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Original Research

Self-Selected Inspiratory Volume and Intra-Abdominal Pressure During the Valsalva Maneuver in Healthy Young Men

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Abstract

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The Valsalva maneuver (VM) is often used during short-duration, high-intensity exercise to increase intra-abdominal pressure (IAP) and enhance performance via mechanisms such as spinal stabilization. However, the inspiratory volume self-selected to maximize IAP remains unclear. Therefore, we aimed to examine the effect of inspiratory volume—including a self-selected (spontaneous) condition—on IAP during VM, and to determine the extent of interindividual variation in the self-selected inspiratory volume. Sixteen healthy young men performed the VM under five conditions: maximal expiration, controlled 40% and 80% inspiratory volume, maximal inspiration, and spontaneous VM (self-selected to maximize IAP). Percentage inspiratory volume (%VC) differed significantly across conditions ($p < 0.001$, partial $\eta^2 = 0.966$); %VC during spontaneous VM varied substantially among individuals (65.3 ± 14.5%), far exceeding the variability of the fixed-volume conditions (SD = 1.1–4.7%). IAP also differed significantly across conditions ($p < 0.001$, partial $\eta^2 = 0.602$); spontaneous VM (121.0 ± 39.8 mmHg) produced the highest IAP, significantly exceeding all others (48.3–90.4 mmHg; all $p < 0.01$, d_z = 1.16–1.89). Fourteen of the 16 participants achieved their individual maximal IAP during spontaneous VM, with the remaining two at controlled 80% inspiratory volume or maximal inspiration. These findings indicate that self-selected breathing, rather than a single universally optimal inspiratory volume, most effectively maximizes IAP, likely reflecting individually optimized effort, comfort, and respiratory muscle coordination beyond inspiratory volume alone. Practitioners seeking to enhance IAP-related performance may encourage self-selected breathing during VM while accounting for individual variability.

Keywords: Trunk stability, length-tension relationship, diaphragm, intrathoracic pressure, transversus abdominis

Introduction

The Valsalva maneuver (VM) is an important physiological phenomenon observed during short-duration, high-intensity physical activity. VM is defined as a forced expiratory effort performed with the glottis closed.[1] When external loads exceed 80% of the one-repetition maximum or maximal voluntary contraction, a short-duration VM becomes inevitable.[2] Based on these findings, VM has been used in various resistance training exercises.[1] Moreover, VM is frequently observed in sports activities that require short-duration, high-intensity force generation, such as maximal throwing and swinging movements or tackling in contact sports.

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Intra-abdominal pressure (IAP) refers to the internal pressure generated within the abdominal cavity, which is surrounded by the deep trunk muscles, including the diaphragm. An increase in IAP contributes to spinal stability by enhancing lumbar stiffness.[3–8] Marked elevations in IAP have been reported during various resistance training exercises, such as squats,[9] and vertical jumping has also been shown to elevate IAP.[10] These findings indicate that IAP increases during short-duration, high-intensity exercises involving VM.[1]

The increase in IAP during VM likely depends on inspiratory volume and abdominal muscle strength.[1] Regarding inspiratory volume, IAP rises as inspiratory volume is increased before glottis closure.[11,12] A study examining IAP and spontaneous inspiratory volume during isometric lifting suggested that increased inspiratory volume and suppression of excessive exhalation are important for elevating IAP, as increased IAP is associated with lifting effort.[13] Regarding abdominal muscle strength, the degree of IAP increase may depend on whether the abdominal muscle fibers are positioned at an optimal length for generating maximal tension.[14]

However, previous studies have only suggested general trends regarding the inspiratory volume conducive to IAP elevation, and how this relationship manifests when individuals self-select their breathing strategy remains unclear. Furthermore, the extent to which this volume varies among individuals, and whether a universal inspiratory volume exists, have not been established.

Therefore, this study aimed to examine how IAP during VM is affected by inspiratory volume across a range of conditions—including controlled, fixed-volume conditions and a self-selected (spontaneous) condition—and to characterize the extent of interindividual variation in the inspiratory volume self-selected to maximize IAP. As noted above, abdominal muscle tension is also thought to depend on muscle fiber length; accordingly, waist circumference was additionally assessed across conditions as an indirect indicator of abdominal wall muscle length, providing mechanistic insight into the observed IAP responses. This study may therefore provide useful insights for improving performance and establishing appropriate instructional strategies in activities where increased IAP is beneficial.

Two hypotheses were tested in this study: 1) the inspiratory volume self-selected by individuals during spontaneous VM to produce the highest IAP would fall within a moderate-to-high range; and 2) VM performed at a moderate-to-high inspiratory volume would produce a greater increase in IAP than VM performed at a low inspiratory volume.

Methods

Participants

This study employed a repeated-measures experimental design to compare IAP during the VM under five different inspiratory volume conditions in healthy young men. The required sample size was calculated using G*Power 3.1 based on the results of a preliminary study, assuming an effect size of $f = 0.40$, $\alpha = 0.05$, and statistical power $(1–\beta) = 0.80$, indicating that a minimum of 16 participants was required. We included healthy men aged 18–30 years who could complete all measurements and engaged in regular physical activity at least twice a week for ≥30 min per session. Because this study involved rectal pressure measurements and all researchers were male, participation was limited to men for ethical and psychological considerations. We excluded men who were currently participating in competitive sports; had low back pain or pain induced by VM within the past 3 months; had a history of severe cardiovascular disease or diabetes;

had any anatomical or medical condition preventing catheter insertion; or had contraindications to bioelectrical impedance analysis, such as the presence of a pacemaker or metallic implants. Based on these criteria, 16 participants were recruited (age: 22.2 ± 1.3 years; height: 169.7 ± 4.9 cm; body mass: 63.5 ± 7.5 kg; body mass index [BMI]: 22.0 ± 2.4 kg/m^2). The mean vital capacity (VC) of the participants was 5.22 ± 0.69 L. Participants were instructed to refrain from vigorous or unfamiliar physical activity for 24 h before testing. Written informed consent was obtained from all participants, and eligibility was confirmed under physician supervision. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Graduate School of Chukyo University (approval number: 2024-064, approval date: 26 August 2024). Additionally, written informed consent was obtained for the publication of the participant's images used in this manuscript. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science.[15]

Protocol

We measured IAP, inspiratory volume, and waist circumference.

