

Original articles

Impact of neoprene wetsuits on lung volumes and work of breathing: implications for military diver safety and performance

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Keywords

Airway resistance; Chest wall compression; Diving physiology; Forced oscillation technique; Lung volume

Abstract

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Introduction: Neoprene wetsuits may impose mechanical constraints on the chest wall, potentially altering respiratory function. This study investigated the impact of neoprene wetsuits on lung volumes, airway mechanics, and work of breathing (WOB) in healthy male divers.

Methods: A randomised crossover trial was conducted with 31 male divers at the Royal Netherlands Navy Diving Medical Centre. Participants underwent pulmonary function testing, including spirometry, body plethysmography, the forced oscillation technique (FOT), and diffusion capacity measurements, both with and without a hoodless standardised 5 mm neoprene full body wetsuit with a neoprene neck seal. Primary outcomes included changes in forced vital capacity (FVC), functional residual capacity (FRC), airway resistance (R_{aw}), reactance (X_{rs}), and WOB.

Results: Wearing a neoprene wetsuit led to statistically significant reductions in FVC (2.8%, $P < 0.05$), forced expiration in one second (2.9%, $P < 0.05$), FRC (4.0%, $P < 0.05$), and expiratory reserve volume (10.9%, $P < 0.05$), alongside increases in inspiratory capacity and tidal volume. R_{aw} increased significantly ($P < 0.05$), while the FOT revealed altered airway mechanics, evidenced by increased X_{rs} at multiple frequencies ($P < 0.05$). Diffusion capacity remained unchanged, suggesting preserved alveolar-capillary function.

Conclusions: Neoprene wetsuits induce mechanically restrictive effects on the chest wall, reducing static and dynamic lung volumes and increasing WOB. While these changes may not be clinically relevant at rest, their impact needs to be determined during strenuous or prolonged dives, particularly when combined with other equipment that limits thorax excursions. Future research should explore the effects of the military 5 mm wetsuit under immersed conditions to better understand their operational impact on diver performance and safety.

Introduction

Scuba diving is a physically demanding activity that exposes individuals to hydrostatic pressure, thermal stress, and equipment-related constraints, which requires psychological and physiological adaptation.¹ Neoprene wetsuits provide thermal insulation and buoyancy but also impose mechanical constraints on the chest wall.² Previous research has demonstrated that wetsuits can alter respiratory mechanics, reducing dynamic lung volumes (e.g., forced vital capacity [FVC] and forced expiratory volume in one second [FEV₁]).^{3,4}

While the observed changes in these studies are likely irrelevant to recreational divers,⁵ minor changes in respiratory function can have significant consequences for performance, safety, and operational efficiency among military, technical or commercial divers. Additionally, the broader impact of wetsuits on pulmonary function, including static lung volumes, airway resistance, and diffusion capacity, remains poorly understood.^{3,4}

Although a decrease in static lung volumes may seem obvious due to the external compressive forces on the chest wall, it is essential to emphasise that a neoprene wetsuit insulates the whole body, and therefore may also restrict

abdominal breathing manoeuvres.⁶ A lower functional residual capacity (FRC) is particularly concerning for divers, as it increases the work of breathing (WOB) and reduces the lung's buffering capacity during ventilation, especially while performing physical tasks, potentially leading to earlier onset of dyspnoea, and greater susceptibility to alveolar collapse during exertion or at depth.⁷⁻⁹ Buffering refers to the ability of the lung to maintain the acid-base balance in the body, primarily by regulating carbon dioxide levels. This buffering role is critical for maintaining stable alveolar oxygen and carbon dioxide levels and for preventing atelectasis.¹⁰

The forced oscillation technique (FOT) is a non-invasive method for assessing respiratory mechanics. It offers a unique opportunity to evaluate airway resistance, the opposition of airflow in the respiratory system, and reactance, which refers to the elastic and inertial properties of the respiratory system that oppose changes in airflow, under restrictive conditions.¹¹ However, its application in diving research is not well-established, leaving a gap in our understanding of how wetsuits influence these aspects of respiratory physiology. This gap is due to a lack of comprehensive data on how chest wall restriction from wetsuits alters airway mechanics and the work of breathing at rest and under simulated diving conditions.

To comprehensively address these challenges, a multimodal approach, incorporating techniques such as body plethysmography, diffusion, and FOT is required. The latter may be able to detect restriction of small airways, reduced lung compliance, and increased work of breathing, as observed in studies of restrictive lung conditions.¹¹ Such changes could contribute to dyspnoea and respiratory fatigue, particularly during prolonged and strenuous dives.

