (T1) and immediately following the intervention (T2) measurements were carried out. The evaluator who assessed all participants was blinded with respect to group allocation.

Primary outcomes

Maximal inspiratory pressure

Maximal inspiratory pressure (MIP) was objectively monitored utilizing the MicroRPM® Respiratory Pressure Measurement Device (MicroMedical, UK) in sitting position. In order to facilitate airflow through the mouth, nasal occlusion was used. Subjects were asked to do up to six moves, with a 1-minute rest interval in between each one. The highest value, with less than 5% of variation, was recorded after three consecutive attempts [14].

Diaphragmatic thickness and thickening fraction

Diaphragmatic thickness measurement was conducted utilizing a linear probe (L13-3s) which worked at 3.2–12.3 MHz. Participants were placed in supine, and the probe was set perpendicular to the chest wall at the anterior and mid-axillary lines, between the 8th and 9th intercostal spaces. B-mode ultrasonography aided to have a clearer view of diaphragm in the juxtaposition region. At the end of expiration ($Thick_{esp}$) and peak inspiration ($Thick_{insp}$), diaphragm thickness was measured three times, and the mean values were noted (Fig. 1). Diaphragmatic thickness was considered when expiration ended. The thickening fraction (TF%) was determined by the use of the formula TF = [(Thickness at end of maximum inspiration - Thickness at end of expiration) / Thickness at end of expiration] × 100% [15].

Diaphragm movement curve

The diaphragmatic movement curve was tested using a convex probe (C5-1s) running at 1.2-6 MHz. Patients remained supine as the probe was placed longitudinally on the mid-clavicular line of the right costal margin, oriented cephalically, and utilizing the liver as an acoustic window. The diaphragmatic movement curve during maximal deep breathing and sniff breathing was recorded with the ultrasound M-mode. Diaphragmatic movement (Mob_{insp} and Mob_{sniff}), inspiration time ($Time_{insp}$ and $Time_{sniff}$), and maximum contraction velocity (Vel_{insp} and Vel_{sniff}) were gathered in both breathing modalities. Three respiratory cycles in a row were noted, and the average value of each parameter was obtained. [15].

Secondary outcomes

Counter movement jump

The Countermovement Jump (CMJ) test initiated with the participant standing straight, with hands on hips. Next, each subject performed a quick upward jump by flexing and extending the knees in an eccentric, isometric, and concentric manner. The Quattro Jump force

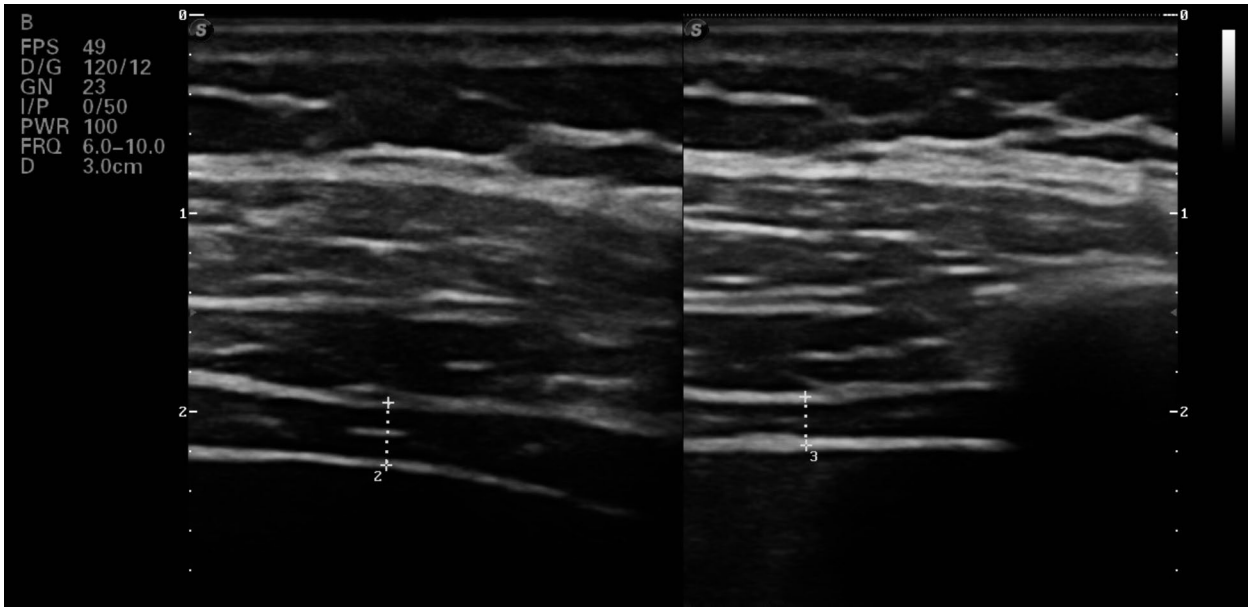

Fig. 1 Ultrasound image of diaphragmatic thickness at: maximum inspiration (**a**) and maximum expiration (**B**)