IAP was measured using a sterile catheter pressure transducer (MPR-500, Millar Instruments, Pearland, TX, USA) connected to a 16-bit A/D converter (PowerLab 16/35, ADInstruments, Sydney, Australia). Data were recorded and analyzed using LabChart software (ver. 8.1.21, ADInstruments, Sydney, Australia). The sensor was inserted approximately 15 cm into the rectum to record rectal pressure as an indirect index of IAP. The catheter was immersed in saline for 30 min before measurement to prevent sensor drift. A perforated rubber cover (NIKKISO-THERM, Tokyo, Japan) was attached to ensure pressure transmission and was secured with surgical tape (Micropore Skin Tone Surgical Tape, 3M, St. Paul, MN, USA). The procedure was conducted according to previously published methods.[13,16,17] A 2% lidocaine gel (Xylocaine Jelly, Sandoz Pharma K.K., Tokyo, Japan) was used after confirming safety by a skin patch test to minimize discomfort.

VC and inspiratory volume during VM were measured using a respiratory gas analyzer (AE-310s, Minato Medical Science, Osaka, Japan). Participants wore a nose clip to avoid errors due to nasal breathing; if wearing the clip was difficult, the nostrils were manually pinched. VC was measured three times according to pulmonary function testing guidelines,[18] and the highest value was used. Inspiratory volume during each trial was normalized and expressed as a percentage of VC. During the VM, glottic closure and the absence of air leakage were continuously monitored in real time by confirming that there was no airflow (i.e., inspiratory or expiratory volume output remained completely static) on the LabChart recording. Furthermore, proper glottic closure was retrospectively verified during data analysis by visualizing the ventilation waveforms using MATLAB (version R2025a, MathWorks, Natick, MA, USA).

Waist circumference was measured using a thoracic cage mobility measurement device (Sanka Co., Sanjo, Niigata, Japan). A wire sensor was positioned between the lower margin of the rib cage and the upper iliac crest (Figure 1). The system continuously applied retraction force, allowing detection of abdominal expansion and contraction. Data were digitized through the same 16-bit A/D converter and analyzed with LabChart. The mean value of the three end-expiratory measurements at rest (variation ≤ 1 mm) was adopted as the reference value, and the waist circumference during trials was normalized to this baseline and expressed as a percentage of the baseline value, hereafter referred to as percentage waist circumference.

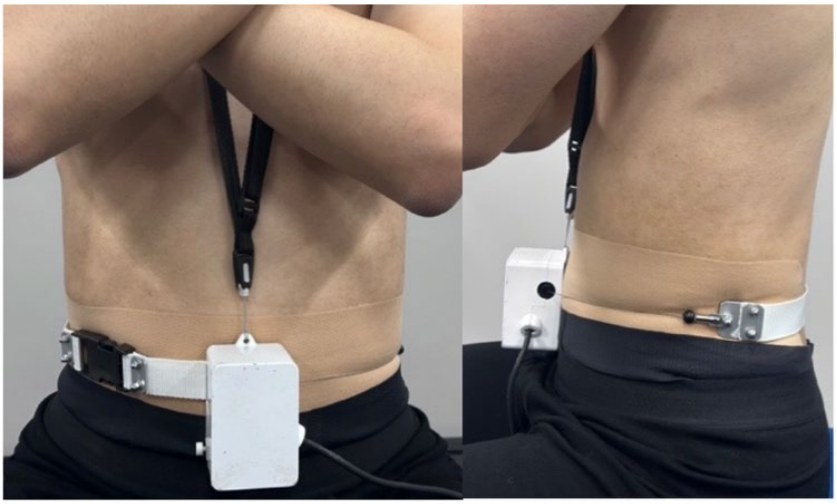


Figure 1. Frontal and lateral views during waist circumference measurement. The circumferential wire was positioned between the lower edge of the ribs and the upper edge of the iliac crest.

Execution of the Valsalva maneuver: VM was performed in the seated position using a trunk rotation torque device (Sanka Co., Sanjo, Niigata, Japan). Two factors were considered: 1) seated spontaneous VM produces the highest IAP, reflecting 100% of individual pressure capacity,[1] and 2) the device belts stabilize the trunk while minimizing posture-induced variation in lung volume. Effort during VM gradually increased.[16] Participants were instructed to increase effort gradually over the first 2 s, maintain maximal effort for the next 3 s, and release after 5 s ("perform the maneuver over 5 s: build up gradually for 2 s, maintain maximal effort for 3 s, and release").

Participants performed VM under the following five inspiratory conditions:
Maximal expiration: VM performed after full expiration.
Controlled 40% inspiratory volume: VM performed after inhaling to 40% of VC.
Controlled 80% inspiratory volume: VM performed after inhaling to 80% of VC.
Maximal inspiration: VM performed after full inspiration.
Spontaneous VM: VM performed at the self-selected inspiratory volume perceived by the participant to produce maximal IAP.

IAP, inspiratory volume, and waist circumference were recorded simultaneously under each condition (Figure 2). For the controlled 40% and 80% inspiratory volume conditions, participants received real-time visual feedback via a display showing target guidelines. A trial was considered valid if the achieved volume was within ±5% of the target. To prevent excessive fatigue, if a trial fell outside this tolerance range, the data were not recorded, and no additional trials were performed.

The experiment was conducted over 2 days, separated by an interval of 1–7 days: Day 1 (familiarization) and Day 2 (main measurement). The familiarization session was conducted to minimize learning effects during the main measurement.[19] After measuring height, body mass, and BMI, a patch test was conducted, and resting waist circumference and VC were recorded as baseline values. As part of the warm-up and familiarization process, participants performed three practice trials at approximately 50%, 80%, and 100% effort, with at least 1 min of rest between trials. Subsequently, two maximal-effort VMs were performed for each of the five conditions, with at least 2 min of rest between trials. Condition order was randomized for each participant. On Day 2, a rectal catheter was inserted, and the same protocol was repeated in the same order

(Figure 3). Although continuous instrumented monitoring of blood pressure or heart rate was not performed, participant safety was closely monitored throughout the experiment. After each trial, the experimenter verbally confirmed the participant's physical condition to ensure the absence of adverse symptoms such as dizziness. Furthermore, upon a participant's request, the rest interval between trials was extended to ensure full recovery and safety.



Figure 2. Measurement setup during a VM trial with all devices attached.