Drawing on existing literature, we anticipated that wearing a wetsuit would reduce dynamic lung volumes, including FVC and FEV₁.^{3,4} Additionally, we expected a reduction in static lung volumes, including FRC and expiratory reserve volume (ERV), due to the restrictive effect of the wetsuit on the chest wall as fulfilled by hydrostatic pressure in naked subjects.¹² We further hypothesised that the wetsuit would increase airway resistance (R_{rs}) and decrease reactance (X_{rs}) due to mechanical compression of the chest wall and altered respiratory mechanics, as described above.¹² We expected that diffusion capacity would remain unaffected.

Methods

A prospective, randomised crossover trial was conducted in a controlled laboratory setting at the Royal Netherlands Navy Diving Medical Centre. This trial was approved by the Medical Research Ethics Committee of the University of Utrecht (ref: NL87993.041.24/24-304/A) and the Surgeon General of the Ministry of Defence (ref: DOSCO 2025002961), and it follows the Declaration of Helsinki 2024.¹³

PARTICIPANTS

Eligible participants included healthy male diving personnel (e.g., navy divers, hyperbaric technicians, and hyperbaric medical staff) who were fit to dive. For simplicity, these participants are referred to as 'divers' throughout this study. Exclusion criteria were an upper or lower respiratory infection (within the last six weeks). Due to limited wetsuit size availability, a minimum height of 172 cm was required. Participants were recruited voluntarily through presentations and posters. Written informed consent was obtained from all participants before the study.

MEASUREMENTS

Baseline characteristics, including age, height, weight, chest circumference, and waist circumference, were recorded for all participants. Chest circumference was measured at nipple level, and the waist circumference was measured at the umbilicus. Body mass index (BMI) and body surface area (BSA)¹⁴ were calculated for each participant. New 5 mm thick super stretch neoprene military wetsuits (Northern Diver, United Kingdom) were used to minimise variation due to degradation or usage. Suit sizes (ranging from M to XXL) were selected based on chest circumference, with adjustments for height if necessary.

Measurements were conducted during a single visit, both with and without the neoprene wetsuit. The order of testing (with or without the suit) was randomised for each participant to minimise learning effects or fatigue. To prevent the influence of spirometry manoeuvres on respiratory mechanics, these were assessed before spirometry.¹⁵

To address unresolved questions regarding R_{rs} and X_{rs} , FOT parameters were measured using a Resmon Pro V3 (Accuramed, Belgium) in accordance with ERS/ATS guidelines.¹⁶ The enhanced optimised multi-frequency approach (5–11–19 Hz) was employed. R_{rs} , X_{rs} , the resonant frequency (F_{res}) where X_{rs} crosses zero, the reactance area (AX), and the difference between resistance at low and higher frequencies ($R5-R19$), a measure of possible airway heterogeneity, were recorded.¹⁷ The device was calibrated prior to the first measurement of each testing day in accordance with the manufacturer's guidelines.

Spirometry, lung volumes, and diffusion capacity for carbon monoxide (DL_{CO}) were measured using the Vyntus Body (Jaeger Medical, the Netherlands), in accordance with the respective guidelines.¹⁸⁻²⁰ Spirometry performed in a seated position according to the ATS/ERS guidelines is the standard approach, as this posture promotes consistency, patient comfort, and reproducibility of measurements.

While the seated position may have a minor effect on the neck seal, this influence is generally minimal and considered acceptable within the guidelines. Calibration was performed once daily before the first measurements, corresponding with

the manufacturer's guidelines. A single experienced lung function technician performed all measurements to minimise interobserver bias. The DL_{CO} was corrected for haemoglobin (Hb), which was measured at the end of the test run for each participant. The results were interpreted in accordance with the reference values of the Global Lung Initiative.^{21,22}

STATISTICAL ANALYSIS

Based on an anticipated 7% reduction in lung function (references 3 and 4) and assuming a normal distribution of the data, a sample size calculation indicated that at least 25 participants were required ($\alpha = 0.05$, $\beta = 0.80$). To account for potential dropouts or failed measurements, 20% more participants were included, resulting in a study population of at least 30 participants.

The normality of the data was evaluated using the Shapiro-Wilk test. Normally distributed data were analysed using paired *t*-tests, while non-normally distributed data were assessed using Wilcoxon signed-rank tests (full details of the statistics are available on reasonable request). The significance threshold (alpha) was set at 0.05. For normally distributed data, results are presented as mean (standard deviation) (SD), whereas non-normally distributed data are reported as median with interquartile range (IQR). Statistical analyses were performed using Stata (version 18.5, StataCorp, USA).

