Sport Sciences for Health
https://doi.org/10.1007/s11332-025-01472-0

RESEARCH

The effect of asymmetric lifting tasks on hemidiaphragm movement: a cross-sectional study

Martin Sembera[1] · Andrew Busch[2] · Michaela Poskocilova[1] · Richard Ulm[3] · Alena Kobesova[1]

Received: 31 May 2025 / Accepted: 17 June 2025

Abstract

Purpose The aim of this study was to determine whether lifting a weight with the left or right hand has a different effect on the right hemidiaphragm.

Methods This study investigated the motion of the right hemidiaphragm during asymmetric lifting tasks using M-mode ultrasonography. Forty healthy adults (30 women and 10 men, aged 27.6 ± 5.4 years) performed tidal breathing and loaded breathing, with the latter involving lifting a weight with either the left or right hand.

Results Using one-way ANOVAs, significant differences were observed for the right hemidiaphragmatic position when holding the weight with the contralateral (left) hand for inspiration ($p = .004$) and total excursion ($p < 0.001$), but not for expiration ($p = 0.872$) compared to tidal breathing. When tidal breathing positions were compared to holding the weight with the ipsilateral (right) hand, significant differences were observed for all three measures: inspiration ($p = 0.005$), expiration ($p < 0.001$), and total excursion ($p = 0.023$). Comparison of the right hemidiaphragmatic position during contralateral and ipsilateral holds showed significant differences in expiration ($p < 0.001$) and total excursion ($p < .001$), but not for inspiration ($p = 0.997$).

Conclusion The right hemidiaphragm showed different responses during one-handed weight lifting on the ipsilateral side compared to the contralateral side. Specifically, under ipsilateral loading, the expiratory position of the right hemidiaphragm was observed to be more caudal.

Keywords Weight lifting · Posture · Ultrasonography · Respiratory mechanics

Introduction

The diaphragm is a principal inspiratory muscle that performs both respiratory and postural functions [1–3]. Under postural loading, it co-contracts with other muscles of the trunk to increase stiffness of the spine [4, 5]. Although the diaphragm is a single muscle, it is composed of costal and crural subunits that have different anatomical and structural characteristics with distinct mechanical effects [6, 7]. Since the crura diaphragmatis forms the external portion of the lower esophageal sphincter [8], they are activated to some extent independently, especially when swallowing or vomiting [9, 10]. The neural supply to the diaphragm is separate for each half. In cases of unilateral diaphragmatic paralysis, the hemidiaphragm on the unaffected side can still be controlled independently [11, 12].

Ultrasonography represents the non-invasive, non-ionizing imaging technique that is widely available for direct assessment of diaphragmatic motion [13]. Furthermore, the accuracy of ultrasonographic assessment of the diaphragm is comparable to other medical imaging techniques [14] and was found to be excellent for quantitative evaluation of diaphragmatic excursion, comparable to fluoroscopy. The M-mode examination of the right hemidiaphragm was found to achieve high intra- and inter-observer agreement indicating satisfactory accuracy and reproducibility of this method [15]. In clinical practice, imaging of the diaphragm is most frequently used to diagnose its dysfunction [16].

✉ Andrew Busch
ambusch@owu.edu

1 Department of Rehabilitation and Sports Medicine, Second Medical Faculty, Charles University and University Hospital Motol, Prague, Czech Republic

2 Department of Health and Human Kinetics, Ohio Wesleyan University, 61 S. Sandusky St, Delaware, OH 43015, USA

3 Columbus Chiropractic and Rehabilitation Center, Dublin, OH, USA

Dysfunction of the left or right hemidiaphragm is considered to be an excursion of less than 10 mm [17]. The identification of abnormal right-to-left excursion ratios during breathing can be also a diagnostic tool to detect unilateral diaphragmatic dysfunction [18]. An excursion ratio difference greater than 50% between the hemidiaphragms would be considered abnormal [19]. There are many causes of unilateral diaphragmatic dysfunction, including neuromuscular diseases, trauma, surgery, chest tumors, metabolic and inflammatory disorders [20], cervical spondylosis [21, 22] or, rarely, as a neurological complication of COVID-19 [23, 24]. The loss of function in one side of the diaphragm may be an important factor in dyspnea, which usually results in reduced exercise capacity [25, 26]. In these patients, exertional dyspnea is associated with a higher respiratory rate and increased effort of the extra-diaphragmatic inspiratory muscles [26].