platform (Kistler; Winterthur, Switzerland) was used to collect CMJ data. Watts (W), meters per second (m/s), milliseconds (ms), Newtons (N), and centimeters (cm) were the units of measurement of CMJ's power (P), velocity (V), flight time (FT), strength (S), and height (H), respectively. Each participant executed two CMJ trials, with a ten second rest interval in between each leap [16].

Muscle oxygen saturation

The Moxy Monitor instrument (Fortiori Design LLC, Hutchinson, MN, USA) was used to assess the levels of muscle oxygen saturation (SmO_2). This portable and wireless device emits infrared spectroscopy to monitor SmO_2. Computer software was used to analyze data (Moxy Software v1.5.5; Idiag, Fehraltorf, Switzerland). According to the protocol established by Contreras-Briceño et al., measurements were conducted involving a 180-second resting interval followed by continuous monitoring throughout inspiratory muscle fatigue. Participants were evaluated while standing, focusing on the vastus lateralis of the dominant leg (Fig. 2). The scores chosen were the average recorded from the last 30 s of each phase [17].

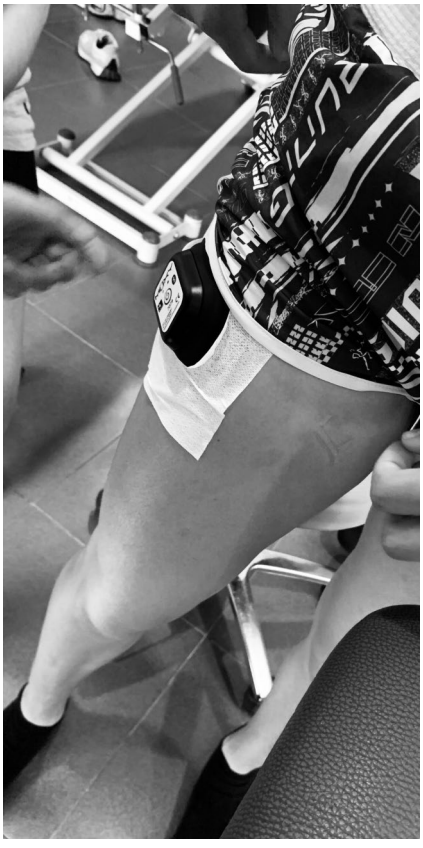

Fig. 2 Measurement of muscle oxygen saturation in vastus lateralis

Statistical analysis

The statistical analyses were performed using IBM SPSS Statistics v.22.0, with a significance threshold set at $p<0.05$. The normality of each variable was assessed through the Kolmogorov-Smirnov test, which confirmed a normal distribution across all variables. Demographic characteristics were examined using descriptive statistics, with results expressed as mean±SD. To investigate the outcome variables, a 2-way repeated measures ANOVA was employed (group x time), analyzing the interactions among the Experimental group, Activation group, and Control group across different time points (Baseline and Post-treatment). When significant differences were identified, post hoc Bonferroni multiple-comparisons tests were applied. Effect sizes (ES) were calculated and interpreted based on Cohen's scale: low (<0.20), medium (0.50), and high (>0.80).

Results

Demographic data

A total of 24 young participants were enlisted for the study, divided into three groups: IMFG (4 males, 4 females), AG (4 males, 4 females), and CG (5 males, 3 females). There were no dropouts due to complications, adverse effects, or during the follow-up period. The CONSORT flowchart was included (Fig. 3). Analysis revealed no significant differences in demographic characteristics among the IMFG, AG, and CG groups (Table 1).

Changes in primary and secondary variables after fatigue and activation

Results for primary and secondary outcomes are presented in Tables 2 and 3, respectively.

