



Original Research

Chest Wall Vibration Enhances Cardiopulmonary Recovery and Reduces Dyspnea Following High Intensity Exercise in a Forward-Leaning Posture

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Abstract

International Journal of Exercise Science 19(3): 3006, 2026. Cardiopulmonary recovery after peak exercise is a critical component of exercise performance and overall health management. This study investigated whether combining chest wall vibration with a trunk forward-leaning posture could enhance recovery efficiency in healthy adults. Twenty-three participants performed a graded treadmill exercise using the Bruce protocol and were randomly assigned to either a vibration group (n = 11) or a control group (n = 12). During the 5-minute recovery period, all participants assumed a seated forward-leaning position, while the vibration group additionally received low-frequency chest wall vibration at the intercostal space between the second and third ribs. Heart rate (HR), oxygen saturation (SpO₂), forced vital capacity (FVC), forced expiratory volume in one second (FEV₁), FEV₁/FVC ratio, and subjective dyspnea (using a modified cross-modality matching method) were measured at baseline, immediately post-exercise, and at 1, 3, and 5 minutes of recovery (R1, R3, R5). Both groups demonstrated significant changes over time in HR, SpO₂, and subjective dyspnea, whereas pulmonary function measures (FVC, FEV₁, and FEV₁/FVC) remained unchanged. HR peaked immediately post-exercise (Control: 184.25 ± 8.24 bpm; Experimental: 186.72 ± 9.14 bpm) and decreased progressively during recovery, reaching 124.91 ± 13.54 bpm in the control group and 116.00 ± 13.84 bpm in the experimental group at 5 minutes. The experimental group showed significantly lower HR at 1 and 3 minutes post-exercise compared with the control group (p = .008 and p = .003, respectively), while no between-group differences were observed at Rest, immediately post-exercise, or at 5 minutes (all p > .05). SpO₂ decreased immediately after exercise (Control: 87.75 ± 6.22%; Experimental: 91.00 ± 5.54%) and returned toward resting levels by 1 minute of recovery. No significant between-group differences were observed at any time point (all p > .05). Subjective dyspnea scores peaked immediately after exercise (Control: 38.25 ± 3.64 cm; Experimental: 39.27 ± 3.13 cm) and declined progressively through recovery (Control: 16.50 ± 3.72 cm; Experimental: 4.09 ± 2.77 cm at 5 minutes). Dyspnea scores were significantly lower in the experimental group at 1, 3, and 5 minutes into recovery (all p < .001). These results suggest that the addition of chest wall vibration to a forward-leaning posture may facilitate early autonomic recovery and alleviate post-exercise breathlessness, offering a practical non-invasive intervention for post-exertional recovery.

Keywords: Non-invasive recovery strategy, post-exercise intervention, respiratory support technique

Introduction

Maximal or high-intensity exercise is a widely accepted method for assessing cardiopulmonary capacity, primarily through measurements such as maximal oxygen uptake and maximal heart rate (HR).¹⁻⁴ In healthy adults, it is used to improve fitness, while in athletes, it helps analyze training effects.⁵ In clinical rehabilitation, it is essential for evaluating exercise tolerance and

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determining the appropriate exercise intensity in patients with heart failure or chronic obstructive pulmonary disease (COPD).⁵ However, such high-intensity exercise rapidly increases HR, oxygen consumption, and ventilation, leading to significant physiological responses such as altered arterial oxygen and carbon dioxide pressures, increased sympathetic activity, and subjective dyspnea.⁶⁻⁷ This sympathetic dominance is accompanied by a delayed parasympathetic recovery, which may prolong elevated HR and blood pressure, increase stress hormone release, and ultimately delay recovery while placing additional burden on the cardiovascular system.⁸⁻⁹ When HR recovery is delayed after high-intensity exercise, the clearance of metabolic byproducts is impaired, which may diminish performance and impede cardiopulmonary recovery.¹⁰⁻¹³ Accordingly, appropriate recovery interventions are necessary to accelerate post-exercise recovery.