During postural tasks, the diaphragm increases its activity [4], resulting in its more caudal position and greater postural-respiratory excursions [2, 3]. The diaphragm, abdominal, back, and pelvic floor muscles all contribute to stabilizing the spine [4, 27–29]. Asymmetric one-handed lifting may result in different side-to-side contractions of certain spinal stabilizing muscles. Marras and Davis [30] have noted greater activity in the erector spinae, obliquus externus, and obliquus internus on the contralateral side. Alternatively, another study by Danneels et al. [31] found no difference in EMG activity between the right and left obliquus internus and lumbar multifidus muscles during various asymmetric lifting tasks with 5 kg weights. Nevertheless, other studies have demonstrated that the contralateral transversus abdominis, obliquus internus, erector spinae, and multifidus muscles are recruited earlier than the ipsilateral muscles during rapid arm raising [32, 33]. Based on these findings, it could be inferred that the left and right hemidiaphragms might also respond unequally to asymmetric postural loading, however, this has not yet been investigated. Therefore, the purpose of this study was to analyze the difference in postural-respiratory movement of the right hemidiaphragm during an ipsilateral and contralateral one-handed lifting task. We hypothesized that postural loading on the contralateral side would lead to the more caudal position of the hemidiaphragm and greater excursions due to its increased contraction.

Methods

Subjects

Forty healthy subjects (30 women and 10 men) aged 18–40 completed the study. Subjects were enrolled through social media and were admitted into the study based solely on inclusive and exclusive criteria. First, a verbal interview with the investigator was conducted, followed by a physical examination, and a basic neurological assessment, which included evaluating reflexes, muscle strength, sensation, coordination, and gait. None of the subjects met the following exclusion criteria: respiratory or musculoskeletal disorders, back pain, previous abdominal or spinal surgery, symptoms of any disease at the time of assessment, medical/surgical procedures, any injury sustained within 4 weeks before the examination, and pregnancy. Considering that body composition affects not only the imaging of the diaphragm by ultrasonography but also its movement [34], individuals with a waist-to-height ratio (WHtR) greater than 0.59 were also excluded. The inclusion criteria were: the ability to comply with the study protocol, age 18–40 years and being healthy as determined by the investigator based on medical history, physical examination, vital signs, and neurological examination. All subjects were familiarized with the experimental protocol in advance and signed an informed consent form. The procedure was approved by local University Ethics Committee and was prospectively registered at *ClinicalTrials.gov* with identification code NCT05767411.

M-mode ultrasonography

The examination of right hemidiaphragmatic motion was performed using M-mode ultrasonography (Toshiba Aplio i600, Canon Medical Systems Corporation, Otawara, Japan) with the 3.5 MHz convex transducer (Toshiba PVI-475BT). All subjects were examined in a standing position, holding the handle of a kettlebell (KB) with one hand, and wore a rubber headband with a plumb line attached to identify any possible lateral deviation of the body (Fig. 1). The ultrasound probe was oriented vertically and positioned in the right subcostal region, near the mid-clavicular line. It was directed dorsally, cranially, and medially to display the posterior third of the right hemidiaphragm perpendicularly. To minimize potential measurement errors associated with probe positioning, the probe was consistently placed at the same location throughout the entire procedure. Additionally, each procedure was repeated three times for all subjects. Previous research [35] has confirmed that ultrasound imaging is a reliable technique for accurately detecting and measuring diaphragm movement in vivo. We did not analyze the left hemidiaphragm in this study because of the greater difficulty of imaging with ultrasonography due to the smaller acoustic window provided by the spleen [36].