In the analysis of the MIP variable, there were no differences between groups at any measurement time ($p>0.05$). Within the IMFG analysis, a decrease is shown between baseline and pot-treatment of -9.60±1.60 cmH2O ($p<0.01$; ES=0.62; 95% CI of the difference = -10.22 to -7.78). On the other hand, the AG showed an increase between baseline and post-treatment of 2.88±2.10 cmH2O ($p<0.01$; ES=0.18; 95% CI of the difference=1.66 to 4.09).

In the analysis of the $Thick_{insp}$ variable, there were no differences between groups at any measurement time ($p>0.05$). In the IMFG analysis, there was a decrease between baseline and post-treatment of -0.03±0.01 cm ($p<0.01$; ES=0.42; 95% CI of the difference = -0.04 to -0.03). In contrast, the AG showed an increase between baseline and post-treatment of 0.02±0.01 cm ($p<0.01$; ES=0,21; 95% CI of the difference=0.00 to 0.02).

In the analysis of the Mob_{sniff} variable. The IMFG had lower values than the activation group and the control group after performing the treatment ($P<0.01$). Within

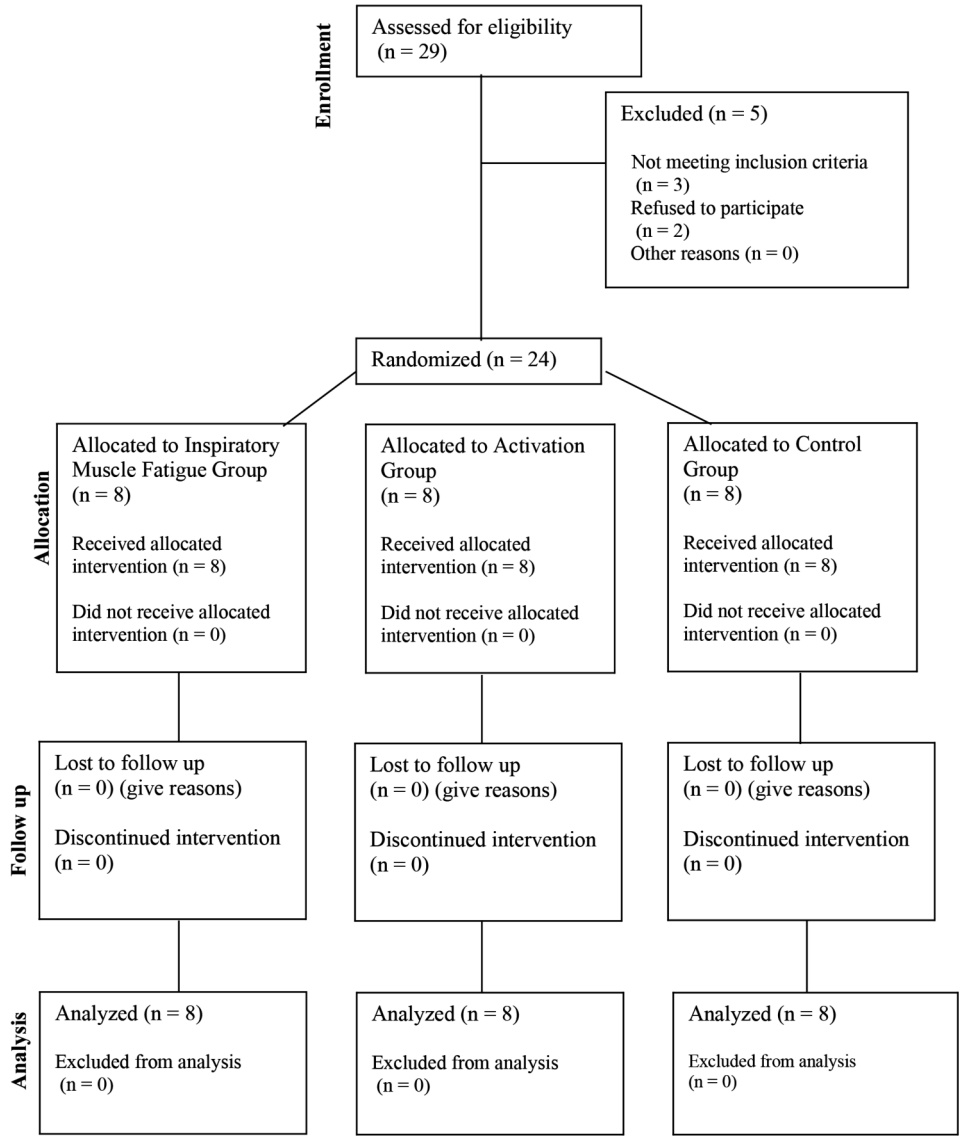

Fig. 3 CONSORT flow diagram

Table 1 Demographic characteristics of subject

	IMFG (*n* = 8)	AG (*n* = 8)	CG (*n* = 8)	*p*
Sex (male/female)	4/4	4/4	5/3	
Age (yrs)	20.13 ± 2.03	20.38 ± 1.77	20.25 ± 1.49	n.s
Weight (kg)	67.38 ± 6.55	66.63 ± 7.29	66.25 ± 7.96	n.s
Height (cm)	170.50 ± 5.24	169.00 ± 3.55	168.75 ± 5.70	n.s

IMFG, Inspiratory muscle fatigue group; AG, Activation group; CG, Control group

the IMFG analysis, an increased value was obtained between baseline and post-treatment of -1.01 ± 0.23 cm ($p < 0.01$; ES = 2.25; 95% CI of the difference = -1.12 to -0.91). In contrast, the AG showed an augmented value between baseline and post-treatment of 0.50 ± 0.09 cm ($p < 0.01$; ES = 1.47; 95% CI of the difference = 0.40 to 0.61).

In the analysis of the SmO_2, the IMFG had lower values than the activation group and the control group after performing the treatment ($P < 0.01$). Within the analysis of IMFG showed a decreased score between baseline and posttreatment of -15.31 ± 5.25% ($p < 0.01$; ES = 2.02; 95% CI of the difference = -17.69 to -12.93).

When analyzing strength outcomes, there were no differences between groups at any measurement time ($p > 0.05$). Within the IMFG, the analysis showed a decreased value between baseline and post-treatment of -211.10 ± 121.60 N ($p < 0.01$; ES = 0.26; 95% CI of the difference = -283.27 to -138.93). On the other hand, the strength showed an increase between the posttreatment measurement and the baseline of 188.77 ± 117.88 N ($p < 0.29$; ES = 2.00; 95% CI of the difference = 116.59 to 260.94).