Among such interventions, the trunk forward leaning posture (FLP) has been proposed as an effective recovery strategy.¹⁴ This posture increases the anteroposterior diameter of the thorax, facilitating pulmonary expansion and improving the recovery of forced vital capacity (FVC) and forced expiratory volume in one second (FEV₁).¹⁴⁻¹⁶ It also enhances intra-abdominal pressure, supporting the downward contraction of the diaphragm and thereby improving breathing efficiency.¹⁴ Several studies have demonstrated its positive effects on dyspnea relief and oxygen saturation even in healthy populations, in addition to those with COPD.¹⁵⁻¹⁶ However, the posture alone may have limitations in resolving severe dyspnea immediately following maximal exercise.¹⁵ Some studies suggest that the decline in subjective dyspnea is gradual, and recovery of autonomic balance and HR may be insufficient with posture alone during the acute recovery phase.¹⁶⁻¹⁷ Therefore, additional interventions may be necessary to enhance the effectiveness of FLP.

Chest wall vibration is a physical therapy technique involving mechanical vibration applied to the thoracic wall. It assists in mucus clearance, improves ventilation efficiency, and enhances pulmonary circulation.¹⁸⁻¹⁹ In patients with COPD, chest wall vibration has been shown to significantly increase FEV₁, facilitate sputum clearance, and reduce rebreathing by improving alveolar ventilation.¹⁸⁻²⁰ Manning et al demonstrated a significant reduction in post-exercise dyspnea following chest wall vibration application.²⁰ Preliminary studies using low-cost home-use vibration devices have also suggested that chest wall vibration can help maintain oxygen saturation and reduce respiratory muscle fatigue during recovery.²¹⁻²² However, research exploring the effects of chest wall vibration during cardiopulmonary recovery is still in its early stages, and studies examining the combined effects of posture and vibration are particularly scarce.

Most prior research has focused on either FLP or chest wall vibration individually. While both have shown potential in improving pulmonary function and alleviating dyspnea, randomized controlled trials examining their synergistic effects immediately following maximal exercise are lacking.^{15-17,20-22} Therefore, this study aimed to compare the effects of FLP alone versus FLP combined with chest wall vibration during the recovery phase after maximal treadmill exercise in healthy adults. Recovery outcomes were assessed by measuring HR, oxygen saturation (SpO₂), FVC, FEV₁, FEV₁/FVC ratio, and subjective dyspnea. We hypothesized: (1) both groups would show progressive recovery in these variables at 1, 3, and 5 minutes post-exercise; and (2) the group receiving chest wall vibration in combination with FLP would demonstrate significantly greater improvements in these outcomes compared to the group with FLP alone.

Methods

Participants

This study recruited 23 healthy adult men and women (all Asian ethnicity, specifically Korean).

All participants were provided written informed consent after receiving a comprehensive explanation of the study's purpose and procedures. A total of 23 individuals completed the study, including 11 participants in the experimental group and 12 healthy individuals in the control group. The general characteristics of the participants are summarized in Table 1. The sample size was calculated using G*Power (version 3.1.6) based on an effect size estimated from a pilot study involving four participants (two per group). An a priori power analysis ($d = 1.256$; $\alpha = 0.05$; power = 0.80) indicated that a total sample size of 22 participants was required, with 11 participants allocated to each group. The effect size ($d = 1.256$) was calculated from the mean and standard deviation of the pilot data. The inclusion criteria were as follows: adults aged 18 years or older, cognitively capable of understanding and following the investigator's instructions, and no participation in similar studies within the previous year. The exclusion criteria included: voluntary withdrawal during the study period; unstable cardiovascular conditions such as hypertension, arrhythmia, or angina; a history of thoracic or abdominal surgery; orthopedic impairments; visual field defects that could interfere with the study; congenital thoracic deformities; rib fractures; and diagnosed pulmonary, renal, endocrine, orthopedic, or rheumatic disorders. Participants with skin hypersensitivity or intolerance to vibration stimuli were also excluded.

All participants' privacy rights were strictly protected, and no personally identifiable information was collected or disclosed without explicit informed consent. Experiments involving human participants were conducted in accordance with the ethical standards of the Declaration of Helsinki. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science.²³ The study protocol was approved by the Institutional Review Board (IRB) of B University (IRB No. BUIRB-202506-HR-52).

Table 1. Participant Demographics (N=23).

	Control group (N=12)	Experimental group (N=11)	Z	p
Gender (M/F)	(5/7)	(4/7)		
Age (yrs)	23.25±1.05	23.73±2.57	-.096	.924
Weight (kg)	66.50 ± 14.58	64.09 ± 10.75	-.216	.829
Height (cm)	167.83 ± 7.29	165.72 ± 8.58	-.586	.558
Body mass index	23.49 ± 4.19	23.23 ± 2.53	-.308	.758

* $p < .05$

Note: Results are presented as mean ± SD; Control group: Trunk forward leaning posture group, Experimental group: Trunk forward leaning posture with chest wall vibration group.