On the M-mode image (Fig. 2), the position of the diaphragm was evaluated as the distance on the vertical axis of the tracing between the most distant point at the end of inspiration and expiration and the baseline; its excursions were then calculated as the difference of these values. In a previous study by Sembera et al. [37], strong positive

Fig. 1 Participant assessed using M-mode ultrasonography during the procedure. The probe was held in the right subcostal area and oriented to capture the clearest image of the right hemidiaphragm

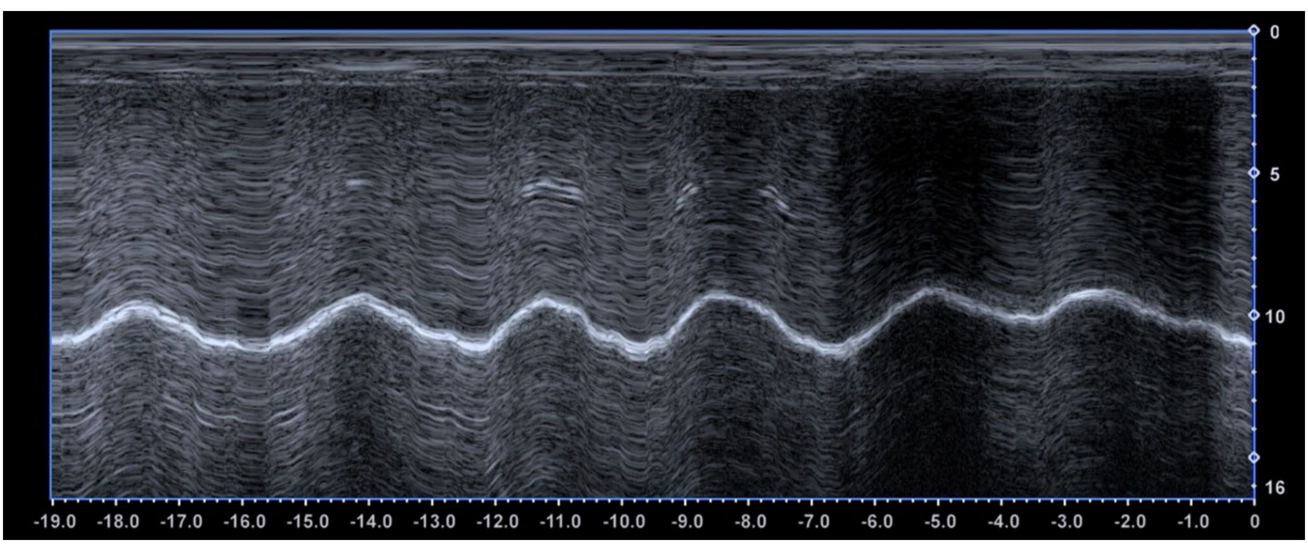

Fig. 2 Hyperechoic diaphragmatic motion curve displayed in M-mode. The upper peaks show the end-inspiratory position and the lower peaks show the end-expiratory position of the right hemidiaphragm. The first two breaths represent tidal breathing, the two following breaths represent loaded breathing while lifting the KB with the left (contralateral) hand, and the last two breaths represent lifting the KB with the right (ipsilateral) hand

correlations were demonstrated to exist between diaphragmatic excursions measured by M-mode ultrasonography and respiratory volumes during both tidal breathing and loaded breathing while lifting a weight.