Table 2 Outcome measurements of primary variables

	Baseline	Post-treatment		f	*p*	n^2	pot
MIP (cmH2O)							
IMFG	99.63 ± 14.63	90.63 ± 14.20**	Group	0.09	0.91	0.01	0.06
AG	96.00 ± 16.02	98.88 ± 15.82**	Time	34.91	< 0.01	0.62	1
CG	98.25 ± 16.02	98.38 ± 16.00	Group x Time	112.41	< 0.01	0.92	1
$Thick_{insp}$ (cm)							
IMFG	0.46 ± 0.08	0.43 ± 0.08**	Group	0.36	0.71	0.03	0.10
AG	0.47 ± 0.07	0.48 ± 0.07**	Time	8.25	< 0.01	0.28	0.78
CG	0.47 ± 0.08	0.47 ± 0.07	Group x Time	43.87	< 0.01	0.81	1
$Thick_{esp}$ (cm)							
IMFG	0.23 ± 0.04	0.24 ± 0.04**	Group	0.03	0.97	< 0.01	0.05
AG	0.23 ± 0.04	0.23 ± 0.03	Time	9.00	< 0.01	0.30	0.82
CG	0.23 ± 0.04	0.23 ± 0.04	Group x Time	7.60	< 0.01	0.42	0.91
$TF_{\%}$ (%)							
IMFG	104.86 ± 10.64	76.21 ± 11.33**##	Group	5.83	0.01	0.36	0.82
AG	103.53 ± 8.26	110.60 ± 11.40*	Time	20.74	< 0.01	0.50	0.99
CG	102.54 ± 11.64	100.200 ± 10.50++	Group x Time	38.46	< 0.01	0.79	1
Mob_{insp} (cm)							
IMFG	6.46 ± 0.45	5.45 ± 0.50**##	Group	10.64	< 0.01	0.50	0.98
AG	6.49 ± 0.34	6.99 ± 0.27**	Time	37.11	< 0.01	0.64	1
CG	6.62 ± 0.31	6.59 ± 0.32++	Group x Time	231.60	< 0.01	0.78	1
$Time_{insp}$ (ms)							
IMFG	1577.14 ± 68.73	1681.43 ± 76.2**5##	Group	8.25	< 0.01	0.45	0.93
AG	1562.50 ± 82.59	1443.75 ± 53.70**$	Time	0.15	0.70	0.01	0.07
CG	1537.50 ± 53.65	1538.75 ± 64.46++	Group x Time	32.17	< 0.01	0.76	1
Vel_{insp} (cm/s)							
IMFG	3.97 ± 0.55	3.15 ± 0.48**##	Group	15.76	< 0.01	0.60	1
AG	4.17 ± 0.34	4.84 ± 0.12**$$	Time	2.02	0.17	0.09	0.27
CG	4.30 ± 0.25	4.30 ± 0.28++	Group x Time	136.67	< 0.01	0.93	1
Mob_{sniff} (cm)							
IMFG	1.78 ± 0.17	1.65 ± 0.14**##	Group	4.79	0.02	0.31	0.73
AG	1.85 ± 0.07	1.94 ± 0.11**	Time	1.53	0.23	0.07	0.22
CG	1.84 ± 0.13	1.81 ± 0.09$$+	Group x Time	17.33	< 0.01	0.62	1
$Time_{sniff}$ (ms)							
IMFG	171.25 ± 28.00	205.00 ± 20.00**##	Group	2.29	0.13	0.18	0.41
AG	175.00 ± 15.12	153.75 ± 19.23**	Time	1.17	0.29	0.05	0.18
CG	181.25 ± 33.14	181.25 ± 28.00	Group x Time	17.29	< 0.01	0.62	1
Vel_{sniff} (cm/s)							
IMFG	10.58 ± 1.75	8.13 ± 1.13**##	Group	7.05	< 0.01	0.40	0.89
AG	10.61 ± 0.95	12.75 ± 1.20**$$	Time	0.63	0.44	0.03	0.12
CG	10.36 ± 1.55	10.15 ± 1.40+	Group x Time	35.96	< 0.01	0.77	1