Procedure

After providing written informed consent, all participants completed a brief health history questionnaire to confirm eligibility. Baseline assessments were conducted in a controlled laboratory environment under standardized conditions. Participants were instructed to rest in a seated position for at least 30 minutes before testing to ensure physiological stabilization. All assessments were performed barefoot. Baseline measurements included HR, SpO₂, FEV₁, FVC, FEV₁/FVC ratio, and subjective dyspnea using a modified cross-modality matching technique. All values were recorded with the participants in an upright seated posture. Participants were then randomly assigned to either the experimental or control group using a sealed envelope randomization method. A number slip (1 or 2) was drawn from an opaque container; "1" indicated assignment to the experimental group (chest wall vibration), while "2" indicated the control group. Both groups underwent a maximal graded treadmill exercise following the Bruce protocol, continuing until volitional fatigue. Immediately following exercise cessation, participants were seated in a forward-leaning posture for a 5-minute recovery period. During this

phase, the experimental group received low-frequency mechanical vibration (15–30 Hz) applied to the intercostal region between the second and third ribs using a chest wall vibrator, whereas the control group maintained the same posture without vibration. HR, SpO₂, FEV₁, FVC, FEV₁/FVC ratio, and subjective dyspnea were assessed at four time points: immediately post-exercise, and at 1, 3, and 5 minutes into the recovery period. To ensure assessor blinding and reduce measurement bias, physiological parameters were recorded by an assistant who was blinded to group assignment. Data from the devices were read and recorded by a separate student assistant. Following the final measurement, participants remained seated in a forward-leaning posture for up to 30 minutes to ensure full cardiopulmonary recovery and minimize adverse effects.

Measurements

Heart Rate and Oxygen Saturation.

HR and SpO₂ were continuously monitored using a non-invasive fingertip pulse oximeter (MD300C19, Beijing Choice Electronic Technology Co, Ltd, China), which has a measurement accuracy of approximately $\pm 2\%$.²⁴ HR was expressed in beats per minute and served as a marker of autonomic regulation during recovery, reflecting parasympathetic reactivation and sympathetic withdrawal over time. SpO₂, defined as the percentage of oxygen-bound hemoglobin in peripheral blood, was interpreted in relation to respiratory gas exchange efficiency. Normal SpO₂ ranges from 95% to 100%, and increased levels during recovery indicate improved oxygen delivery to peripheral tissues.

Pulmonary function was measured using a portable spirometer (Pony FX, COSMED Inc, Italy). While participants primarily maintained a seated forward-leaning posture during the 5-minute recovery period, they temporarily transitioned to an upright seated position with their feet flat on the floor and head in a neutral position for each measurement. This transition ensured standardized lung expansion and measurement accuracy. Each assessment—performed immediately post-exercise and at 1, 3, and 5 minutes of recovery—was completed within 30 seconds, after which participants immediately resumed the forward-leaning posture. Additionally, for the experimental group, chest wall vibration was briefly suspended during these measurements to prevent mechanical interference. Measurements included FVC, FEV₁, and the FEV₁/FVC ratio. FVC represents the total volume of air exhaled forcefully after a full inspiration and is a key indicator of lung elasticity and recovery. FEV₁ reflects airway resistance and respiratory muscle performance, and its increase indicates reduced bronchoconstriction and enhanced expiratory flow. The FEV₁/FVC ratio quantifies the percentage of the FVC exhaled in the first second; values below 70% may indicate obstructive ventilatory dysfunction.²⁵ The intra-rater reliability of the Pony FX spirometer has been reported to be excellent, with intraclass correlation coefficients (ICC) ranging from 0.94 to 0.99.²⁶

Subjective dyspnea was assessed using a modified cross-modality matching technique.²⁷ This method enables participants to quantify the intensity of dyspnea by comparing it to a more familiar sensory modality, such as length. A 3-meter measuring tape was used, and participants were instructed to indicate their perceived dyspnea by extending their arm to a point on the tape that best represented its severity. Zero centimeters indicated no dyspnea, while greater lengths reflected increased discomfort. The tape was hidden from view, and only the examiner recorded the value. This approach demonstrated a 92% agreement with the Borg scale in prior validation studies. Dyspnea was evaluated at rest, immediately post-exercise, and at 1, 3, and 5 minutes into recovery.