Procedures

The procedure was performed under the same conditions (time of day, equipment, temperature, lighting, and noise level) in the same temperature-controlled room. Before the examination, all subjects were instructed to avoid consumption of food for at least 1.5 h. During the whole assessment, the subjects were in a bipedal upright stance with their feet shoulder-width apart. The test protocol was always performed in the same order and consisted of two tidal inspirations and expirations, two inspirations and expirations while lifting the KB (Jordan chrome/rubber kettlebell) with the left hand, and two inspirations and expirations while lifting the KB with the right hand. Subjects were instructed to lift the kettlebell using only elbow flexion without tilting the body. A trial of kettlebell lifting was performed prior to the ultrasound assessment. The weight of the KB corresponded to approximately 10% of the subject's body weight. As the weights were graded in 2 kg increments, we used 6 kg, 8 kg, and 10 kg KBs in this experiment. If the weight could not be unambiguously assigned on the basis of body weight, we selected the heavier weight, on the premise that the individual was able to lift it without unintended body movement. If the subject was unable to lift the KB only by elbow flexion without body movement, a lighter KB was then chosen to ensure stable visualization of the diaphragm. The position of the KB was slightly wider than the shoulder width of the individual in order to comfortably perform the procedure. The examination of each individual was carried out three times and the average values were calculated from the recorded data.

Statistical analysis

Descriptive statistics were calculated for all variables. Data are mean ± standard deviation, unless otherwise noted. The right hemidiaphragmatic position data was processed by averaging three measurements taken during two different breath cycles (six total measurements for inspiratory position, and six total measurements for expiratory position). Hemidiaphragm excursion was calculated from the average difference between each expiratory and inspiratory position. Two variables contained one outlier, which occurred in the same subject, as assessed by skewness and kurtosis values outside the acceptable range with calculated z-scores above + 3. These two outliers were handled by winsorizing the values (replacing its value with the next largest value in the dataset, maintaining its rank order). This improved both variables' skewness and kurtosis values, and improved all z-scores to within the acceptable range of (-3–3) for all variables [38]. The full de-identified dataset of hemidiaphragmatic motion is made publicly available to download via Figshare as File 1: https://figshare.com/articles/dataset/De-identified_dataset_hemidiaphragm/23807328

The hypotheses were tested with separate one-way repeated measures analysis of variance (ANOVA) to determine the effect on the right hemidiaphragm position for inspiration, expiration, and total diaphragmatic excursion when comparing tidal breathing with holding a KB in the contralateral left hand, and the ipsilateral right hand. The power analysis, using G*Power 3.1 [39] indicated an 80% chance of detecting a medium effect size ($\eta^2 = 0.06$) in 28 subjects with the alpha level for statistical significance determined *a-priori* at $p < 0.05$. Effect sizes, using partial eta squared (η^2), were interpreted as small (< 0.01–0.05), medium (0.06–0.14), or large (> 0.14). All data were analyzed using the Statistical Package for the Social Sciences (SPSS v29 for Mac; IBM Corp, Armonk, NY).

Results

For this study, intra-rater reliability was determined using intraclass correlation coefficients ($ICC_{3,1}$) and their 95% confidence intervals (CI) between two separate trials of tidal breathing, in which three measures were recorded for the first breath cycle and compared to three measures from the second breath cycle for both inspiration and expiration per subject, based on a single-rating (k = 1), absolute agreement, 2-way mixed model, with results presented in Table 1. Reliability was defined as poor (ICC < 0.50), moderate (ICC

Table 1 Intra-rater reliability of right-hemidiaphragm values (mm) during tidal inspiration and expiration ($ICC_{3,1}$)

Diaphragm position	ICC	95% confidence interval			F test with true value 0		
		Lower bound	Upper bound	SEM	Value	*df*1	Sig
Inspiration	0.991*	0.987	0.994	1.96	252.22	117	< 0.001
Expiration	0.990*	0.978	0.994	2.26	240.89	119	< 0.001

Note: *ICC* Intraclass correlation coefficient

SEM Standard error of measurement.