Results

STUDY POPULATION

The study was conducted in accordance with the protocol, and 31 healthy male volunteers were included. All participants were fit to dive, and baseline measurements were within normal ranges based on z-scores. Baseline characteristics are presented in Table 1.

Table 1
Baseline characteristics of the study population

<i>n</i> = 31	Mean (SD)	Range
Age (years)	40.7 (11.1)	23–59
Height (cm)	184.3 (7.7)	166–198
Weight (kg)	85.8 (10.9)	69–109
Chest circumference (cm)	98.4 (7.1)	85–115
Waist circumference (cm)	89.3 (8.0)	76–107
Body mass index (kg·m ⁻²)	25.2 (2.5)	20.1–30.8
Body surface area (m ²)	2.09 (0.16)	1.8–2.4

Changes in spirometry, lung volumes, airway resistance, and diffusion capacity while wearing a wetsuit are presented in Table 2. FVC and FEV_1 decreased statistically significantly by 0.16 L (2.8%) and 0.13 L (2.9%), respectively, when wearing a wetsuit. FRC and ERV also showed significant reductions (see Figure 1), whereas inspiratory capacity (IC) and tidal volume (VT) increased significantly. Alveolar volume (VA_{sb}) decreased significantly, which is consistent with a decreased FRC, but the DL_{CO} remained unchanged. This pattern suggests intact alveolar-capillary function, often seen in extrapulmonary restriction, such as a neoprene wetsuit.

Airway resistance (R_{aw} 0.5 in) measured in the flow range of -0.5 to 0.5 L·s⁻¹ during a panting manoeuvre in the body plethysmograph, increased significantly relative to the resistance measured with FOT; see Table 3.

FOT parameters were assessed to evaluate airway resistance and reactance. Changes in these parameters while wearing a wetsuit are presented in Table 3. R_{rs} at 5 Hz, 11 Hz, and 19 Hz were not normally distributed. Wilcoxon Signed-Rank Tests revealed no significant differences. X_{rs} at 5 Hz, 11 Hz, and 19 Hz, along with Fres, AX, and R5-R19, were all normally distributed across participants. These parameters demonstrated significant changes when participants wore the neoprene wetsuit, indicating altered airway mechanics likely due to chest wall restriction, which may reflect increased stiffness of the lung. The reduction in lung volume and the supposed higher work of breathing resembles the mechanism of increased work of breathing during immersion.¹² During swimming, these effects may reinforce each other.

Discussion

This study was the first to investigate the influence of wearing a neoprene wetsuit on respiratory parameters, including dynamic and static lung volumes, impedance and diffusion capacity. This multimodal approach enabled us to assess both the mechanical constraints imposed by the wetsuit and the physiological consequences for divers' WOB.

Consistent with the existing literature, we observed a statistically significant decline in FVC and FEV_1 during neoprene suit wear. However, the approximately 3% decrease in both parameters is not clinically relevant and is slightly smaller than previously reported.^{3,4} These findings may be attributed to our larger and more homogeneous study population (exclusively male participants) and the absence of a possible fatigue effect, due to randomisation. More notably, we observed significant declines in FVC, FRC, and ERV, alongside significant improvements in IC and VT, findings not previously reported.

The observed reduction in FRC and increase in VT indicate restricted thoracic and abdominal expansion due to external

Table 2

Respiratory parameters and change when wearing a wetsuit; * $P < 0.05$; DL_{CO} – diffusing capacity for carbon monoxide; $DL_{CO}Adj/VA_{sb}$ – the ratio between diffusing capacity for carbon monoxide adjusted for haemoglobin and alveolar volume measured in a single breath; ERV – expiratory reserve capacity; FEV_1 – forced expiratory volume in one second; FEV_1/FVC – the ratio between forced expiratory volume in one second and forced vital capacity; FRC – functional residual capacity; FVC – forced vital capacity; IC – inspiratory capacity; R_{aw} 0.5 in – airway resistance at a flow of 0 ± 0.5 ; sG_{aw} 0.5 in – specific airway conductance at a flow of 0 ± 0.5 ; TLC – total lung capacity; VA_{sb} – alveolar volume measured in a single breath; VT – tidal volume