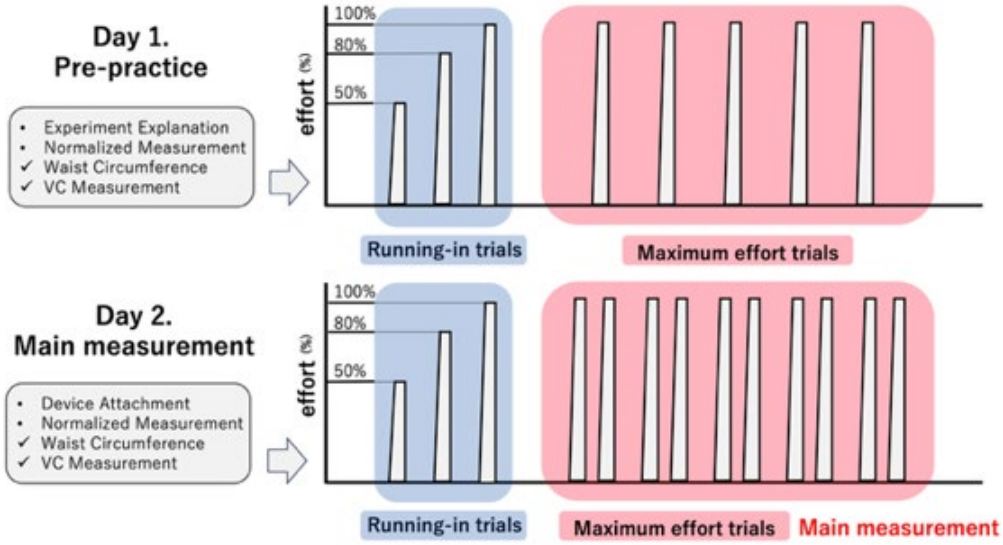


Figure 3. Timeline of the experimental procedures and variations in exertion level. The line progression represents changes in exertion across trials.

Statistical Analysis

All data were averaged over 200 ms intervals for analysis.[16,20] Two trials were conducted for each condition, and to ensure data robustness and address potential bias from selecting a single maximal value, the mean of the two trials was used for analysis. Additionally, the intraclass correlation coefficient (ICC) was calculated to assess the test-retest reliability of inspiratory volume and IAP during the spontaneous VM. The primary outcome was peak IAP recorded during each VM trial. The secondary outcome was percentage inspiratory volume at the time of peak IAP, and an additional outcome was percentage waist circumference at the same time point. Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 29.0 (IBM Corp., Armonk, NY, USA). Normality of percentage inspiratory volume, IAP, and percentage waist circumference was verified using the Shapiro–Wilk test, and parametric tests were applied. A one-way repeated-measures analysis of variance (ANOVA) was used for percentage inspiratory volume, IAP, and percentage waist circumference. For repeated-measures ANOVA, sphericity was assessed using Mauchly's test, and the Greenhouse–Geisser correction was applied when the assumption of sphericity was violated. Post hoc pairwise comparisons were conducted using the Bonferroni correction, and Cohen's d_z was calculated based on paired differences.[21] To determine the dose-response relationship between percentage inspiratory volume and IAP, a linear mixed model was employed. In this model, IAP was the dependent variable, participant was set as a random effect (intercept), and percentage inspiratory volume (continuous) along with its quadratic term were included as fixed covariates. The significance level was set at $p < 0.05$. Effect sizes were interpreted according to Cohen's criteria[21]: partial $\eta^2 = 0.01$, 0.06, and 0.14 for small, medium, and large effects, respectively; Cohen's d_z was interpreted using the same benchmark values as Cohen's d (0.2, 0.5, and 0.8 for small, medium, and large effects, respectively), as both indices share the same underlying scale. 95% confidence intervals (CIs) for both mean differences and effect sizes were reported.

Results

The intraclass correlation coefficient (ICC) for the two spontaneous VM trials demonstrated excellent reliability for both IAP (ICC = 0.928) and percentage inspiratory volume (ICC = 0.845). Table 1 presents the descriptive statistics for all outcomes. In addition, Table 2 shows the %VC recorded in the two trials of spontaneous VM.

An ANOVA was conducted to examine differences in percentage inspiratory volume across conditions. Mauchly's test indicated that the assumption of sphericity was violated ($p < 0.05$); therefore, the degrees of freedom were corrected using the Greenhouse–Geisser method ($\varepsilon = 0.305$). The corrected ANOVA revealed a significant main effect of condition (F [1.221, 18.314] = 427.154, $p < 0.001$, partial $\eta^2 = 0.966$), indicating a large effect size. Post hoc comparisons using the Bonferroni method revealed that all five conditions differed significantly from one another (all $p < 0.01$) (Figure 4). Specifically, the percentage inspiratory volume during spontaneous VM (65.3 ± 14.5%) was significantly higher than during maximal expiration (mean difference = 64.2%, 95% CI [52.3, 76.2]; Cohen's d_z = 4.41 [95% CI: 2.77, 6.04]) and controlled 40% inspiratory volume (mean difference = 24.5%, 95% CI [12.7, 36.4]; Cohen's d_z = 1.70 [95% CI: 0.91, 2.47]), and was significantly lower than during controlled 80% inspiratory volume (mean difference = -15.1%, 95% CI [-26.9, -3.3]; Cohen's d_z = -1.05 [95% CI: -1.65, -0.42]) and maximal inspiration (mean difference = -25.9%, 95% CI [-39.0, -12.7]; Cohen's d_z = -1.61 [95% CI: -2.35, -0.85]). Table 1 shows the means, SDs, and 95% CIs for each condition, confirming that the 95% CI for spontaneous VM did not overlap with those of the controlled 40% and 80% conditions. Table 2 also presents the individual percentage inspiratory volumes and trial-to-trial differences for the two spontaneous VM trials.

Table 1. Descriptive Statistics and Outcomes.

Inspiratory volume (%)						
			95% CI			
	Mean	SD	Lower	Upper		
MaxExp	1.1	1.6	0.2	1.9		
C-40% InspV	40.8	1.1	40.2	41.3		
C-80% InspV	80.4	1.9	79.4	81.4		
MaxInsp	91.2	4.7	88.7	93.7		
Spont VM	65.3	14.5	57.6	73.0		
IAP (mmHg)			Post-hoc: vs. MaxExp		Post-hoc: vs. Spont VM	
	Mean	SD	p	d_z	p	d_z
MaxExp	48.3	19.3	-	-	< 0.01	1.89
C-40% InspV	86.5	29.5	< 0.01	1.56	< 0.01	1.36
C-80% InspV	90.1	45.1	< 0.01	1.06	< 0.01	1.21
MaxInsp	90.4	35.0	< 0.01	1.09	< 0.01	1.16
Spont VM	121.0	39.8	< 0.01	1.89	-	-
waist (%)			Post-hoc: vs. MaxExp		Post-hoc: vs. C-40% InspV	
	Mean	SD	p	d_z	p	d_z
MaxExp	98.2	1.3	-	-	< 0.01	1.27
C-40% InspV	99.9	1.5	< 0.01	1.27	-	-
C-80% InspV	101.2	2.0	< 0.01	1.46	< 0.01	1.28
MaxInsp	101.2	1.9	< 0.01	1.55	< 0.01	1.15
Spont VM	101.6	2.0	< 0.01	1.60	< 0.01	1.46

Abbreviations: SD: standard deviation; CI: confidence interval; MaxExp: Maximal expiration; C-40% InspV: Controlled 40% inspiratory volume; C-80% InspV: Controlled 80% inspiratory volume; MaxInsp: Maximal inspiration; Spont VM: Spontaneous Valsalva maneuver, d_z: Cohen's d_z calculated from paired differences.