Correlation coefficients using absolute agreement

The single examiner was a trained DNS professional

*Denotes: Excellent reliability

Table 2 Descriptive statistics of subjects (Mean ± Standard Deviation)

Subjects	Age (y)	Height (cm)	Weight (kg)	Waist circumference (cm)	WHtR	BMI (kg/m^2)
All (n = 40)	27.6 ± 5.4	171.0 ± 8.0	66.6 ± 11.5	76.0 ± 8.5	0.45 ± 0.04	22.6 ± 2.4
Males (n = 10)	26.9 ± 3.5	180.7 ± 5.8	81.9 ± 8.0	86.4 ± 6.2	0.48 ± 0.03	25.1 ± 1.9
Females (n = 30)	27.9 ± 5.9	167.8 ± 5.8	61.5 ± 7.0	72.6 ± 6.0	0.43 ± 0.04	21.8 ± 2.0

Note: *WHtR* Waist-to-Height Ratio, *BMI* Body Mass Index

0.50—0.75), good (ICC 0.75—0.90), and excellent (> 0.90) [40].

Forty subjects completed this study. The selected participant characteristics including age, height, weight, waist circumference, WHtR, and BMI are shown in Table 2. Table 3 presents the results of the one-way ANOVAs, with means and standard deviations, comparing the right hemidiaphragm positions during tidal breathing to holding the KB in the contralateral and ipsilateral hands. These results are shown graphically in Fig. 3. During inspiration, there were significant main effects between tidal breathing and holding the KB in the contralateral and ipsilateral hands, $F(2, 78) = 7.28$, $p = 0.001$, partial $\eta^2 = 0.16$. Post hoc analysis with a Bonferroni adjustment revealed the diaphragm

Table 3 ANOVA means and standard deviations for each type of KB hold and diaphragm position (mm) Total, $n = 40$

	Tidal breathing *M*(*SD*)	Contralateral hold *M*(*SD*)	Ipsilateral hold *M*(*SD*)	*df*	*F*	*p*	η^2
Inspiration position	105.51 (20.38)	103.33 (20.98)	103.33 (20.38)	(2, 78)	7.28	0.001 *	0.157
Expiration Position	124.81 (22.24)	124.89 (22.27)	121.64 (22.66)	(2, 78)	24.70	< 0.001*	0.388
Diaphragm Excursion	19.30 (5.74)	21.30 (6.08)	17.76 (4.36))	(2, 78)	16.66	< 0.001*	0.299