Parameter	No wetsuit Mean (SD) [Range]	Change (wetsuit vs no wetsuit) Mean (SD)
Spirometry		
FVC (L)	5.75 (0.70) [4.06–7.14]	-0.16 (0.17)*
FEV_1 (L)	4.51 (0.58) [3.26–5.71]	-0.13 (0.15)*
FEV_1/FVC (%)	78.6 (5.3) [65.1–87.0]	0.00 (0.02)
Lung volumes		
TLC (L)	7.54 (0.85) [5.54–9.6]1	-0.01 (0.17)
IC (L)	3.54 (0.68) [2.10–4.87]	0.16 (0.42)*
VT (L)	1.15 (0.28) [0.69–1.82]	0.10 (0.18)*
FRC (L)	4.00 (0.76) [2.59–5.64]	-0.16 (0.40)*
ERV (L)	2.01 (0.55) [0.88–3.27]	-0.22 (0.35)*
Airway resistance		
R_{aw} 0.5 ($kPa \cdot s^{-1} \cdot L^{-1}$)	0.139 (0.047) [0.06–0.22]	0.02 (0.04)*
sG_{aw} 0.5 ($L \cdot kPa^{-1} \cdot s^{-1}$)	1.79 (0.65) [0.96–3.09]	-0.25 (0.57)
Diffusion capacity		
DL_{CO} ($mmol \cdot min^{-1} \cdot kPa^{-1}$)	10.36 (1.19) [8.18–13.44]	-0.01 (0.56)
VA_{sb} (L)	6.73 (0.78) [4.84–8.48]	-0.13 (0.36)*
$DL_{CO}Adj/VA_{sb}$ ($mmol \cdot min^{-1} \cdot kPa^{-1} \cdot L^{-1}$)	1.55 (0.19) [1.21–2.15]	0.02 (0.08)

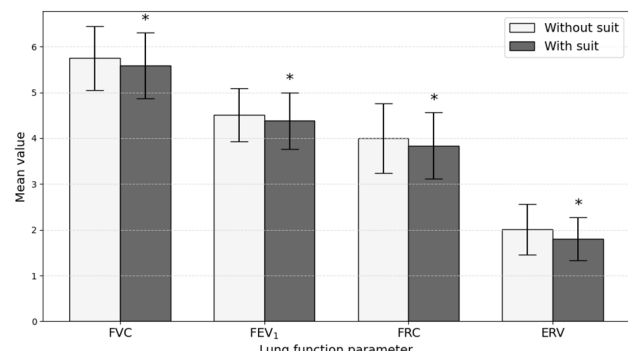
compression from the neoprene wetsuit. Theoretically, these changes likely contribute to an increased WOB, which can be visualised in a Campbell diagram. As FRC decreases and VT rises, the respiratory system operates at a less efficient point on the pressure-volume curve, demanding greater effort from respiratory muscles. Over time, this can lead to respiratory muscle fatigue and dyspnoea.²³

Additionally, airway resistance, measured by body plethysmography, reflects the resistance to airflow in the large airways early in the respiratory cycle, and its elevation suggests that the neoprene wetsuit compresses the chest wall or airways, thereby increasing airflow resistance and further contributing to the increased WOB.^{24,25}

While these physiological adjustments may not pose clinically significant challenges under resting conditions, they could exacerbate the physical demands of strenuous diving activities, in which divers experience hydrostatic pressure and wear not only a neoprene wetsuit but also additional equipment, such as diving cylinders, weight systems, harnesses, and the hydrostatic compression

Figure 1

The main lung function parameters significantly decreased by wearing a neoprene wetsuit; * $P < 0.05$; ERV – expiratory reserve volume; FEV_1 – forced expiratory volume in one second; FRC – functional residual capacity; FVC – forced vital capacity



of thorax and abdomen. Under these conditions, where increased respiratory effort is already required, the cumulative effect of restrictive equipment may further compromise lung mechanics and gas exchange.

Table 3

Forced oscillation parameters; * $P < 0.05$; AX – reactance area the area under the reactance (X_{rs}) curve between 5 Hz and F_{res} ; $F_{res\ insp}$ – resonant frequency inspiratory (the frequency at which X_{rs} crosses zero); R_{rs} – resistance at frequencies 5, 11 and 19 Hz (measures airway resistance at specific frequencies); X_{rs} – reactance at frequencies 5, 11 and 19 Hz (represents the elastic and inertial properties of the respiratory system)