Table 2. Percentage Inspiratory Volume During Spontaneous Valsalva Maneuver Trials.

No.	Trial 1 (%)	Trial 2 (%)	Mean (%)	Difference (%)
1	57.7	71.8	64.7	14.1
2	43.0	49.0	46.0	6.0
3	44.2	38.6	41.4	5.6
4	76.0	89.2	82.6	13.2
5	81.3	81.2	81.2	0.1
6	71.6	71.2	71.4	0.4
7	51.8	61.6	56.7	9.8
8	54.3	51.5	52.9	2.8
9	70.4	55.9	63.2	14.4
10	85.3	83.7	84.5	1.6
11	67.6	66.5	67.0	1.1
12	63.7	48.0	55.8	15.7
13	49.2	46.4	47.8	2.8
14	75.1	82.4	78.7	7.3
15	82.4	90.5	86.5	8.1
16	64.1	64.7	64.4	0.7
Mean	64.8	65.8	65.3	6.5
SD	13.6	16.5	14.5	5.5

Note: All values are presented as percentages of vital capacity (%VC). Intra-class correlation coefficient (ICC) for percentage inspiratory volume across the two spontaneous VM trials was 0.845 (95% CI: 0.612–0.943), demonstrating excellent test-retest reliability.

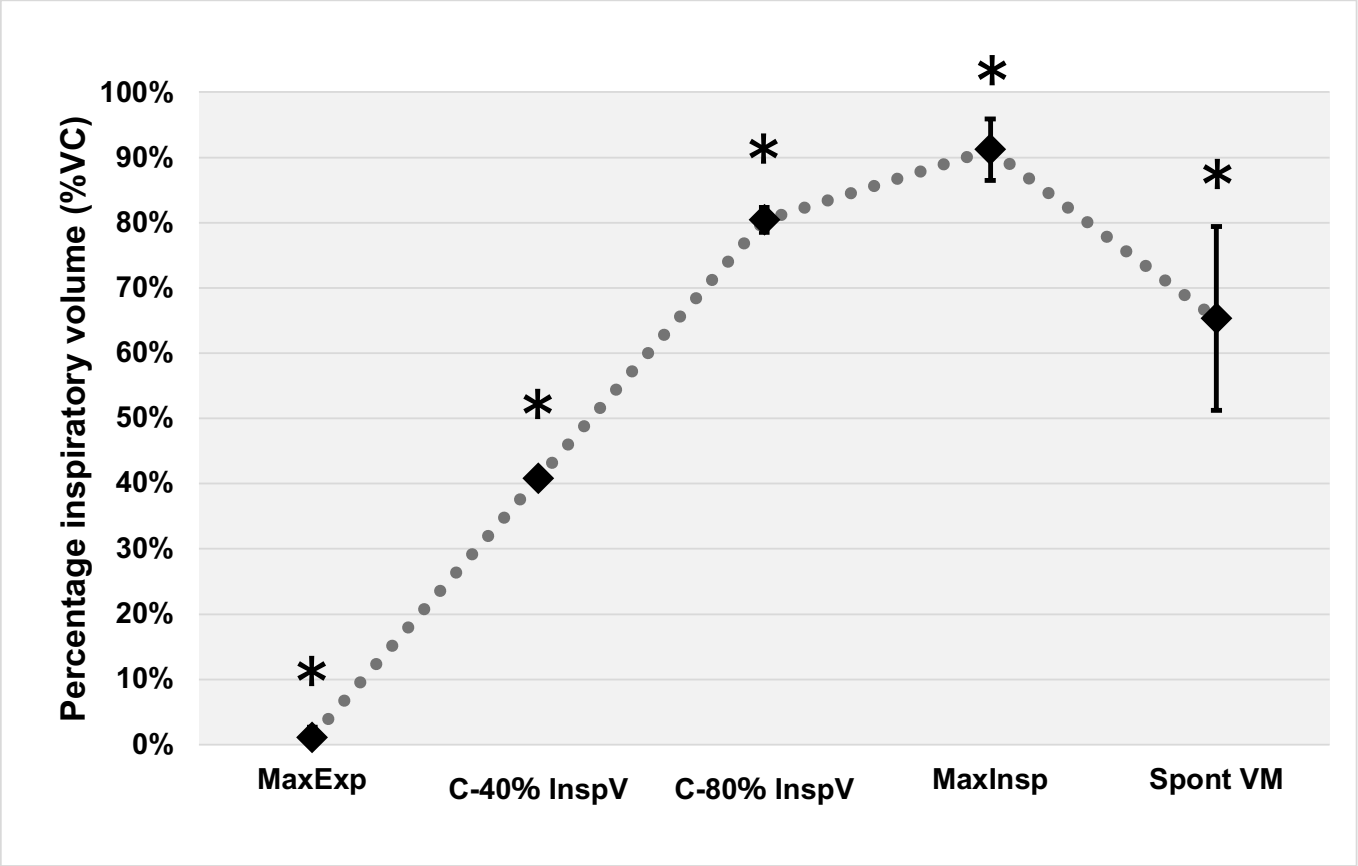


Figure 4. Mean ± standard deviation of percentage inspiratory volume for each condition.

* Significantly different from the other four conditions (p < 0.01).
Abbreviations: MaxExp: Maximal expiration; C-40% InspV: Controlled 40% inspiratory volume; C-80% InspV: Controlled 80% inspiratory volume; MaxInsp: Maximal inspiration; Spont VM: Spontaneous Valsalva maneuver.

A repeated-measures ANOVA was conducted to examine differences in IAP across conditions. Mauchly's test indicated that the assumption of sphericity was met ($p = 0.107$). The results revealed a significant main effect of condition (F [4, 60] = 22.708, $p < 0.001$, partial $\eta^2 = 0.602$), indicating a large effect size. Post hoc comparisons with the Bonferroni method showed that the maximal expiration condition yielded significantly lower values than all other conditions (all $p < 0.01$). Furthermore, the spontaneous VM condition produced significantly higher values than maximal expiration ($p < 0.01$, mean difference = 72.6, 95% CI [41.1, 104.1]; Cohen's $d_z = 1.89$ [95% CI: 1.05, 2.71]), controlled 40% ($p < 0.01$, mean difference = 34.5, 95% CI [13.7, 55.3]; Cohen's $d_z = 1.36$ [95% CI: 0.66, 2.04]), controlled 80% ($p < 0.01$, mean difference = 30.8, 95% CI [10.0, 51.7]; Cohen's d_z = 1.21 [95% CI: 0.55, 1.85]), and maximal inspiration ($p < 0.01$, mean difference = 30.5, 95% CI [8.9, 52.2]; Cohen's $d_z = 1.16$ [95% CI: 0.51, 1.79]). No significant differences were observed among the controlled 40%, controlled 80%, and maximal inspiration conditions (all $p > 0.05$) (Figure 5). Table 1 shows the means and SDs for each condition. Among all participants, the condition with the highest IAP was the spontaneous VM condition for 14 participants, the controlled 80% inspiratory volume condition for one participant, and the maximal inspiration condition for one participant.