Note: KB = kettlebell

* = Significant main effects

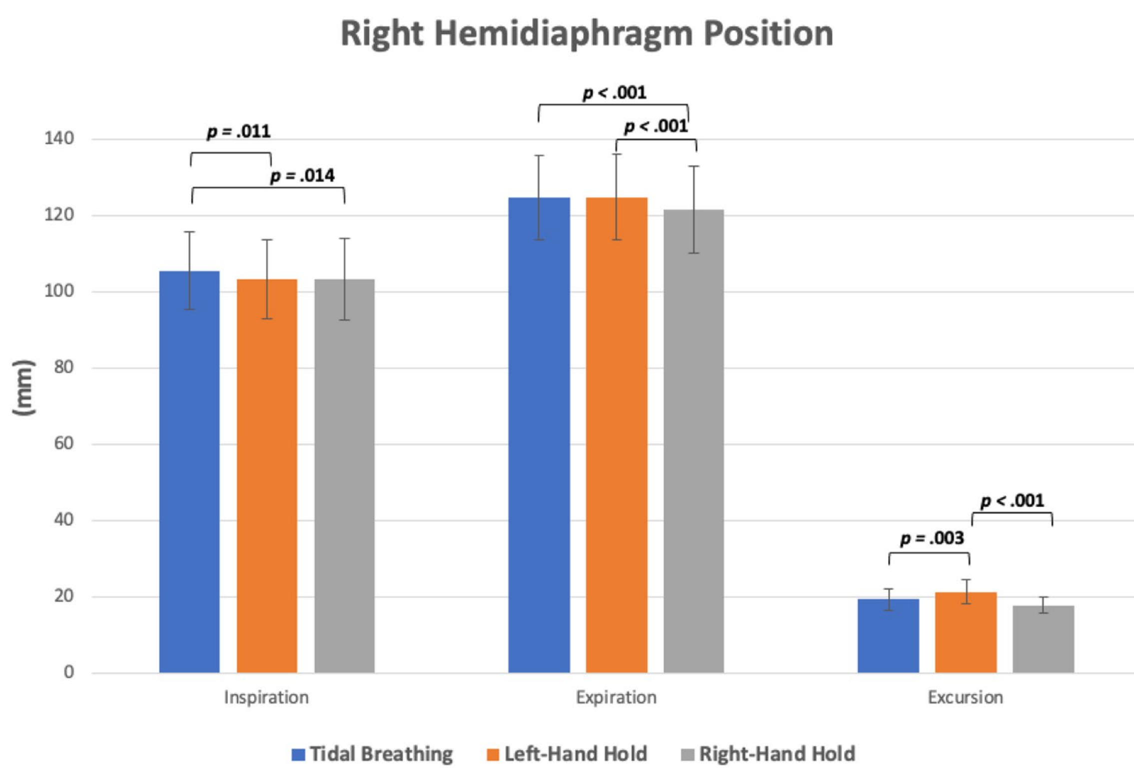

Fig. 3 Ultrasonographic assessment values of the position and excursion (mm) of the right hemidiaphragm during tidal breathing and holding a KB in the left (contralateral) hand or right (ipsilateral) hand

position significantly lowered from tidal breathing during both the contralateral KB hold by 2.18 (95% CI, 0.42 to 3.94) mm, $p = 0.011$, and during the ipsilateral KB hold by 2.18 (95% CI, 0.36 to 4.0) mm, $p = 0.014$, with no differences noted between contralateral or ipsilateral holds.

During expiration, there were significant main effects between tidal breathing and holding the KB in the contralateral and ipsilateral hands, $F(2, 78) = 24.70$, $p < 0.001$, partial $\eta^2 = 0.39$. Post hoc analysis with a Bonferroni adjustment revealed the diaphragm position significantly lowered from tidal breathing during the ipsilateral KB hold by 3.17 (95% CI, 1.67 to 4.68) mm, $p < 0.001$, and the ipsilateral hold was significantly lower than the contralateral KB hold by 3.25 (95% CI, 2.04 to 4.47) mm, $p < 0.001$, with no differences noted between tidal breathing and the contralateral hold positions.

For total diaphragm excursion, there were significant main effects between tidal breathing and holding the KB in the contralateral and ipsilateral hands, $F(2, 78) = 16.66$, $p < 0.001$, partial $\eta^2 = 0.30$. Post hoc analysis with a Bonferroni adjustment revealed total excursion significantly increased from tidal breathing during the contralateral KB hold by 2.00 (95% CI, 3.40 to 0.60) mm, $p = 0.003$, and the contralateral hold was also significantly greater than the ipsilateral KB hold by 3.54 (95% CI, 5.12 to 1.96) mm, $p < 0.001$, with no statistically significant differences noted between tidal breathing and the ipsilateral hold.