IMFG, Inspiratory muscle fatigue group; AG, Activation group; CG, Control group; MIP, Maximal inspiratory pressure; $Thick_{insp}$, Diaphragmatic thickness in inspiration; $Thick_{esp}$, Expiratory diaphragmatic thickness; TF, Thickness ratio inspiration/expiration; Mob_{insp}, Maximal inspiration diaphragmatic mobility; $Time_{insp}$, Maximum inspiratory contraction time; Vel_{insp}, Maximum inspiration contraction velocity; Mob_{sniff}, Diaphragmatic mobility sniff; $Time_{sniff}$, Sniff contraction time; Vel_{sniff}, Sniff contraction velocity

Values are mean ± SD

*$P < 0.05$, **$P < 0.01$, post-treatment, with baseline

#$P < 0.05$, ##$P < 0.01$, comparisons between the IMFG and AG groups at corresponding time points

+$P < 0.05$, ++$P < 0.01$, comparisons between the IMFG and CG groups at corresponding time points

$$P < 0.05$, $$$P < 0.01$, comparisons between the AG and CG groups at corresponding time p

Discussion

The results of this study seem to confirm the proposed hypothesis regarding the influence of the inspiratory muscle fatigue protocol on respiratory muscle strength, vertical jump, and muscle oxygen saturation, suggesting a decrease in inspiratory muscle strength, as well as a drop in vertical jump performance and muscle oxygen saturation when isolated inspiratory muscle fatigue occurs in