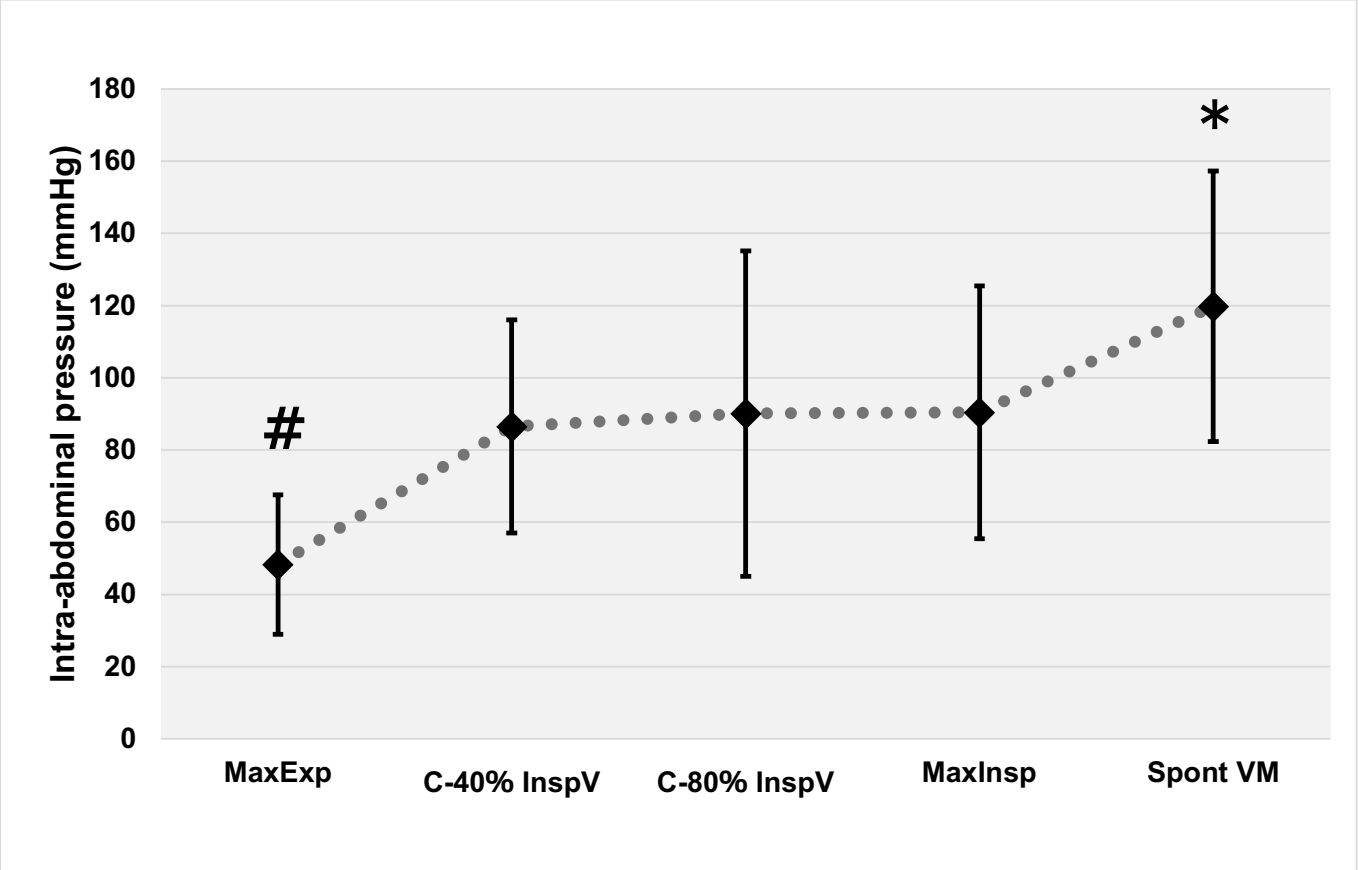


Figure 5. Mean ± standard deviation of intra-abdominal pressure (IAP) for each condition.

* Significantly higher than all other four conditions ($p < 0.01$).
# Significantly lower than all other four conditions ($p < 0.01$).
Abbreviations: MaxExp: Maximal expiration; C-40% InspV: Controlled 40% inspiratory volume; C-80% InspV: Controlled 80% inspiratory volume; MaxInsp: Maximal inspiration; Spont VM: Spontaneous Valsalva maneuver.

An ANOVA was conducted to analyze differences in percentage waist circumference across conditions. Mauchly's test indicated that the assumption of sphericity was violated ($p < 0.05$); therefore, the degrees of freedom were corrected using the Greenhouse–Geisser method ($\varepsilon = 0.53$). The corrected ANOVA revealed a significant main effect of condition (F [2.101, 31.511] = 28.404, $p < 0.01$, partial $\eta^2 = 0.654$), indicating a large effect size. Post hoc comparisons using the Bonferroni method showed that maximal expiration had significantly lower values than the controlled 40% inspiratory volume ($p < 0.01$, mean difference = -1.7, 95% CI [-2.9, -0.6]; Cohen's d_z = -1.25 [95% CI: -1.89, -0.57]), controlled 80% inspiratory volume ($p < 0.01$, mean difference = -3.0, 95% CI [-4.7, -1.3]; Cohen's d_z = -1.46 [95% CI: -2.16, -0.73]), maximal inspiration ($p < 0.01$, mean difference = -3.0, 95% CI [-4.6, -1.4]; Cohen's d_z = -1.55 [95% CI: -2.27, -0.80]), and spontaneous VM conditions ($p < 0.01$, mean difference = -3.4, 95% CI [-5.1, -1.6]; Cohen's d_z = -1.60 [95% CI: -2.33, -0.84]). Furthermore, the controlled 40% inspiratory volume condition yielded significantly lower values than the controlled 80% inspiratory volume ($p < 0.01$, mean difference = -1.3, 95% CI [-2.1, -0.5]; Cohen's d_z = -1.31 [95% CI: -1.97, -0.62]), maximal inspiration ($p < 0.01$, mean difference = -1.3, 95% CI [-2.2, -0.4]; Cohen's d_z = -1.17 [95% CI: -1.81, -0.52]), and spontaneous VM ($p < 0.01$, mean difference = -1.7, 95% CI [-2.6, -0.7]; Cohen's d_z = -1.46 [95% CI: -2.16, -0.74]) conditions (Figure 6). Table 1 shows the means and SDs for each condition.