Discussion

This study revealed that different motion occurs in the right hemidiaphragm during asymmetric postural loading on the spine. Contrary to our hypothesis, based on previous studies showing increased activity of the contralateral muscles during asymmetric lifting tasks, it was demonstrated that when lifting the weight on the ipsilateral (right) side, the right hemidiaphragm was positioned significantly more caudal during the expiratory phase of the breathing cycle, which resulted in decreased movement into the expiratory position along with reduced postural-respiratory excursions. Thus, these findings suggest the hemidiaphragm responds in an opposite manner to asymmetric loading compared with other trunk muscles. While the obliquus internus, transversus abdominis, rectus abdominis, quadratus lumborum, and erector spinae muscles are more activated on the contralateral side during one-handed lifting tasks [30, 41–43], the hemidiaphragm was found to be more involved (i.e., positioned more caudally) during ipsilateral loading. The explanation for this response may be as follows: holding the KB on the right (ipsilateral) side, produces a right-bending torque on the torso. To resist this torque, the torso must increase its overall stiffness. It has been demonstrated previously that the diaphragm increases in activity with postural loading [1–3]. It has also been demonstrated that increased diaphragm activity (more caudal positioning of its central tendon) elevates the intra-abdominal pressure, which increases torso stiffness [5]. The abdominal contents are made up of solids (e.g., the liver), liquids (e.g., water in the colon), and gas (e.g., digestive gas), collectively making it a semi-solid/semi-liquid, amorphous object which can be pushed in different directions. Concentric contraction of the diaphragm pushes the abdominal contents downward against the pelvic floor, outward against the abdominal wall, and posteriorly into the dorsal musculature (iliocostalis lumborum, quadratus lumborum, etc.). In response to this outward-pushing force, the torso muscles eccentrically activate, providing resistance to the contracting diaphragm. This co-contraction of the diaphragm and apposing trunk musculature increases intra-abdominal pressure, thereby increasing torso stiffness. Because the abdominal contents are semi-solid, they can be pushed in a specific direction (e.g., to the left). This is the reason for our observation of the right hemi-diaphragm's increased activity with ipsilateral holding of the KB. Since the KB produces a right-bending torque on the torso, to maintain vertical positioning, the left torso muscles must increase in activity. To facilitate this, the right (ipsilateral) diaphragm will increase in activity to *push* the abdominal contents into the left torso musculature. This action of pushing the abdominal contents into the left torso musculature not only increases intra-abdominal pressure (because of the more caudal positioning of the diaphragm's central tendon), but also synchronizes the left-bending torso muscles into a harmonious co-contraction; both resulting in an increased torso stiffness necessary to maintain the torso's initial position.

The present study observed no difference in the inspiratory position of the hemidiaphragm between ipsilateral and contralateral postural loading. Because the abdominal contents are substantially incompressible, the caudal movement of the diaphragm must be met by equal displacements of the abdominal wall [44]. If the compliance of the abdominal wall is decreased by its greater tension, the descent of the diaphragm in response to a given muscle activation is smaller [45]. Due to the increased abdominal wall tension (AWT) during postural loading, the diaphragm was limited in its caudal (inspiratory) displacement, and therefore its greater contraction while holding the KB on the right side resulted only in its decreased motion to the relaxed position (expiration) [46]. The movement of the right hemidiaphragm and AWT was recently investigated during lifting the KB weighing 20% of the subject's body weight with both hands [3]. The diaphragmatic displacement during this postural task was measured to be about 3.5 mm on average in the end-inspiratory position, whereas the AWT was more than two times greater compared to tidal breathing. In the current study, when compared with tidal breathing, the end-inspiratory position of the right hemidiaphragm was shifted equally about 2 mm during KB lifting with the right and left hands. The smaller postural-respiratory movement of the diaphragm during inspiration was probably caused by lifting a lighter weight.

For KB lifting with both hands [3] and the single contralateral hand, no change in hemidiaphragmatic expiratory positions were found in comparison to tidal breathing. However, when the weight was lifted with the ipsilateral hand, the end-expiratory position of the diaphragm shifted caudally by about 3 mm on average. It follows that under symmetric or contralateral asymmetric loading the hemidiaphragm moves fully to the tidal expiratory position, whereas with ipsilateral loading the tidal expiratory position is not achieved. The diaphragmatic excursions were consistently found to be greater during loaded breathing compared to tidal breathing [2, 3], however, when lifting the weight with the ipsilateral hand, postural-respiratory excursions of the hemidiaphragm are lower than in tidal breathing. It has been reported that during lifting the weight, there is a strong positive correlation between diaphragmatic movement and tidal volume [37]. Therefore, it appears that the tidal volume may decrease during asymmetric loading due to the smaller motion of the hemidiaphragm on the loaded side. In this study, we did not measure tidal volumes to minimize the interference with the natural movement of the diaphragm caused by breathing through the spirometer mouthpiece.