$n = 31$	No wetsuit Mean (SD) or Median [IQR]	Change (wetsuit vs no wetsuit) Mean (SD) or Median [IQR]
R_{rs} 5 Hz ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)		
R_{insp}^*	0.213 [0.076]	-0.014 [-0.018]
R_{exp}	0.238 [0.110]	+0.020 [0.001]
R_{tot}^*	0.225 [0.091]	+0.019 [0.011]
R_{rs} 11 Hz ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)		
R_{insp}	0.192 [0.074]	+0.001 [-0.015]
R_{exp}	0.254 [0.106]	+0.004 [0.020]
R_{tot}	0.227 [0.087]	+0.004 [0.018]
R_{rs} 19 Hz ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)		
R_{insp}	0.214 [0.071]	-0.010 [-0.007]
R_{exp}	0.244 [0.082]	+0.003 [0.030]
R_{tot}	0.238 [0.085]	+0.000 [0.012]
X_{rs} 5 Hz ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)		
X_{insp}	-0.055 (0.004)	-0.0122 (0.003)*
X_{exp}	-0.045 (0.004)	-0.008 (0.004)*
X_{tot}	-0.049 (0.004)	-0.010 (0.003)*
X_{rs} 11 Hz ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)		
X_{insp}	0.030 (0.004)	+0.008 (0.003)*
X_{exp}	0.022 (0.004)	+0.013 (0.004)*
X_{tot}	0.025 (0.004)	+0.011 (0.003)*
X_{rs} 19 Hz ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)		
X_{insp}	0.116 (0.006)	+0.010 (0.005)*
X_{exp}	0.098 (0.006)	+0.013 (0.005)*
X_{tot}	0.105 (0.006)	+0.012 (0.005)*
Derived parameters		
$F_{res\ insp}$ (Hz)	8.831 (0.289)	+0.660 (0.190)*
AX insp ($\text{hPa}\cdot\text{L}^{-1}$)	0.122 (0.016)	+0.042 (0.136)*
R5 19 insp ($\text{hPa}\cdot\text{s}^{-1}\cdot\text{L}^{-1}$)	-0.004 (0.004)	+0.009 (0.004)*

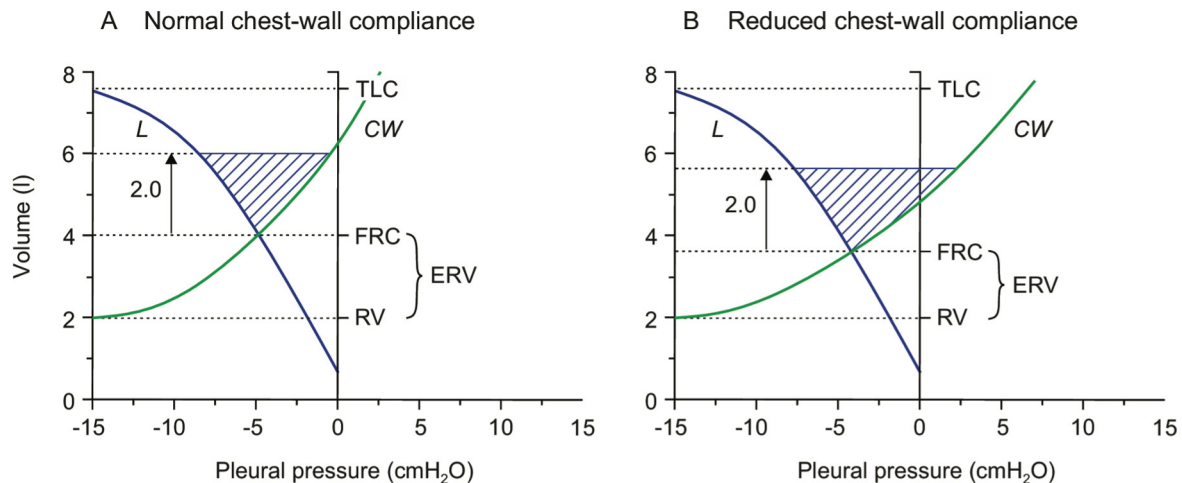
Additionally, the FOT results, particularly the increase in the reactance, suggest altered airway mechanics, likely due to mechanical compression of the chest wall or airways. While resistance may not show significant changes, the shift in reactance – especially at lower frequencies (e.g., 5 Hz) – often reflects increased stiffness of the respiratory system or peripheral airway narrowing, which may not be captured by resistance measurements (R_{rs} or R_{aw}) alone.²⁶ However, the broader implications of these FOT findings, including their effects on WOB, gas-exchange efficiency, and respiratory muscle fatigue, remain challenging to interpret. Further investigation is necessary to fully understand the

implications for diver performance and safety, particularly under operational conditions where increased respiratory demand may exacerbate these effects.