Exercise Intensity Protocol.

All participants performed a graded exercise test using the standardized Bruce treadmill protocol.²⁸ The treadmill's speed and incline increased every 3 minutes, as described. This protocol allows for systematic cardiopulmonary stress testing and is commonly used in both clinical and performance settings due to its reliability and safety.^{1,28} During the test, the rating of perceived exertion (RPE) was assessed every 30 seconds using the Borg scale (6–20). The test was terminated when participants met at least three of the following criteria: (1) HR exceeded 85% of age-predicted maximum ($220 - \text{age}$), (2) $\text{RPE} \geq 17$, (3) inability to maintain treadmill speed, (4) SpO_2 dropped below 80%, or (5) signs of cardiovascular distress (e.g., chest pain, dizziness, extreme fatigue), or the participant voluntarily requested to stop.¹⁵ Following the test, effort intensity was retrospectively adjudicated to distinguish “maximal” from “peak” efforts. In accordance with established criteria, a true maximal response was defined as achieving 95% or more of the age-predicted maximal heart rate or an RPE of 19 or higher at termination.²⁹ Under this classification, no participants ($n = 0$) reached a true maximal state, and all ($n = 23$) were categorized as having completed a peak exercise test.

Recovery Interventions

Forward-Leaning Posture (FLP).

Immediately after completing the treadmill test, all participants assumed a seated forward-leaning posture. While seated with hips and knees flexed to 90 degrees, participants rested their forearms on a table in front of them and leaned their torso forward in a relaxed manner to facilitate recovery.^{14–15}

Forward-Leaning Posture with Chest Wall Vibration.

In the experimental group, a portable vibration device (Accel Vibe Thrive, Daito Electric Machine Industry Co, Ltd, Higashiosaka, Japan) was used to apply low-frequency mechanical vibration (15–30 Hz) to the bilateral second and third intercostal spaces while participants maintained the forward-leaning posture. The vibration was applied continuously for 5 minutes during the recovery period. This intervention was intended to stimulate the upper thoracic respiratory muscles, enhance ventilation, and promote pulmonary clearance.^{18,20} (Figure 1).



Figure 1. Trunk forward leaning posture with chest wall vibration.

Statistical analysis

All data were analyzed using SPSS software (version 22.0; IBM Corp., Armonk, NY, USA). Descriptive statistics were used to summarize participants' general characteristics. The Kolmogorov-Smirnov test was conducted to assess data normality. As normality was not satisfied for all variables, non-parametric statistical methods were applied. Within-group comparisons across time points were analyzed using the Friedman test. When significant differences were identified, post hoc pairwise comparisons were performed using the Wilcoxon signed-rank test. Between-group comparisons were conducted using the Mann-Whitney U test. A significance level of $p < .05$ was set for all analyses. Effect sizes (d) were calculated for the between-group comparisons by dividing the difference between group means by the pooled standard deviation.³⁰ Effect sizes for the Wilcoxon signed-rank tests were calculated by converting the standardized test statistic (Z) into an r value using the formula $r = Z / \sqrt{N}$.³¹ In accordance with Cohen's guidelines (1988), these effect sizes were interpreted as small (0.2), moderate (0.5), and large (0.8).³⁰

Results*Within-Group Comparisons Over Time*

In the control group, significant time-dependent changes were observed in HR ($\chi^2 = 47.82$, $p < .001$, Kendall's $W = .99$), SpO₂ ($\chi^2 = 24.94$, $p < .001$, $W = .52$), and subjective dyspnea ($\chi^2 = 48.00$, $p < .001$, $W = 1.00$). Similarly, the experimental group demonstrated significant changes over time in HR ($\chi^2 = 42.47$, $p < .001$, $W = .97$), SpO₂ ($\chi^2 = 24.83$, $p < .001$, $W = .56$), and subjective dyspnea ($\chi^2 = 43.16$, $p < .001$, $W = .98$).