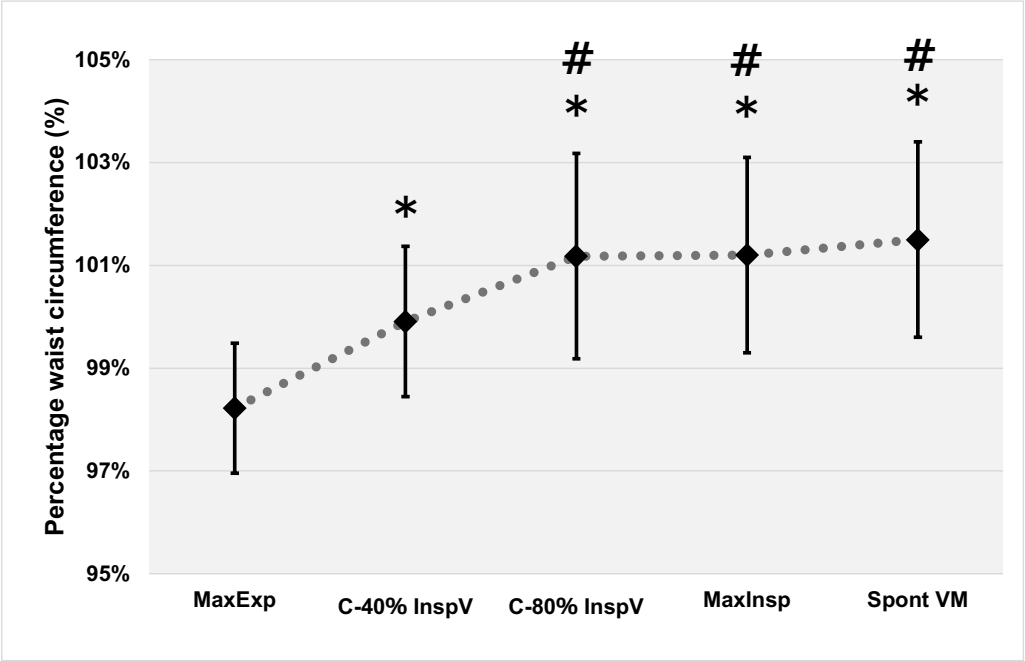


Figure 6. Mean ± standard deviation of percentage waist circumference for each condition.

* Significantly different from maximal expiration ($p < 0.01$).
# Significantly different from maximal expiration and controlled 40% inspiratory volume ($p < 0.01$).
Abbreviations: MaxExp: Maximal expiration; C-40% InspV: Controlled 40% inspiratory volume; C-80% InspV: Controlled 80% inspiratory volume; MaxInsp: Maximal inspiration; Spont VM: Spontaneous Valsalva maneuver.

Finally, Figure 7 shows the relationship between IAP and percentage inspiratory volume (%VC) for each condition in the group and individual participants. The linear mixed-model analysis, which included both linear and quadratic terms for percentage inspiratory volume (%VC), revealed that both terms were significant predictors of IAP. The linear term was positive (Estimate = 1.834, *SE* = 0.312, $t(62.316) = 5.872$, $p < 0.001$, 95% CI [1.210, 2.458]), whereas the quadratic term was negative (Estimate = -0.014, *SE* = 0.003, $t(62.446) = -4.441$, $p < 0.001$, 95% CI [-0.021, -0.008]). This significant negative quadratic term demonstrates an inverted U-shaped, non-linear relationship between %VC and IAP, indicating that IAP is maximized at moderate-to-high inspiratory volumes and is attenuated by excessive inspiration.

At the individual level (N = 16, mean of two trials), gray circles represent data from the MaxExp, C-40% InspV, C-80% InspV, and MaxInsp conditions, open squares represent data from the Spont VM condition, and thin gray lines connect each participant's data across conditions. At the group level, black diamonds represent the mean IAP for the MaxExp, C-40% InspV, C-80% InspV, and MaxInsp conditions, and the large open square represents the mean IAP for the Spont VM condition; error bars indicate ± SD, and the black dashed line represents the group mean trend across conditions. The solid curve represents the fitted quadratic relationship from the linear mixed-model analysis ($IAP = 45.207 + 1.834 \times \%VC - 0.014 \times \%VC^2$; both linear and quadratic terms, $p < 0.001$), illustrating an inverted U-shaped, non-linear relationship with peak IAP occurring near 65% VC. Participant IDs (P1–P16) are labeled adjacent to each participant's individual maximum IAP value, which occurred predominantly during the Spont VM condition (n = 14), and occasionally during the C-80% InspV (n = 1) and MaxInsp (n = 1) conditions.