The present study demonstrated that it is possible to selectively affect hemidiaphragmatic motion by adding an asymmetric postural load to the ipsilateral side, which sharpens our understanding of spinal stabilization mechanics. The diaphragm activity and trunk musculature function as two separate contractile units, the activity of which can be modulated depending on the stabilizing strategy. This knowledge can allow for better assessment of spinal stability when examining dysfunction (i.e., lack of expansion on one side may be due to reduced contralateral diaphragm activity). This might imply that repeated unilateral training may produce greater benefits in hemidiaphragm performance. Since unilateral diaphragmatic paralysis has been found to involve dysfunction of the nonparalyzed hemidiaphragm [46], asymmetric postural training may be beneficial as it increases the motion of both hemidiaphragms, with greater involvement of the ipsilateral one during expiration. Further studies are warranted to determine the effectiveness of such protocols in patients with unilateral diaphragmatic dysfunction and using a stratified loading protocol (10%, 20%, and 30% of body weight) may help determine if a load-dependent response exists.

Limitations

This study has a few limitations. First, the hemidiaphragmatic motion was only measured during a unilateral postural loading of 10% of the subject's body weight. This limitation was due in large to the unintended body movement heavier KBs created in most subjects, which negatively influenced proper ultrasonographic imaging of the diaphragm. Therefore, further research is warranted to understand how heavier unilateral loads affect diaphragmatic activity. Furthermore, the examination was not accompanied by an assessment of pulmonary function, so we can only speculate how tidal volumes changed under asymmetric loading when differences in hemidiaphragmatic motion were observed. Finally, we did not assess the movement of the left hemidiaphragm as it is more difficult to visualize due to air in the gastrointestinal tract, which may interfere with imaging, especially during deeper breathing. As a result, it remains unclear how the other half of the diaphragm responds to asymmetric postural loading. Future studies should evaluate the difference between the right and left halves of the diaphragm under asymmetric postural loading, for example, using ultrasound measurements of diaphragm thickening fraction.

Conclusion

This study demonstrated that the right hemidiaphragm moves differently during asymmetric lifting tasks. Lifting a weight with the ipsilateral hand displaced the expiratory position of the hemidiaphragm more caudally compared to contralateral loading.

Acknowledgements The authors acknowledge Professor Pavel Kolar for providing the laboratory space and equipment at his center to carry out this study.

Author contributions M.S.: Conceptualization, Project administration, Methodology, Resources, Investigation, Data curation, Writing—original draft. A.B.: Formal analysis, Visualization, Writing—review & editing, Funding acquisition. M.P.: Resources, Investigation, Data curation. R.U.: Supervision, Writing—review & editing. A.K.: Supervision, Writing—review & editing.

Funding No funding sources were reported for this study.

Data availability The full de-identified dataset of hemidiaphragmatic motion is made publicly available to download via Figshare as File 1: https://figshare.com/articles/dataset/De-identified_dataset_hemidiaphragm/23807328.

Declarations

Conflict of interest The authors declare no competing interests.

Practical applications

Lifting weights affects postural-respiratory movement of the diaphragm.
The hemidiaphragm is more involved during ipsilateral asymmetric postural loading.

Ethicakl approval This study was approved by the Institutional Ethical Board, University Hospital Motol, Prague, Czech Republic, and adhered to the Helsinki declaration.

Informed consent All subjects were familiarized with the experimental protocol in advance and signed an informed consent form.

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