HR increased significantly from Rest to Immediate in both groups. In the control group, HR was significantly higher at Immediate compared to Rest ($Z = -3.06$, $p = .002$, $r = .88$). Thereafter, HR decreased significantly from Immediate to R1 ($Z = -3.06$, $p = .002$, $r = .88$), R3 ($Z = -3.06$, $p = .002$, $r = .88$), and R5 ($Z = -3.06$, $p = .002$, $r = .88$). Similarly, in the experimental group, HR was significantly higher at Immediate compared to Rest ($Z = -2.93$, $p = .003$, $r = .88$). Thereafter, HR decreased significantly from Immediate to R1 ($Z = -2.94$, $p = .003$, $r = .88$), R3 ($Z = -2.94$, $p = .003$, $r = .88$), and R5 ($Z = -2.93$, $p = .003$, $r = .88$). However, HR at R5 remained significantly higher than Rest ($Z = -2.58$, $p = .010$, $r = .77$).

SpO₂ decreased significantly from Rest to Immediate in both groups. In the control group, Immediate values were significantly lower than Rest ($Z = -3.06$, $p = .002$, $r = .88$). Thereafter, SpO₂ increased significantly from Immediate to R1, R3, and R5 (all $Z \approx -3.06$, $p = .002$, $r = .88$). However, no significant differences were observed between R1 and R3 ($Z = -0.51$, $p = .607$). Similarly, in the experimental group, SpO₂ decreased significantly from Rest to Immediate ($Z = -2.94$, $p = .003$, $r = .88$). Thereafter, SpO₂ increased significantly from Immediate to R1 ($Z = -2.94$, $p = .003$, $r = .88$). However, no significant differences were observed between R1 and R3 ($Z = -0.11$, $p = .914$) or between R3 and R5 ($Z = -0.33$, $p = .739$).

Subjective dyspnea scores increased significantly from Rest to Immediate in both groups. In the control group, dyspnea was significantly higher at Immediate compared to Rest ($Z = -3.08$, $p = .002$, $r = .89$). Thereafter, dyspnea decreased significantly from Immediate to R1 ($Z = -3.11$, $p = .002$, $r = .90$), R3 ($Z = -3.07$, $p = .002$, $r = .89$), and R5 ($Z = -3.10$, $p = .002$, $r = .90$). However, dyspnea remained significantly elevated at R5 compared to Rest ($Z = -3.08$, $p = .002$, $r = .89$). In the experimental group, dyspnea was significantly higher at Immediate compared to Rest ($Z = -2.95$, $p = .003$, $r = .88$). Dyspnea decreased significantly from Immediate to R1 ($Z = -2.95$, $p = .003$,

$r = .88$), from R1 to R3 ($Z = -3.03$, $p = .002$, $r = .91$), and from R3 to R5 ($Z = -2.95$, $p = .003$, $r = .88$). In addition, dyspnea at R5 remained significantly higher than Rest ($Z = -2.51$, $p = .012$, $r = .75$).

In the control group, no significant time-dependent changes were observed in FVC ($\chi^2 = 6.42$, $p = .170$, Kendall's $W = .13$), FEV₁ ($\chi^2 = 2.89$, $p = .577$, $W = .06$), or the FEV₁/FVC ratio ($\chi^2 = 6.33$, $p = .176$, $W = .13$). Likewise, the experimental group showed no significant changes in FVC ($\chi^2 = 5.45$, $p = .244$, Kendall's $W = .12$), FEV₁ ($\chi^2 = 0.41$, $p = .982$, $W = .01$), or the FEV₁/FVC ratio ($\chi^2 = 1.01$, $p = .909$, $W = .02$).

Between-Group Comparisons

Significant differences between groups were observed only for HR and subjective dyspnea. At 1 minute post-exercise, the experimental group showed significantly lower HR compared to the control group ($Z = -2.67$, $p = .008$, $d = 1.32$). This difference remained significant at 3 minutes ($Z = -3.02$, $p = .003$, $d = 1.44$). However, no significant between-group differences in HR were observed at Rest ($Z = -0.19$, $p = .853$, $d = 0.22$), immediately post-exercise ($Z = -0.25$, $p = .805$, $d = 0.28$), or at 5 minutes into recovery ($Z = -1.30$, $p = .195$, $d = 0.65$, Figure 2).

Dyspnea scores were significantly lower in the experimental group at 1, 3, and 5 minutes into recovery (R1: $Z = -4.06$, $p < .001$, $d = 2.58$; R3: $Z = -4.04$, $p < .001$, $d = 2.77$; R5: $Z = -4.10$, $p < .001$, $d = 3.79$, Figure 2). However, dyspnea scores did not differ significantly between groups at Rest ($Z = -0.69$, $p = .493$, $d = 0.28$) or immediately post-exercise ($Z = -0.67$, $p = .504$, $d = 0.30$; Figure 2).