Table 3 Outcome measurements of secondary variables

	Baseline	Post-treatment		F	*p*	n^2	pot
Vertical Jump (cm)							
IMFG	28.85 ± 6.88	24.91 ± 5.83**	Group	0.14	0.87	0.01	0.07
AG	26.86 ± 6.11	29.31 ± 6.40**	Time	3.34	0.08	0.14	0.41
CG	28.34 ± 5.84	28.44 ± 5.82	Group x Time	54.21	< 0.01	0.84	1
Flight Time (ms)							
IMFG	482.38 ± 62.29	445.88 ± 57.99**	Group	0.23	0.79	0.02	0.08
AG	467.00 ± 54.18	486.25 ± 55.77**	Time	8.42	< 0.01	0.29	0.79
CG	482.25 ± 47.44	482.38 ± 48.80	Group x Time	69.13	< 0.01	0.87	1
Velocity (m/s)							
IMFG	1.19 ± 0.15	1.09 ± 0.15**	Group	0.23	0.80	0.02	0.08
AG	1.14 ± 0.14	1.19 ± 0.14**	Time	3.73	0.07	0.15	0.45
CG	1.11 ± 0.18	1.12 ± 0.17	Group x Time	48.44	< 0.01	0.82	1
Strength (N)							
IMFG	2170.55 ± 809.22	1959.45 ± 730.96**	Group	0.15	0.86	0.01	0.07
AG	1875.89 ± 643.29	2064.65 ± 664.50**	Time	0.07	0.79	< 0.01	0.06
CG	2159.37 ± 694.73	2165.81 ± 689.86	Group x Time	33.27	< 0.01	0.76	1
Power (w)							
IMFG	2578.83 ± 1119.52	2221.61 ± 955.82**	Group	0.04	0.97	< 0.01	0.06
AG	2146.85 ± 821.69	2430.03 ± 941.93**	Time	0.58	0.46	0.03	0.11
CG	2378.98 ± 776.62	2382.41 ± 742.56	Group x Time	35.87	< 0.01	0.77	1
SmO_2 (%)							
IMFG	81.20 ± 7.59	65.89 ± 7.47##**	Group	2.68	0.09	0.20	0.47
AG	80.88 ± 6.73	82.16 ± 5.68	Time	50.60	< 0.01	0.71	1
CG	79.40 ± 8.07	79.33 ± 8.00++	Group x Time	64.91	< 0.01	0.86	1

IMFG, Inspiratory muscle fatigue group; AG, Activation group; CG, Control group

Values are mean ± SD

*P < 0.05, **P < 0.01, post-treatment, with baseline

#P < 0.05, ##P < 0.01, comparisons between the IMFG and AG groups at corresponding time points

+P < 0.05, ++P < 0.01, comparisons between the IMFG and CG groups at corresponding time points

$$P$ < 0.05, $$$P$ < 0.01, comparisons between the AG and CG groups at corresponding time points

healthy youths. Furthermore, both inspiratory strength and vertical jump performance appear to improve with inspiratory muscle activation.

Regarding the results obtained for the variables related to inspiratory muscle strength (MIP and ultrasonography), our findings suggest a significant decrease in IMFG as well as a significant improvement in AG. The results obtained in our study regarding these variables are consistent with previous studies where subjects underwent an isolated inspiratory muscle fatigue protocol [11, 12]. Among all methods that evaluate inspiratory muscle strength, Maximum Inspiratory Pressure (MIP) is considered a gold standard, being an easy-to-perform and well-tolerated test by patients [14], as well as a variable correlated with maximal oxygen consumption and aerobic performance [18, 19].

Additionally, the use of ultrasonography for the non-invasive assessment of diaphragm muscle provides an objective evaluation of this structure and its contractile capacity. Measurements in M-mode of diaphragmatic mobility and contraction speed during deep inspiration and sniff maneuvers, as well as B-mode measurements of diaphragmatic thickness during inspiration, correlate with markers of diaphragmatic strength and fatigue such as respiratory muscle strength, esophageal pressure, or transdiaphragmatic pressure [20, 21]. Including these variables in this study ensured the presence of inspiratory muscle fatigue in the Inspiratory Muscle Fatigue Group (IMFG), as well as the condition of the inspiratory muscles in all groups.

As previously mentioned, the respiratory system plays a fundamental role during physical exercise, particularly during moderate-to-high intensity exercise. For instance, tidal volumes of about 500 ml/min at rest significantly increase during exercise to 50–200 L/min, resulting in an increase in resistance within the airway that needs greater pressure exerted by the respiratory muscles to achieve the volumes required to meet the body's needs [1]. Therefore, the energy cost of the respiratory muscles in healthy individuals rises from approximately 1% of the total energy expenditure to 12–15% during high-intensity exercise, thereby reducing the cardiac output available to other active muscles due to the need for redistributing blood flow to the respiratory muscles [22, 23].

The inspiratory muscles, particularly diaphragm, as happens with locomotor muscles, can experience fatigue, which impairs their contractile capacity, reducing their ability to overcome a certain pleural pressure and facilitate gas exchange [24]. When this occurs, a phenomenon known as the metaboreflex is triggered, wherein a supraspinal stimulus mediated by III and IV afferent fibers induces peripheral vasoconstriction, redistributing blood flow from peripheral muscles to the respiratory muscles [6], leading to decreased exercise tolerance, increased dyspnea, and reduced athletic performance [25, 26].