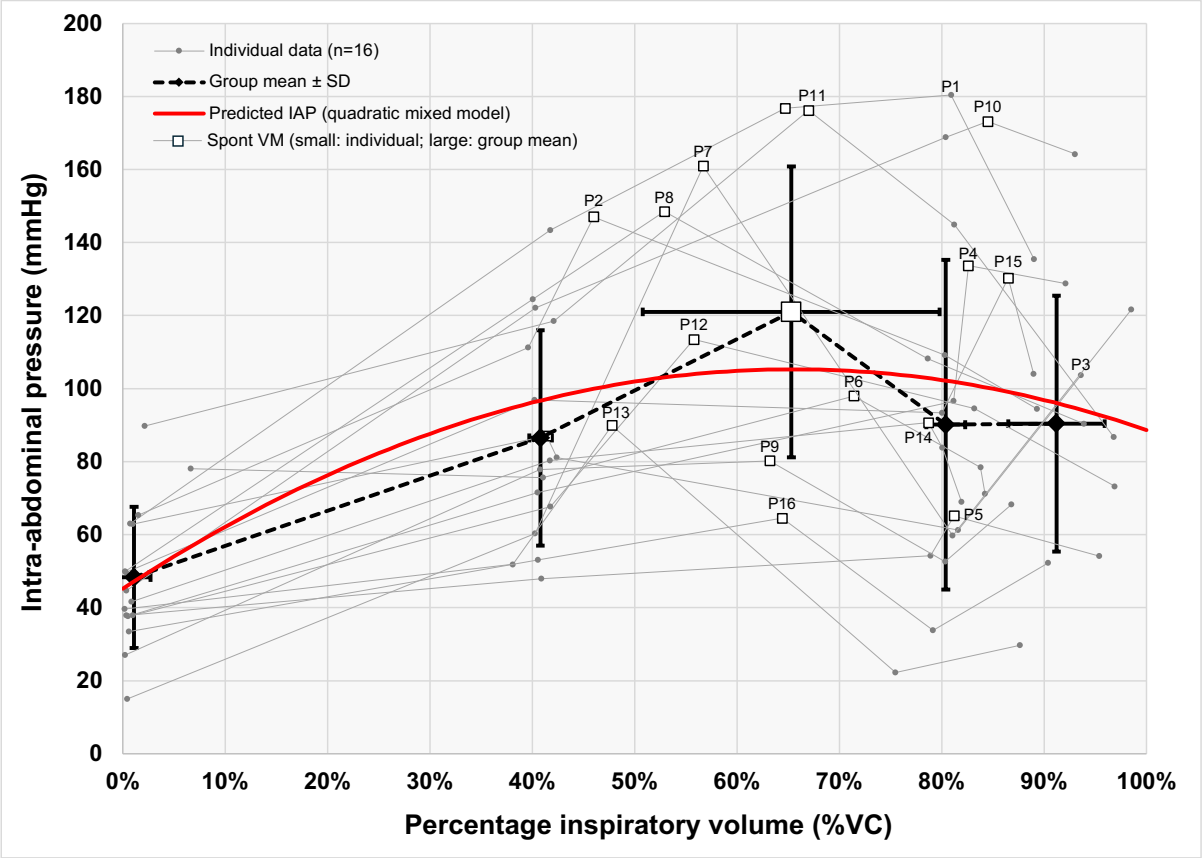


Figure 7. Relationship between intra-abdominal pressure (IAP) and percentage inspiratory volume (%VC) across conditions in the group and individual participants.

Discussion

This study examined how IAP during VM is affected by inspiratory volume across a range of conditions, including controlled, fixed-volume conditions and a self-selected (spontaneous) condition, and characterized the extent of interindividual variation in the inspiratory volume self-selected to maximize IAP. Two hypotheses were tested accordingly. First, we hypothesized that the inspiratory volume self-selected by individuals during spontaneous VM to produce the highest IAP would fall within a moderate-to-high range. Although the inspiratory volumes observed across participants generally fell within a moderate-to-high range, supporting this hypothesis, no single, universal inspiratory volume was identified; rather, considerable interindividual variation was evident. Second, we hypothesized that, compared with a low inspiratory volume, VM performed at a moderate-to-high inspiratory volume would produce a greater increase in IAP. Our results supported this hypothesis, demonstrating that the moderate-to-high inspiratory volume conditions yielded significantly greater IAP than the maximal expiration condition.

The inspiratory volume for each condition differed significantly from that of the other four conditions. Notably, the 95% CI for inspiratory volume during spontaneous VM did not overlap with those for the controlled 40% and 80% inspiratory volume conditions. This indicates that the inspiratory volume during spontaneous VM lies between the controlled 40% and 80% conditions, suggesting that this difference is significant. Furthermore, the mean within-subject variability of inspiratory volume during spontaneous VM across two trials was 6.5%, which

is considerably smaller than the SD of interindividual variation for the representative value (±14.5%). Thus, inspiratory volume during spontaneous VM was stable within subjects, while some interindividual variation was evident. These results generally support the hypothesis regarding inspiratory volume during voluntary VM but reveal interindividual variation in the inspiratory volume selected to achieve maximum IAP.

Regarding natural respiratory control during exercise, a study using lifting tasks with varying load conditions reported increased inspiratory volume immediately before lifting at all load levels.[22] Furthermore, under high-load conditions, both inspiratory volume and VM occurrence frequency were significantly greater than under low- and medium-load conditions. This present study's findings provide new insights into natural respiratory control during VM execution under no-load conditions.

Importantly, the highest IAP observed during spontaneous VM may not solely be attributed to the specific inspiratory volume itself. Because participants self-selected their breathing strategy, this condition likely involved variations in bracing strategy, effort level, diaphragm and abdominal coordination, psychological cues, and overall comfort compared with the controlled fixed-volume conditions. Previous studies have indicated that differences in breathing strategy substantially influence the magnitude of IAP generation.[23] In particular, coactivation of the diaphragm and abdominal muscles has been shown to produce a sustained increase in IAP,[7] and coordinated activation of the abdominal musculature more broadly has been closely linked to effective IAP generation.[24] In addition, perception of effort—and the central motor command that drives voluntary muscle activation—is thought to be generated centrally via corollary discharge rather than solely reflecting peripheral afferent feedback from the muscles themselves.[25] This suggests that self-selected differences in effort level and psychological state between conditions could independently modulate the magnitude of trunk muscle activation, and consequently IAP generation, beyond what is attributable to inspiratory volume or muscular coordination alone. Furthermore, in the fixed-volume conditions, the requirement to consciously adjust inspiratory volume immediately before each trial may have disrupted this muscular coordination, potentially attenuating IAP generation relative to the spontaneous condition. Therefore, these self-selected execution factors likely acted as confounders, contributing to the maximization of IAP during spontaneous VM.

The results are best interpreted as evidence that, in healthy young active men performing seated VM without an external load, self-selected moderate-to-high inspiratory volume was associated with higher IAP. Application to loaded resistance exercise and sport-specific movements, such as jumping, pitching, and swinging, requires further testing.

However, while significant condition differences existed in inspiratory volume during voluntary VM, considerable interindividual variation was also present, and several factors may explain this. A previous study using a lifting task reported a close association between increased lifting effort and increased voluntary inspiratory volume, with a positive correlation between the two.[13] In the VM trials of this study, differences in the "perceived effort required" during spontaneous VM among participants may have contributed to the variability in inspiratory volume. Furthermore, since all participants had sports or training experience, differences in exercise background and the nature of previous coaching received may also have influenced the results. However, body fat percentage and detailed training history were not quantitatively assessed in this study; therefore, the potential contribution of these factors to the observed interindividual variation could not be statistically examined. In addition, the VM trials in this study were conducted in a seated

position without an external load. Inspiratory volume and VM occurrence frequency significantly increased during high-load lifting.[13] Therefore, inspiratory volume during spontaneous VM under load conditions may show a different trend than that observed in this study. This study's findings indicate that caution is required when applying them to the increase in IAP during high-load sports movements, such as weightlifting or contact sports, which demand VM execution under load. Further investigation is necessary.

The relationships between conditions concerning IAP were expressed as follows: maximal expiration < controlled 40% inspiratory volume = controlled 80% inspiratory volume = maximal inspiration < spontaneous VM. These results support the two hypotheses, and combined with the percentage inspiratory volume findings, indicate that VM increases IAP at moderate-to-high inspiratory volumes (40–80% VC). Previous studies have suggested that IAP elevation during VM depends on lung capacity and abdominal muscle strength.[1] Regarding lung capacity, a larger inspiratory volume before glottic closure leads to higher IAP[11,12]; preventing excessive exhalation is important.[13] In this study, the difference in percentage inspiratory volume between conditions was significant, and this likely contributed substantially to the IAP differences between the maximal expiration condition and the other four conditions. Therefore, this study's findings generally support previous research. However, the novelty of this study lies in demonstrating that "excessive inspiration" can also hinder IAP elevation.