No significant differences between groups were found at any time point for SpO₂, FVC, FEV₁, or the FEV₁/FVC ratio ($p > .05$) (Table 2).

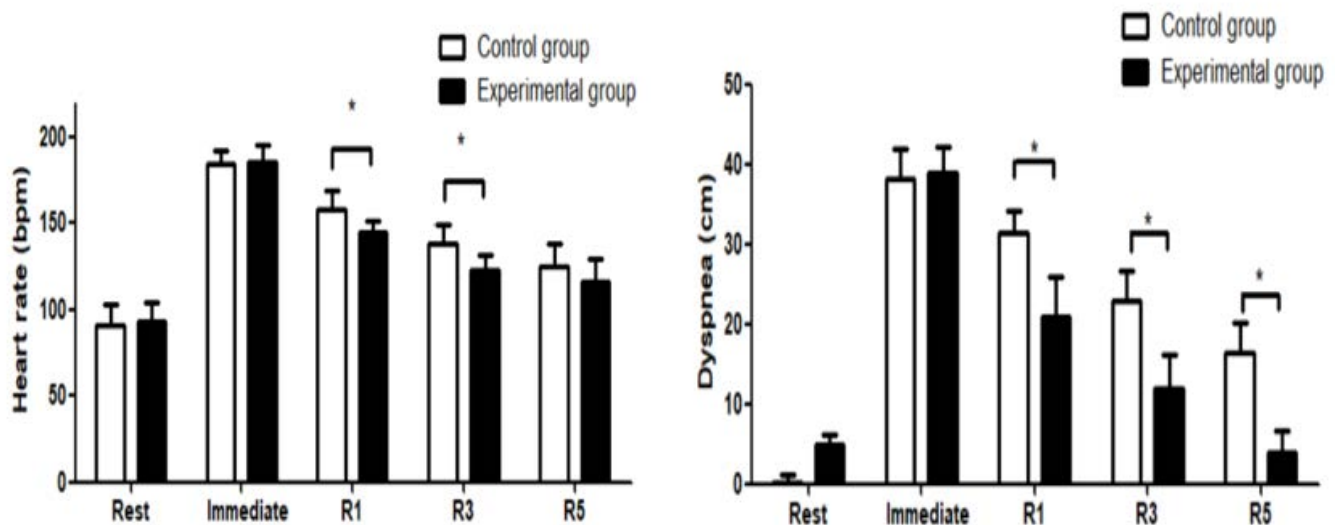


Figure 2. Comparison of heart rate and dyspnea between groups across time points.

Values are presented as mean \pm SD. R1, R3, R5: recovery periods at 1, 3, and 5 minutes.

*indicates a significant difference between the control group and the experimental group at the same time point ($p < .05$).

Table 2. The comparisons of physiological responses and dyspnea across time points with effect sizes.

Variable	Group	Rest	Immediate	R1	R3	R5
HR (bpm)	Control	91.00 ± 11.83 ^{#†‡§}	184.25 ± 8.24 ^{†‡§}	157.58 ± 11.64 ^{*#†§}	138.16 ± 11.05 ^{*#†§}	124.91 ± 13.54 ^{*#†‡}
	Experimental	93.63 ± 11.55 ^{#†‡§}	186.72 ± 9.14 ^{†‡§}	145.00 ± 6.81 ^{*#†§}	123.63 ± 8.94 ^{*#†§}	116.00 ± 13.84 ^{*#†‡}
	d	0.22	0.28	1.32 [¶]	1.44 [¶]	0.65
SpO ₂ (%)	Control	98.33 ± 0.88 [#]	87.75 ± 6.22 ^{†‡§}	97.41 ± 3.02 [#]	98.16 ± 1.02 [#]	97.91 ± 0.90 [#]
	Experimental	97.63 ± 1.36 [#]	91.00 ± 5.54 ^{†‡§}	98.00 ± 0.94 [#]	98.09 ± 0.83 [#]	98.00 ± 1.09 [#]
	d	0.61	1.15	0.27	0.08	0.09
Dyspnea (cm)	Control	0.25 ± 0.86 ^{#†‡§}	38.25 ± 3.64 ^{†‡§}	31.50 ± 2.71 ^{*#†§}	23.00 ± 3.69 ^{*#†§}	16.50 ± 3.72 ^{*#†‡}
	Experimental	0.54 ± 1.21 ^{#†‡§}	39.27 ± 3.13 ^{†‡§}	21.54 ± 4.80 ^{*#†§}	12.00 ± 4.24 ^{*#†§}	4.09 ± 2.77 ^{*#†‡}
	d	0.28	0.30	2.58 [¶]	2.77 [¶]	3.79 [¶]
FVC (L)	Control	4.01±0.91	3.96±1.03	3.91±0.91	3.92±0.92	3.94±0.93
	Experimental	3.56±0.72	3.40±0.70	3.57±0.80	3.55±0.81	3.55±0.79
	d	0.55	0.64	0.40	0.43	0.45
FEV ₁ (L)	Control	3.25±0.79	3.28±0.98	3.25±0.93	3.22±0.90	3.24±0.82
	Experimental	2.90±0.60	2.86±0.66	2.99±0.98	2.95±0.91	3.00±0.96
	d	0.49	0.50	0.27	0.30	0.27
FEV ₁ /FVC (%)	Control	81.05±7.83	82.83±10.83	83.12±11.03	82.14±11.12	82.28±9.02
	Experimental	81.46±5.43	84.12±6.51	83.10±10.65	82.01±10.73	84.51±11.04
	d	0.06	0.15	0.00	0.01	0.22