Regarding the results obtained in the CMJ, a reduction in vertical jump performance can be observed in the IMFG, while the AG subjects show an improvement in the same variable. This study is the first to objectively analyze the influence of respiratory muscle fatigue, as well as its activation, on vertical jump performance. The Countermovement Jump (CMJ) test is used to assess power and performance, particularly in the lower limbs, across various sports disciplines. Higher CMJ values can imply better performance in sports such as basketball, volleyball, or soccer [27, 28], as well as greater professional development [29]. Conversely, CMJ is also related to injury risk in different sports, where lower CMJ values may indicate a higher risk of injury [30].

Our study's results suggest a decrease in the various components of the CMJ in the IMFG, which can be hypothesized in different ways. First, the induction of the metaboreflex can cause blood flow redistribution towards the respiratory muscles, resulting in reduced blood supply to peripheral muscles, decreasing their oxygen consumption and thus their contractile capacity [31, 32]. Additionally, a significant variation in muscle oxygen saturation in the IMFG supports the suggested hypothesis and aligns with previous study findings [5, 33]. Furthermore, diaphragm is part of the core and plays a fundamental role in lumbar stabilization through intra-abdominal pressure modifications [4, 34]. The core is crucial during vertical jumping, providing stability and facilitating force transfer from the lower limbs [35], contributing to postural control during takeoff and landing phases [36] and forming part of injury prevention strategies [37]. Therefore, it is understandable that inspiratory muscle fatigue, especially from diaphragm, results in a deficit in stabilization and postural control that affects vertical jumping, as demonstrated in previous studies [38]. Regarding the improvements observed in the AG, previous studies in various sports disciplines have shown performance enhancements following an inspiratory muscle warm-up protocol, in variables such as aerobic performance [39] or running power [40]. This may be due to increased oxygen consumption and the contractile capacity of the warmed-up muscles [41], as well as greater excitability improving the coordination of inspiratory muscles and reducing co-contraction between inspiratory and expiratory muscles [39].

This study has several limitations that should be mentioned. First, the results should be interpreted with caution, as the observed effects are based on immediate post-treatment evaluation, without conducting multiple measurements over time to assess the duration of these effects. Regarding the assessment of the subjects' physical activity levels, only physical activity questionnaires were used, which may result in less precise measurements. Additionally, despite having calculated the minimum number of subjects required to detect significant differences, studies with larger sample sizes and in different population groups are necessary to corroborate these results. Finally, despite using validated respiratory variable measurements, such as transdiaphragmatic pressure could provide more objective values regarding diaphragmatic strength and fatigue. Additionally, the results obtained in this study may lead to future research analyzing the long-term effects of inspiratory muscle fatigue on the variables studied, exploring the influence of these effects on performance and injury risk, as well as more specifically evaluating the implications of inspiratory muscle activation on performance.

Conclusions

Inspiratory muscle fatigue appears to negatively impact inspiratory muscle strength, peripheral muscle strength, muscular oxygenation, and vertical jump performance. Conversely, activation of the inspiratory musculature seems to enhance respiratory muscle strength and vertical jump performance in healthy young individuals.

Abbreviations

IMFG	Inspiratory muscle fatigue group
AG	Activation group
CG	Control group
MIP	Maximal inspiratory pressure
$Thick_{insp}$	Diaphragmatic thickness in inspiration
$Thick_{esp}$	Expiratory diaphragmatic thickness
TF	Thickness ratio inspiration/expiration
Mob_{insp}	Maximal inspiration diaphragmatic mobility
$Time_{insp}$	Maximum inspiratory contraction time
Vel_{insp}	Maximum inspiration contraction velocity
Mob_{sniff}	Diaphragmatic mobility sniff
$Time_{sniff}$	Sniff contraction time
Vel_{sniff}	Sniff contraction velocity
CMJ	Counter movement jump
SmO_2	Muscle oxygen saturation

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Author contributions

ALM and ASS carried out the design and idea of the project, ASS and ALM and DMV wrote the introduction to the manuscript, DMV and ALM wrote the methodology and JSIGE statistics part, and ASS, JSIGE and ALM wrote the Discussion and conclusions part. ASS, DMV and JSIGE reviewed the manuscript.

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Data availability
We have the availability of the data, and the materials are available at the request of the publisher.

Declarations

Ethics approval and consent to participate
The current study was approved by the Research Ethics Committee of Toledo University Hospital Complex (Spain). In addition, written informed consent was obtained from the participants.

Consent for publication
Not applicable.

Conflict of interest
The authors declare that they have no competing interests.

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