Regarding abdominal muscle strength, it has been proposed that it depends on whether abdominal muscle fibers are at the optimal length to exert maximum tension.[14] In this study, the percentage waist circumference was used as an indirect indicator to estimate abdominal wall muscle fiber length. The relationship between percentage waist circumference across conditions was as follows: maximal expiration < controlled 40% inspiratory volume < controlled 80% inspiratory volume = maximal inspiration = spontaneous VM. During maximal expiration, the waist circumference decreased significantly compared to the other four conditions. This suggests that abdominal wall muscle fiber length changed, hindering the ability of the abdominal wall muscle group to exert tension. Whether the abdominal wall muscle fibers were shortened or relaxed at this time remains unclear; however, in either case, the decrease in circumference indicates a change in fiber length, suggesting they were not at the optimal length for exerting tension. Conversely, waist circumference increased relative to baseline in the controlled 80% inspiratory volume, maximal inspiration, and spontaneous VM conditions. This suggests the abdominal wall muscle fibers were at an optimal length for tension generation, enabling greater force production. This mechanism is supported by the finding that maximal bracing to expand the waist significantly increased transversus abdominis and internal oblique muscle activity compared to the abdominal drawing-in maneuver.[26]

However, this length–tension explanation remains speculative. Waist circumference may reflect multiple factors, including abdominal expansion, rib-cage motion, posture, pelvic position, abdominal contents, soft-tissue displacement, and subcutaneous fat thickness, rather than direct muscle length. Therefore, the proposed mechanistic relationship between IAP and abdominal wall muscle length is a hypothesis that requires further validation through direct measurements, such as ultrasonography, electromyography, or respiratory kinematics.

Furthermore, despite no significant difference in the percentage waist circumference between the three conditions (controlled 80% inspiratory volume, maximal inspiration, and spontaneous VM), differences in IAP were observed. This suggests that the percentage waist circumference

alone cannot completely explain the role of abdominal muscle strength in IAP elevation. Other factors, such as the involvement of the pelvic floor muscles and diaphragm—part of the deep core surrounding the abdominal cavity—may be considered. Excessive inspiration may cause diaphragm shortening or postural changes (such as shoulder elevation or rib flare), potentially disrupting coordinated contraction of the trunk muscle groups during VM and thereby inhibiting IAP elevation.[14,27]

These findings indicate that IAP elevation during VM depends on lung capacity and abdominal muscle strength and cannot be completely explained by either factor alone. The relationship between IAP and inspiratory volume in the population resembles the bell-shaped curve of the muscle length-tension relationship (Figure 7).[28] This bell curve model represents the sum of active and passive tension. The observation of an IAP equivalent to 80% VC during maximal inspiration is thought to be due to the contribution of passive tension from the peritoneal tissues. In any case, the relationship between inspiratory volume during VM and IAP elevation can be considered a phenomenon following the fundamental physiological principle of the muscle length-tension relationship.

Note that this study did not consider thoracic stiffness related to VC. Lung expansion occurs through diaphragmatic contraction and an increase in the thoracic vertical and anteroposterior diameters due to rib mobility. Thoracic stiffness due to factors such as poor thoracic spine posture or intercostal muscle tension may limit thoracic mobility, potentially restricting maximum inspiratory/expiratory volumes and total lung capacity. Such restrictions could influence percentage inspiratory volume and IAP. Whether participants in this study had thoracic stiffness is unknown. However, measuring these parameters after interventions to improve stiffness could potentially reveal different trends, such as reduced interindividual variation in inspiratory volume during spontaneous VM.

Based on these findings, which show that many participants spontaneously achieved a high IAP through natural VM, a practical recommendation is to avoid excessive expiration or inspiration and to inhale to the point where IAP feels maximally elevated. Although this approach may provide useful foundational insights for respiratory instruction and core training program design, direct application to actual sports movements characterized by short duration and high intensity requires further empirical testing. Indeed, a previous study demonstrated that a breathing strategy that restricts inspiratory volume, such as the abdominal drawing-in maneuver, significantly attenuates both IAP elevation and trunk rotational torque.[29] Therefore, optimizing and managing inspiratory volume, as demonstrated in the present study, is crucial not only for maximizing IAP but also for enhancing mechanical output during rotational motor tasks.

This study has some limitations. First, participants were limited to healthy young men who were not engaged in competitive sports, which limits the generalizability of the results to other populations. Relative IAP during resistance exercise varies substantially according to sex and training status,[1] possibly owing to differences in lung capacity and abdominal muscle strength.[30] Future studies should involve larger samples with diversity in age, ethnicity, sex, and competitive level. Second, in discussing the increase in IAP, we inferred the muscle length–tension relationship from changes in waist circumference; however, the actual lengths of the abdominal wall muscles were indirectly measured. In this study, we inferred changes in the sarcomere length of the transversus abdominis—which substantially contributes to an increase in IAP and runs in almost the same direction as the tension wire of the measuring device—and considered this a reasonable

assumption. Nevertheless, to establish more robust evidence regarding the muscle length–tension relationship of the abdominal wall muscles,[28] it will be necessary to directly measure muscle length, thereby enabling more definitive assumptions about sarcomere behavior. Third, the mean inspiratory volume during the maximal inspiration condition averaged 91.2% VC rather than 100%, and the maximal expiration condition averaged 1.1% VC rather than 0%. This discrepancy likely resulted from the timing of the measurements and muscular fatigue. Baseline VC was measured at the beginning of the experimental schedule to establish a reference. However, because the trial order for the five VM conditions was randomized, the maximal inspiration and expiration trials were often performed in the middle or later stages of the session. It is possible that cumulative fatigue in the respiratory and accessory respiratory muscles made it difficult for participants to reach their absolute maximum end-inspiratory or end-expiratory volumes during these later trials.

This study demonstrated that self-selected VM breathing (spontaneous VM) produced the highest IAP among the five conditions examined in this sample of healthy young men, rather than identifying a single, universal inspiratory volume that maximally elevates IAP. Although the specific inspiratory volume varied across individuals, it typically fell within a moderate-to-high range (approximately 40–80% of VC). These findings underscore the effectiveness of natural, self-selected breathing strategies during VM and offer foundational insight for future efforts to optimize IAP regulation in exercise and sport-specific contexts.

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Conflict of Interest

The authors declare no conflicts of interest.

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