Note: Values are presented as mean ± SD.

* indicates a significant difference compared to Rest ($p < .05$).

indicates a significant difference compared to Immediate ($p < .05$).

† indicates a significant difference compared to R1 ($p < .05$).

‡ indicates a significant difference compared to R3 ($p < .05$).

§ indicates a significant difference compared to R5 ($p < .05$).

¶ indicates a significant difference between groups at the same time point ($p < .05$).

Cohen's d was calculated to indicate the between-group effect size for each time point.

Discussion

This study examined the physiological recovery effects of a FLP alone versus FLP combined with chest wall vibration following maximal exercise in healthy adults. Over time, both groups showed significant improvements in HR, SpO₂, and subjective dyspnea. HR and dyspnea peaked immediately after exercise and declined progressively during recovery. However, no significant time-dependent changes were observed in pulmonary function variables including FVC, FEV₁, and the FEV₁/FVC ratio. Between-group comparisons revealed that the experimental group, which received chest wall vibration, exhibited significantly lower HR at 1 and 3 minutes and significantly reduced dyspnea at 1, 3, and 5 minutes post-exercise. No significant group differences were observed in SpO₂ or pulmonary function indices. The significant reductions in HR over time in both groups suggest enhanced autonomic recovery following exercise.

In the control group, HR decreased from 202.5% of resting values post-exercise to 137.3% at 5 minutes, whereas the experimental group showed a steeper decline from 199.4% to 123.9%. Prior research also observed a reduction in HR from 171.8% to 146.3% within one minute when FLP was applied alone.¹⁵ These findings are consistent with the physiological benefits of FLP, which may include increased cardiac efficiency, enhanced oxygenation, and improved autonomic balance. FLP reduces mechanical strain on the thoracic musculature by offloading the upper body onto the forearms, facilitating diaphragmatic excursion and increasing intra-abdominal pressure. This promotes venous return from the lower extremities to the heart via enhanced abdominal venous compression, increasing end-diastolic volume and stroke volume through the Frank-Starling mechanism. Consequently, the heart can maintain cardiac output with a lower HR. Additionally, the rapid normalization of SpO₂ (99–100%) within one minute in both groups may reduce the physiological need for elevated HR, further promoting recovery. Psychologically, FLP offers postural comfort, alleviates muscular fatigue, and contributes to parasympathetic reactivation by reducing perceived exertion. The progressive reduction in dyspnea observed in both groups supports this interpretation, consistent with prior research highlighting the effects of posture on subjective recovery.¹⁴⁻¹⁷

The experimental group showed a significantly faster HR recovery than the control group—8.0% and 10.5% lower at 1 and 3 minutes, respectively. Chest wall vibration likely contributed to this difference through two primary mechanisms: (1) relaxation of hyperactive accessory respiratory muscles such as the intercostals, reducing the mechanical workload of breathing and cardiovascular strain;^{18,20,32} and (2) somatosensory stimulation of mechanoreceptors (e.g., Pacinian corpuscles), which activates parasympathetic pathways via the vagus nerve and suppresses sympathetic overactivity.^{12,25} Together, these mechanisms may have facilitated faster HR normalization in the experimental group.