The findings of this study indicate that wearing a neoprene wetsuit not only reduces spirometric parameters but also decreases the resting lung volume, thereby increasing WOB. This can contribute to dyspnoea and respiratory muscle fatigue, particularly during prolonged dives, with increased gas usage as a relevant consequence to divers. At greater depths, the neoprene wetsuit compresses and becomes thinner, potentially reducing its restrictive effect

Figure 2

Schematic pressure-volume relations for lung (L, blue) and chest wall (CW, green) in case of normal (A) and reduced chest-wall compliance (B); in both panels, the hatched area represents the elastic work of breathing needed to inhale 2.0 L of air from functional residual capacity (FRC). The volumes correspond to the mean values of Table 2. The volume change specified in these two diagrams depicts the group-mean results. The reduced chest-wall compliance appears as a flatter pressure-volume relation (the green curve in panel B). This leads to a lower intersection of both pressure-volume curves (a lower FRC, where the opposing elastic forces of lung and chest wall cancel each other out). The result is a greater work of breathing (the hatched area in panel B). ERV – expiratory reserve volume; RV – residual volume; TLC – total lung capacity



on breathing. However, WOB is likely more influenced by the increased density of breathing gases at depth. Less experienced or less trained divers may experience these effects more acutely, potentially impacting their operational effectiveness and safety.

Hypercapnia, or an elevated carbon dioxide (CO₂) level in the blood, is another critical concern in this context. The increased WOB imposed by the neoprene wetsuit's restrictive nature can lead to inadequate alveolar ventilation, resulting in CO₂ retention. This is particularly problematic during dives, where the combination of increased metabolic CO₂ production and restricted ventilation can rapidly elevate PaCO₂ levels. Hypercapnia can cause symptoms such as headache, confusion, and dyspnoea, and, in severe cases, loss of consciousness. Besides, an increase in PaCO₂ can also lead to a higher risk of decompression sickness.²⁷ Finally, for divers, this poses a significant risk, as impaired cognitive function and physical performance can compromise safety and operational efficiency.

STRENGTHS AND LIMITATIONS

To the best of our knowledge, this is the first study to assess the effects of neoprene wetsuits on resting lung volume using multiple modalities. The research was conducted in a controlled environment. All participants wore new wetsuits, and all measurements were performed in a pulmonary function laboratory under consistent conditions, using the same equipment and guidelines. This enhances the reliability of the findings. The study employed rigorous methodology, including randomisation of intervention order, standardised

conditions, and measurements in a controlled environment, ensuring high scientific rigour.

However, several limitations should be acknowledged. First, given that all measurements were conducted in a controlled pulmonary laboratory, this is not the environment in which these neoprene wetsuits are worn. It would be valuable to investigate how immersion influences these results. Further studies are needed to examine the interactions among wetsuits, breathing effort, and physical exertion during actual diving.

Second, the Netherlands armed forces use 'one size fits all' wetsuits, based on chest circumference and height. While 17 of the 31 participants received a suit matching their chest circumference, the remaining participants required larger sizes due to their height. This resulted in a less pronounced but still statistically significant decline in FVC, FEV₁, FRC, and ERV, suggesting slightly reduced chest wall restriction in these individuals. However, the clinical or military relevance of these findings may be more nuanced, especially because neoprene wetsuits tend to be less restrictive in (deep) water due to pressure effects on the suit. Divers with pre-existing conditions, e.g., obesity, may experience more pronounced effects, whereas the impact on healthy individuals may only become clinically relevant during extended or high-intensity exercising dives. Although the dataset is not large enough to support valid subgroup analyses, the results for the aforementioned groups regarding matching suits are consistent with the manuscript's main conclusions.

Finally, there may have been a minor learning effect between pre- and post-measurements, particularly for spirometry. However, analysis of the data taking randomisation into account showed no learning effect. As all participants were experienced divers and, therefore, familiar with the tests, which are part of the annual medical assessment, we consider this risk is negligible.

Conclusions

This study shows that wearing a neoprene wetsuit leads to statistically significant reductions in spirometric parameters and lung volumes, particularly FRC and ERV, thereby increasing WOB. These changes may contribute to dyspnoea and respiratory muscle fatigue, especially during physically demanding or prolonged diving.

To better understand these dynamics, future research should examine these effects under submerged or immersed conditions, when environmental stressors, such as hydrostatic pressure, could exacerbate the physical challenges posed by restrictive dive gear.

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