Despite these benefits, chest wall vibration did not exert a significant additional effect on oxygen saturation. Both groups exhibited a rapid return to near-resting SpO₂ levels (99–100%) within 1 minute post-exercise. This finding aligns with previous studies indicating that in healthy young adults, arterial oxygen saturation typically remains within a narrow physiological range and recovers quickly following acute exercise, provided that exercise-induced arterial hypoxemia does not occur.³³ The lack of significant difference between the groups is likely attributable to a ceiling effect, as SpO₂ levels in healthy subjects are already near-maximal during rest and the recovery phase. Furthermore, the forward lean posture alone may have sufficiently optimized ventilatory efficiency and gas exchange, thereby limiting any observable incremental benefit from chest wall vibration on oxygenation.

Pulmonary function indicators (FVC, FEV₁, and FEV₁/FVC) showed minimal fluctuations over time and no significant differences between groups. Both groups maintained stable pulmonary function after exercise, consistent with previous findings that short-duration high-intensity exercise has limited impact on lung volumes.^{7,25,34} These results suggest that pulmonary function may be preserved in healthy adults even after maximal effort, and additional interventions may be more impactful in populations with impaired respiratory function.

Subjective dyspnea was quantified using a modified cross-modality matching method, revealing a significant decline over time in both groups. The experimental group demonstrated greater reductions at all recovery time points—31.6%, 47.8%, and 75.2% lower than the control group at 1, 3, and 5 minutes, respectively. These findings highlight chest wall vibration as an effective method for relieving post-exercise dyspnea through stimulation of thoracic mechanoreceptors,

improved respiratory muscle efficiency, and modulation of autonomic responses.^{7,20,21} Taken together, the combination of FLP and chest wall vibration appears to offer a synergistic effect on subjective and physiological recovery following maximal exercise. As a non-invasive and safe strategy, this combined intervention may be particularly useful for promoting autonomic and cardiopulmonary recovery in athletic or rehabilitative settings.

Several limitations should be considered when interpreting the findings of this study. First, the small sample size (n=23) and the recruitment of a homogeneous group of healthy young adults may limit the generalizability of the results to other populations. Future studies should employ a larger sample size and involve a broader range of age groups and clinical populations, such as patients with chronic obstructive pulmonary disease (COPD), to enhance external validity. Second, while significant physiological changes were observed, this study did not directly measure respiratory mechanics, such as diaphragmatic excursion or thoracic expansion. Integrating advanced imaging or electrophysiological tools—including ultrasound, MRI, or electromyography—in future research would provide a more granular understanding of the underlying physiological mechanisms. Third, the current study only assessed the immediate effects following a single exercise session. As the long-term or cumulative impact of chest wall vibration remains unknown, longitudinal studies are warranted to investigate the sustained benefits of repeated applications over time. Most importantly, this study focused on the additive effect of chest wall vibration when combined with a specific recovery posture (forward lean). Consequently, the independent contribution of vibration alone, separate from the postural effect, was not evaluated. To address this, future research should employ a three-condition design—comparing forward lean alone, vibration alone, and their combination—to definitively determine whether the observed recovery benefits are driven by the vibration itself or by a synergistic interaction between the intervention and the posture.

This study compared the effects of a forward-leaning posture alone versus a combination of forward-leaning posture with chest wall vibration on physiological recovery following maximal exercise in healthy adults. Both groups demonstrated significant improvements over time in HR, SpO₂, and subjective dyspnea, with HR and dyspnea peaking immediately after exercise and progressively decreasing during recovery. No significant time-dependent changes were observed in pulmonary function indicators, including FVC, FEV₁, and the FEV₁/FVC ratio. Between-group comparisons revealed that the experimental group receiving chest wall vibration had significantly lower HR at 1 and 3 minutes and lower subjective dyspnea at 1, 3, and 5 minutes post-exercise compared to the control group. However, no significant group differences were found in SpO₂ or pulmonary function measures. These findings suggest that combining chest wall vibration with a forward-leaning posture may be an effective, non-invasive strategy to accelerate recovery of HR and reduce subjective dyspnea after maximal exercise. This approach is therefore recommended for promoting early cardiopulmonary recovery in healthy adults following high-intensity physical exertion.

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